SECTION 14

MODULATOR CIRCUITS

PART A. ELECTRON-TUBE CIRCUITS

AMPLITUDE MODULATION (AM).

Modulation is the process by which a signal (or signals) containing intelligence (modulating signal) is impressed on some other signal (usually a radio frequency, called the carrier). There are three basic methods for accomplishing modulation:

a. **Amplitude Modulation.** In this method the modulating signal and carrier signal are combined in such a manner as to cause the amplitude of the resultant waveform to vary in step with the changes in the modulating signal.

b. **Frequency Modulation.** In this method the output frequency is varied in accordance with the modulating signal.

c. **Phase Modulation.** In this method the phase of the output signal is varied in accordance with the modulating signal.

Only amplitude modulation will be discussed in this paragraph.

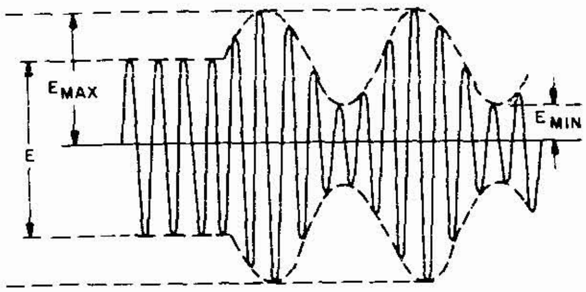
Usually, in amplitude modulation, the modulation varies at an audio rate because the intelligence to be transmitted consists of voice, music, or other audio frequencies; the signal which is modulated is a radio-frequency signal of a constant amplitude and frequency, known as the r-f carrier. As will be seen later, once the modulation is achieved, the r-f carrier is no longer necessary and need not be transmitted, or may be transmitted at a reduced amplitude, for certain special applications.

Modulation is normally achieved by varying the voltage applied to one of the elements of an electron tube, and the modulator circuits are classified accordingly. For example, varying the grid bias of a tube to obtain modulation is known as grid modulation, while varying the cathode voltage to obtain modulation (a similar process) is called cathode modulation. Modulators are further subdivided into two general classes - high level and low level. The high-level modulator usually employs plate circuit modulation; it usually modulates the final (output) stage of a transmitter, and it usually requires an audio power amplifier (modulator) capable of supplying 50 percent additional power over the normal maximum unmodulated output of the final transmitter amplifier stage for 100 percent modulation. The low-level modulator usually modulates a stage preceding the final stage of the transmitter. The exact audio power required depends upon the stage modulated. When low-level modulation is employed then the stages following the modulated stage must be operated as linear power amplifiers.

Strictly speaking, high-level modulation is defined as modulation produced at a point in the system where the power level approximates that at the output of the system. Low-level modulation is defined as modulation produced at a point in a system where the level is low as compared with the power level at the output of the system. This does not mean that high-level modulation must always be applied to the plate of the output tube, or that low-level modulation is always applied to the grid of an intermediate stage. In some Navy equipment, modulation applied to the grid circuit of the power amplifier is referred to as **low-level modulation.** A combination of plate and screen modulation is referred to as **high-level modulation.**

High-level modulation seems to predominate in the low- and moderate-power fields, since it gives somewhat better efficiency and less distortion for the same powers. However, in the extremely high-power field or where broad-band stages are necessary (as in television), low-level modulation seems to be preferred. Theoretically, with the same amount of sideband power, both modulation methods are equal.

The original concept of the modulated signal was that of a basic carrier frequency with an envelope which varied with the modulation impressed upon it, as shown in the accompanying figure. This concept is still valid, but is misleading inasmuch as it appears that for the signal to be reproduced, the carrier is required. Further analysis and investigation have proved that when modulation is accomplished, three signal frequencies are generated. One frequency is higher in frequency than the carrier by the frequency of the modulating signal; the second is the middle frequency, or carrier; the third frequency is that of the lower sideband, which is lower than the carrier by the frequency of the modulated signal. The sidebands are produced by mixing the audio modulating frequency against the carrier to produce the sum and difference frequencies. At the time modulation is accomplished, and at the time of detection or demodulation, the carrier is required, but it can be either partially or entirely suppressed from the output as long as a similar signal (with same phase and polarity) is reinserted at the receiver. It must also be understood that each sideband is independent, and contains exactly the same modulating frequencies as the other sideband, being displaced in frequency above and below the carrier by this amount. Thus the carrier and one (either) sideband can be eliminated, which is done in single-sideband operation.

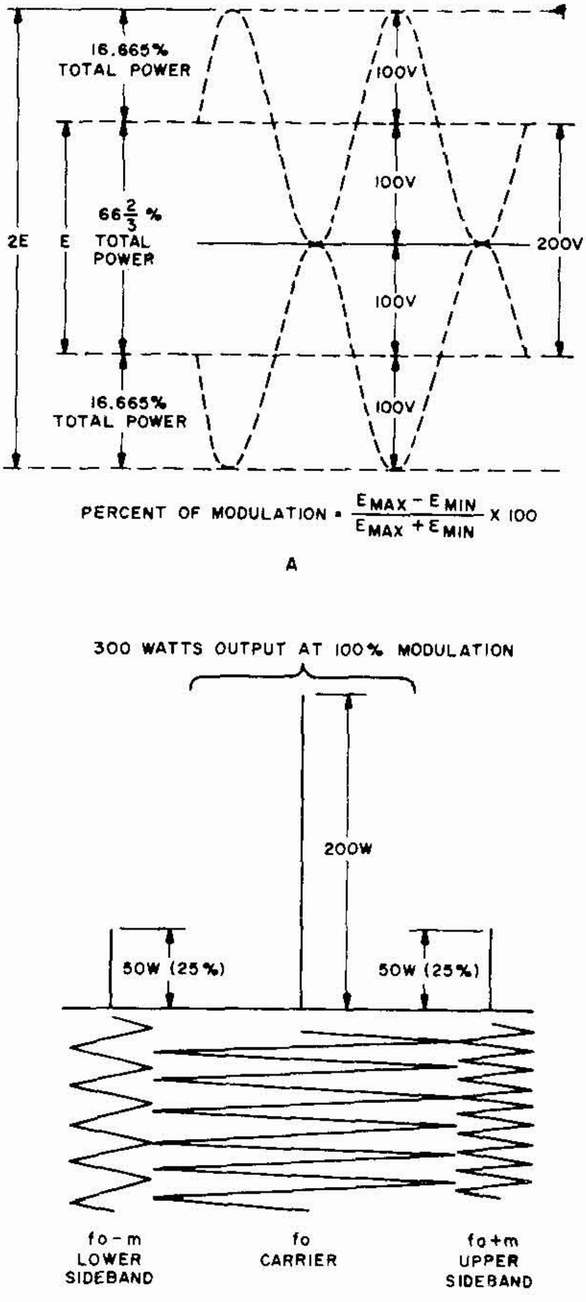


Modulation Envelope

Since the sideband frequencies are transmitted along with the carrier frequency, it is evident that the total bandwidth occupied is twice that of the modulating frequency. Therefore, the modulated signal requires more space than the unmodulated signal. Since frequencies up to 3000 cps must be reproduced for good, intelligible speech, it can be seen that a 6-kc bandwidth is necessary for radiotelephony using AM double sideband. For single-sideband operation on a comparative basis, with only one sideband transmitted, only 3 kc is required. To broadcast music and speech with reasonably good quality, a 10-kc bandwidth is required when using AM double sideband.

As stated before for plate modulation, a 50% increase in power above the normal carrier power is required to achieve 100% modulation. The following figure illustrates these conditions. Thus each sideband contains one-half of the total audio power supplied (that is, 25 percent of the carrier power). For the composite signal, however, the carrier contains 66-2/3% of the total energy, with 33-1/3% of the total energy represented in the two sidebands. That is, approximately one-sixth of the total power is contained in each sideband (50 + 200 + 50, or a total of 300 divided on a 2-to-1 basis). To achieve this result, the modulator must drive the modulated amplifier plate voltage down to zero and then to twice the normal plate voltage, as illustrated previously. Since the peak power varies as the square of the plate voltage, a peak power of four times normal is produced at 100% modulation. For plate modulation a Class C biased r-f amplifier is used because its output varies linearly with plate voltage. To produce low-level modulation a Class B linear amplifier is employed, in which the output varies as the square of the excitation voltage. The Class B amplifier is adjusted for maximum output and then reduced to one-quarter maximum output and driven to four times this power on peaks. Or, as is generally done with most of the efficiency types of modulation, the plate current on the output stage is adjusted (by changing the output load) for one-half maximum plate current (the output varies as the square of the plate current) and the peak power output is four times normal. In any event, plate modulation is characterized by a steady d-c plate current indication, and low-level and efficiency types by a varying d-c plate current indication. In each case the results are similar as far as amplitude variations are concerned; however, the distortion and linearity vary from type to type.

The amount of modulation is expressed in percentage based upon the amplitude of the carrier. When the amplitude of the modulated signal reaches twice the carrier amplitude on positive peaks and reduces to zero on negative peaks, as illustrated above, the modulation is 100%. At any in-between values the modulation is less than 100%. Since the power in the sidebands varies as the square of the amplitude, it also varies as the square of the modulation percentage. Therefore, for a 50% modulated signal the sideband power is only one-quarter of that available at 100% modulation. It is evident, then, that the percentage of modulation must always be kept as near 100% modulation as possible. When the modulation exceeds 100%, the negative peaks cross the zero level and the signal is effectively chopped off, creating carrier shift, distortion, and severe adjacent-channel interference with other stations. For a sine-wave signal the amplitude variations above and below the average are even. There are other waveforms, however, which are not equally spaced or symmetrical, such as speech. Certain speech sounds contain large positive peak components and if the system is properly polarized, the negative component is of smaller amplitude. In this special case it is possible to modulate more than 100% on positive



A

B

Modulation Amplitude and Power Relationships peaks without causing carrier shift. Therefore, the criterion for 100% modulation is generally considered as being the amplitude at which the negative peaks are just driven to zero, regardless of the positive peak amplitude. On the same basis, since speech is complex and not a sine wave, it can easily be seen that setting the modulation level with a tone signal for 100% will result in a loss of modulation, as only occasional peaks will reach this value. Thus the general practice of advancing the gain control so that occasional positive peaks exceed that value required for 100% modulation produces more effective speech communication with a slight amount of distortion and external interference. In the design of modern transmitters and speech equipment for voice communication, peak clippers are used to permit a greater average level of modulation without exceeding the 100% limit. For broadcast and high-fidelity transmissions, however, the modulation must be set so that the peaks never exceed 100%.

Because the intelligence which is impressed as modulation on the carrier is of prime importance, the modulator (and output stage) must be linear; that is, it must produce a minimum of distortion. Distortion can be caused by incorrect amplitude, extraneous (spurious) frequencies injected during the modulation process, phase shift at some frequencies exceeding that at others, and other conditions. These items will be discussed as the circuits are analyzed.

Since modulation involves an increase of power in the modulated stage, it is important that the electron tubes used to supply the output signal have sufficient reserve emission to permit 100% modulation on peaks; otherwise, the signal will be clipped. Also, the tubes must be operated at reduced ratings so they will handle the excess power dissipated during modulation without exceeding the voltage and current ratings for the elements. With good design the tubes will operate without showing any sign of plate heating, and under average conditions they may show just a trace of color on modulation peaks.

CHOKE (HEISING) MODULATOR.

APPLICATION.

The choke (Heising or constant current) modulator circuit is used to produce 100% high-level plate modulation of the transmitter output stage. In the early days of radio it was the most popular modulator circuit because of its simplicity and economy of parts, plus good performance.

CHARACTERISTICS.

Uses a single choke in an impedance-coupled arrangement to match the modulator to the output stage.

Operates at a higher voltage level than the transmitter output stage.

Can be adjusted to obtain 100% modulation or more.

It is the most economical modulator from a cost standpoint.

It is not as efficient as the transformer-coupled circuit.

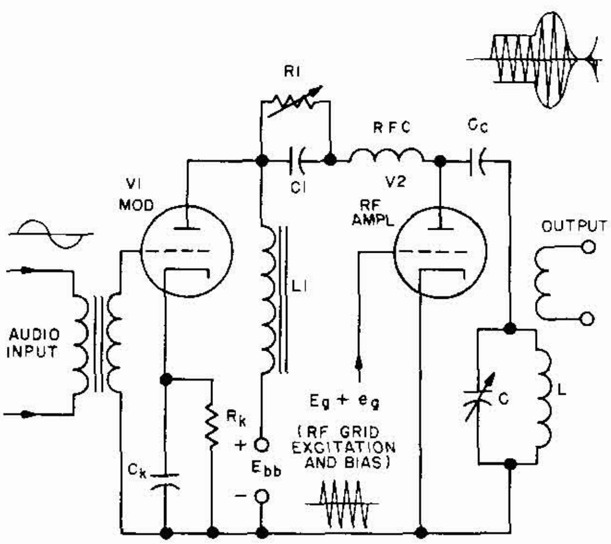
CIRCUIT ANALYSIS.

General. There are three versions of this type of circuit, two of which will not be discussed further than to indicate their form and the reasons for omitting the discussion. One version uses a tapped choke, which is usually connected as an autotransformer. Basically, then, the tapped-choke type is equivalent to the transformer-coupled type except for the transformer's isolation of the primary and secondary windings and the effects incidental thereto. Also, it is practically as expensive to build the tapped-choke circuit as the transformer-coupled circuit, so little is gained by its use. In the second version the transmitter plate voltage dropping resistor is not used, so that 100% modulation cannot be obtained; therefore, it is considered a less desirable circuit. The remaining circuit to be described is the basic Heising circuit, which is also known as a "constant current" modulator. This latter name is derived from the use of a common choke in the power supply lead, which tends to keep a constant current flowing; thus when the transmitter current reduces because of modulation, the modulator current increases a like amount, and vice versa. A simpler and more easily understood analogy is to consider that the modulator output voltage is equal to the plate voltage applied to the transmitter, and that on positive peaks they add, making the instantaneous total plate voltage equal to $2E_b$; on negative peaks they subtract and drive the voltage to zero. Thus the instantaneous voltage varies from zero to two times maximum, and the current does likewise. For this type of circuit the modulator is simply a Class A power amplifier capable of supplying 33-1/3% of the total transmitter output power (50% of rated carrier power, neglecting losses). Since a Class A amplifier is normally linear, the instantaneous signal varies equally for positive and negative signals (assuming equal drive, equal signals, and no distortion); thus the average plate current remains steady (for 100% or less modulation) and does not vary as indicated by a plate meter. The instantaneous signals, however, are constantly varying in accordance with the modulation impressed.

The Heising circuit has not been very popular up to now because of its lack of plate efficiency, and because advances in the art have developed other more efficient modulator circuits requiring much less audio power. However, the Heising circuit once again is gaining in popularity because of its simplicity, and does serve as a basic circuit for studying and understanding basic modulator principles, thus leading to an understanding of other types of modulator circuits.

Circuit Operation. A typical choke modulator circuit is shown schematically in the figure below. For simplicity and ease of discussion, only the pertinent circuit parts are shown, as the basic modulator may be applied to any transmitter amplifier or oscillator stage. Functionally, V1 is a Class A audio power amplifier, which is impedance-coupled through choke L1 to r-f power amplifier V2 operating Class C. See Section 6 for a discussion of a-f and r-f power amplifier circuits.

From an inspection of the illustration it is evident that V2 is a conventional r-f amplifier, with the output tank circuit shunt-fed. The RFC keeps the rf out of the modulator and the d-c power supply, which in this circuit is connected through choke L1 and dropping resistor R1. Resistor R1 is adjusted to keep the applied d-c plate voltage of V2 at a value less than that at the plate of modulator tube V1



Typical Choke (Heising) Modulator Circuit

Capacitor C1 is selected to offer minimum reactance at the lowest usable frequency so as to pass the lower audio frequencies around R1 without attenuation. Since the higher frequencies are offered much less attenuation, C1 effectively bypasses R1 completely for the audio frequencies (assuming that the modulation is audio). The grid drive of V2 is considered to be more than that necessary to drive the tube to saturation, with a d-c bias voltage of twice the amount needed for cutoff operation. Therefore, V2 is operating as a Class C amplifier and is assumed to be linear. That is, the plate current and r-f tank current of V2 vary linearly with a change in plate voltage. Thus, as the instantaneous plate voltage of V2 is varied, the instantaneous plate current and r-f tank current vary likewise. In this mode of operation, V2 appears as if it were a pure resistance connected between R1 and ground, and the value of this resistance is: $R_p = \frac{E_p}{I_p}$

The output of V2 is designed to produce the proper plate current at full load for the plate voltage set by R1, to produce the desired plate load resistance for modulator V1.

Tube V1 is operated as a Class A audio amplifier, with cathode bias supplied by R_k bypassed by C_k. In this case the method of supplying bias is immaterial; it can be any of the methods applicable to a power amplifier. The modulator input to the grid of V1 is shown transformer-coupled, but can be by any method that will supply sufficient drive. Since the tube is operating Class A, no grid current is drawn, and only sufficient voltage need be supplied to operate the tube over the linear portion of the tube grid-plate transfer characteristic. When the input (modulation) signal goes positive, the plate current of V1 increases and produces a voltage drop across choke L1 in a negative direction; for a negative input the plate current of V1 decreases, reducing the drop across L1, so that effectively the voltage at the plate of V1 increases (goes positive). Since tube V1 normally operates at a quiescent value of current and voltage (Class A biased), the result of an input signal is to instantaneously increase or decrease the plate voltage and current in accordance with the grid modulation. When the plate voltage of V1 goes positive, the polarity is such that it adds to the source voltage E_{bb} obtained from the power supply; when it goes negative, the source voltage is reduced. It can be seen then, that at the peak of the negative modulator swing, the maximum positive instantaneous plate voltage applied to V2 is the sum of the d-c power supply voltage, set by R1 and the audio component on the plate of V1 coupled through C1. If properly adjusted, the audio voltage developed by V1 will just equal the d-c voltage supplied V2, and the instantaneous plate voltage supplied to V2 will be zero, while on the positive modulator swing it will be twice that of the normal applied d-c plate voltage. Without resistor R1 in the circuit, the plate voltage of V1 would have to be driven to zero to reduce the instantaneous plate voltage of V2 to zero. When reduced to zero no plate current would flow in V1, the tube would no longer operate Class A, and distortion would be produced. Likewise, on the positive swing, the d-c voltage drop through L1 would be subtracted from the V2 plate voltage, and the instantaneous plate voltage would never reach the two-times-normal value. With R1 correctly adjusted, the d-c plate voltage of V2 is always less than that of V1, and the positive and negative swings of V1 are sufficient to drive the plate voltage of V2 from zero to two times normal, thus producing 100% modulation. It is evident that, since the output of V2 is varying linearly in accordance with the plate voltage swings produced by the modulating signal, V2 is amplitude-modulated. When the plate voltage of V2 is increased, the plate current is increased also. To increase the plate voltage of V2 instantaneously, it is necessary for the plate current of V1 to be reduced during that instant. Choke L1 supplies the energy for this power change through its collapsing field as the plate current of V1 reduces. Thus the power supply current drain remains substantially constant, even though the instantaneous variations of current and voltage in this circuit are from zero to twice the normal value; hence the derivation of the term **constant current modulation**, as applied to the average d-c drain.

The modulated tube (r-f amplifier) must be operated at below maximum ratings of tube current and voltage during modulation because of the possibility that the instantaneous variations of voltage and current will exceed the safe ratings during sustained peaks of modulation when the peak power is four times maximum. Conversely, the modulator tube (which supplies half the power taken by the r-f amplifier) is at best only 30% efficient as compared with 70 to 80% for the r-f amplifier, and is subject to the same range of instantaneous voltages and currents (or peak power). Therefore, this type of modulator usually uses a tube of equivalent or greater power rating than the r-f amplifier being modulated. Like the Class A amplifier, the modulator just discussed produces the least amount of distortion; however, because of its low efficiency, it has become practically obsolete in favor of other more efficient types.

Vacuum Tube Considerations. While the preceding circuit discussion was based upon triodes, this modulator may be used with other types of electron tubes if the proper electrode voltages and currents are applied. For screen-grid tubes of the tetrode, beam, or pentode type, it is important that the modulation be applied to the screen grid as well as to the plate. This is usually accomplished by using a series voltage-dropping resistor from the plate to screen, for screen voltage supply, so that both electrodes have the same modulation impressed upon them. Thus, as the screen controls the plate current, it permits full swing on positive peaks and reduced swing on negative peaks, effectively aiding the modulation process. The reduced swing on the negative peaks prevents the plate voltage from falling below that of the screen and creating a virtual cathode. Since the series screen resistor does not permit plate current cutoff, bias is chosen on the basis of projected cutoff for a fixed screen voltage under quiescent conditions. In addition, the power from the modulator must be sufficient to supply the screen modulation power, or about 10% additional. In circuits using a fixed screen voltage supply, 100% modulation is achieved by inserting a series choke of about 5 henries between the screen and the screen supply. The electrical inertia of the choke produces an effect similar to the constant current action. When the plate current is greatest and tends to increase beyond the limits fixed by the screen voltage, the plate robs the screen of electrons and decreases the screen current. Whereupon, the reduction of current through the choke produces an induced voltage because of the collapsing lines of force in the choke field. This voltage is in the direction which continues current flow (that is, an increase in screen voltage), and the effect is similar to that caused by the modulation superimposed on the series screen connection. Likewise, on the negative peaks of the modulating signal, the screen current tends to increase, because less plate current is drawn and the screen tends to become the plate. The increased screen-current flow through the screen choke produces an opposing voltage, which tends to decrease the screen voltage and the total current permissible, and reduces plate swing. Thus the raising and lowering of screen voltage with modulation is simulated by the choke, permitting practically 100% modulation. Without the choke the modulation is limited to about 90 to 95%.

FAILURE ANALYSIS.

No Output. Lack of output should first be isolated to either the transmitter r-f amplifier or the modulator circuit. Even though the modulator is operative, an open RFC or tank circuit, a shorted or gassy electron tube, or a lack of grid excitation in the amplifier will produce a no-carrier indication. Checking the r-f amplifier plate meter will indicate whether the circuit is complete and whether a resonant dip can be obtained; also, a check on the grid drive meter will determine whether excitation exists. Lack of grid drive indicates trouble in the transmitter, while lack of plate current places the trouble in either the transmitter or the modulator. Where the modulator plate meter indicates but the transmitter does not, the probability is an open dropping resistor, open RFC, or poor transmitter tube; the trouble can be isolated with a high-voltage voltmeter (turn off the high voltage and use a shorting bar before connecting the meter). If both the modulator and transmitter meters are not indicating, either the power supply is defective or modulator choke L1 is open. With both meters indicating but with no modulation, either a shorted modulation choke, a bad modulator tube, or lack of modulator drive may be suspected. High plate current usually indicates short-circuited components or lack of bias, while low plate current indicates excessive bias, high-resistance joints, or poor tube emission. Voltage checks on the grid and plate elements will indicate continuity as well as terminal voltages. No output generally indicates lack of voltage, lack of continuity, or short-circuit conditions. A resistance check to ground will be helpful, but is normally unnecessary. With the voltages and currents usually involved in high-power transmitters and modulator, breakdowns are usually obvious from external symptoms such as arcing, charring, and burning; on low-power equipment additional test equipment may have to be used. But remember, DANGEROUS voltages are involved; take all safety precautions before connecting or disconnecting any test equipment.

Low Output. It must first be determined whether the low output is lack of audio power or reduction in percentage of modulation. While low modulation is normally due to lack of sufficient audio power, this can occur from a reduced setting of the audio driver gain control, or from trouble in the speech amplifier stages which drive the modulator. An oscilloscope is very useful in determining the cause of malfunctioning since the waveform may be directly observed. For simple, quick tests of modulation percentage, the trapezoidal pattern is useful. The waveform check, however, can show both percentage of modulation and distortion, and is more useful. Too high a grid bias will cause a reduction of output (with the same drive). A short-circuited coupling capacitor will eliminate the dropping resistor for the r-f amplifier, so that the percentage modulation will be reduced, and even with increased drive the 100% level will not be reached. But, since the capacitor is shunted by the dropping resistor, such trouble is rather infrequent. On the other hand, since the dropping resistor is constantly carrying the current of the r-f amplifier, it will most likely change in value with age. If it increases in value sufficiently, overmodulation will occur, even though the stage can be loaded by antenna coupling adjustments to the operating value of current. While the modulator load will be correct, the reduced voltage will permit less swing; thus the same audio output will overdrive and cause carrier shift, as indicated by a varying plate meter with modulation. Note that normally with modulation, if the power supply regulation is insufficient in either the transmitter or the primary d-c supply line, there will be some movement of the plate current meter. Overmodulation will be indicated by more than normal movement. Where the power supply regulation is satisfactory, the normal meter indication will be rock-steady, and any meter movement will indicate overmodulation or a distorted condition.

A modulation choke that has partially shorted turns may not be easy to locate from external appearance, but will probably show up as low power output, as well as insufficient and usually distorted modulation. Ordinarily, this condition can be located only by substitution of a new choke after the other parts have been eliminated by systematic analysis.

Lack of filament emission in the r-f amplifier or modulator tube will cause peak clipping and inability to obtain 100% undistorted modulation.

Distorted Output. Distortion is usually obvious when monitoring audio modulation. It may occur from a number of causes. For example, overmodulation will cause carrier shift, severe interference with other stations, and distortion. Changing of the modulator load impedance, by adjusting the r-f amplifier output loading for different currents than normal, will change the modulator load line; depending upon the magnitude of the change, this condition may be easily detected, or a special check may be required to determine the amount of distortion. Any change of grid bias will shift the operating point and require a change of drive. With low bias the input will be clipped and distorted, and with high bias a larger input signal will be required; thus speech amplifier distortion will most likely be increased. Should the bias reach the Class B point, actual plate current cutoff will cause distortion, while with Class AB operation there is the possibility that grid current being drawn on peaks may cause some distortion. Thus the region of operation between Class A and Class B becomes somewhat of a problem. With proper drive and with symmetrical modulation, little or no distortion will occur; on the other hand, with improper drive and with large unsymmetrical or sustained peaks of modulation, excessive distortion can result.

Lack of sufficient plate voltage will cause a reduction of plate swing, and thus cause distortion by plate clipping. Shorted modulator turns can cause an insufficient inductive effect to produce the amount of modulation required, and thereby result in distortion. A change in the value of the coupling capacitor will result in different attenuation for different frequencies, so that attenuation of these frequencies (usually the low frequencies) will cause another form of distortion.

Lack of sufficient filament emission in the r-f amplifier (and modulator) tubes will cause peak clipping, produce distortion, and make it impossible to obtain 100% modulation.

TRANSFORMER-COUPLED PLATE MODULATOR.

APPLICATION.

The transformer-coupled plate modulator circuit is used to produce high-level modulation of the transmitter r-f output stage. It is used for both low- and high-power applications, particularly where it is desired to use a triode as a high-level modulator.

CHARACTERISTICS.

Uses a transformer to match the modulator stage to the transmitter output stage.

Supplies an audio (modulator) output equivalent to one-half the d-c input power of the r-f output stage.

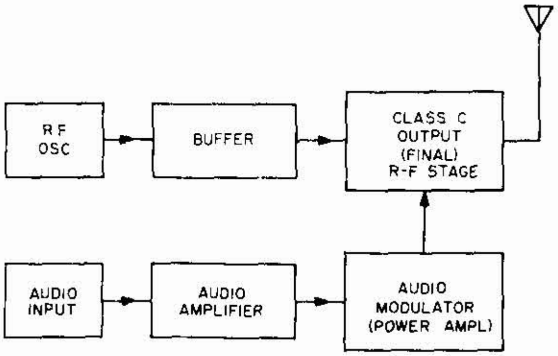
Operated class A for a minimum of distortion with low efficiency and low output, or class B for highest efficiency with some distortion. When operated between the two classes (Class AB or AB′), intermediate values of efficiency and distortion are produced.

Uses triode type electron tubes only (see Transformer-Coupled Plate and Screen Modulator circuit for tetrodes).

CIRCUIT ANALYSIS.

General. Before reading this discussion, read the introduction to this section covering Amplitude Modulation (AM), page 14-1, for background. A better understanding of the various voltage and current relationships in class C amplifiers will also be obtained by reviewing RF Power Amplifier Circuits (Class B or C) for both single-ended and push-pull applications, in Section 6, Part A of this handbook.

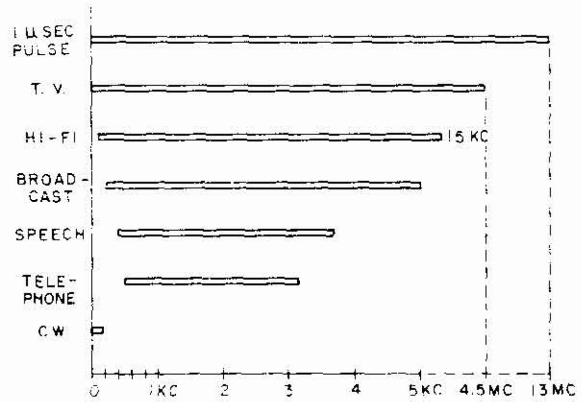
The **high-level plate modulator** uses the audio output of a conventional **a-f power amplifier** (the modulator) to produce a modulated r-f output signal in the **plate** circuit of the transmitter r-f amplifier connected to the antenna. A typical high-level system is shown in the accompanying block diagram. The **transformer-coupled plate and screen** modulator which is used with screen-grid tetrodes and pentodes employed as the final RF power amplifier is a variation of this type of modulator circuit; it is discussed separately later in this section of the handbook.



High-Level Modulation System

High-level modulation is defined as modulation produced at a point in the system where the power level approximates that at the output of the system. Therefore, plate modulation always involves considerable power output from the modulator. For 100-percent modulation, the plate modulator must produce an output equivalent to 50 percent of the d-c input power to the final r-f power amplifier. For an r-f power amplifier having an efficiency of 80 percent and an r-f carrier output power of 100 watts, the total d-c input power would be 125 watts. The power required from the modulator would be one half of this, or 62.5 watts, and the resulting output to the antenna would be 100 watts of carrier power and 50 watts of audio (sideband) power. For high-power operation the circuit must incorporate design considerations to prevent corona loss, arcing and flashover, and damage or destruction of parts. On the other hand, for low-power applications as in mobile operations, the audio power is relatively small (for example, 50 percent of 5 watts is only 2.5 watts) and may be handled by receiving type audio amplifier output stages. Regardless of power output, however, the basic principles of operation are the same.

Modulation involves frequencies other than audio, such as video (television) or pulses (control systems, or telemetry); however, since modulators are conventionally associated with audio frequencies, other types of signals which may affect modulator circuit operation are discussed only as required to bring out the manner in which they differ from audio use. The accompanying chart illustrates some typical ranges of frequencies involved for various forms of modulating signals.



Frequency Ranges Required

The maximum power from a particular transmitter with a given type of electron tube operating at its maximum ratings can be obtained when operating the transmitter in the A1 (CW) mode of emission. When using the A3 (AM) mode of emission, the power output for plate modulation is about 20 percent less than for CW operation. The reason for this is that during plate modulation, at the peak of the modulation cycle (at 100% modulation), the plate voltage is doubled and the input power is increased by a factor of four. In order that the maximum tube ratings will not be exceeded, the tube must be operated below its normal operating point as a class C amplifier. Other factors that affect the power output from a plate-modulated stage are the loading of the antenna (the amount of antenna coupling) and the value of the load impedance that the r-f amplifier presents to the modulator. The power output of the modulator and the amount of distortion it develops are directly dependent upon the loaded value of plate current and voltage applied to the r-f stage.

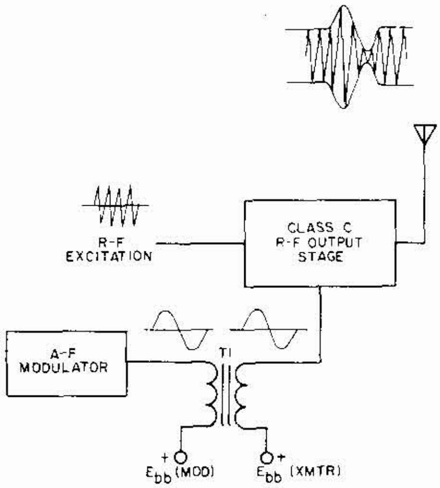
The plate efficiency of the high-level, modulated r-f stage is constant at about 70 percent, and does not change with modulation. Therefore, the r-f output (carrier) produced by a given type of electron tube with no modulation is at a maximum value in the plate-modulated high-level transmitter (although not as large as can be produced for CW operation). Low-level modulation, using the same type of electron tube, produces a carrier output of half this value. The reason for this is that during low-level modulation the tube efficiency varies with the percentage of modulation. At no modulation the efficiency is approximately 33 percent, and represents the condition of greatest tube loading (maximum plate dissipation because of low efficiency). At the peak of modulation the highest efficiency (about 66 percent) is obtained. Although the plate voltage and current are doubled to produce a four-time power increase at the peak of modulation (which is necessary for all AM modulators), the low-level modulator must obtain this increase from the transmitter power supply. In the high-level modulator, the additional power required for modulation is obtained from the modulator.

Since in high-level plate modulation the modulation occurs in the final stage of the transmitter, the r-f driver stages can be operated more efficiently (they need not be linear as in the low-level transmitter); therefore, they can be operated without considering distortion to produce maximum r-f output. Hence, the r-f section of the high-level plate-modulated transmitter is most efficient for r-f production, and its power supply need only be large enough to supply the power required to produce the r-f carrier. When fully modulated, the audio output (modulator) stage of the high-level modulator supplies an additional 50 percent of the power required to produce the carrier. The additional power supplied by the modulator represents the output power in the sidebands, which is equal to 50 percent of the carrier (25 percent in each sideband). Therefore, the total average power output of the high-level plate-modulated stage at full modulation is 1.5 times the unmodulated (carrier) power.

Since the low-level modulator must be operated at a carrier level which is one-quarter of the maximum power obtainable from the same type of electron tube in high-level operation, it is adjusted to operate at one-half the maximum plate current. Thus it is clear why, for a given type of electron tube, the high-level modulated stage produces a greater power output. To do this, the audio (modulator) stage must also produce considerable power (to supply the 50 percent additional (sideband) power necessary for 100 percent modulation). For high-power transmitters such a powerful modulator is costly and involves special component design to operate at the high voltages and currents required.

The various power relationships and differences between high- and low-level modulation methods will become clearer and will be more fully explained as the various modulator circuits involving these methods are discussed. It should be borne in mind, however, that regardless of whether operation is at a **high level** or at a **low level**, the **equivalent ratings are the same.** For example, a 1000-watt 100-percent modulated transmitter produces the same output whether or not the modulation is accomplished by high-level or low-level methods.

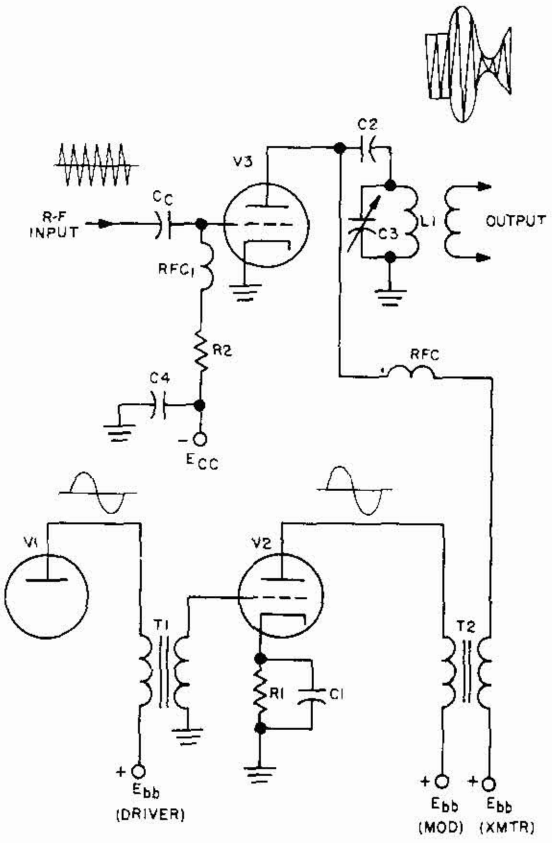
Circuit Operation. A simplified diagram of the basic transformer-coupled plate modulator is shown in the accompanying figure. The a-f modulator stage is represented as a block since it may be any one of a number of audio amplifier combinations as long as the proper audio power output is obtained. Likewise, the r-f output stage is also represented as a block since it may consist of any arrangement of tube(s) to produce the desired carrier output to the antenna. The r-f output stage is always biased so that it operates as a class C amplifier. Since class C operation requires a bias of two times the cutoff value, a separate bias supply is used to provide fixed bias. Since the r-f excitation to the r-f stage is relatively constant, grid leak bias (produced by grid drive) is also used, with the total bias being the combination of the fixed and grid-leak (grid-drive) bias. In case of failure of the grid drive, the fixed bias provides a protective bias to prevent the final-stage tube ratings from being exceeded.



Basic Transformer-Coupled Modulator

With no modulation applied, the carrier r-f output is developed by the application of the normal d-c plate voltage to the plate of the class C stage, with sufficient r-f grid drive and antenna loading to produce the desired r-f carrier. When modulation is applied, the audio output of the modulator is applied through the secondary of T1 in series with the d-c plate voltage, and adds to or subtracts from this voltage to produce an instantaneous plate voltage which increases the r-f output to 1.5 times the rated carrier power at 100 percent modulation. To do this, the plate voltage of the r-f stage is varied from two times the normal plate voltage at the positive audio peak down to zero on the negative peak, both varying in accordance with the modulating frequency.

Class A Modulator. The schematic diagram of a simple triode modulator which operates to modulate a triode r-f output stage is shown in the accompanying figure.



Triode Plate Modulator

This single-tube triode modulator can be operated class A, A1, or A2, depending upon the fidelity desired and the amount of distortion that can be permitted. Class A operation provides the best fidelity with the least amount of distortion, but uses a large power input to obtain a small power output (low efficiency). Conversely, class A2 operation uses the smallest input to obtain the largest power output (highest efficiency), with usable fidelity for the amount of distortion allowed. Class A1 operation is intermediate between these two levels.

Although the modulator driver may be r-c coupled, if the modulator is operated class A2, grid current is drawn. Therefore to minimize grid-voltage drop and the development of a reverse bias which will seriously affect the operating point and produce excessive distortion, it is necessary to provide a low-impedance grid circuit. Thus the illustration shows transformer coupling to the modulator. Through the use of a transformer with taps, the driver stage can be made to operate at the desired load point to produce maximum audio output with minimum distortion by selecting the taps that provide the required turns ratio for matching impedances (output to input). Thus the input and output impedances of the transformer can be selected for sufficient distortionless voltage drive at all times, including the time during which the modulator grid draws grid current (when the positive drive peak voltage exceeds the modulator grid bias). Modulator bias is produced by cathode resistor R1, which is bypassed to prevent degeneration (see paragraph 2.2.1 in Section 2 for an explanation of degeneration effects). Since cathode bias is used, current must flow throughout the cycle to produce the bias; therefore, this circuit is limited to class A operation (a class B modulator will be described later). Since transformer coupling is used, T1 in the input and T2 in the output, the frequency response is somewhat limited (see Section 2, paragraph 2.4 for an explanation of transformer coupling response limitations). Because of a loss of low and high frequencies causing a non-uniform audio response, the modulation signal is similarly affected. In practice, this condition is overcome by operating the modulator at less than the maximum output over the mid-range of frequencies, and by providing bass and high frequency boost to provide reasonably linear response over the audio frequency range when necessary. Actually, for ordinary speech-transmissions the desired frequency response is usually easily obtained with transformers of good design, but for the higher audio frequencies and for video applications special design is required, including both high and low boost compensating circuits.

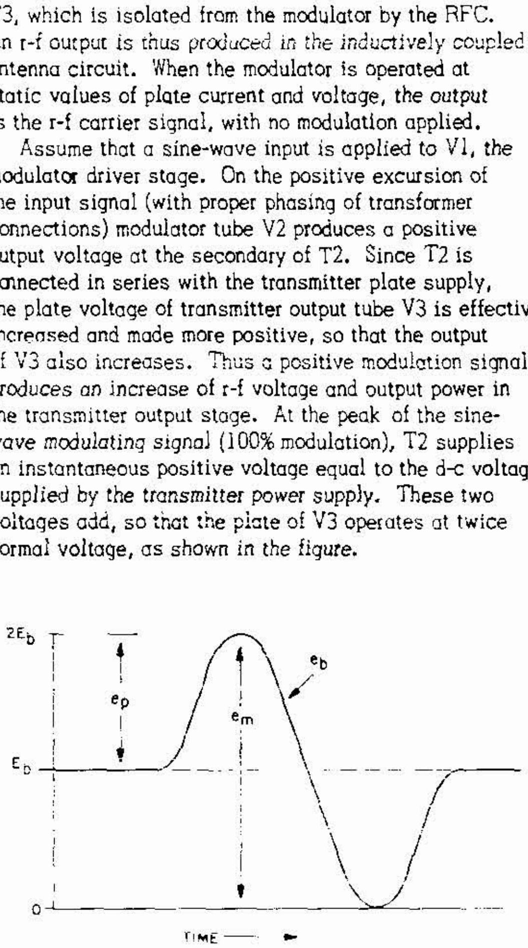
Since the output of the modulator is developed across transformer T2, the transformer must be provided with the proper load impedance to produce the desired output (both voltage and power) from V2. This is achieved by employing the transmitter output tube (a class C r-f stage) as the load across the secondary of T2. The r-f stage can be used as the audio load because radio-frequency choke RFC presents a high r-f impedance to the r-f signal developed by tube V3 and prevents it from feeding back into, and being shorted out by, the power supply filter capacitor. Thus T2 remains unaffected by the rf and sees only a resistive d-c path from the plate to the cathode of V3 and ground. This d-c path is the effective resistance placed across the secondary of T2 (the modulator load), and is equal to the d-c plate voltage applied to V3 divided by the d-c plate current, a simple Ohm's law relationship

$$(R = E/I).$$

Since the transformer has the inherent property of transforming impedance in accordance with the square of the turns ratio of primary to secondary, with a multi-tapped transformer it is possible to select the proper turns ratio to make the d-c plate resistance of V3 properly match V2 for maximum output. (Taps are not necessary if the proper ratio is used, but they do provide a convenient and easy method for load matching.) Final adjustment of the load is achieved, once the proper turns ratio is obtained, by setting the output coupling of V3 for the exact plate current at the rated plate voltage.

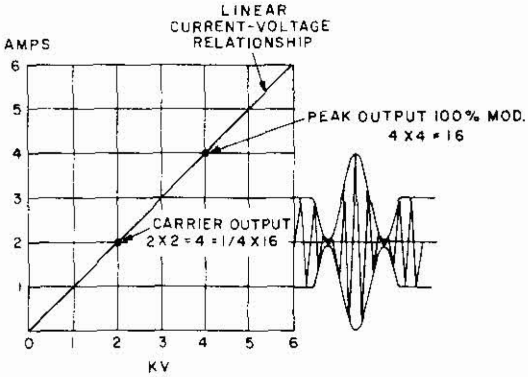
Transmitter output amplifier V3 operates as a conventional shunt-fed r-f amplifier, with combination fixed and grid-leak bias being supplied by R2, which is bypassed by C4. The plate voltage is applied in series with the secondary of transformer T2, and C2 is the conventional shunt-feed coupling and d-c blocking capacitor which connects tank L1, C3 to the plate of V3. In addition to the bias supplied by R2, fixed bias is applied through RFC_1 to the grid of V3 from a separate "C" supply. Thus the final bias applied to V3 is the sum of the fixed and grid-leak bias voltages, with the fixed bias providing protection in case of failure of the grid-drive (r-f excitation). The r-f output of the transmitter driver stage is capacitively coupled to the grid of V3 by Cc. When the grid of V3 is driven above its bias level by the r-f grid drive from the buffer amplifier, plate current flows and develops an r-f voltage across the parallel resonant tank circuit consisting of L1 and C3, which is isolated from the modulator by the RFC. An r-f output is thus produced in the inductively coupled antenna circuit. When the modulator is operated at static values of plate current and voltage, the output is the r-f carrier signal, with no modulation applied.

Assume that a sine-wave input is applied to V1, the modulator driver stage. On the positive excursion of the input signal (with proper phasing of transformer connections) modulator tube V2 produces a positive output voltage at the secondary of T2. Since T2 is connected in series with the transmitter plate supply, the plate voltage of transmitter output tube V3 is effectively increased and made more positive, so that the output of V3 also increases. Thus a positive modulation signal produces an increase of r-f voltage and output power in the transmitter output stage. At the peak of the sine-wave modulating signal (100% modulation), T2 supplies an instantaneous positive voltage equal to the d-c voltage supplied by the transmitter power supply. These two voltages add, so that the plate of V3 operates at twice normal voltage, as shown in the figure.



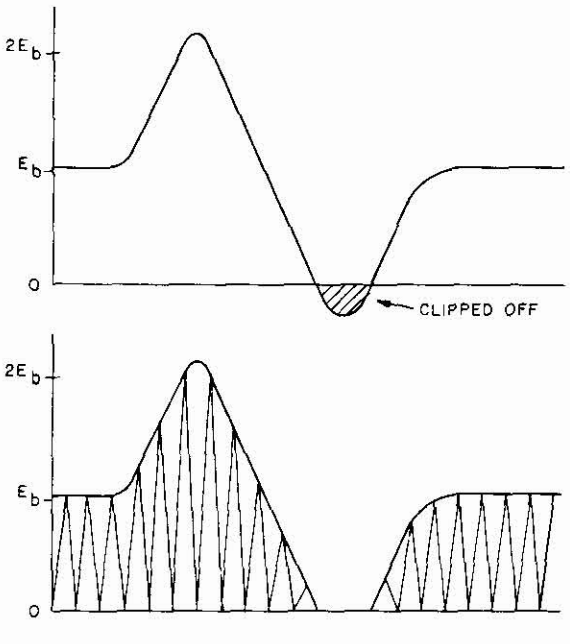
Equivalent Plate Voltage at 100-Percent Modulation

The d-c applied voltage is E_b, and the instantaneous a-c plate voltage component is e_p; when added, they produce the maximum instantaneous voltage, e_m, which varies throughout the cycle as shown by the heavy line; this is the effective plate voltage, e_b. When e_m equals $2E_b$, the instantaneous plate voltage is twice the normal d-c value, thus producing a plate current which is also twice the normal value. As a result, the instantaneous (peak) power output is four times the normal (carrier) value. As the sine-wave modulation signal decreases, it reaches the zero (no modulation) level or starting value, and the r-f amplifier plate voltage consists of the d-c supply voltage alone, which produces normal carrier output, completing the positive half cycle of modulation. In a similar manner, as the modulating sine wave goes through its negative alternation, it produces a negative voltage in the secondary of transformer T2. At the peak of the negative half-cycle, the voltage at the secondary of T2 exactly equals that of the d-c power supply feeding V3, but it is of opposite polarity. Thus both voltages cancel (instantaneously), and the instantaneous voltage applied to the plate of V3 is zero. At this time the r-f output is zero. The r-f output rises to the normal carrier value as the negative half-cycle of the modulating sine wave goes positive, and returns to zero at no modulation. Thus, by varying the instantaneous plate voltage, the sine-wave modulating signal produces a similar and amplified sine wave of r-f voltage at the plate of V3, which is coupled to the tank and thence to the antenna, where the modulation envelope is radiated. It is an amplified replica of the original sine-wave modulating signal. Thus, it can be seen that during modulation by a sine wave, the instantaneous r-f output power of the transmitter varies as follows: it is increased from its normal carrier value to four times normal, it is reduced to zero, and it is returned to the original carrier level. Therefore, in a plate-modulated amplifier, during modulation the instantaneous power varies from zero to four times normal, and the instantaneous plate voltage and current vary from zero to twice normal to produce 100 percent modulation, as shown in the accompanying illustration.



Modulation Power Relationships

Actually, only the instantaneous values of current and voltage change, and these vary at the rate of the modulating signal. For a sine wave applied over a complete cycle, the positive and negative variations are equal and opposite; since the plate meter cannot follow the audio variations at the carrier frequency (and the average value is unchanged), the d-c plate current appears to remain steady at the normal input value without modulation. Therefore, as long as the positive and negative alternations average out to zero, the plate meter remains steady. In practice, however, this is true only if there is perfect regulation of both modulator and r-f amplifier plate supplies. Since the plate current is instantaneously varying in both tubes and since the voltage regulation is usually not perfect, there is a slight amount of meter movement with modulation. On the other hand, when the negative alternation exceeds the normal carrier level, the plate current is cut off for the time that the zero voltage line is exceeded, as shown in the following figure. Such interruption of the carrier appears as a noticeable jump in the plate meter indication each time the **negative** peak is exceeded. In actual practice, the r-f amplifier (transmitter) tube is not driven to zero plate voltage, because at zero plate voltage the current would become zero and the carrier would be interrupted in the same manner as when the negative peak is exceeded. To prevent such undesirable action, the modulator is adjusted to swing the r-f amplifier plate voltage between predetermined minimum and maximum values. Such adjustment prevents cutoff of the carrier (provided these values are not exceeded). It also prevents excessive interference, known as **splatter,**



Effect of Excessive Negative Drive

from being produced by the chopped-up carrier. When the carrier is interrupted, it acts as if it were a highly damped wave instead of a continuous wave. This type of emission is a form of ICW (interrupted continuous wave), and is similar to that produced by spark transmitters and some types of noise generators. Instead of a single frequency, a number of harmonics and spurious frequencies are produced in bursts each time the carrier is interrupted. Thus the radiation is spread over a spectrum of a few hundred kilocycles about the carrier frequency, and causes interference to other signals since the receiver cannot tune it out. The actual plate voltage relationships in the transmitter tube plate circuit are shown in the figure above, together with the actual instantaneous plate cathode voltage. Since the transmitter stage is operating class C, current flows for less than a half-cycle, usually somewhere between 120 and 150 degrees. Therefore, the illustration shows operation on only one side of the zero line during the conducting period. The smooth envelope which varies above and below the zero level, as shown by the plate-cathode voltage, is the result of tank circuit action. Although pulses are supplied to the tank, since the tank circuit charges and discharges sinusoidally, any output taken from the tank, directly or indirectly, will also be sinusoidal. Thus, the upper and lower portions of the plate voltage ($E_b + e_m$) effectively add and subtract from the tank current. The result is the production of the modulation envelope shown, since the tank provides the impedance across which the rf is generated, and sees no zero level. In addition to supplying what might be considered as the missing half of the modulation waveform, the tank is also the frequency-selecting device, permitting only those frequencies within its pass band to be amplified. If the tank is too selective (has a high Q), some of the sideband frequencies may be cut off, in which case distortion is produced because of the missing frequencies. For radiotelephony the Q is usually 10 to 15 to prevent excessive selectivity. For CW (unmodulated) signals it can be much higher. For very wide band transmissions, as in television, it must be much lower. The highest sideband frequencies to be transmitted determine the allowable Q of the tank circuit.

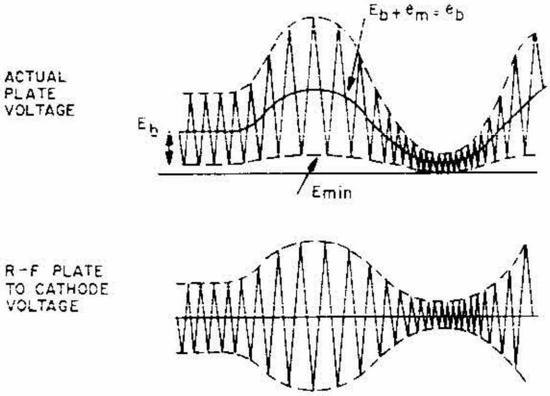


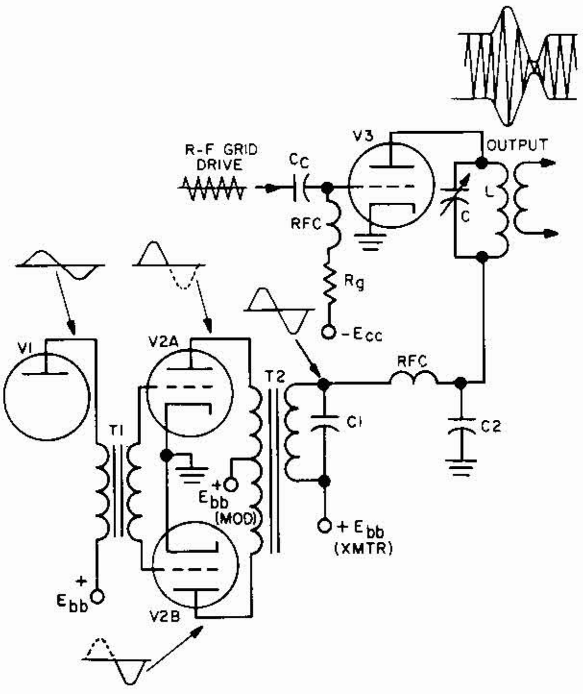
Plate Voltage and R-F Voltage Relationship

The transmitter output amplifier is always operated class C to produce linear modulation with high efficiency. In class C operation, the power output of an r-f amplifier varies as the square of the plate voltage while the plate current varies directly with the plate voltage. Therefore, a high-level plate modulator can be used to vary the effective plate voltage in accordance with the modulating signal and produce an output which varies exactly as the modulating signal. The r-f amplifier acts as a resistive load on the modulator because the plate tank is tuned to the same frequency as the r-f grid-driving signal. Since the tank appears as a resistive load, the plate voltage and plate current are in phase. Therefore, the current flow is limited only by the effective resistance in the plate circuit, which can be determined by the simple Ohm's law relationship of E/I. Although the r-f amplifier could be operated class B and modulated with the plate modulator, serious distortion would be produced because the r-f class B amplifier output varies as the square of the input voltage and not linearly with plate voltage. For full efficiency and minimum distortion, the class B r-f stage would be better modulated by applying the modulation to its grid circuit. In this case it would be operated as a linear r-f amplifier with low-level modulation.

The modulator can be operated class B (instead of class A) provided that two tubes are employed (one for each half of the audio cycle).

Class B Modulator. Since class B audio amplifiers provide a more efficient modulator and are in popular use, a schematic of a typical class B driven plate modulator is shown in the accompanying illustration:

The actual operation of the class C modulated stage is exactly as just described for the class A modulator. The difference between them is in the manner in which the audio modulation is obtained. When the output of preamplifier V1 is applied to T1, the grids of V2A and V2B are simultaneously driven in opposite directions. These tubes are class B zero-bias tubes, which are normally inoperative without grid drive (although with some tube types a small plate current may flow). When tube A is driven positive, the grid of tube B is driven further negative. On the opposite half-cycle, tube B is driven positive and tube A is driven below cutoff. The current pulses produced in the plates of each tube flow through the primary of modulator transformer T2 in opposite directions, and are added together in the secondary to produce the complete and amplified replica of the signal applied to the primary of driver transformer T1. The output of the secondary of T2 is connected in series with the plate voltage of the r-f stage, V3. On the positive alternation, the plate of V3 is driven to twice the normal plate voltage; on the negative alternation, the audio output voltage is of opposite polarity and reduces the instantaneous plate voltage of V3 to almost zero. Thus, the circuit operates as previously described. For a more detailed and complete story on the operation of class B audio



Class B Audio Driven Plate Modulator

amplifiers, see Section 6, PUSH-PULL (Class A, AB, and B) AUDIO PLIFIER.

Capacitor C1, across the secondary of T2, is a simple high-pass filter, which attenuates any high frequencies produced on modulation peaks to prevent splatter. Capacitor C1 is not necessary for operation of the modulator, but it does minimize distortion products produced by overmodulation on voice peaks.

The plate of r-f stage V3 is shown with series plate feed, rather than shunt-feed as is used in the class A modulator previously discussed, to illustrate that there is no essential difference between the two. In either case, the secondary of modulator transformer T2 is connected so that the audio output is in series with the d-c plate voltage applied to V3, and the rf is isolated from the power supply and modulator by an rfc. To avoid loss of frequency response, C2 is limited to a size which will not bypass any of the audio modulation. Otherwise, the operation is identical with the operation of the class A modulator just discussed. In practice, the use of a class B modulator results in some problems with power supply regulation and audio distortion products. These effects, however, are all a part of the audio power amplifier design, and do not change the modulation action previously described.

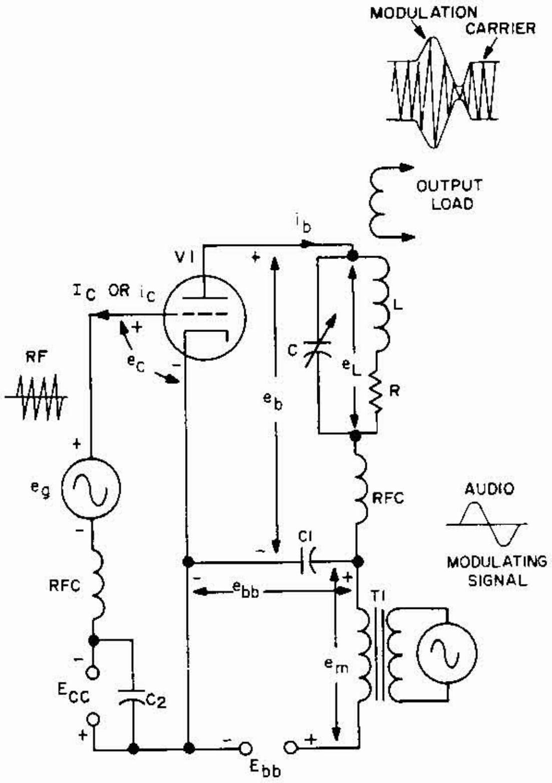
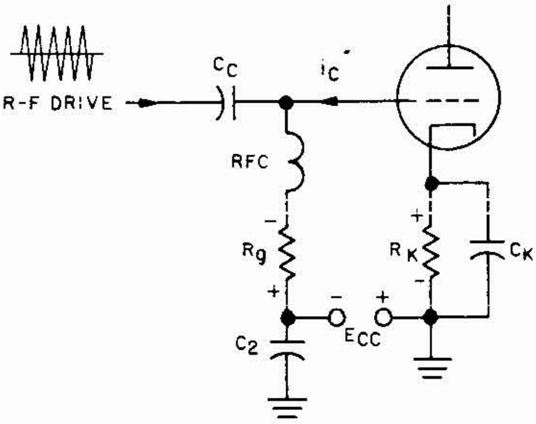


Plate Modulator Equivalent Circuit

Detailed Analysis. In the high-level plate modulator, the modulator consists of an audio power amplifier whose output is applied to a class C r-f amplifier which operates as both a mixer and a frequency and power converter to superimpose the modulation signal on the r-f carrier. A simplified equivalent circuit is shown in the following figure. The audio modulator stage is represented as a sine wave generator coupled by T1 to the plate circuit of the r-f stage, V1. The modulator functions exactly as any class A, AB, or B audio power amplifier capable of producing an audio output equal to one-half the carrier power of the r-f stage, with the desired fidelity. The instantaneous a-c output of the modulator at the secondary of T1 is represented by the instantaneous voltage e_m. Under conditions of no modulation, e_m is zero and the power for the carrier is supplied by the transmitter power supply, represented by the voltage E_{bb} connected in series with e_m and the plate of V1. Under modulation conditions, the additional power needed for 100 percent modulation is obtained from the modulator stage, which at 100-percent modulation must supply exactly one-half of the d-c input power to V1 at zero modulation. The rfc isolates both modulator and power supply from the class C r-f stage, with C_1 acting as a bypass to ground for any rf which might leak through the rfc. For the circuit to operate properly, the rfc must offer a very high impedance to the rf and little or no opposition to the audio modulation frequency, since it is desired to vary the plate voltage at the audio frequency. Although capacitor C_1 must have a low enough reactance to bypass the carrier frequency and a small range of sidebands around this frequency, it must not be low enough to bypass any of the audio output from the modulator. Otherwise, there will be a progressive loss of high frequencies and consequent lack of fidelity with a predominantly bass response. Since the plate current of V1 flows through the secondary of T1, the effects of core saturation produced by the flow of I_p must be taken into account by the use of a heavier core than would normally be required for an ordinary a-f power output transformer. In addition, the transformer windings must have the proper power handling capacity (proper wire size) so as to handle the maximum current taken by V1. In this respect, the design of the output transformer of the audio modulator represents a slight difference from that of a conventional audio amplifier. Since the modulator output must produce considerable undistorted audio output power, it must be properly matched to the load. This is achieved by providing a transformer (preferably multi-tapped), which through the impedance transformation produced by the difference in turns ratio between primary and secondary provides the desired load impedance for maximum output with minimum distortion. The modulator load is essentially resistive, being the quotient of the d-c plate voltage applied to V1 and the loaded d-c plate current to which V1 is adjusted. In the equivalent schematic, e_{bb} represents the instantaneous applied plate voltage, which is $E_{bb} + e_m$. The voltage between plate and cathode is represented by $e_b = e_{bb} - e_L$, where e_L represents the voltage drop across the r-f load offered by the tank circuit impedance. This load is represented by resistor R, which is the effective d-c load presented to the modulator, and is equal to the applied d-c plate voltage, E_{bb}, divided by the d-c plate current, I_p, neglecting the small d-c resistance in tank coil L. Since the tank circuit is resonant, X_c equals X_L, and the tank appears solely as a resistive load to V1. Because the tank circuit is resonant to a single frequency (the carrier) which is much higher than the relatively low modulating-signal frequencies, no audio voltage is developed across the tank. The instantaneous plate current is represented by i_b, and the plate-to-cathode resistance, which is equal to E_p/I_p, is transformed by T_1 to the proper value to load the modulator for maximum undistorted output. Although the instantaneous values of plate voltage and current change during modulation, the average values remain unchanged so that tube V_1 could be replaced by a resistor as far as modulator loading is concerned.

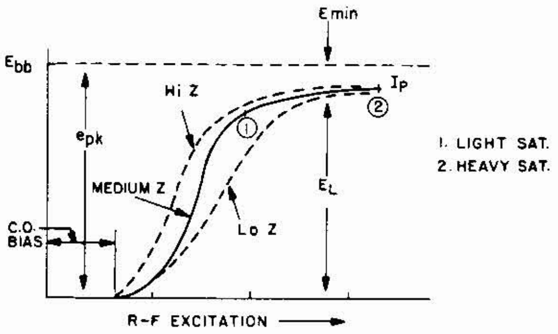
Consider now the grid bias applied by E_{cc}. This represents a fixed negative bias, but actually may be a combination of protective cathode bias, fixed bias from a separate supply, and bias developed across a series resistor as a result of grid current flow produced by the r-f driver. The driver signal (r-f grid excitation) is represented by a-c generator voltage e_g, which on the positive half-cycle is polarized in opposition to the fixed bias, as shown in the plate modulator equivalent circuit above. The effective grid voltage is the instantaneous value from grid to cathode, represented by e_c. The d-c value of grid current is represented by I_c, and the instantaneous value, by i_c. The grid rfc isolates the bias supply from the driving source and prevents shorting the input to ground, and C2 acts as a conventional r-f bypass shunting the bias supply. An illustration of a typical bias circuit is shown in the following figure.



Typical Bias Circuit

When used, the cathode bias produced by cathode resistor R_K offers protection from excessive plate current when either the drive or fixed bias fails. The cathode resistor is conventionally bypassed by C_K. Usually cathode bias is used only when the fixed bias supply is not employed, since double protection is unnecessary. For high-voltage transmitter tubes, it is also desirable to keep the cathode at ground potential, so cathode bias is used only in low-power applications. The fixed bias is obtained from a separate bias supply and is usually set for about 1.5 times cutoff, with the remaining bias (that developed by the r-f drive) being developed across grid leak R_g. Placing R_g after the rfc helps attenuate any rf which may leak through the rfc, and C2 bypasses any r-f residue to ground. Note that i_c flows in a direction which adds to the polarity of E_{cc} so that the total effective bias value is fixed by the amount of grid drive from the preceding r-f amplifier. Normally, tube V1 operates in a lightly saturated condition, that is, where an increase of grid excitation will not increase the plate current very much, if at all, but an increase of plate voltage will, as explained below.

The accompanying figure illustrates how the output voltage varies with an increase of excitation before and after saturation is obtained. Since fixed bias is used the output is zero for values of excitation lower than the cutoff-bias voltage with a corresponding high plate to cathode voltage. As the cutoff-bias voltage is exceeded plate current flows and the drop across the load, E_L, becomes greater while the plate-to-cathode voltage is reduced. When the drive reaches the value at point 1 on the curve, the tube is just starting to saturate (light saturation), and it takes much more

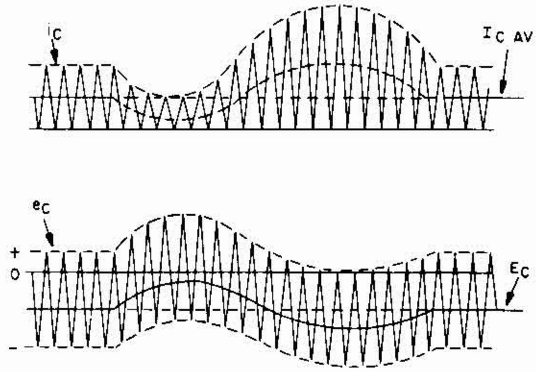


Saturation Characteristics

drive to increase the current sufficiently to develop an appreciably greater output voltage. At this point the effective plate voltage reaches its minimum value (approximately), which is the applied value less the drop across the load ($E_{bb} - E_L = E_{min}$). At this point the tube is operating most efficiently and produces an output voltage almost as great as the applied voltage. At point 2 heavy saturation is obtained, and it takes almost twice as much drive to obtain a slightly greater output. If the applied voltage, E_{bb}, is increased, a greater drive is required to reach saturation, and a greater output voltage results.

It can be seen, then, that when the excitation is adjusted for saturation at the peaks of modulation, during the resting or carrier condition the drive will be much more than is required. Thus it is evident that while the r-f drive voltage is essentially constant, it will tend to vary somewhat in accordance with modulation and loading. Under resting conditions, the grid current is about the rated tube value, and produces the remaining bias needed (plus the fixed bias) to attain twice the plate current cutoff value. When an input is applied to the modulator grid, the output at the plate of the modulator adds to the plate voltage, and more plate current flows. At the same time, if the grid excitation is obtained from a source which is barely able to supply the required drive at modulation peaks, the effect of poor regulation is obtained and the grid current tends to decrease (the source cannot supply more excitation). At the peak of the modulation cycle, the r-f grid excitation is made just sufficient to drive the tube to twice normal plate current (assuming perfect linearity). The tendency of the grid current to decrease during modulation peaks lowers the effective bias (since it is partially produced by grid drive) and permits a greater plate current to flow, producing the same effect as though the drive were increased at the peak of the cycle, just when the most drive is needed to handle the increased plate voltage. Since the grid current is at a minimum at this time, it represents the lowest drive power during the operating cycle and the grid dissipation is also the lowest. Conversely, as the modulation decreases and reaches the trough of the signal, the effective voltage applied to the plate (E_{min} in the preceding figure) is the lowest, since the modulation and d-c plate voltage are canceling each other; and the drop across the load is at its lowest with an output voltage just greater than zero. For best efficiency, E_{min} is made just equal to e_c; hence, the grid becomes more effective than the plate (since it is closer to the cathode), and more electrons are attracted to the grid, increasing i_c. As i_c increases, the grid dissipation becomes greater since the tube is also overdriven, having much more drive than is needed to swing the small plate current at the minimum plate voltage. The result is excessive heating of the grid.

By using grid-leak resistor R_g (together with the fixed bias), the effect of poor regulation in the grid circuit is achieved. Thus the excessive grid dissipation caused by the low plate voltage at the trough of modulation (discussed above) is reduced. The waveforms in the accompanying figure illustrate the use of the grid leak in providing poorer grid regulation and improved operation.



Grid-Leak and Fixed Bias Relationships

At the peak of the modulation, the reduction of grid current caused by poor regulation from the source produces less voltage drop in the grid leak, and the bias is reduced as before (but to a larger extent). On the other hand, as the modulation trough is reached, the increase of grid current (because of the increased drive, since the plate voltage is now low) produces greater grid bias, which is the same as reducing the drive, just at the time it is needed least. Thus, the addition of the grid leak helps reduce grid heating, and helps the plate reach its maximum and minimum swings so that full 100-percent modulation is achieved. Although the circuit operates satisfactorily without the grid leak, use of the grid leak results in less distortion and cooler tube operation.

Note that, while the instantaneous grid current and grid voltage change, their meter indications appear as an average steady d-c value since a sinusoidal symmetrical modulating signal is being applied. Therefore, as in the constant-current system, proper operation is indicated by steady grid and plate current indications (assuming perfect power supply regulation and neutralization of the r-f output stage).

Assuming no modulation and a steady input to the plate of the r-f amplifier, with the proper load coupling a steady r-f carrier is produced. As the modulating signal is applied, the power in the plate circuit and in the tank of the r-f stage is increased to a peak value of four times normal (output power varies as the square of the plate voltage). Since the tank circuit cannot absorb all the additional power (the load does not change), the additional power mostly appears as an increase in output (except for the amount replacing the losses in the circuit and a small percentage wasted in extra plate dissipation). Because the modulator furnishes this power increase, it is clear that the r-f power supply furnishes only the carrier power, while the modulator provides the audio or sideband power. Hence, the reason for requiring the large amount of power needed for plate modulation. Although a peak power of four times normal exists, the average output over the entire cycle is only 1.5 times normal at full 100 percent modulation. That is, for a 100-watt radiated carrier modulated 100 percent by a continuous tone, the radiated power would be 150 watts total. For this condition, 25 watts resides in each of the two sidebands developed by the modulation.

Other Considerations. Because of the requirement that the r-f amplifier tube handle peak powers of four times normal, the tube is operated 20 percent below the ratings for class C operation. Although the efficiency does not change during modulation, the plate dissipation is greater because more power is developed and applied. Therefore, the tube cannot be operated at maximum rating during periods of no modulation. As a result, the normal carrier output is less than the maximum output possible using the same tube unmodulated.

Since the tank circuit must pass both the carrier frequency and the sideband frequencies, the tank circuit Q is important. The half-power bandwidth of the tuned tank must be sufficient to pass the carrier frequency plus the sidebands which extend on each side to a frequency equivalent to plus or minus the highest modulation frequency. For example, if the modulation is 5 kc and the carrier is 5 mc, the half-power points must cover a range of 4.995 to 5.005 mc; otherwise the sidebands will be clipped, causing loss of the higher frequencies.

While too great a drive results in excessive grid dissipation, the r-f grid excitation to the class C stage must be great enough to drive the tube at twice normal plate voltage. Otherwise, on the peaks of modulation lack of sufficient drive will cause peak flattening with distortion. There must also be sufficient reserve electron emission to supply the peak power requirements, or peak flattening will also occur.

For efficient operation, the grid signal should never exceed the minimum plate voltage, or excessive grid current will flow. Excessive grid current will cause grid heating and a loss of efficiency.

No Output. Lack of output should first be isolated to either the transmitter r-f amplifier or the modulator stage. Even though the modulator is operative, an open rfc or tank circuit, a defective electron tube, or a lack of r-f grid excitation in the transmitter r-f amplifier will produce a no-carrier indication, and thus no output. Checking the r-f amplifier plate meter for current will reveal whether the circuit is complete, and whether a resonant dip can be obtained. A check on the drive meter (d-c grid current) indication will also determine whether r-f excitation is present. Lack of grid drive indicates trouble in the driver stages or transmitter power supply, and lack of plate current indicates trouble in the transmitter or in the modulation transformer. If the plate meter indicates at all, the trouble is probably in the r-f stages; if no indication is observed, the modulation transformer is open, the transmitter power supply is defective, or the plate circuit in the transmitter is open.

A no-output condition is generally indicative of lack of voltage, lack of continuity in the circuit, or a short-circuited condition. A resistance check to ground will be helpful, but is usually unnecessary. With the voltages and currents commonly involved in high-powered transmitters and modulators, breakdowns are usually obvious from external symptoms, such as arcing, charring, and burning. On low-power equipment, additional test equipment may have to be used. But remember, DANGEROUS VOLTAGES are involved; be certain to take all safety precautions before connecting or disconnecting any test equipment.

A no-plate-current indication is usually indicative of an open circuit, or lack of continuity, which can be determined by a resistance check or a voltage check. Voltage checks on the grid and plate elements will indicate continuity as well as terminal voltages. A low-plate-current indication usually indicates lack of sufficient r-f drive, high-resistance joints (poorly soldered connections), low tube emission, or an excessively high grid bias. A high-plate current indication usually indicates short-circuited components or insulation breakdown, or a lack of sufficient grid bias. In the last two cases, check for proper grid voltage before making any other checks.

Low Output. It must first be determined whether the low output is due to lack of audio power or a reduction in the percentage of modulation. Although low modulation is normally due to lack of sufficient audio power, it can also be caused by a reduced setting of the audio drive gain control or by trouble in the speech amplifier stages which drive the modulator. An oscilloscope is very useful in determining the cause of malfunctioning since it permits direct observation of the waveform. For a simple quick test of the modulation percentage, the trapezoidal pattern is helpful. The envelope waveform check, however, can show both percentage of modulation and waveform distortion, and is more useful in trouble analysis. Too high a grid bias (with the same drive) will cause a reduction of output. Insufficient r-f drive on the peaks of modulation will also cause flattening of the waveform peaks and prevent full 100-percent modulation. A similar effect is also obtained when the r-f amplifier plate voltage is too high for the amount of audio voltage supplied (indicating loss of modulator output), and when the modulator output exceeds the r-f plate voltage. In the latter case the negative peaks are clipped and carrier shift results, with accompanying distortion, reduced output, splattering, and a shifting plate current indication (this immediately pinpoints the trouble as overmodulation). Refer to the BASIC MEASUREMENTS section of NAVSHIPS 900,000.103, Test Methods and Practices, for specific modulation tests, oscilloscope connections, and waveforms.

Normally, with modulation, if the power supply regulation is inadequate in either the transmitter or the primary a-c supply line, there will be a slight movement, or flicker, of the plate current meter during the process of modulation. Overmodulation will be indicated by a sharp noticeable movement each time the peak exceeds the maximum value. If the power supply regulation is satisfactory, the normal meter indication will be rock-steady, and any meter movement will indicate either overmodulation or the presence of distortion products.

A modulation transformer which has partially shorted turns or which is partially shorted to ground may not be easy to locate from external appearances. If the short is to ground, there may be a noticeable arcing or an audible indication. If the short is between turns, however, it will probably result in an unusually low or distorted output. If the short circuit is severe, the output voltage will be too low to provide 100-percent modulation; a less severe short circuit will probably indicate itself by distortion and a mismatched type of presentation on the oscilloscope. Failure of the modulation transformer that is not visible by external symptoms is difficult to determine, and usually can be remedied only by replacement of the transformer with a good one after all other components have been checked and found satisfactory.

Lack of sufficient electron tube emission to develop the extreme peaks of modulation in the r-f amplifier can cause peak clipping, more than usual distortion, and inability to obtain 100 percent modulation. Such a condition is usually progressive and can be observed by noticing that the output indicator (r-f ammeter) fluctuations become less for modulating signals known to produce large indications. (At 100-percent modulation the output indication on an r-f ammeter will increase approximately 22 percent above the normal indication without modulation.)

Distorted Output. Any distortion in the output is usually obvious when the audio modulation is monitored. It may occur from a number of causes. For example, overmodulation will cause carrier shift, severe interference with other stations because of spurious signals, and audio distortion. Changing the modulator load impedance, by adjusting the r-f amplifier loading (r-f output) for a value of plate current which is different from the normal value, will change the modulator load line; depending upon the magnitude of the change, this condition may be easily detected, or a special check may be necessary to determine the amount of distortion. Any change of modulator grid bias will shift the operating point and require a corresponding change in the r-f drive. With low bias (for a given drive voltage) the input will be clipped and distorted, and with high bias a larger input signal (drive) will be required; thus speech amplifier distortion will most likely be increased. If the audio gain control is advanced too far in the speech amplifier, the modulator can be overdriven, regardless of whether it operates class A, AB, or B. This can cause peak distortion in both the modulator and the r-f amplifier. With proper drive and symmetrical modulation, little or no distortion will occur. On the other hand, with improper drive and with large unsymmetrical or sustained peaks of modulation, excessive distortion can result. Use of a modulation indicator to indicate the percentage of modulation is a help in determining whether distortion is caused by overmodulation. Only a waveform check can positively determine whether distortion is present. An oscilloscope arranged to check waveforms at key points is most helpful in isolating trouble.

Lack of sufficient plate voltage in either the modulator or the r-f amplifier can cause a reduction in plate-voltage swing with a consequent loss of the peaks in the output. In the modulator, this is evidenced by a rounding off of the peaks and an inability to reach 100-percent modulation with a further increase in the audio drive. In the r-f amplifier, it is shown by peak clipping caused by overdrive from the modulator. In either case, distortion components can be heard in a monitor, as well as seen on the oscilloscope.

Operating at a higher than rated load can also cause core saturation effects in the modulation transformer and thus produce a flattening off of the peaks. Such a condition will return to normal when the load is readjusted for the proper current. Poor frequency response in the transformer can also cause distortion by loss of low or high frequencies, but this is an inherent design problem and will not occur unless the modulation transformer is defective or is replaced with an inferior part. Poor connections or internal d-c leakage will most likely be shown by the presence of noise components in the modulation. Use of a harmonic analyzer will usually indicate the source of the distortion.

Lack of sufficient filament (cathode) emission in the r-f amplifier and modulator tubes can cause distortion due to peak clipping and make it impossible to obtain 100-percent modulation.

TRANSFORMER-COUPLED, CONTROL GRID MODULATOR.

APPLICATION.

The control grid modulator is employed as a low-level modulator in applications where it is desired to use a minimum of audio (modulator) power. It is widely used in portable and mobile equipments to reduce size and power consumption. It is also used in extremely high-power, wide-band equipment such as television transmitters, where plate modulation is more difficult and costly to achieve, and grid modulation is considered standard.

CHARACTERISTICS.

Varies effective grid bias of transmitter r-f stage to achieve modulation.

Operates as a basic low-level modulator, with mixing process occurring in grid circuit.

Requires very little audio power (on the order of 1 percent of carrier power).

Is more critical in adjustment than plate-modulated class C amplifier.

Produces very little distortion up to 75-percent modulation limit, with greatest distortion occurring between levels of 75 and 100 percent.

Has lowest efficiency for unmodulated (carrier) condition, and highest efficiency at 100-percent modulation.

Has greater bandwidth capabilities than plate modulator when full 100-percent distortionless modulation is not required.

Usually uses triodes, although tetrodes and beam power tubes may also be employed to provide greater power gain and to utilize their inherently low-grid-to-plate capacitance, thus avoiding necessity of neutralization.

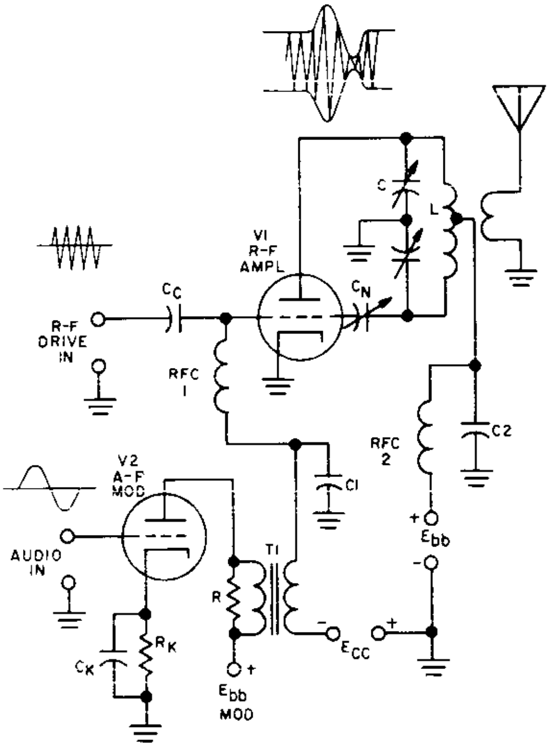
CIRCUIT ANALYSIS.

General. Before starting this circuit analysis, the reader should review the discussion on RF Power Amplifiers, in Section 6 of this Handbook, for background on class C amplifiers.

The grid modulator utilizes the variation of grid bias (at the frequency of the modulating signal) to vary the instantaneous plate current and voltage, and thus achieve modulation. The modulating signal is introduced into the grid circuit in series with the fixed bias, so that on each half-cycle the modulating signal alternately aids and opposes the bias. Although the modulation actually takes place in the plate circuit, the modulating signal is applied to the grid circuit, where the power is at a relatively low level (as compared with the plate circuit); thus, the modulator power requirement is low. For this reason, the grid modulator is also classified as a low-level modulator.

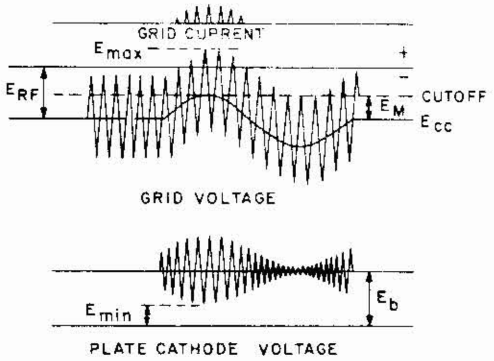
Under ideal conditions, only a voltage amplifier would be necessary to produce grid bias modulation. However, in actual practice, the grid will draw current at the positive crest of the signal, and extra power is dissipated in the grid circuit. Therefore, grid modulation does require a modulator capable of supplying a few watts of power (on the order of 2 to 5 watts for moderate power applications). This condition also requires that the r-f driver stage be capable of supplying sufficient drive power to prevent peak flattening on the modulation peaks.

Unlike the plate modulator, the sideband power and the carrier power are both developed from the same power source. Since this power supply must furnish all of the power on the peaks of modulation, it is necessary to operate the electron tube so that it produces a carrier power which is only one-fourth of that available from the same tube operating as an ordinary class C amplifier. (The plate modulator operates at approximately two-thirds of the rated class C amplifier output.)



Triode Modulator

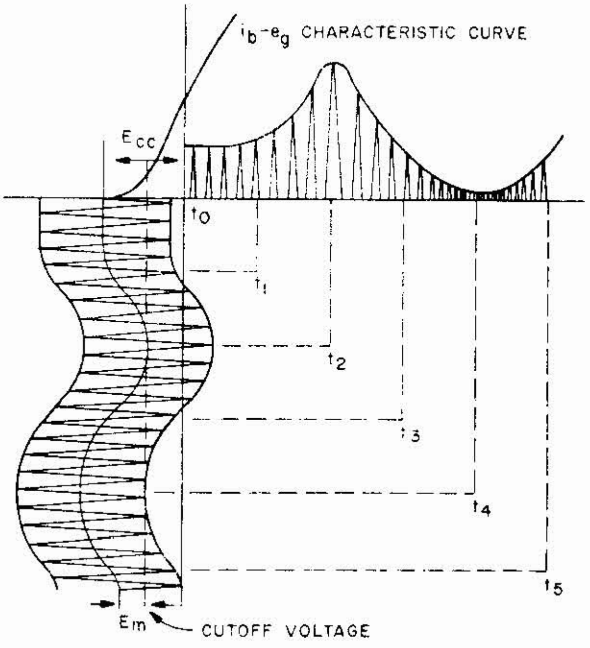
Circuit Operation. The schematic of a typical triode modulator is shown in the accompanying illustration. The r-f excitation (drive), which is at the same frequency as the output, is coupled capacitively through C_c to the grid of V1, and a fixed negative bias is supplied through RFC1. The modulating (audio) signal is coupled in series with the bias through T1. Capacitor C1, a decoupling and bypass capacitor, prevents any rf that leaks through RFC1 from entering the audio circuits or the bias supply. Capacitor C1 has a value high enough to bypass the rf, but not high enough to bypass any of the modulation and cause a loss of high frequencies. Since the r-f output is at the same frequency as the r-f input, capacitor C_n, together with a portion of tank coil L, provides a neutralizing arrangement to prevent self-oscillations from being produced as a result of feedback from plate to grid through the grid-plate interelectrode capacitance. To provide a tank connection for neutralizing the modulator and also to provide a low Q, a split-stator capacitor is used to tune tapped coil L. Since the plate end of coil L is 180 degrees out of phase with the neutralizing end, a signal of the proper phase can be fed back to the grid (through C_n) to prevent self-oscillations. RFC2 and C2 form a conventional series plate-feed decoupling arrangement (shunt plate feed may also be employed, if desired). The r-f drive voltage, the modulation voltage, and the fixed bias are selected so that, on the positive peaks of the modulation signal, the tube operates as a lightly saturated class C amplifier. As shown in the following waveforms, the fixed bias is slightly greater than 1.5 times the cutoff voltage for the tube, and the modulation signal (E_m) varies the effective bias about E_{cc}, with the positive peaks of E_m approximating cutoff. With the effective bias varying in this manner, the r-f drive voltage (E_{rf}) is of such an amplitude that: (1) on the positive swing of E_m, the r-f signal drives the grid positive, grid current flows, and the plate draws current for approximately 120 to 150 degrees of the r-f cycle; (2) on the negative swing of the modulation cycle, the r-f signal drives the grid just barely above cutoff, and plate current flows for just a few degrees of the r-f cycle; (3) with no modulation present, the plate current and voltage are approximately half their maximum values, and the output carrier produced is one-fourth the power of the same tube operating as an ordinary class C amplifier. The most positive swing of the instantaneous grid voltage is E_{max}, and is equal to $-E_{cc} + E_m + E_{rf}$. E_{min} is the minimum instantaneous plate voltage, and must never be less than the instantaneous grid voltage, E_{max}. That is, the grid must never go more positive than the plate. (This is explained fully in Section 6 under Class C Amplifiers.) Since the plate current consists of pulses of current, it may appear that the plate-to-cathode voltage would be in the shape of pulses extending downward from E_b. However, the other half of the sine wave is supplied by the flywheel effect of the tuned tank circuit, and the output is as shown in the diagram. The pulses of plate current in effect reinforce the oscillations of the tank circuit, and thereby make up for any losses in the tank.



Grid and Plate Waveforms

To accomplish modulation, the varying grid bias drives the plate current from zero to twice normal, and the plate voltage from approximately half the applied d-c potential to the full value. This is the same as driving the plate voltage (and current) to two times normal, as in the plate modulator.

Grid bias modulation uses the linear variation of plate tank current with bias voltage variations to produce the modulated envelope, as shown in the following illustration. The grid voltage versus plate current transfer curve is essentially linear over the operating portion, but drops off nonlinearly at the beginning and end. The operating bias is selected so that the resting value (E_{cc}) is at the center of the linear portion of the curve.



Grid Voltage Versus Plate Current Relationships

With no modulation (time t_o to t_1), the bias is E_{cc}, the r-f signal drives the grid above cutoff, with the positive peaks just below 0 volts. Plate current flows for the portion of the r-f cycle that is above cutoff, with an amplitude approximately half that for the modulation peaks. The plate voltage is one-half the applied voltage, and the power output is one-fourth the maximum power available. As the modulation signal swings in the positive direction (time t_1 to t_2), the grid bias is now $-E_{cc} + E_m$, the r-f signal now drives the grid positive, and grid current begins to flow. Because of the reduced bias, the plate current increases and the instantaneous plate voltage is reduced. At the most positive peak of the modulation signal (time t_2), i_p is maximum and e_p is minimum, E_{min} in the diagram (previously shown). At time t_2, the operation is much the same as for an ordinary class C amplifier (with full r-f drive and fixed grid bias). At time t_3, the grid bias is once again E_{cc}. As the modulation cycle continues in the negative direction, the bias becomes $-E_{cc} - E_m$, this increased bias reduces the plate current to its minimum value, and the plate voltage increases toward the applied voltage. At time t_4, the negative peak of the modulation cycle, the r-f drive voltage is just able to bring the tube out of cutoff (assuming slightly less than 100 percent modulation), and plate current *flows for just a few degrees of the* r-f cycle. At this time i_p is minimum and e_p is almost *equal to the applied voltage.* The power output varies between 4 times the unmodulated carrier on the positive modulation peaks and zero power on the negative troughs, resulting in an average power of 1.5 times the unmodulated carrier. Thus, 100-percent modulation is attained.

The d-c plate current during the time of no modulation is one-half of that supplied during the peaks of modulation. However, the power output during this time is only one-fourth of that supplied during the peaks of modulation. Thus, the efficiency during unmodulated times is only half of that for 100 percent modulation. Typical values of efficiency are 33 percent for no modulation, and 66 percent for 100-percent modulation.

The linearity of the output depends *on the linearity* of the $i_p - e_g$ characteristic curve. In the preceding discussion it was assumed that *the curve was linear* from the maximum value of grid bias ($-E_{cc} - E_m$). However, the *curve is actually nonlinear in the region* near cutoff (and near saturation); thus, some *distortion occurs on the negative* peaks of the modulation cycle. Distortion also occurs on the positive peaks *of the modulation cycle.* This is true because of nonlinearity of the curve at saturation, and for the following reason. When the grid is driven positive, grid current is drawn, which places a load on the modulator, the r-f source, and the bias supply. This load is not present during the remainder of the modulation cycle. Because of this varying load, good regulation is required for these circuits. Distortion-free operation may be realized by decreasing the modulation voltage. However, this decreases the percentage of modulation, the power output, and the efficiency of the circuit.

To improve the regulation of the modulator circuit, the primary of the modulation transformer is usually shunted with a load resistor equal to the rated d-c modulator load, and the audio output stage is usually designed to have a [illegible] output of two to three times the output actually needed. In addition, some form of inverse feedback is used in the audio output stage to keep load variations and distortion to a minimum.

Various combinations of bias supplies are used. Good regulation is achieved by providing a bias supply capable of supplying two or three times the required load. Since the d-c (average) power to the plate is constant throughout the modulation cycle, a convenient means of obtaining bias is the use of a cathode resistor. The cathode resistor must be bypassed for the modulating frequencies as well as for the r-f frequencies.

Good regulation in the r-f driver stage is usually accomplished by designing the driver stage to be able to supply more power than is *actually required.*

The total result is that, because of these interacting requirements, *the full theoretical advantages* of grid bias modulation are not obtained practically, *and the basic distortion is* always greater than that obtained with plate modulation. Although extra r-f and audio drive power is needed to minimize distortion, the small amount of modulator power needed for full modulation makes it economical to use grid modulation where the increased distortion can be tolerated.

FAILURE ANALYSIS.

No Output. Lack of output should first be isolated to failure of the r-f amplifier stage or the modulating signal circuit(s). Even though the modulator is operative, an open rfc or tank circuit, a *shorted* or defective electron tube, or a lack of grid excitation to the r-f amplifier *will produce a no-carrier condition.* Check the r-f plate current meter for an indication to *determine whether the plate circuit* has continuity, and check the grid-drive meter for an indication to determine whether grid excitation is present. With both indications normal, and with the tank tunable for a minimum *dip of plate* current, a lack of coupling or continuity in the output circuit of the r-f amplifier is indicated.

Lack of grid drive places the trouble in the exciter stages of the transmitter or the input circuit to the r-f output stage, whereas lack of plate current indicates possible power supply trouble or an open circuit in the r-f stage.

With an r-f carrier existing, the trouble is definitely in the audio circuits or modulation transformer. An open transformer secondary would remove the grid bias to the r-f stage and cause excessive plate current; a shorted transformer would allow the r-f stage to operate normally and produce a carrier, but no modulation could occur.

High transmitter plate current usually indicates *short-circuited components* or lack of bias; low plate current indicates excessive bias, high-resistance joints, low tube emission, or a possible lack of coupling to the load. With open-circuited or short-circuited conditions indicated on the equipment meters, a simple resistance analysis made with the power OFF and with the **high-voltage supply grounded for safety**, will reveal the defective components.

Low Output. It must first be determined whether the low output is from lack of sufficient audio drive or from an actual reduction in percentage of modulation. Although low modulation is usually due to lack of sufficient audio drive, it can also be caused by a reduced setting of the audio gain control, *by trouble in* the speech stages, or by lack of sufficient r-f drive. An oscilloscope is very useful in determining the cause of malfunctioning, since the waveform may be directly observed. For simple, quick tests of modulation percentage, a trapezoidal pattern is helpful

A waveform check, however, can show both percentage of modulation and waveform distortion, and is more useful. Too high a grid bias will cause a reduction of output and an inability to reach 100-percent modulation with the same drive.

Loading too heavily will increase the r-f carrier output, but it will also result in inability to obtain 100-percent modulation; on the other hand, loading too lightly will produce a reduced carrier, overmodulation on the peaks, and a greater amount of distortion as indicated by a flickering plate meter reading. In the plate modulator, a flickering plate meter reading always indicates distortion and carrier shift, but this is not always true of the grid modulator. Because of the use of a changing efficiency to obtain the modulation, and since the power is obtained from the same source, distortion and lack of full modulation (and even overmodulation) can exist sometimes without greatly disturbing the normal meter indications. Therefore, it is important that the grid modulator be adjusted for proper results, using an oscilloscope.

A partially shorted modulation transformer will not indicate its condition externally by arcing or burnt spots since it operates at a very low level; instead, it will probably cause a loss of output combined with distorted modulation. Such a condition can be determined by substitution of a new transformer known to be good after the other parts have been eliminated by a systematic analysis.

Lack of sufficient filament emission in the r-f amplifier or modulator tube will produce peak clipping and a lower output because of inability to obtain 100-percent undistorted modulation at the peaks.

Distorted Output. Distortion is usually obvious when the audio modulation is monitored. It can result from a number of causes. For example, overmodulation will cause carrier shift, severe interference with other stations, and distortion. Since the grid modulator is inherently subject to more distortion than the plate modulator, any slight change in load conditions or misadjustment will usually be indicated by an increase in distortion.

Since the grid modulator essentially supplies voltage, it is necessary for the primary of the modulation transformer to be damped with a stabilizing resistor in order to maintain a substantially constant load. With a varying load caused by an open stabilizing resistor, the distortion will be excessive. In those stages that must be neutralized, it is important that the neutralization be correct; otherwise, during the peaks of modulation, self-oscillations either will occur continuously or will start to occur on the voice peaks. In either case, the distortion produced by poor neutralization is excessive and noticeable. This condition is easily identified on the oscilloscope by a fuzzy and blurred pattern, which is indicative of oscillation. (See EIMB, NAVSHIPS 900,000.103, Test Methods and Practices, Basic Measurements Section, for typical modulation tests and waveforms.)

Distortion in the preamplifier stages can easily be detected by supplying an undistorted signal to the input and checking the output waveform of the modulator transformer with an oscilloscope. If low power and low voltages are involved, a quick but less accurate check can be made by using a speaker or set of headphones instead of an oscilloscope.

TRANSFORMER-COUPLED, SUPPRESSOR-GRID MODULATOR.

APPLICATION.

The suppressor-grid modulator is employed as a low-level modulator for pentodes in applications where a minimum of audio (modulator) power is desired. It is particularly useful in portable or mobile communications equipment to reduce size and power consumption.

CHARACTERISTICS.

Varies grid-plate transconductance to achieve modlation.

Requires less audio power than grid modulator since only voltage drive is required, and no power is needed for modulation.

Produces maximum efficiency at 100 percent modulation, and minimum efficiency with unmodulated (carrier) conditions.

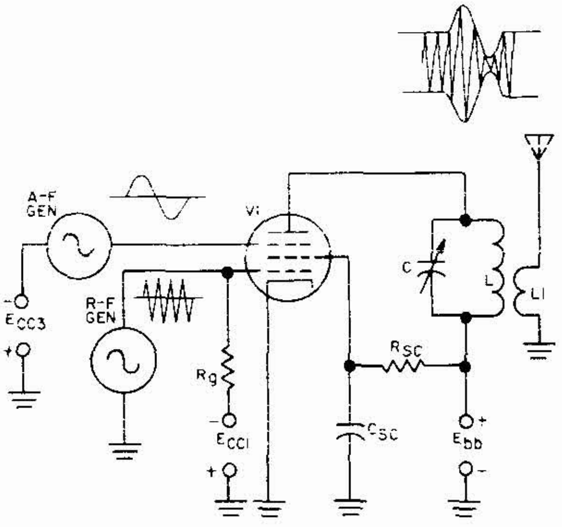
Provides a carrier power of only 1/4 that available for same tube in CW operation, and about 1/3 that possible with high-level plate modulation.

CIRCUIT ANALYSIS.

General. Suppressor-grid modulation is practically identical to control-grid modulation, with the exception that the suppressor grid is used to achieve the modulation instead of the control grid. This type of modulator, like the grid modulator, uses a form of efficiency modulation. It normally operates at half the maximum current under carrier conditions with no modulation, and at full current (twice normal) at 100 percent modulation. The efficiency is approximately 33 percent with no modulation and approximately 66 percent with full modulation. The carrier power represents 1/4 the maximum power available for the same tube operation, as a class C amplifier, with a peak power of four times the carrier value at 100 percent modulation. During modulation the average power increases to a maximum of 1.5 times normal at the peaks of modulation, and this power is obtained from the same power supply by a change of efficiency within the tube.

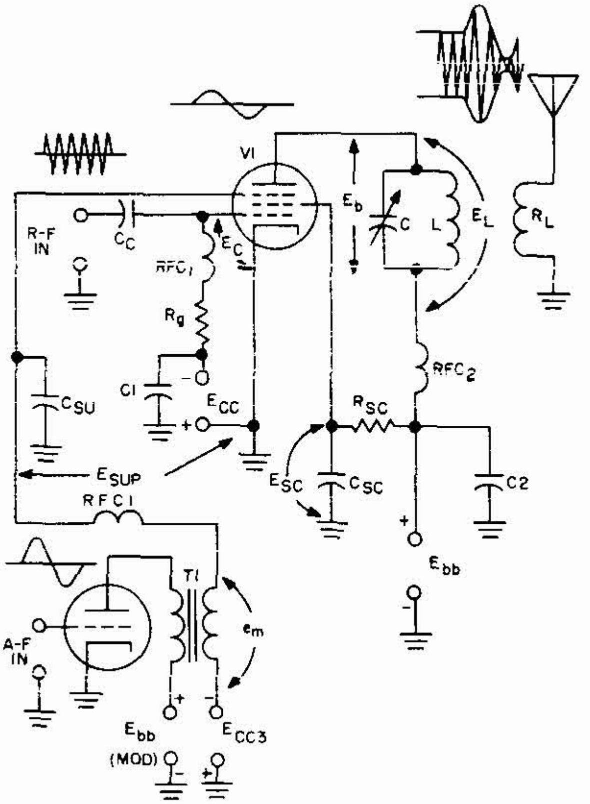
It requires a negative supply for biasing the suppressor grid, which, since it acts as a gate between the screen and plate and is always negative, draws no current. Thus, very low modulation power is required, since only audio voltage is needed for control of the modulation. It does have the disadvantage, however, of causing a higher than normal screen dissipation. This is due to the fact that the plate current is cut off on the negative swing of the modulation signal, and the positive screen acts as a plate, resulting in greatly increased screen current. Distortion is approximately of the same order as that for grid modulation, since the linearity of the grid-plate transfer characteristic determines the basic minimum distortion inherent in the tube.

Circuit Operation. The basic suppressor-grid modulator is shown in the accompanying figure; for simplicity, sine wave generators are used to represent audio and r-f excitation. It is clear from the figure that the circuit is practically identical to that of the grid modulator except for the tube element used. The r-f amplifier stage operates as a conventional class C amplifier. Screen voltage is obtained through dropping resistor R_{sc}, bypassed by C_{sc}, and a fixed control-grid bias supplemented by grid-drive bias from R_g is used. With the suppressor grid biased negative from a separate supply, the carrier value of current is one-half the *maximum current.* As the a-f voltage from the speech amplifier (represented by the a-f generator) is applied to the suppressor, it is (considering a sine wave) alternately aiding and opposing the suppressor fixed bias. Thus on the positive half-cycles, it operates to reduce the suppressor bias and allow a heavier flow of plate current, while on the negative half-cycles, it adds to the suppressor bias to reduce the plate current. Therefore, the modulation is developed by plate current flow under control of the suppressor-grid voltage; in effect, the suppressor varies the grid-plate transconductance to achieve modulation.



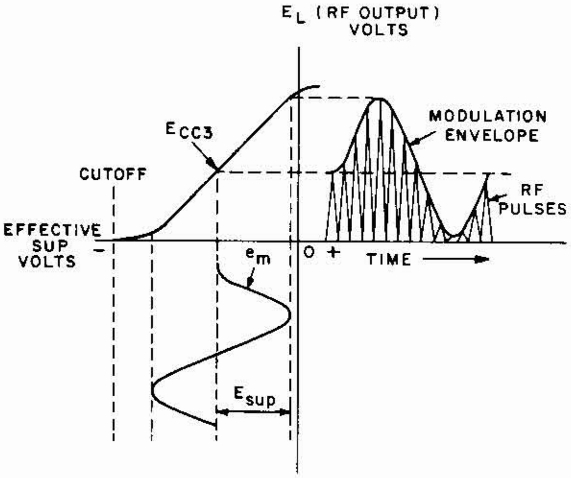
Basic Suppressor-Grid Modulator

The schematic of a typical suppressor-grid modulator is shown in the accompanying figure. In the figure, T1 couples the output of the speech amplifier to the suppressor grid through RFC1, which prevents any feedback of rf into the audio circuit; capacitor C_{su} grounds the suppressor for rf. Thus the d-c suppressor bias and instantaneous audio output signal (e_m), connected in series, are combined to provide an effective bias value, which adds on the negative peaks to increase the total bias, and subtracts on the positive peaks to decrease the total bias. The tube is biased class C with fixed grid bias E_{cc}, bypassed by C1. The fixed bias is supplemented by grid drive bias through grid leak R_g, coupled from the r-f exciter stage through C_c. RFC1 isolates the bias supply, and C1 bypasses any excitation which may leak through the choke. The effective control-grid bias is that from cathode to grid, indicated by E_c. Screen voltage is applied through screen dropping resistor R_{sc}, bypassed by C_{sc}, with the plate series-fed through RFC2 and bypassed by capacitor C2 in a conventional series-feed arrangement. Tank LC is tuned to the excitation frequency applied to the grid, and is coupled inductively to the output load, R_L.



Suppressor-Grid Modulator

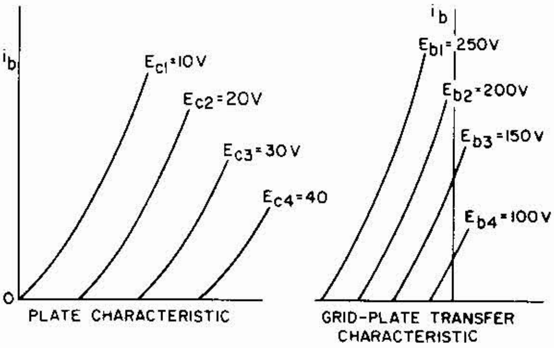
When the modulating signal is applied, e_m varies from some negative value to a positive value which just cancels E_{cc3}, producing a variation of suppressor bias, E_{sup}, from zero at the maximum positive peaks of modulation to some negative value at zero modulation, or carrier level; it then increases to a greater negative value which is sufficient to reduce the plate current almost to zero on the negative peaks of modulation. Thus the plate voltage varies from a small minimum to practically full plate voltage as the plate current varies from maximum to zero in accordance with the modulation. The voltage drop across the tank circuit, E_L, varies simultaneously from zero to maximum and back to zero, and the tank current is increased during the positive peak and decreased during the negative peak, effectively producing the modulation envelope. Since the tank is oscillating sinusoidally, the output is also sinusoidal, and is produced by pulses of plate current which increase the tank current to form the envelope shown in the accompanying figure. It is clearly seen from the figure that while the transfer characteristic between the grid and screen is mostly linear, it curves off at the beginning and end, which corresponds to a biased-off suppressor condition and a zero-voltage suppressor condition, respectively. This shape is similar to that of the grid modulator transfer curve, and indicates that distortion is inherent and must always be more than that produced by plate modulation.



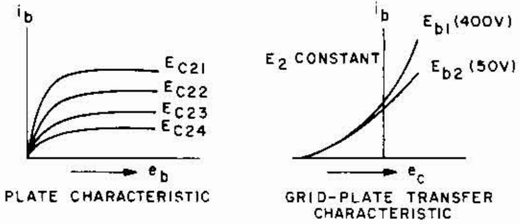
Suppressor-Grid Voltage and Output Voltage Relationships

Use of the series screen-voltage dropping resistor, R_{sc}, tends to reduce the screen voltage more as the screen current increases. Thus when the suppressor is being biased-off to the nonconducting state between screen and plate (by the negative modulation signal) the increased current attracted to the screen (it tries to act as the plate) automatically reduces the effective applied screen voltage by the increased drop across the screen-voltage dropping resistor, R_{sc}. In this manner the extra screen dissipation is reduced somewhat at just the time it is becoming excessive. Hence, fixed screen voltage is usually never employed with this type of modulator.

Detailed Analysis. The basic functioning of the pentode modulator depends upon the suppressor grid and its control action. Consider the basic triode, for which a set of typical plate characteristics and transfer characteristics are shown in the accompanying figure. It is evident from the plate characteristics that for a fixed bias, there is a different plate current for each change of plate voltage. Note that the curves tend to be similar and equally spaced for equal steps of bias voltage. Likewise, on examining the transfer characteristic, it is seen that for each change of bias (with fixed plate voltage) there will be a different plate current; like the plate characteristic curves, these curves are similar and almost equally spaced for equal plate voltage steps. Thus it is clear that in a triode, one can vary the plate voltage and the plate current will follow, which is what is done in plate modulation. Likewise, one can vary the grid bias and the plate current will follow, which is what is done in grid modulation. Now examine the plate characteristics and transfer characteristics of a pentode, as shown in the following figure.

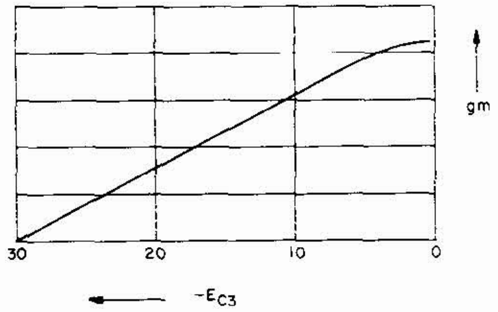


Triode Plate and Transfer Characteristics



Pentode Plate and Transfer Characteristics

With the inclusion of the screen grid in the pentode, the plate current no longer follows the plate voltage, but is determined mainly by the screen voltage (assuming a fixed control grid voltage). That is, for a particular screen voltage, the plate current quickly reaches a particular value, as the plate voltage is advanced from zero toward a maximum, and remains substantially constant over a large range of plate voltage. Thus, varying the plate voltage has little effect on the plate current. Since these curves are parallel and almost equally spaced (for equal screen voltage steps), it can be seen that variation of the screen voltage will produce the desired variation of plate current, which is what is done in screen modulation (to be discussed separately). Upon examining the transfer characteristic it is seen also that for a specific screen voltage and for plate voltages from a low to a high value, there is little change in plate current as the bias is changed; in fact, for at least half of the operating curve they are identical. Let us now examine how the grid-plate transconductance varies with a change of suppressor voltage as the control-grid bias and screen voltage remain fixed, as shown in the following figure.



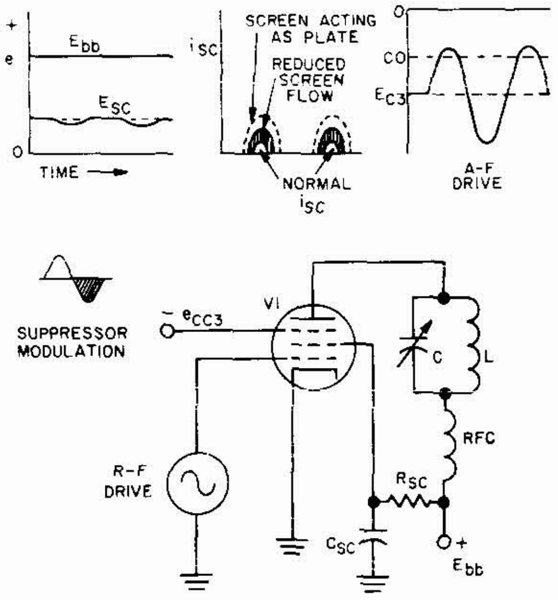
Gm Variation with Suppressor Voltage

As can be seen, the transfer characteristic is practically linear, starting from a high value of transconductance at zero suppressor voltage and ending at a very small or zero value with a large negative suppressor voltage. It follows, therefore, that variation of the suppressor voltage will produce a relatively linear change in tube output. As a result, the suppressor-grid modulator is operated with a fixed negative control grid bias and a fixed screen voltage. (Since the control grid bias does not vary, the r-f excitation source need not have as good regulation as with the grid modulator; consequently, it need not supply as much grid drive power.)

Since the suppressor is placed between the screen and the plate, it exerts complete control over the plate current; when biased sufficiently negative it will cause plate current cutoff, while at just about zero bias it will permit maximum plate current flow. Because the suppressor is never raised above zero and is always negative, it draws no current; thus very little modulator power is needed — less than that for any other type of modulator. The suppressor bias is usually on the order of — 100 volts, and a simple voltage amplifier will completely modulate a high-powered pentode.

As the plate current is prevented from flowing to the plate by the negative suppressor bias, the screen becomes the only collector of electrons, and the screen tends to absorb them, acting as the plate. Thus screen-grid power dissipation becomes large on the negative portion of the modulation signal (the troughs), as shown in the accompanying figure. By obtaining the screen voltage through dropping resistor R_{sc} from the plate source, the increased screen current (i_{sc}) automatically causes a lower applied screen voltage, which reduces screen current flow during this period. Even so, the maximum screen dissipation is usually excessive during this period, because plate current cannot flow and all electrons are being handled by the screen.

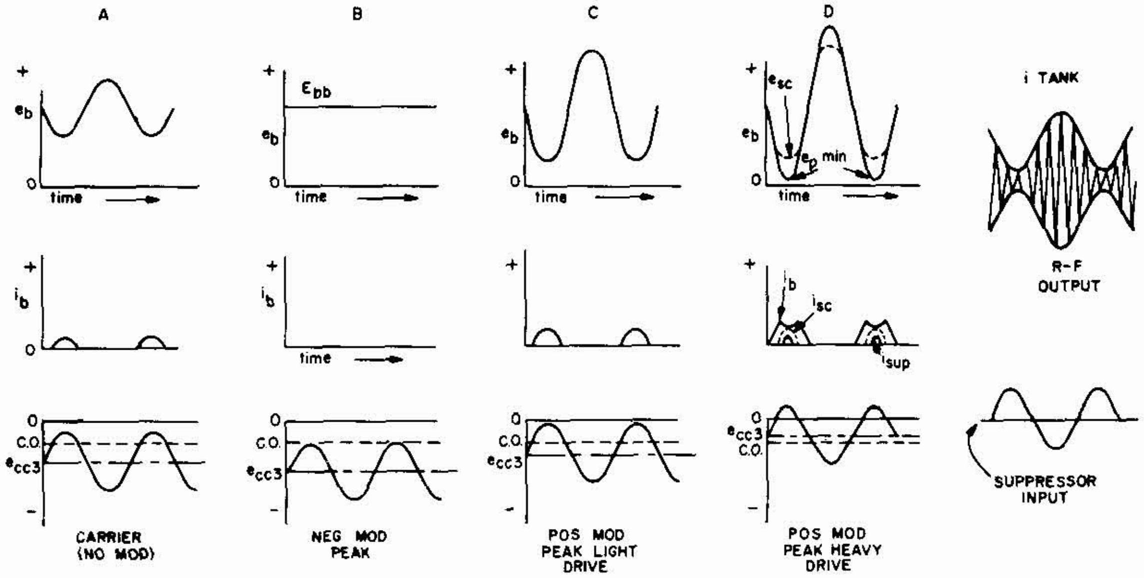
Now consider the tube's operation under carrier conditions with no modulation. Here the d-c suppressor bias is adjusted for a negative value which produces half the maximum (full class C) value of plate current. The r-f drive and grid bias are set for the optimum values to produce this maximum loaded plate current. No modulation is applied to the suppressor (only the fixed d-c bias), and plate current flow is as shown in part A of the following figure.



Screen Circuit Conditions

As the modulation signal goes negative, the effective suppressor voltage is increased to further bias off plate current flow. At the negative peak of modulation (the trough), the instantaneous suppressor voltage, e_{cc3}, is just below cutoff (part B of the figure), and no plate current can flow. This is the time at which the screen is dissipating all the cathode (space) current, as explained in the previous paragraph. During the remaining half of the negative modulation cycle the suppressor voltage rises, becoming more positive as the negative modulation cycle approaches the zero modulation (carrier) level. At no modulation the conditions are as first represented in part A of the figure, with one-half the cutoff value of suppressor bias. Each drive pulse produces an output pulse of rf and a plate current pulse. The plate current averaged over the cycle is half maximum.

During the positive half of the modulation cycle, the negative suppressor bias rises above the cutoff level and reaches zero at the maximum positive modulation peak. At this time the plate current is twice normal (maximum) and



Typical Operating Waveforms

the plate voltage is reduced to its minimum value, as shown in part C of the figure, but not to less than that of the screen voltage. If the modulation is sufficient to make the suppressor voltage positive, the suppressor tends to become the plate, and so does the screen (the screen voltage is now greater than the plate voltage as shown in part D of the figure). Thus, both the screen and suppressor grids carry the space current, and their dissipation ratings are exceeded. This is why the suppressor grid is **never** driven positive.

Once the modulation peak is reached, considering sine wave operation, the suppressor voltage becomes negative-going, and the resting or carrier condition is again reached at zero modulation. During the time of the positive peak the drop across the load (the tank circuit) is the greatest, and the greatest output voltage is developed and coupled to the antenna. Also, during this interval, the tank is actually absorbing power to replace any losses present as a result of resistance in the coil and leads. Conversely, during the negative peak, the tank is supplying the output since the tube is cut off and inoperative.

It can be understood from the previous discussion, then, that varying the instantaneous suppressor voltage in accordance with the modulation signal over a complete modulation cycle will vary the plate current to twice normal, and cause the plate voltage to vary similarly. Thus, on the modulation peaks, the power output is four times that of the carrier. Since sine-wave modulation is used, the average value of plate power will vary from the carrier value to 1.5 times the carrier at 100 percent modulation. Thus, the conditions for AM modulation are produced by effectively varying the tube plate current flow, using the suppressor grid to accomplish the variation under the control of a modulation voltage. Because the power is low, this is effectively an efficiency type of low-level modulator. Actually, the suppressor varies the final load line by controlling the grid-plate transconductance to vary the efficiency from a minimum value (about 33%) at zero modulation to full value (about 66%) at 100 percent modulation, as in the grid modulator.

FAILURE ANALYSIS.

No Output. Lack of output should first be isolated to failure of the r-f amplifier stage or the modulation signal circuit(s). Even though the modulator is operative, an open plate r-f choke (RFC2) or tank inductor (L), a defective electron tube, or a lack of grid excitation to the r-f amplifier will produce a no-carrier condition. Observation of the r-f plate current meter will determine whether the plate circuit has continuity. Tuning the tank capacitor for a maximum plate current indication with a resonant dip will determine that the tank circuit is operative, and that sufficient drive, a load, and the proper bias exist for operation without modulation. Grid drive meter indications will also show whether the proper amount of r-f drive exists. With the proper grid current, if the plate tank can be resonated for a minimum dip and then loaded to the maximum current, the trouble is in the modulator circuit.

Lack of grid drive places the trouble in the exciter stages of the transmitter or in the coupling network to the final stage. Lack of plate current indicates possible power supply trouble or an open-circuited r-f stage. Otherwise, proper performance but lack of ability to load to maximum current indicates antenna trouble, improper tuning, a weak power amplifier tube, or a defective transmission line.

With an r-f carrier existing, the trouble is definitely in the audio circuits or in the modulation transformer, r-f choke, or suppressor bypass capacitor. An open transformer secondary would remove the bias to the suppressor grid and cause an abnormal plate current reading without modulation, while a shorted transformer would allow the proper plate current and apparently normal carrier operation, but no modulation could occur (depending upon the effectiveness of the short circuit).

High transmitter plate current usually indicates short-circuited components or a lack of proper bias, while low plate current indicates excessive bias, high-resistance joints, low tube emission, or a possible lack of sufficient coupling to the load. With open-circuited conditions indicated on the equipment meters, a simple resistance analysis made with the power OFF, and with the **high-voltage supply grounded for safety,** will quickly determine the defective components.

Low Output. It must first be determined whether the low output is from lack of sufficient audio drive or from an actual reduction in the percentage of modulation. While low modulation is usually due to lack of sufficient audio drive, this can also occur because of a reduced setting of the audio gain control or because of trouble in the speech stages. An oscilloscope is very useful in determining the cause of malfunctioning, since the waveform itself may be directly observed. For simple, quick tests of modulation percentage, a trapezoidal pattern is useful. A waveform check, however, will not only show percentage of modulation but will also indicate waveform distortion, so that it is usually more useful. Too high a suppressor-grid bias will cause a reduction of output and an inability to reach 100 percent modulation with the same drive. The same effect will also occur if the control-grid bias is too high. Temporarily grounding the suppressor grid will produce maximum output if the control-grid bias is satisfactory. If incorrect control-grid bias is suspected, the bias can easily be checked by a simple voltmeter indication (use an r-f choke in series with the meter probe to avoid erroneous indications). As with the grid modulator, a steadily indicating plate meter does not necessarily indicate that there is no distortion or overmodulation. Since the changing of efficiency in the plate circuit is used to obtain the modulated output, although the plate current is changing instantaneously, one condition may cancel the other. Thus, either a steady current indication or a flickering current indication can be indicative of the same condition. It has been found that satisfactory operation requires the use of an oscilloscope to properly adjust the suppressor voltage and load for 100 percent modulation with a minimum of distortion.

Because of the low power involved, a partially shorted modulation transformer will not usually indicate its condition by external burnt spots or arcing. It will probably show as an inability to obtain 100 percent modulation, with all other components checked and the circuit apparently working normally in all respects. Where available, a negative variable d-c source can be used to simulate the change in bias with modulation, to quickly determine whether the stage is operating properly; if it is operating, the transformer certainly must be defective. Lack of sufficient filament emission in the r-f amplifier or modulator tube will cause peak clipping and a lower output because of the inability to obtain 100 percent undistorted modulation.

Distorted Output. Distortion can occur from a number of causes, and is easy to detect when monitoring audio modulation. Overmodulation will cause a chopping off of the carrier with carrier shift, producing severe interference to stations operating within a few hundred kilocycles of the carrier, and distortion. Nonlinearity in the control of the *grid-plate transconductance* by the suppressor grid bias will show as distortion; that is similar to the distortion caused by curvature of the grid-plate transfer characteristic in grid modulation.

In stages operating on the same input and output frequencies, there is the possibility of feedback from plate to grid, causing self-oscillation with severe distortion. Although the low plate-grid capacitance of the pentode makes this almost impossible, it does occur sometimes as a result of poor layout and external coupling between the tube elements, particularly at high frequencies. Self-oscillation can be easily detected by the characteristic fuzzy pattern produced on an oscilloscope. Oscilloscope connections and waveforms are shown in the BASIC MEASUREMENTS section of the EIMB, NAVSHIPS 900,000.103, Test Methods and Practices.

Since the suppressor grid does not draw current, the modulator has no trouble with changing load conditions as in the grid modulator; thus the distortion is usually limited to that caused in preceding speech amplifier stages. Generally speaking, there should be less distortion present in the suppressor-grid modulator than in other types of grid modulators.

TRANSFORMER-COUPLED, SCREEN-GRID MODULATOR.

APPLICATION.

The screen grid modulator is employed as a low-level modulator for screen grid tubes (tetrodes and pentodes) in applications where it is desired to use a minumum of audio (modulator) power. It is particularly useful for portable or mobile communications equipment to reduce size and power consumption.

CHARACTERISTICS.

Varies screen voltage to achieve modulation.

Requires slightly more power than control-grid modulator (about 1/4 the rated screen input for CW).

Produces maximum efficiency at 100 percent modulation and minimum efficiency for unmodulated (carrier) conditions.

Provides a carrier power of 1/4 that available from same tube in CW operation, and about 1/3 that possible with high-level plate modulation.

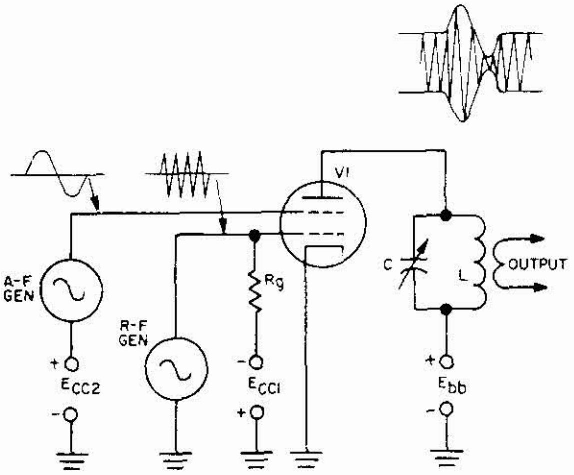
CIRCUIT ANALYSIS.

General. Screen-grid modulation is practically identical to the other types of grid modulation, with the exception that the screen grid is used to achieve the modulation instead of one of the other grids. This type of modulator, like the grid modulator, uses a form of efficiency modulation. It normally operates at half the maximum plate current in the resting or carrier condition, with no modulation, and at full current (twice normal) at 100 percent modulation. The efficiency is lowest, (about 33%) with no modulation, and highest (about 66%) with full 100 percent modulation. The carrier power represents one-quarter of the maximum power available with normal class C operation, with a peak power of four times the carrier value at 100% modulation. During sine wave modulation, the average power increases to a maximum of 1.5 times normal at the peaks of modulation, and this power is obtained from the same power supply by the change of efficiency wihin the tube.

This type of modulator requires a screen supply with good regulation, since the load, plate, and screen currents are instantaneously varying during modulation. It has the inherent disadvantage of being unable to achieve 100 percent modulation without distortion unless special compensation is provided.

Circuit Operation. The circuit of the basic screen-grid modulator is shown in the accompanying figure, using sine wave generators to represent audio and r-f excitation for simplicity.

It is clear from the figure that the circuit is practically identical to that of the control-grid or suppressor-grid modulator except for the tube grid element used. The conventional LC tank appears in the plate circuit, inductively coupled to the output load (antenna). The r-f drive is simulated by the rf generator, and supplies grid drive bias through R_g in addition to the fixed negative bias, E_{cc1}. As can be seen in the figure, the a-f generator supplies the modulation in series with the applied screen voltage. Thus as the modulation increases on the positive half-cycle (assuming a sine wave), the screen voltage and modulation add to produce a larger screen voltage. This increased screen voltage causes a greater plate current flow. On the negative half-cycles the modulation opposes the positive screen voltage, so that at the negative peak of modulation (at the trough) the screen voltage is effectively zero, almost preventing plate current flow.



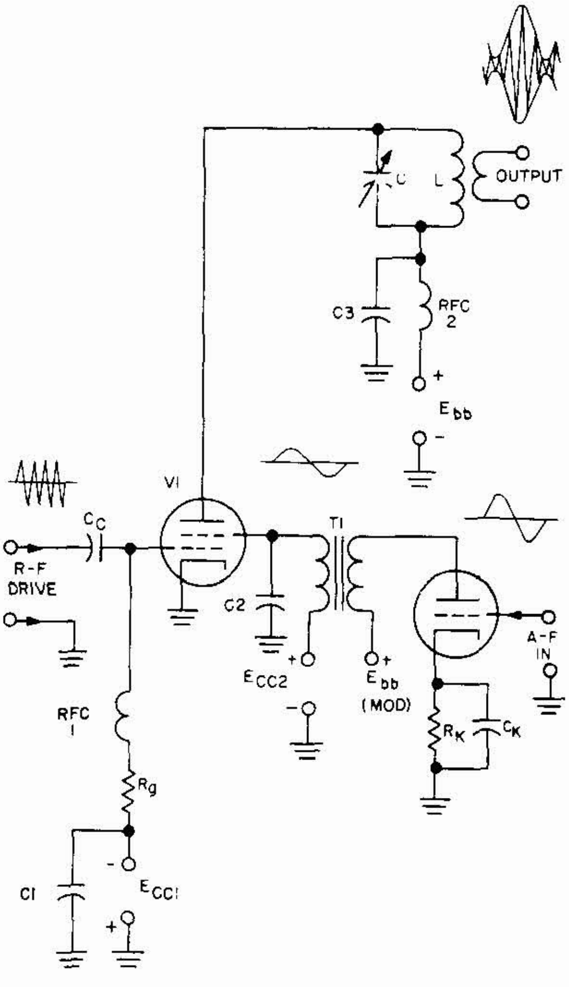
Basic Screen-Grid Modulator

Although the screen voltage is zero, the inherent construction of the tube requires that a negative potential be applied to the screen to completely stop plate current flow. Therefore, this type of modulator provides approximately 75% maximum modulation without distortion. If completely (100 percent) modulated, considerable distortion is produced.

Basically, however, by varying the screen potential in accordance with the modulation, a corresponding change in plate current is achieved, driving the plate current to twice the normal (carrier) value at 100% modulation and to almost zero on the negative peaks. This can be recognized as the same variations of current and voltage as described in the previous forms of grid modulators to produce amplitude modulation.

A schematic of a typical screen-grid modulator is shown in the accompanying figure.

In the figure, the r-f drive is coupled through C_c to the grid of V1, producing grid current and developing grid-drive bias across R_g, which is effectively in series with the fixed negative bias supplied by E_{cc1}. (Actually, cathode bias could be used instead of E_{cc1} since screen current always flows.) The plate circuit contains the conventional series-fed tank, isolated from the power supply by the rfc

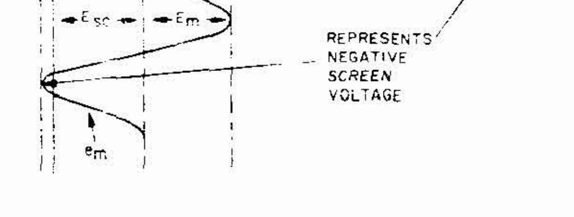


Screen-Grid Modulator

and bypassed by C3. In the grid circuit the rfc isolates the rf drive from the bias supply; it is bypassed by C1, which shunts to ground any rf leaking through the choke.

The audio modulation is coupled from the speech amplifier plate through transformer T1, whose secondary carries the d-c screen supply. Capacitor C2 serves to ground the screen grid as far as r-f variations are concerned, but is not large enough to bypass any of the audio modulation; otherwise, frequency distortion would result from a loss of the high frequencies bypassed to ground.

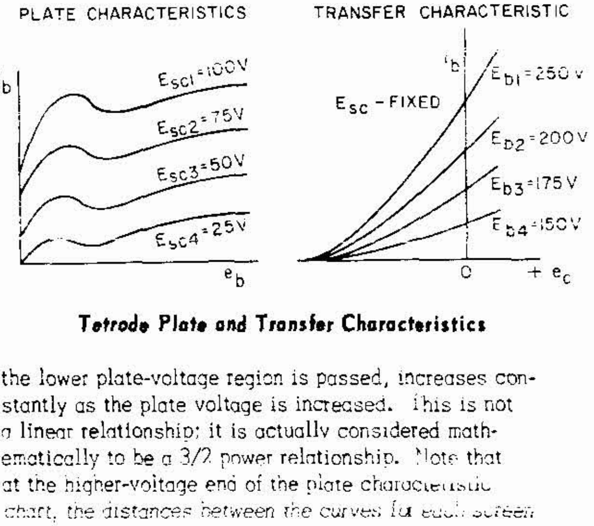
When the audio is applied to the screen of V1 through T1, and assuming a sine wave modulating signal, the screen voltage is increased on the positive half-cycle, and decreased on the negative half-cycle. Thus, as the positive modulating signal adds to the screen voltage, the screen current and the plate current both increase, reaching a peak at 100% modulation. Since the output voltage is the drop across the load, the output is the greatest at maximum plate current, and the actual plate voltage is at a minimum. As the modulation swings downward toward the negative half-cycle, the screen voltage is opposed by the negative modulation signal from T1. At the negative peak of modulation (the trough), there is practically complete cancellation of the screen voltage, and the screen current decreases to a minimum at this point. The output voltage is also minimum at this point, and the actual plate voltage, E_b, is practically equal to the applied plate voltage, E_{bb}. At resting or carrier value, the screen voltage is such as to produce one-half the maximum plate current obtained at 100 percent modulation (approximately one-half the value used for CW). Thus, as in other forms of grid modulation, the carrier value is one-fourth maximum, with a peak of four times the carrier value of power. The average power varies with sine wave modulation to 1.5 times the carrier value at full (100 percent) modulation. This extra power is obtained from the plate power supply. The power change is achieved by the changing efficiency of the plate circuit, produced by varying the screen voltage of the tube in accordance with the modulating signal. The figure below shows the screen voltage and output voltage relationships assuming that 100 percent modulation could be achieved, and illustrates the reason that screen-grid modulation cannot achieve 100% modulation without distortion. On the positive modulation peaks (approaching saturation), the grid-plate transfer curve flattens off so that large drive in the positive direction will flatten the peaks, causing distortion. Likewise, since zero screen voltage cannot produce plate current cutoff, the transfer curve drops off considerably at the zero screen voltage level. The effect is as though the bottom portion of the negative peak (the trough) of the modulation were cut off. To minimize this distortion, the screen must be operated between the limits where it is most linear; the practical result is to limit the modulation to about 70% for minimum distortion. In specially designed circuits where both the grid and screen are simultaneously modulated, this inherent fault can be overcome, but the modulation is no longer screen modulation; it is rather a combination of both types, and thus will not be further discussed.



Screen Grid Voltage and Output Voltage Relationships

Detailed Analysis. To understand the functioning of the screen-grid modulator, it is necessary to review the basic tube action and design. The accompanying figure shows a set of characteristic curves for a typical tetrode.

First examine the plate characteristics and note that for each fixed value of screen voltage ($E_{sc1,\,2}$ etc) a particular plate current can be obtained, which, after the lower plate-voltage region is passed, increases constantly as the plate voltage is increased. This is not a linear relationship; it is actually considered mathematically to be a 3/2 power relationship. Note that at the higher-voltage end of the plate characteristic chart, the distances between the curves for each screen voltage are nearly the same, and the lines are roughly parallel. Hence, it can be inferred that if the plate voltage is held fixed while the screen voltage is varied, there will be a somewhat linear relationship. That is, for a corresponding increase or decrease in screen voltage, there will be a proportional change in plate current. This means, then, that as the screen voltage is changed the plate current will follow, varying in a similar fashion. Since the output voltage is produced by the flow of plate current through the plate load, it is clear that the output voltage will vary similarly with the plate current. Examination of the grid-plate transfer characteristic shows that



Tetrode Plate and Transfer Characteristics

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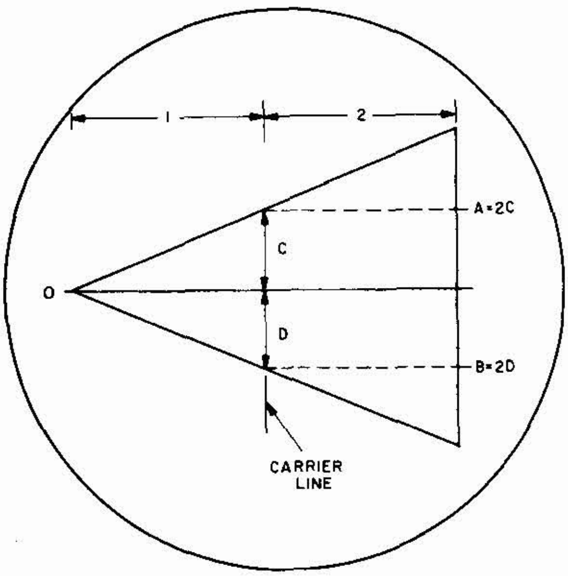
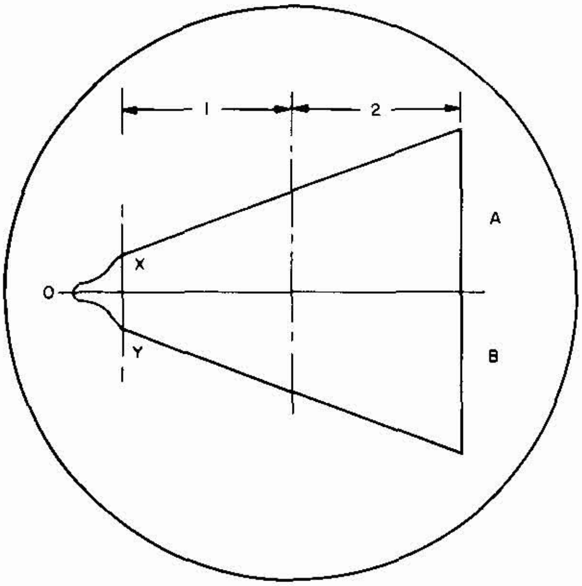
for a fixed screen voltage (E_{sc}) the plate current (i_p) does not vary much for low voltages (such as E_{b3} or E_{b4}), but does change somewhat for larger voltages (such as E_{b1}); it is affected more by control grid voltage changes (e_c). Thus, basic tube action indicates that either control-grid or screen-grid modulation is possible, and that plate modulation by variation of the plate voltage alone on screen grid tubes is not feasible.

Consider now the r-f drive and bias. Since the modulated r-f amplifier is to operate as a class C stage, the bias must be approximately twice the value of cutoff for a fixed screen voltage, and sufficient drive must be applied to drive the stage into light saturation on the positive peaks of the drive signal. (Refer to Section 6, Part A, RF Power Amplifiers Class B or C for background on class C operation.) The value of bias and excitation must be such that the plate voltage never drops lower than the screen voltage on the peaks of the modulation. Otherwise, excessive screen dissipation would occur, with the screen trying to act as the plate. The resting or carrier value of current is adjusted for exactly half the maximum load current, with the stage operating over the linear portions of its characteristics. Because of the varying efficiency and load changes, it is necessary to use an oscilloscope to determine proper operation.

Assuming perfect linearity, a typical oscilloscope presentation showing 100% modulation would appear as shown in the following figure. Note that the amplitudes between the line representing the carrier (C and D) and the ends of the pattern are equal, with straight sides indicating equal and linear modulation. Also, note that lines A and B extend equal distances above and below the carrier level (with AB = 2 × CD), and that the pattern extends to a perfect point at 0, indicating 100% modulation. Let us now examine a similar pattern illustrating screen-grid modulation, and note the differences.



Ideal Trapezoidal Pattern



Trapezoidal Pattern for Screen Modulation

Note that the sides are straight from points X and Y upward, indicating linearity between these points, but between O and X-Y the curvature indicates serious distortion. The distance XY as compared with AB indicates that the distortion occurs at about 70 to 75% modulation. Thus, the carrier must be adjusted so that it is centered at the point where line segments 1 and 2 mark off equal distances over the linear portion of operation if distortion is to be avoided. The illustration graphically shows the limitations on maximum modulation percentage without distortion for screen modulation. If operation is held to the left of the indicated carrier line to achieve 100% modulation, the distortion shown between points O and XY must be accepted.

The inability of the pattern to attain a point at O indicates that the maximum negative portion of the modulation signal does not quite reach cutoff and 100% modulation is not obtained. The distortion shown between O and XY is caused by actually driving the screen negative with the modulated signal on the negative peaks, to attempt to produce the cutoff of plate current. The reason for the departure from linearity is that with zero screen voltage at points X and Y, any slight change in the negative direction of screen voltage changes the plate current much more rapidly than does a similar positive increase in screen voltage. Hence, the line no longer remains straight; it has a faster slope, and curves rapidly downward toward zero or maximum negative modulation (the trough). In effect, we can say that at the zero screen voltage level, the tube no longer modulates equally above and below this point; hence the reason for the rapid change of waveform. The point of zero screen voltage is determined to some extent by the bias and grid drive. Thus, for particular value of bias it is possible to apply just sufficient drive to reach the peaks on the positive modulation cycle and move point XY to the left slightly to attain linear modulation over a greater portion of the cycle. Such an adjustment, however, must be made with an oscilloscope; it cannot be predetermined by design.

In Navy equipment, the design and adjustments are preset by the manufacturer so that by setting the operating values of plate current and voltage to those listed in the Technical Manual for the equipment, the proper results will be obtained to meet the manufacturer's specifications.

Consider now the modulator power requirements. Since the screen is being modulated, the peak screen voltage divided by the peak screen current will provide the maximum load impedance value. A rough approximation of power can be obtained by using the peak screen voltage and current and dividing by 8. Thus, for a 400-volt, 10-milliampere screen load, 500 milliwatts (1/2 watt) is required for maximum modulation. To help stabilize the constantly varying load and keep power supply fluctuations to a minimum, and to achieve good regulation of the modulator, a power capacity of three to four times this value would be used (1-1/2 to 2 watts), and the modulator would be loaded down with a swamping resistor to stabilize the load. With the 400-volt, 10-ma load, 40,000 ohms would be indicated. By providing 40,000 ohms for each half-watt, a total load of 10,000 ohms would be obtained with a 2-watt amplifier as modulator. Thus, reflected load changes in the screen circuit are minimized so that the modulator provides sufficient current and voltage for stable operation.

Another method of accomplishing the same thing is to use negative feedback in the modulator. This tends to reduce the plate resistance and the sensitivity to voltage changes caused by load changes. In addition, negative feedback helps improve the modulator frequency response, so that resistance loading has been generally discarded, although it may be occasionally encountered.

It it evident, then, that screen-grid modulation requires somewhat more power than the other types of grid modulation (because of screen load and regulation requirements); in turn, however, it provides better over-all linearity. In summation, it can be said that screen-grid modulation achieves its changing efficiency by operating on a different load line for each value of screen voltage, with maximum plate dissipation occurring at the carrier level.

FAILURE ANALYSIS.

No Output. Lack of output should first be isolated to failure of either the modulated r-f stage or the modulator and speech circuits. Lack of a carrier output indicates failure of the r-f stage, while lack of modulation on the otherwise normal carrier indicates failure in the speech or modulator stages, or a lowered gain control. A no-carrier indication can be caused by an open plate rfc or tank circuit, a shorted or gassy electron tube, lack of grid excitation, too high a bias, or lack of screen voltage due to a defective modulation transformer, a shorted screen capacitor, or a defective screen supply.

Observation of the r-f plate current meter will determine whether the plate circuit is open, and tuning for maximum indication with a resonant dip will determine whether sufficient drive and load and the proper bias are present. Where grid current meters are part of the equipment, the obtaining of normal or greater than normal grid current indicates that the exciter stages are operating properly; with lower than normal grid current, the driver stages are at fault or the d-c bias on the control grid is too high. The bias may be determined by a simple voltage check (use an rfc in series with the voltmeter test prod, and check the grid to ground voltage). Inability to load the stage indicates a faulty antenna or a transmission line trouble.

With the r-f stage normal, the trouble must be in the modulation transformer, screen bypass capacitor, or the preceding speech stages. An open modulation transformer would remove the d-c screen voltage, and the r-f stage would give a no-output indication. With a short-circuited transformer, the r-f stage would appear to operate normally, but no modulation would be obtained. With the low power usually involved, it is doubtful that visible evidence such as charred insulation or arcing would be apparent, so that it may be difficult to isolate modulation transformer trouble if the transformer is internally shorted. Usually a resistance analysis will check continuity. Checking the transformer for turns ratio with an a-c source and a voltmeter will usually determine whether it is operating properly.

High plate current usually indicates short-circuited components or a lack of proper bias, while low plate current indicates excessive bias, high-resistance joints (poor soldering), low tube emission, or possible lack of sufficient coupling to the load. With open-circuited or short-circuited conditions indicated on the equipment meters, a simple resistance analysis made with the power OFF, and the **high-voltage supply grounded for safety,** will quickly determine the defective components.

Low Output. First determine whether the low output is due to lack of sufficient audio drive, or to an actual reduction of percentage modulation as a result of trouble in the modulator. With the speech gain control at its proper setting, low output indicates loss of audio (modulator) power or lack of r-f drive. Use an oscilloscope to determine the cause of malfunctioning. Make a trapezoidal check of modulation percentage to determine whether 100% can be obtained. Since some distortion is normal, the trapezoidal check can be used as a rough check on linearity by determining whether the sides of the pattern are straight and observing that the pattern expands equally on both sides of the carrier line; otherwise, the positive and negative peaks are unequal.

If you are unable to reach the 100% modulation mark, reduce the loading and see whether the percentage improves. Too great a load can produce too high an efficiency and make it impossible to obtain the proper output from the modulator. Under normal operation (no modulation) the tube must be drawing no more than half the maximum plate current possible in normal class C operation.

Since grid drive determines the efficiency to some extent, reduce the drive and see whether the percentage of modulation improves. It will probably be found that there is a point of minimum grid drive and minimum loading that will produce a completely modulated signal. At other settings the output may be greater, but it will be impossible to obtain complete modulation. Use the lower output, since loss of modulation varies as the square of the modulation factor; that is, 25% loss of modulation is actually a 50% loss of usable power, and can be the difference between being heard and not heard at all.

Low output caused by lack of sufficient drive will be indicated by a flattening of the positive peaks because of inability to reach full peak power. Lack of sufficient filament emission can also cause a similar condition.

Distorted Output. Distortion can occur from a number of causes, and is easy to detect when monitoring audio modulation. Overmodulation will result in a chopping off of the carrier, with carrier shift, causing excessive distortion and severe interference at stations within a few hundred kilocycles of the carrier. Since in screen-grid modulation it is necessary to drive the screen negative to obtain 100% modulation, it is to be expected that a large amount of distortion will occur on the peaks. For undistorted output, the screen should never be driven negative.

Because of the constantly varying load, the speech amplifier producing the audio modulation will contain excessive distortion unless swamping resistors are used to load the modulation transformer, or unless negative feedback is used. In this event, using an oscilloscope to determine linearity between the input and output signals in the modulator will quickly locate any excessive distortion in those stages. (Refer to NAVSHIPS 900,000.103, Test Methods and Practices, Basic Measurements Section, for oscilloscope connections and waveforms.)

Although screen-grid tubes provide sufficient grid-plate isolation, so that neutralizing is unnecessary, it is possible that at the very high frequencies self-oscillation can occur in the r-f stage and cause distortion. This is particularly true if parts have been replaced and the lead dress has been disturbed. The characteristic fuzzy pattern (on an oscilloscope) produced by oscillation will quickly reveal this condition.

Inability to obtain full modulation can be due to the lack of filament emission in the r-f stage, which will cause flattening of the positive peaks and a consequent increase in distortion. This condition can be seen on an oscilloscope, but it will not normally be revealed by meter indications, except by a gradual reduction of plate current over a long period of time. A similar condition can result from drying out of electrolytic filter capacitors in the power supply, but it will usually show as hum on the carrier before the loss of peak current and voltage causes noticeable distortion. Such conditions are not apparent unless an oscilloscope is employed to monitor the waveform.

TRANSFORMER-COUPLED PLATE AND SCREEN MODULATOR.

APPLICATION.

The plate and screen modulator is employed as a high-level modulator for screen-grid tubes (tetrode and pentode) in applications where the simplicity and fidelity of plate modulation are desired.

CHARACTERISTICS.

Varies both the plate and screen voltages to achieve modulation.

Requires a modulator power equivalent to 50 percent of rated carrier plate and screen power.

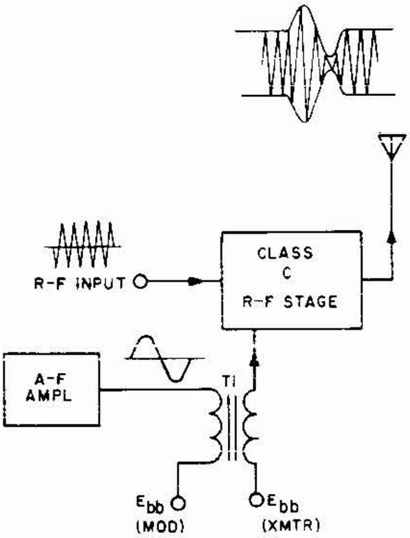
Operates at a constant efficiency of 70 percent or better.

Provides maximum carrier power for a given tube type.

CIRCUIT ANALYSIS.

General. The plate and screen modulator is practically identical to the triode plate modulator, except for provisions to accommodate the changes caused by introduction of the screen grid into the tube. This type of modulator is not a low-level form of modulator; instead, it is a high-level constant (high) efficiency type of circuit. The modulator itself must furnish the 50 percent additional power required for the production of the side-bands. The modulated r-f stage must also have a power supply capable of supplying the additional power for the screen circuit, or have a separate screen supply to furnish the power for the screen. During sine wave modulation the plate voltage and current are doubled to provide a peak power of four times normal, and the average power is increased to a maximum of 1.5 times normal carrier value, thus providing the proper conditions for 100 percent AM modulation. The use of the screen-grid tube, with its low grid-plate capacitance and shielding effect, reduces the internal plate-to-grid feedback, minimizing the possibility of self-oscillation and the need for neutralizing circuit arrangements. The increased sensitivity of the screen-grid tube also permits less excitation and driving power to be used as compared with the triode.

Circuit Operation. A simplified diagram of the basic transformer-coupled plate and screen modulator is shown in the accompanying figure. The a-f modulator stage is represented as a block, since it may be any one of a number of audio amplifier combinations as long as the proper audio power output is obtained. Likewise, the r-f output stage is also represented as a block, since it may consist of any arrangement of tubes to produce the desired carrier output to the antenna. The r-f stage is always biased so that it operates as a class C amplifier.
Since class C operation requires twice the cutoff bias, a separate bias supply is usually used, with supplemental bias from grid drive through a grid leak. The total bias is a combination of the two types. In case of failure of grid drive, the fixed bias provides a protective bias to prevent exceeding tube ratings and consequent damage to the tube.
Thus far in the discussion the plate and screen modulator is identical with the plate modulator. The difference lies in the manner in which the modulation is achieved, that is, by also modulating the screen voltage. There are three basic methods used; each will be discussed in the following



Basic Plate and Screen Modulator

paragraphs. For the present it suffices to say that both the screen and plate voltages are varied from zero to twice normal to accomplish the modulation exactly as described for the plate modulator discussed previously.

Screen Voltage-Dropping Circuit. Since the screen voltage is always much lower than the plate voltage, it is necessary either to provide the screen voltage from a separate power supply, or to obtain this voltage from the plate supply by means of a series dropping resistor. By far the simpler method, although somewhat wasteful of power, is the use of a series dropping resistor, as shown in the following figure. As can be seen from the illustration, the screen voltage is obtained by a series voltage dropping resistor (R_{sc}) connected to the plate supply. The screen current through this resistor produces sufficient voltage drop to lower the plate supply voltage to the proper value for application to the screen. The actual screen voltage at all times is the supply voltage minus the drop across the resistor ($E_{sc} = E_{bb} - IR_{sc}$).

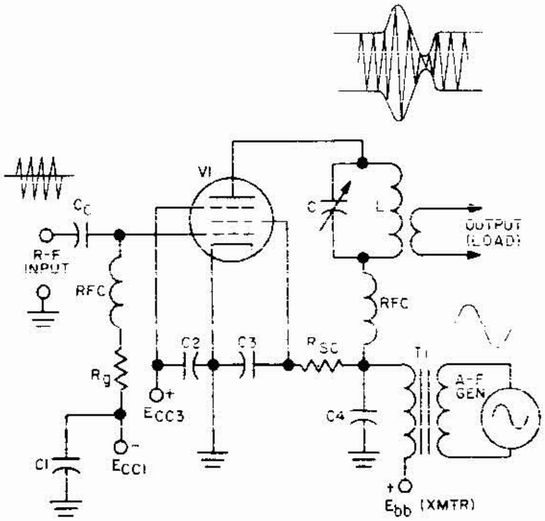
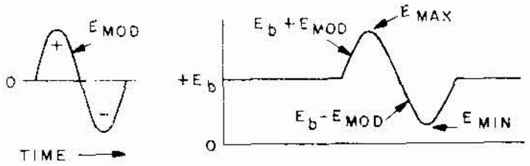


Plate-and-Screen-Modulated Pentode

As shown, the r-f grid excitation is capacitively coupled through C_c, and grid drive bias is obtained through R_g, supplemented by fixed negative bias. The rfc isolates the r-f drive and prevents it from feeding back through the grid supply or from shorting to ground, while C1 provides an r-f shunt to ground for any remaining rf which might leak through the rfc.

The suppressor grid is shown supplied with a small positive bias and shunted to ground for rf by C2. This connection will vary according to the type of tube. In tetrodes (since they do not have a suppressor grid) it is nonexistent. In beam-forming screen grid tubes it will be the beam-forming plates, and will be connected as recommended by the tube manufacturer. In other types of pentodes the suppressor may be internally or externally connected to the cathode directly, and C2 is not needed. In those types of pentodes which require it, the suppressor connection will appear as shown on the schematic above. In this instance the slight positive bias is added to enhance the shielding effect of the suppressor at low plate voltages, and it also prevents the screen from intercepting any secondary electrons and acting as a plate. At almost zero voltage, any electrons will be attracted to the more positive suppressor and returned to ground. Thus zero plate current is possible with a sharper cutoff than when the suppressor has a negative potential applied. The screen grid voltage is obtained from the plate voltage source through screen voltage dropping resistor R_{sc} bypassed by C3 and C4. Capacitor C3 also insures that the screen is at ground potential to rf, permitting only dc or the relatively low-frequency modulation components to vary the screen voltage. Capacitor C4 is the conventional series plate-feed bypass capacitor. The secondary of T1 is connected in series between the plate-and-screen power supply, with the rfc isolating it from the tank circuit rf. Capacitor C4 also insures that any rf which might leak through the rfc is shunted to ground, and its reactance is high to audio frequencies in order to prevent loss of high-frequency response. The conventional tank components, C and L, are inductively coupled to the load. The audio output from the modulator appears at the secondary of T1, and is added to or subtracted from the applied d-c plate voltage (and screen voltage) to produce an instantaneous effective plate (and screen) voltage which varies in accordance with the modulation.

Consider now one cycle of operation. At the resting condition, with no modulation, an unmodulated carrier is produced, and the applied plate and screen voltages at that time consist of only the d-c component from the power supply. As the modulation is started, assuming a sine wave progressing from zero through the positive half-cycle, the instantaneous audio output voltage (from T1) adds to the positive plate and screen voltages, and both voltages are increased. The following illustration shows how the plate and modulation voltages are combined to form the composite instantaneous plate voltage. (The screen voltage is also modulated similarly.) Since a resistor is not frequency-sensitive, equal voltage drops occur across the screen dropping resistor for all audio frequencies in the modulation; thus the screen voltage is dropped linearly and is also increased linearly with respect to the modulation signal. At the positive peak of modulation, the plate voltage is twice normal and the screen voltage is somewhere between 1.5 to 2 times normal, depending upon the screen current (usually around 1.5 times). It can be seen that, since the d-c screen voltage is increased by the addition of the instantaneous modulation component, the same result is produced as in screen modulation; that is, the plate current is increased. Because the plate voltage is also increased simultaneously and the class C output is proportional to the square of the plate voltage, the plate voltage also helps to increase the total tube current. Recalling from basic theory that the screen voltage determines the plate current much more than the plate voltage, it can be understood that variation of plate voltage alone would not produce 100% modulation since the tube current would not increase sufficiently on the peaks. (For an unmodulated screen, about 90 to 95 percent is the highest modulation obtainable.) Thus it is clear that variations of both the plate voltage and the screen voltage combine to produce the 100 percent modulation capability.



Combining of Plate and Modulation Voltages

As the modulation proceeds toward its negative half-cycle, both the screen voltage and the plate voltage are reduced, and the plate current follows. Thus at the negative peak (the trough) of modulation the plate voltage is almost zero, and so is the screen voltage. Actually to avoid excessive screen dissipation, the plate voltage is never driven below the screen voltage. In this case, since the screen voltage is obtained from the plate source through a dropping resistor, the screen voltage is always lower than the plate voltage; thus it is practically impossible to drive the plate voltage to zero, except if the screen is driven negative. With negative screen drive, non-linearity causes distortion, so that normally the modulation is adjusted to just keep from driving the screen below zero. Normally, the plate current is reduced to a value near zero, and full modulation from zero to twice normal plate current and voltage are obtained. The peak power is four times the normal carrier value, and the average power increases supplied by the modulator is 1.5 times normal, or 50 percent of the rated carrier power.

Separate Screen Supply Circuit. The second and more complicated method of supplying screen voltage, but perhaps the more commonly used method, is to supply the screen voltage from a separate power source. This circuit is shown in the accompanying figure, and is seen to be identical to that of the plate and screen modulator just discussed, except for the replacement of R_{sc} with choke L_1 and a separate screen supply. The screen power supply need only supply a fraction of the plate power. Most screen grid transmitting tubes use from 250 to 750 volts on the screen, with a plate voltage of 1000 to 4000 volts, and screen dissipation runs from 5 to 10 percent of the plate dissipation for high-power tubes, to 10 to 20 percent for low-power tubes, or a maximum of about 50 watts for medium power transmitters. This screen power supply provides only d-c voltage; therefore, some provision must be made to increase and decrease the screen voltage in accordance with the modulation, to control the plate current. Such action is produced by the choke, L_1, placed in series with the screen lead. From basic theory it is known that the electrical inertia produced by the field around the choke tends to prevent a change in the flow of current through the choke. When the current ceases or reduces, the magnetic field collapses and tends to produce a voltage from the choke which will keep current flowing in the same direction. To do this it is evident that the voltage produced must be of the same polarity as that applied originally to the choke. When the modulation signal goes positive and increases the plate voltage, more electrons are attracted to the plate and less to the screen grid. That is, the total space current remains about the same, but the current dis-

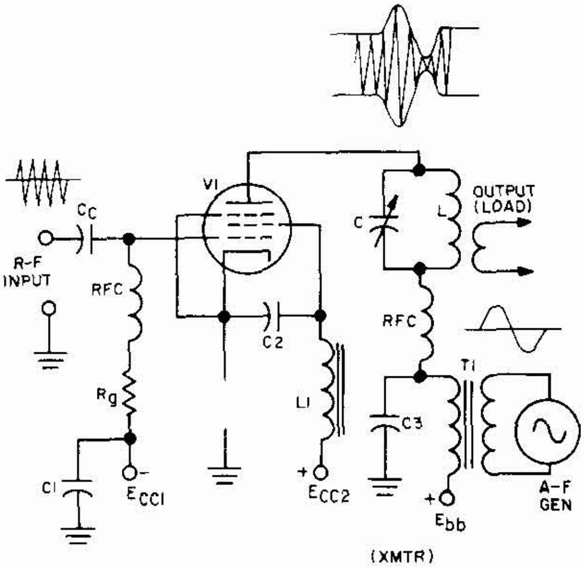


Plate-and-Screen-Modulated Pentode with Separate Screen Supply

tribution between the screen and plate changes. When the screen current reduces, an increased voltage is produced in the same direction, to add to the effective screen voltage before the modulation increased; this produces a slightly higher screen voltage, which, in turn, helps the plate current to increase. On the negative modulation swings, a similar but opposite condition occurs. As the plate current tends to reduce, the screen current tends to rise. The inertia of the choke tries to prevent the rising current and provides a negative-going voltage which decreases the effective positive screen voltage. Thus the plate current is helped to decrease. Since the screen grid controls the plate current much more effectively than changing the plate voltage, the slight changes in screen voltage produced by the choke, in turn, produce the desired effect. Capacitor C2 bypasses the screen to ground and prevents feedback of rf into the audio circuits. Capacitor C3 is the conventional plate bypass for series feed. The value of C3 is usually such that it has a high reactance to the audio frequencies, in order to avoid the possibility of frequency distortion due to shunting of the highs to ground. The screen bypass capacitor is usually about twice this value, since the reactance of choke L_1 is effectively in series with the capacitive reactance, limiting the shunting effect of C2. The choke must have sufficient power-handling capability to carry full screen current, and is usually on the order of 5 to 10 henrys. If it is too small, 100 percent modulation will not be obtained, and if too large it will produce phase shift at the low audio frequencies and attenuation at the high audio frequencies, causing some distortion. The actual value is chosen to have a reactance which is not less than the screen impedance at the lowest desired audio frequency. The screen impedance is approximately equal to the d-c screen voltage divided by the d-c screen current (Z = Esc/Isc).

With this circuit, actual cutoff bias can be obtained, so that the bias can be adjusted for twice the cutoff value for proper class C operation. (With the voltage-dropping resistor type of circuit, the screen voltage becomes so high at low plate current that cutoff can never actually be attained; thus the theoretical value specified by the manufacturer is used to determine the operating bias.) As far as modulation is concerned, the choke produces voltage variations on the screen in phase with the modulation; this causes the plate current to increase on the positive modulation excursions and to decrease on the negative excursions, assisting the plate voltage variation, since variations in screen grid voltage have more control over the plate current than do variations in plate voltage. Thus the full limits of AM modulation are obtained, exactly as if the tube were a triode and were completely controlled by plate voltage variations. Peak power is four times the normal carrier value, and the output increases 50 percent at full modulation, being supplied from the modulator. At the peak of modulation, maximum plate dissipation and power output occurs, with the efficiency remaining relatively constant throughout the audio cycle.

Transformer-Coupled Screen Modulator. The third basic method of plate and screen modulation is to provide an extra winding on the modulation transformer to provide the proper voltage ratio. In this method the d-c screen voltage from a separate supply has a modulation component added which is proportional to the plate change in accordance with the transformer turns ratio. This method is costly, and is seldom used because of the simplicity of the previously described methods. The circuit operation is similar to that for the voltage-dropping method, except that the transformer, instead of the dropping resistor, supplies the proper voltage. Therefore, this method will not be further discussed.

Detailed Analysis. To understand the functioning of the plate-and-screen-modulated circuit, review the operation of the triode plate modulator previously discussed in this section before proceeding further (see TRANSFORMER-COUPLED PLATE MODULATOR circuit). It is evident now that the only differences between the two circuits are those resulting from the addition of the screen grid to the tube. It is necessary to return to elementary electron tube theory to explain some of the differences in operation caused by the screen grid.

The addition of the screen grid provides a greater grid-plate transconductance, and, consequently, requires less drive power from the r-f driver to excite the modulated class C stage to saturation. Since the screen is located between the grid and the plate and always has a positive voltage applied, the problem of minimizing grid dissipation at minimum plate voltage is eliminated. (On the peak of the negative plate excursion, during modulation, the triode grid tends to become more positive than the minimum value of plate voltage. As a result, excessive grid current flows and causes the grid dissipation to increase.)

While in the preceding discussions we have spoken of having the modulation voltage reduce the screen and plate voltages to zero, during the modulation cycle, this does not exactly occur. The action which does occur can be understood more clearly if the desired action is first explained. In this instance, the object is to reduce the plate current to zero, during the conducting period of the class C cycle, coincidentally with **minimum** (almost zero) plate voltage, which is produced when the negative peak (trough) of the modulation effectively cancels the applied plate voltage. Since the screen voltage exercises a greater controlling factor than the plate voltage, it is possible to reduce the plate voltage practically to zero without actually reducing the screen voltage to zero. When the drop across the load makes the actual plate voltage zero, the applied voltage is still above zero by the amount of voltage drop in the load. This is the applied screen voltage, which is still further reduced by the screen dropping resistor. However, the actual screen voltage always remains more positive than the small positive grid voltage swing. Thus grid dissipation because of low plate or screen voltage is minimized.

Consider now the effect of screen voltage on plate current, which mathematically follows a 3/2 power law as shown in the following table.

Multiplying Factor	Plate Current Value (3/2)
.25	.125
.5	.35
.75	.65
1.0	1.0
1.25	1.4
1.5	1.84
1.75	2.3
2.	2.8

If the screen voltage exactly follows the power law, it is only necessary to vary the screen voltage to about 1.6 times normal to double the plate current. Likewise, it is only necessary to reduce the screen voltage to about 15 percent of normal to obtain practically zero plate current. It can be understood, then, why it is not necessary to drive the screen to zero and twice normal in order to drive the plate voltage and current to zero and twice normal. Thus it can be seen that the previous statements are not exactly true; however, since the tube does not exactly and always follow the 3/2 power law, it is not possible to make a more exact statement and be completely accurate. It is probably more accurate to say that the screen grid voltage is varied sufficiently to insure that the full plate current flow of twice normal is possible on the peaks of modulation when the plate voltage is increased twice normal. Under these conditions the requirement of a peak power of four times normal for full modulation is met, and the tube is used to its fullest capability.

Since the plate current does not vary linearly with screen voltage, it can be seen that varying the screen voltage linearly in accordance with modulation does not produce distortion-free plate components. That is, as long as the plate voltage and plate current do not vary exactly and linearly with the modulation, distortion exists. Thus the screen grid modulator inherently produces more distortion than the simple triode modulator produces, but with proper design this distortion is minimized to a low value. A comparison in this instance is the distortion products given with a simple triode audio stage as compared with pentode or beam tube audio stage. In every instance the distortion is greater, but the increased power-handling capabilities and low grid drive requirement make it mandatory to use the triode only where the increase in distortion cannot be tolerated.

In considering the action at low screen and plate voltages, the type of tube becomes an important factor. A typical comparison of plate current variation with plate voltage for two different types of screen grid tubes, and for pentode and beam tubes, is shown in the accompanying graph. It is easy to see that the beam and pentode types of electron tubes have much less variation of plate current at low voltages than the screen grid type has. Thus, when a suppressor grid is not included, reduction of plate voltage below the screen voltage produces undesired secondary emission effects, and can even cause the plate current to go negative (reverse its direction of flow). Since on the troughs of modulation (the negative peak modulation excursions) the plate voltage was said to be reduced practically to zero, together with the screen voltage, it can be seen that some unwanted effects can occur.

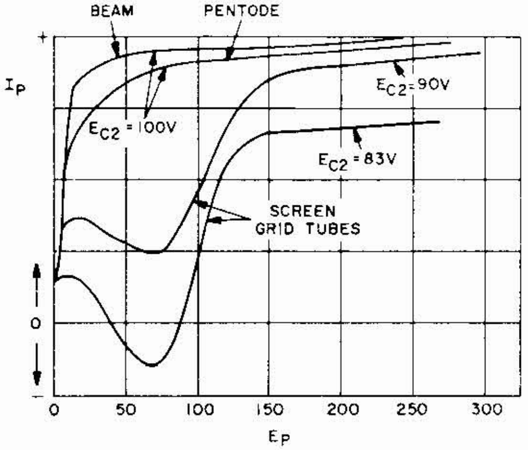


Plate Current Comparisons

Consider first the beam and pentode tubes, since their action is similar. From the graph it is clear that the plate voltage can be reduced to about 10 to 15 volts before the current changes appreciably and suddenly drops off to zero. Thus it is possible to swing the plate voltage lower than the screen voltage without any unwanted effects. The plate current, however, does not change linearly with the plate voltage swing. Therefore, it is necessary to vary the screen voltage in order to change the plate current in accordance with the modulation, even though the plate voltage is varied. Because of secondary emission effects, it is clear from the graph that screen grid tubes (two different tubes are shown) cannot be used at low plate voltages. If they were used, extreme distortion would occur at low plate voltages, and, even though the screen voltage were varied likewise, a similar pattern would follow. Thus the screen grid tube cannot be operated with as low a plate swing as the pentode and beam tubes without excessive distortion. In considering the swing to practically zero voltage and current, it is evident that in most every case the swing is to a small minimum voltage rather than actual zero. Whether the minimum is very small or fairly large depends upon whether or not the tube is a beam-pentode or screen-grid type. It is also clear that because of the relatively high minimum plate voltage on a screen grid tube, less usable output is obtained than for a similar beam or pentode tube.

From a consideration of the small change of plate current with a large plate voltage swing, as shown in the preceding graph, it should also be clear that the screen-and-plate-modulated circuit functions primarily as a screen-modulated type of circuit with the plate voltage aiding.

That is, while the screen voltage changes the plate current, the corresponding change in plate voltage is in a direction which enhances the action. When the plate voltage is increasing, so is the screen voltage, and so is the plate current. Thus the problem of non-linearity on negative swings in the screen grid modulator is overcome because in the plate-and-screen-modulated circuit the plate voltage is reduced at the same time. Therefore, it is not necessary to swing the screen negative to get complete modulation.

FAILURE ANALYSIS.

No Output. Lack of output should first be isolated to failure of the r-f amplifier stage or the modulation signal circuit(s). Even though the modulator is operative, an open rfc or tank circuit, a shorted or gassy electron tube, or lack of grid excitation to the r-f amplifier will produce a no-carrier indication. Observation of the r-f plate current meter will determine whether the plate circuit has continuity, and tuning for a maximum indication with a resonant dip will determine whether sufficient drive, load, and the proper bias exist for operation without modulation. Grid-drive meter indications will also show whether the proper r-f drive exists. When the tank can be resonated for a minimum dip and then loaded to the maximum plate current with normal grid current, the trouble is in the modulator circuit.

Lack of grid drive places the trouble in the exciter stages of the transmitter or in the coupling network to the final stage. Lack of plate current indicates possible power supply trouble, an open-circuited r-f stage, an open screen-voltage dropping resistor (in some tube types a very small plate current may still flow), or a shorted screen bypass capacitor. In the choke-fed screen modulator, an open choke would remove screen voltage and prevent plate current flow. Otherwise, proper performance, but lack of ability to load to maximum plate current, indicates antenna trouble, improper tuning, or a defective transmission line.

With an r-f carrier existing, the trouble is definitely in the audio circuits or in the modulation transformer, rfc, and screen or plate bypass capacitor.

High transmitter plate current usually indicates short-circuited components, a lack of proper bias, or improper tuning, while low plate current indicates excessive bias, high-resistance joints, low tube emission, or possible lack of coupling to the load. When the above conditions are indicated by the equipment meters, a simple resistance analysis made with the power OFF and **the high-voltage supply grounded for safety** will quickly determine the defective component(s).

Low Output. Determine first whether the low output is from lack of sufficient audio drive or from an actual reduction in the percentage of modulation. Low modulation is usually caused by lack of sufficient audio output, but it can also occur from a reduced setting of the audio gain control or from trouble in the speech stages. An oscilloscope is very useful in determining the cause of malfunctioning, since the waveform itself may be directly observed. For simple, quick tests of modulation percentage, the trapezoidal waveform is useful. The envelope or waveform check, however, will show percentage of modulation and also indicate waveform distortion; thus it is usually more useful. Too high a control grid bias will cause a reduction of output and an inability to reach 100 percent modulation with the same drive. The grid bias can be checked simply with a voltmeter (connect an rfc in series with one of the prods). A reduced screen voltage is most likely of all to produce a low output, usually with overmodulation or distortion, since the plate and screen swing will be excessive. Such a condition can be caused by too heavy a screen current causing a large drop in the screen-voltage dropping resistor, by a defective resistor, or by a partially shorted bypass capacitor.

In the choke-fed screen circuit, a defective choke will prevent the obtaining of complete modulation and can also result in reduced output, as can a poorly soldered joint. Check the coil for the proper resistance with an ohmmeter. A partially shorted choke may give the proper indication when measured with a dc ohmmeter, but short across turns when operating. Such a condition will usually be indicated by audible noise or distortion when the signal is monitored.

Lack of sufficient filament emission can cause a flattening of the positive peaks, and inability to obtain 100 percent modulation. Lack of ability to reach 100 percent modulation at the high frequencies, while obtaining it at low and medium frequencies, would indicate a capacitive shunting by screen or plate bypass capacitors, provided the speech amplifier response is satisfactory.

Distorted Output. Distortion can occur from a number of causes, and is easy to detect when monitoring audio modulation. Overmodulation will cause a chopping off of the carrier (carrier shift), producing severe interference to stations operating near the transmitter frequency, and cause distortion.

In stages operating on the same input and output frequencies, there is always the possibility of sufficient feedback from plate to grid to cause self-oscillation, with severe distortion, particularly on the peaks of modulation. Although the low plate-grid capacitance (shielding effect) of the screen and pentode tubes makes this almost impossible, it will sometimes occur, especially at the higher frequencies, because of poor layout and external coupling between the tube elements. Such action can occur, particularly after part replacement and changed lead dress from a repair. Self-oscillation can usually be detected easily by its characteristic fuzzy oscilloscope pattern.

Lack of sufficient capacitance to supply the peak power requirements can occur through drying out of electrolytic filter capacitors, and cause peak flattening with its consequent distortion. Usually, however, such a condition will be indicated by hum on the carrier or in the modulation before the distortion is excessive enough to notice, unless an oscilloscope is used to monitor transmissions.

A similar condition, caused by lack of sufficient emission in the r-f amplifier will cause peak flattening with noticeable distortion. This can sometimes be observed by noticing the lack of ability to respond to high modulation peaks and by a gradual decline in the plate current reading over a long period of time. Under normal conditions an r-f ammeter will indicate approximately a 22 percent increase in output current at 100 percent modulation.

TRANSFORMER-COUPLED CATHODE MODULATOR.

APPLICATION.

The cathode modulator is generally employed for low-level operation where the audio power is limited and the inherent distortion of the grid-modulated circuit cannot be tolerated.

CHARACTERISTICS.

Varies the cathode voltage to achieve modulation.

Operates as a combination plate and grid modulator, and can be designed to function either way.

Requires an audio output of 5 to 50 percent of the r-f plate input, depending on design.

Requires only half the normal r-f drive for class C conditions.

Provides a higher efficiency than the grid-modulated types and lower efficiency than the plate-modulated types, depending on the design. (For the 50 percent grid and 50 percent plate modulation condition, the efficiency is 62 percent.)

Provides better linearity than the grid-modulated types, and can be made equal to the plate-modulated type of circuit.

Can be used equally well with triodes, tetrodes, or pentodes.

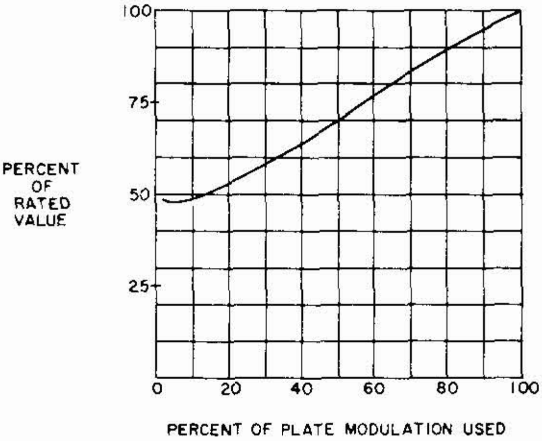
CIRCUIT ANALYSIS.

General. The cathode modulator varies the voltage of the cathode to produce the modulation envelope. Since the cathode is in series with the grid and plate circuits (and the screen circuit for tetrodes), it can be seen that changing the cathode voltage will effectively change the voltage of the other tube elements. By proper proportioning of the voltages, the injected cathode voltage can be caused to operate the tube in a form of grid modulation with relatively low efficiency, or to operate it in a form of plate modulation with high efficiency. Usually, the cathode modulator is made to perform about midway between these two classes, utilizing the advantages of each type. Thus, generalizing, it can be said that the cathode modulator normally operates at efficiencies on the order of 55 to 62 percent, and requires modulator (audio) power of about 20 to 25 percent of the rated carrier power.

As a result, more linear operation is achieved than in other types of grid modulators, with only a slight audio power increase being required to obtain it. As in all forms of AM modulation, the plate voltage and plate current vary from zero to twice normal with a peak power of four times normal at 100 percent modulation. Whereas the grid modulators vary the grid bias to produce a varying efficiency which develops the required power increase from the regular transmitter supply, and operate at half the tube capability with carrier alone, the cathode modulator operates somewhat like the plate modulator. That is, the additional power required for modulation comes mainly from the audio modulator, with the transmitter stage supplying the remaining power by a variation of efficiency. Since the cathode modulator is basically a half grid and half plate modulator, it forms a unique type of circuit. When operated mainly as a grid modulator it offers little if any advantage over other types of grid modulation, and when operated mainly as a plate modulator it offers practically no advantage over straight plate modulation for a triode; however, with a pentode or tetrode it helps achieve 100 percent modulation. When operated between the two levels it does provide a more linear output with moderate efficiency and a modest audio power requirement.

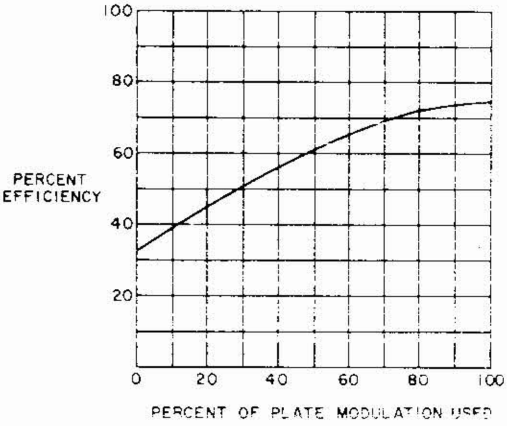
The r-f excitation requirements for the cathode-modulated amplifier are midway between those for plate modulation and for control-grid modulation. More excitation is required as the percentage of plate modulation is increased. Grid bias is always considerably beyond cutoff. Fixed bias from a supply having good voltage regulation is preferable, especially when the percentage of plate modulation is small and the amplifier is operated more nearly like a grid-bias-modulated stage. At the higher percentages of plate modulation, a combination of fixed bias and grid-leak bias can be used, since the variation in rectified grid current is smaller. The grid leak must be bypassed for audio frequencies. The cathode circuit of the modulated stage must be independent of other stages in the transmitter. When directly heated tubes are used, their filaments must be supplied from a separate transformer. The filament bypass capacitors should not be larger than about 0.002μf to avoid bypassing the audio modulation.

The cathode modulator performs differently for each ratio of grid-to-plate modulation selected. The accompanying graph illustrates the manner in which the input power requirement varies. As can be seen, with grid modulation alone the input power is about 48 percent of the normal plate power for plate modulation. At the halfway point, where equal amounts of grid and plate modulation are employed, the input power is just slightly more than 70 percent of the power for a similar plate modulator. This represents an efficiency of approximately 62 percent, as shown in the following graph which illustrates how the efficiency varies.



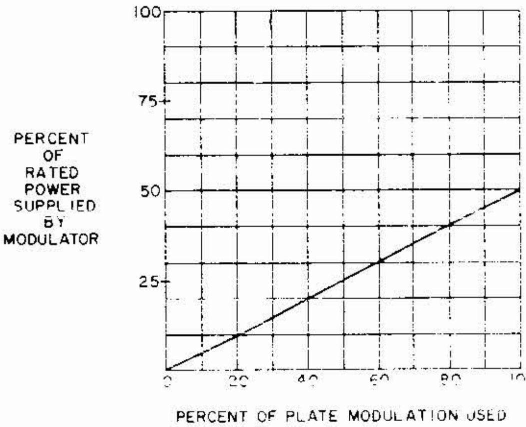
Input Power Variation

Note that neither of the above graphs varies linearly, but that the following graph, showing the audio power



Efficiency Variation

requirements, does vary linearly. At the 50-percent plate modulation point, it requires only about 25 percent audio power from the modulator, as compared with 50 percent for full plate modulation. Thus, it can be seen that while higher efficiency is obtained from the cathode modulator, one must pay for this directly in terms of audio power supplied by the modulator.

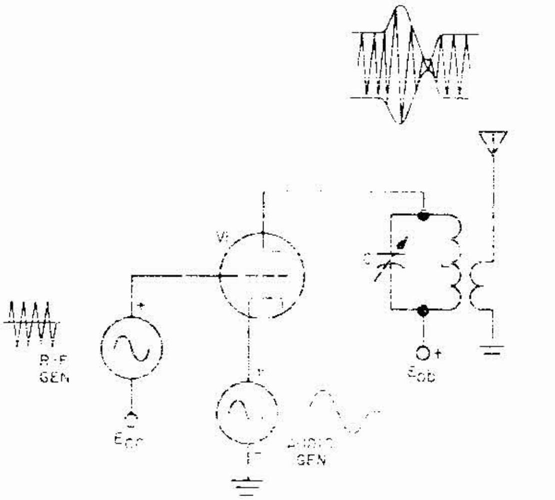


Audio Power Variation

Since the cathode modulator uses only a [illegible] percent change of efficiency as compared with a 50 percent change for the grid modulator, it is evident that the power supply regulation and current handling capacity need not be as stringent or as large as is required for grid modulation. Likewise, a reduction of distortion due to lack of these effects is realized. By similar reasoning it can be understood that since the plate modulator is always more linear than the grid modulator, and a 50-50 ratio of [illegible] modulation is employed, a 50-percent reduction in distortion is immediately realized with cathode modulators.

When tubes with indirectly heated cathodes are used, the heater-cathode breakdown voltage limits the maximum instantaneous voltage which may be applied during modulation. In this case the power employed is low and less plate modulation with more grid modulation is used. For high-powered equipment and large voltage swings, tubes with directly heated cathodes (filaments) are used.

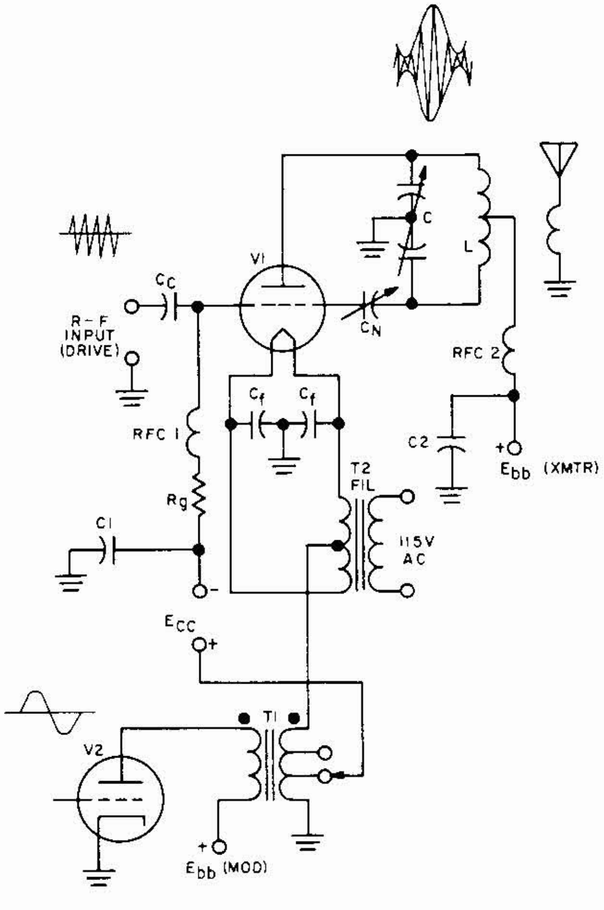
Circuit Operation. The basic cathode modulator in the accompanying illustration is shown using sine-wave generators for audio and r-f power for simplicity. In the illustration the complete biasing and neutralizing arrangements have also been omitted for ease of presentation. As shown, a fixed negative bias of more than cutoff is always employed, and the r-f drive is such that the stage operates as a lightly saturated class C amplifier. (If fully saturated, it would require large grid voltage swings to obtain the desired amount of grid modulation.) The plate circuit employs a conventional LC tank circuit inductively coupled to the load. The output of the audio modulator is transformer-coupled to the cathode circuit, and is represented by the audio generator. As the modulation occurs, assuming a sine wave polarized by transformer connections so that on the positive peak the cathode voltage is positive, the effective grid [illegible] increased, thus [illegible] plate current flow. At the same time this cathode polarity opposes the plate [illegible] is also effectively reduced by a like amount. As the modulation is reduced to zero and goes negative, the opposite effect occurs. The cathode bias is now reduced and plate current is increased, while simultaneously the polarity of the cathode voltage is such as to add to the plate voltage. Thus, both the instantaneous plate current and plate voltage are increased. At the 100 percent modulation level, the [illegible]



Basic Cathode Modulator

and so is the peak plate current, representing a peak power of four times normal and a maximum efficiency of 77 percent, which is equivalent to plate modulation alone. At zero modulation (carrier condition), with the circuit operating halfway between grid and plate modulation conditions, the efficiency is about 62 percent. This represents almost the maximum efficiency obtainable from grid modulation at the peak of the modulation; thus, it can be seen that cathode modulation does provide fuller use of a given transmitting tube's capabilities.

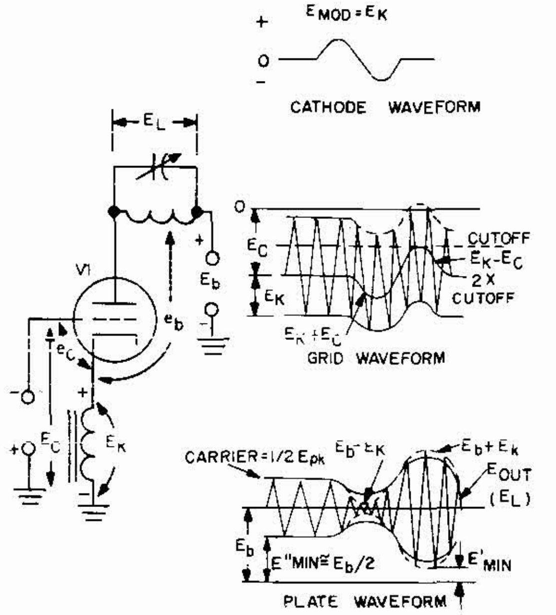
The modulating impedance of a cathode-modulated amplifier is approximately equal to: m x E_b/I_b (where m is the percentage of plate modulation expressed as a decimal, and E_b and I_b are the plate voltage and current of the modulated amplifier, respectively). This modulating impedance is the load into which the modulator must work, just as in the case of pure plate modulation, and is matched by proper choice of the transformer turns ratio. The schematic of a typical cathode modulator is shown in the accompanying figure. A triode using a directly heated (or filament-type) cathode is shown in the illustration; this circuit is sometimes known as a **center-tapped modulator** because the modulation voltage is injected into the filament center tap. Otherwise, the circuit is that of a conventional r-f amplifier, being biased to beyond cutoff by the fixed negative supply and by the bias developed across R_g from the drive current. RFC1 prevents the r-f drive from being shunted to ground, and C1 provides the conventional bypass around the bias supply for any r-f that might leak through the r-f choke. The percentage of grid modulation may be regulated by choice of a suitable tap on the modulation transformer, as shown in the illustration (or by changing the d-c value of the grid bias). Capacitors C_f form the conventional center-tap arrangement of directly heated (filamentary) cathodes to provide an electrical center tap which prevents hum modulation due to unequal voltages across the sides of the filament. The plate tank uses a split-stator capacitor to tune a center-tapped coil, which provides out-of-phase voltages at the ends of the coil. Thus, a neutralizing voltage which is 180 degrees out of phase with the normal plate-to-grid feedback within the tube is provided through neutralizing capacitor C_n (since both input and output voltages are of the same frequency), preventing self-oscillation with the distortion which accompanies it. The antenna is inductively coupled to the tank, and the tank is series-plate-fed through RFC2 bypassed by C2. The modulation is applied through the secondary of T1 to the filament center tap of V1. It is evident, then, that as the modulation signal is applied to V2, considering a sine-wave input, the voltage at the secondary of T1 varies first to a positive maximum and then to a negative maximum, returning to zero as the signal ceases. With the circuit biased so that tube V1 is not driven to saturation, but just to the point where saturation will begin if driven further, only half of the normal r-f grid drive is needed, as compared with full plate modulation.



Cathode Modulator

Consider now one cycle of operation. As the modulating signal increases in the positive direction, an increasing positive voltage is applied in series with the cathode. This cathode voltage is instantaneously added to the fixed bias and to the bias produced by r-f grid drive (through grid resistor R_g). The result is to increase the total effective grid bias by the amount of the modulating signal. Consequently, the instantaneous plate current, i_p, is reduced. At the same time, this cathode voltage is in opposition to the applied plate voltage, and reduces it accordingly. With a lower effective plate voltage, the plate current is still further reduced. This action continues sinusoidally until the modulation peak is reached, which corresponds to the point of almost zero plate current (if the plate current were entirely cut off, the output signal would be interrupted). At this time the plate current through the load impedance is at a minimum, and the output voltage is also at a minimum, as shown in the accompanying illustration.

As the modulating signal turns in a negative direction the total effective bias is decreased, and the cathode voltage adds to the effective plate voltage. Consequently, the instantaneous plate current increases. At the completion of the positive half-cycle of modulation signal, the cathode bias (modulating signal) is zero, and the effective bias is the sum of the fixed negative bias and the bias produced by the r-f drive. This is the quiescent, or resting, condition of the circuit where normal plate current is drawn



Operating Polarities and Waveforms

and only the carrier is produced. While this plate current is about 20 percent higher than it would be in the grid modulator, and represents about 70 percent of the plate modulation rating of the tube, it is the normal value which is doubled at the modulation peak. Therefore, additional power is required when the modulation drives it above the carrier level. The increase of carrier power above that of the grid modulator is obtained from the transmitter power supply by a change in plate efficiency.

As the modulation cycle progresses sinusoidally below zero toward the negative peak, the cathode bias is further reduced by the negative-going cathode voltage. Since the cathode voltage is now in a direction to add to the effective plate supply, the instantaneous plate voltage is increased. With a reduced bias and an increased plate voltage, the plate current is increased. At the peak of the cycle the instantaneous plate current is twice the normal (carrier) value. At this time the drop across the load is the greatest, and the actual plate voltage reaches its minimum value, near zero. The minimum value of plate voltage (for triodes) is kept above the maximum positive grid swing at this point to prevent excessive grid dissipation. (If it were zero, the grid would act as the plate during this interval.) Once the negative modulation peak is reached, the modulation signal again goes in a positive direction toward the zero or carrier level. The cathode voltage is now going in the opposite direction (increasing positive), and once again opposes the plate voltage, increases the total effective grid bias, and reduces the plate current. Thus we can say that the modulation signal effectively drives the tube to twice the normal plate voltage and current on the peaks of modulation, and to almost zero on the troughs of modulation (the negative peaks).

FAILURE ANALYSIS.

No Output. Lack of output should first be isolated to failure of the r-f amplifier stage or the modulator and speech circuits. Even though the modulator is operative, an open rfc or tank circuit, a shorted or gassy electron tube, or lack of grid excitation to the r-f amplifier will produce a no-carrier indication. An open modulator primary will permit a carrier to appear, but no modulation will occur, while an open secondary will produce neither a carrier nor any modulation. Observation of the amplifier r-f plate current meter will determine whether the circuit has continuity, while tuning for a maximum indication with a resonant dip will determine whether sufficient drive and load and the proper bias are present for operation without modulation. Grid-drive-meter indications will also show whether there is proper r-f drive. When the tank can be resonated for a minimum dip and then loaded to maximum plate current with a normal grid-current indication, the trouble is in the modulator or speech circuits.

Lack of grid drive places the trouble in the exciter stages of the transmitter or in the coupling network to the final stage. Lack of plate current indicates possible power-supply trouble, an open-circuited r-f stage, or a defective modulation transformer; if screen grid tubes are used, lack of plate current can also be due to an open screen-voltage dropping resistor or a short-circuited screen bypass capacitor.

High transmitter plate current usually indicates short-circuited components, a lack of bias, or improper tuning; low transmitter plate current indicates excessive bias, high-resistance joints, low tube emission, lack of sufficient r-f drive, a possible lack of sufficient coupling to the load, or possible antenna or transmission -line trouble. A simple resistance analysis made with the power off and the **high-voltage supply** grounded for safety usually will quickly determine the defective components, using the meter indications as a guide to the most probable location of the trouble.

Low Output. Determine first whether the low output is due to lack of sufficient audio drive or to an actual reduction in the percentage of modulation. Low modulation is usually caused by lack of sufficient audio output, and may be the result of a reduced setting of the audio gain control or from trouble in the speech amplifier stages. An oscilloscope should be used to view the waveform to determine whether 100 percent modulation is being obtained. For quick, simple tests of modulation percentage, the trapezoidal waveform check is useful. The envelope or waveform check, however, will show the percentage of modulation and also waveform distortion at the same time, so that it is usually more useful. Too high a grid bias will cause a reduction of output and an inability to obtain 100 percent modulation with the same r-f drive. The grid bias can be easily checked with a voltmeter (use an rfc in series with the test prod). A reduced screen voltage is most likely of all to produce a low output, usually with overmodulation or distortion, since the plate and screen swings will be excessive. Such a condition may be caused by too heavy a screen current, causing a large drop in the screen-voltage dropping resistor, by a defective screen voltage dropping resistor, or by a partially shorted screen bypass capacitor. Where a separate screen supply is used, the latter trouble is the most likely.

Lack of proper tuning can also cause a low output. Too light a loading or too high an excitation will cause a flattening of the upward peaks of modulation, as in grid modulation. The antenna loading must be such that a further increase in loading causes a slight drop in antenna current. For optimum performance, the grid excitation should also be adjusted for minimum plate dissipation with maximum power in the antenna. The cathode current will be practically constant with or without modulation when the proper operating conditions have been established.

Improper load matching by the modulation transformer will produce a lack of sufficient audio power, as well as distortion. Where taps are provided, the proper tap may be selected. Where no taps are provided and the load appears to be mismatched when checked with an oscilloscope, the tube or the transformer may be defective. Substitution of a known good tube or transformer will eliminate these components from suspicion. Lack of sufficient filament emission in the final amplifier tube can cause peak flattening, inability to obtain 100 percent modulation, and distortion.

Distorted Output. Distortion can occur from a number of causes, and is easy to detect when monitoring the audio modulation. Overmodulation will cause a chopping off of the carrier (carrier shift), producing severe interference to stations operating near the transmitter frequency, as well as distortion.

In stages operating on the same input and output frequencies, there is always the possibility of sufficient internal plate-to-grid feedback to cause self-oscillations accompanied by severe distortion, particularly on the peaks of modulation. When this occurs with triodes, it indicates the necessity for readjustment and a check of the neutralization. With pentodes and tetrodes it can occur at the high frequencies, particularly if the lead dress is changed after a repair. Self-oscillation can usually be recognized on an oscilloscope by the characteristic fuzzy appearance of the display. Plate current meter indications will usually be excessive and erratic when this condition is present.

Lack of sufficient capacitance to supply the peak power requirements can occur through loss of filter capacitance, and can cause peak flattening with consequent distortion. Usually, however, such a condition will be indicated by a hum on the carrier, or in the modulation, before the distortion is excessive enough to notice unless an oscilloscope is used to monitor the transmissions.

A similar condition caused by lack of sufficient filament emission in the r-f amplifier stage will also cause peak flattening and resulting distortion. Sometimes this condition can be observed by noting the inability of the r-f output meter to respond to heavy modulation peaks, accompanied by a gradual reduction in plate current readings over a long period of time. Under normal conditions, the r-f ammeter will indicate approximately a 22 percent increase in output current at 100 percent modulation.

Improper bias and drive conditions will also cause distortion, and usually are accompanied by a reduction in output or an inability to attain 100 percent modulation.

SERIES MODULATOR.

APPLICATION.

The series modulator is used to amplitude modulate a carrier (r-f) signal with an audio (or video) intelligence with a minimum of circuitry.

CHARACTERISTICS.

Uses two triodes connected in series.

Has a wide bandpass.

Is critical to adjust.

Used as either a high-level or low-level modulator.

Inefficient in comparison to other methods of producing AM.

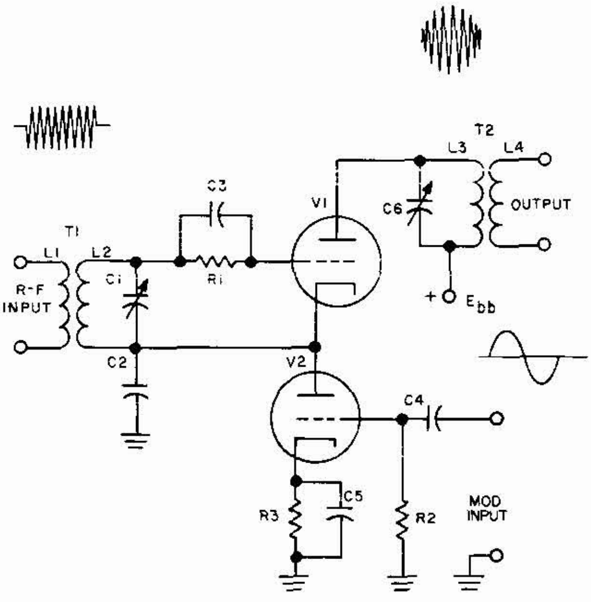
CIRCUIT ANALYSIS.

General. The series plate modulator is used in a-m transmitters where it is desired that the modulator stage pass a wide band of frequencies. Because of its inherent wide-band characteristics and relatively good quality, the series modulator is employed primarily in television applications; however, because adjustments are critical, the series modulator has not been widely accepted for common usage. Basically, the circuit consists of a triode modulator and a Class C r-f amplifier connected in series using a common dc plate supply. The modulator triode may be connected in either the plate or cathode circuit of the r-f amplifier with operation remaining basically the same, regardless of which method is employed. Only the cathode connected circuit is discussed in detail.

Circuit Operation. A cathode connected series modulator is illustrated in the accompanying schematic diagram.

Modulator tube V2 is biased Class A by cathode resistor R3. Capacitor C5 by passes the cathode resistor to prevent degeneration and helps to maintain a constant bias voltage. Resistor R2 is the grid return resistor with C4 acting as a coupling and dc blocking capacitor.

R-f amplifier V1 is biased Class C by the series grid leak circuit comprised of R1 and C3. Transformer T1 couples the r-f signal into the tuned grid tank formed by secondary winding L2 and capacitor C1. Capacitor C2 is the cathode bypass capacitor and prevents degeneration in the cathode and r-f from entering the audio circuits. C6 and L3 form a tuned plate tank (load) for V1, and L4 inductively couples the signal into the following stage.



Series Modulator

When power is initially applied to the circuit no bias exists on either of the series connected triode tubes. As a result, plate current readily flows through the tubes to voltage source, Ebb. As the current flows through R3 and V2 voltage is developed across each component. The voltage dropped across R3 biases the modulator Class A so that any signal arriving on the grid will be faithfully reproduced in the plate circuit. The voltage dropped across the modulator tube, V2, protects the r-f amplifier in the event r-f drive is lost because of failure in the oscillator or multipliers. It will be helpful to remember that placing a positive potential on the cathode has the same effect as placing an equally negative potential on the grid. For the following discussion assume that no audio modulation voltage is applied to the grid of V2 and plate voltage remains relatively stable.

R-f signals arriving from the oscillator (or multiplier) stage are impressed across L1, the primary winding of T1. The signals are transformer coupled into the secondary tuned tank formed by inductor L2 and capacitor C1. The grid tank is tuned to the desired r-f frequency by C1 which is variable over a short range.

On the positive excursions of the r-f signal the grid is driven positive. Grid current flows and C3 charges quickly. As the signal swings negative, grid current ceases to flow and'C3 begins discharging through R1 developing a negative voltage which is applied to the grid. Discharge time is much slower than charge time because of the large grid leak and consequently, the charge on C3 is not completely dissipated before the next positive excursion of the r-f signal. The cycle repeats itself and eventually, after a few more cycles, the voltage applied to the control grid stabilizes. Thus, the tube is now biased by the grid leak (signal) bias on the control grid in addition to the bias voltage applied to the cathode. The sum of the voltage applied to the cathode and control grid of V1 biases the tube Class C (below cutoff) so that only the positive peaks of the r-f input signal results in plate current flow; therefore, plate current is broken into pulses at the signal frequency. Capacitor C2 by-passes any r-f plate current variation in the cathode to ground and prevents degeneration effects. The parallel resonant tank formed by C6 and L3 oscillates (flywheel effect) every time a pulse of current flows in the plate circuit. Hence, even though plate current flows in pulses, tank current flows for the entire cycle and a linear sine wave at the resonant frequency is transformer coupled into L4.

The preceding discussion describes the operation of the r-f amplifier with no modulation signal applied, and if operation was limited to this condition no intelligence could be transmitted. The following discussion concerns operation when modulating signals are applied.

A modulating signal from the final speech (or video) amplifier is r-c coupled through coupling capacitor C4 onto the grid of V2. R2 is the grid return resistor and provides a low impedance path for dc return current. As the positive half-cycle of thé modulating signal is applied to the grid, V2 bias is decreased and the cathode current through V2 increases. Consequently, V2 plate voltage decreases. Decreasing the plate voltage of V2 is the same as decreasing the plate voltage of V1 (since both tubes are in series) and, in effect, reduces the cathode bias from V1 to ground so that conduction in V1 is increased; this results in developing an increased output across the plate load (resonant tank). Conversely, when the modulating signal swings negative the opposite effect takes place, and the output across the plate load decreases.

Hence, in this application, the plate voltage decreases to nearly zero (with respect to the cathode) at maximum output, and increases to nearly the supply value, Ebb, at minimum output. Unlike other modulators, no voltage doubling takes place due to the absence of a reactive element (inductor) in the plate circuit. Instead, the circuit is initially adjusted so that full carrier output is obtained with half the supply voltage applied, so that swinging it from zero to the full supply value is the same as doubling the voltage in other types of modulators.

If the modulating signal is of sufficient amplitude to overdrive V1 into saturation, a loss of intelligence (clipping) results for the period of time the tube is in saturation. Hence, transmitters are usually equipped with a modulator gain control to insure that the modulating signal does not exceed design limitations. From basic theory it is known that when two signals are injected simultaneously into a non-linear device, new frequencies appear in the output. When the r-f and modulator signals are injected into V1, which is operated as a Class C (non-linear) r-f amplifier, (whose output varies as the square of the applies plate voltage) two additional frequencies appear in the output; namely, the sum and difference frequencies. In transmitters these "new" frequencies are referred to as upper and lower sidebands and represent approximately 1/6 of the total power, per sideband with 2/3 of the power in the carrier. The sidebands contain the same modulation as the carrier and in some transmitters, such as single-sideband (ssb) and double sideband (dsb), the sidebands are transmitted in preference to the carrier. However, in this instance the carrier and two sideband frequencies are selected by the tuned tank and coupled into the output circuits by the transformer action of T2.

FAILURE ANALYSIS.

No Output. A loss of r-f or audio signal will result in either a no output or unmodulated carrier condition. Use an oscilloscope equipped with a high impedance probe to check the r-f (across L1) and audio (across input terminals) signals. If either signal is absent the modulator will not function properly, and the absent signal must be secured before further troubleshooting is accomplished. Next, check each tube element on the base of the tube socket for correct operating voltages. Check the bias voltages carefully as an abnormal bias voltage may cause erroneous readings on the plate elements. If voltage are abnormal, use an ohmmeter to measure the dc resistance of R3, R1 and inductors L1, L2, and L3 also, use an in-circuit capacitor checker to check C1, C2, C3 and C5 for a shorted or leaky condition.

Weak or Distorted Output. A weak or distorted output will be caused by: weak or distorted input signals; improper bias; improper power supply voltages; defective tubes; or improper tuning or loading of the grid or plate tank.

DOUBLE SIDEBAND MODULATOR.

APPLICATION.

Double sideband modulation is used in double sideband communication systems where upper and lower sideband are transmitted and the carrier frequency used to generate these sidebands is eliminated.

CHARACTERISTICS.

Generates upper and lower sidebands at high power levels while suppressing the r-f carrier.

Utilizes two push-pull connected triodes operated class C.

Uses low level grid modulation.

Modulating signal is applied to the control grids in push-pull, while the r-f carrier is applied to the control grids in parallel.

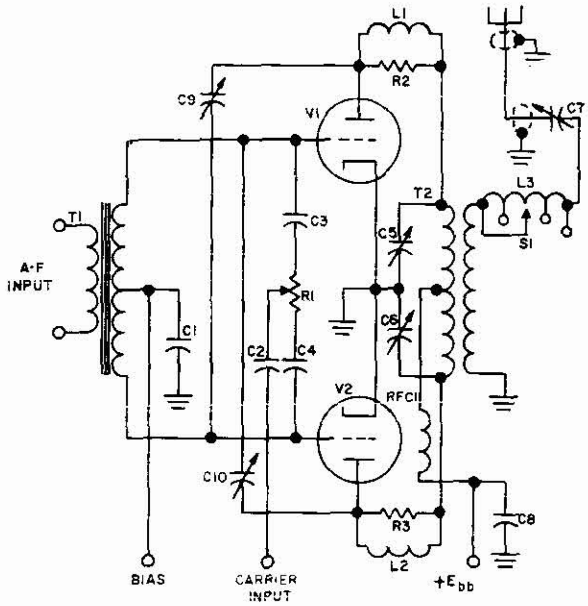
Utilizes nonlinear characteristics of electron tubes to generate sidebands.

Even-order harmonics are cancelled through push-pull action.

CIRCUIT ANALYSIS.

General. Double sideband communications systems differ from conventional a-m systems and from single sideband systems in that both sidebands and no carrier is transmitted. It should be noted that carrier elimination is achieved in a specially designed power amplifier. The modulator is a conventional AM modulator. This discussion will pertain to the power amplifier, since the power amplifier is the only unit in the DSB transmitter which is significantly different from units in the conventional full carrier AM transmitter. Single sideband systems achieve the same result by transmitting only one sideband. Both DSB and SSB provide the advantage of eliminating "whistles" or beats caused by the beating of the carrier with other carriers and sidebands in the receiver, since both DSB and SSB do not transmit a carrier. At first glance it may appear that a single sideband system makes more effective use of the available transmitter power, since the SSB transmitter concentrates all of the available transmitter power into one sideband while the DSB transmitter transmits two identical sidebands. However, this apparent gain of SSB over DSB is not realized at the receiver output, since double sideband signal voltages combine vectorially in the receiver detector and produce audio frequency voltage proportional to twice that produced by one sideband. For example, a double sideband r-f envelope containing 100 watts (50 watts in each sideband) produces the same receiver audio output as a 100 watt SSB r-f envelope (all 100 watts in the sideband). It has been reasoned that a double sideband system can provide results equal to or greater than that produced by a SSB system. In a conventional full carrier AM system the r-f carrier transmitted with the sidebands heterodynes with the sidebands in the receiver detector circuit and audio frequency voltages are produced. In the DSB system and in the SSB system no carrier is transmitted and an artificial carrier, generated in the receiver must be combined with the sideband, or sidebands in the case of DSB, to properly demodulate the signal. This artificial carrier frequency must be very stable and must be as close as possible to the frequency of the carrier used to generate the sidebands in the transmitter in order to keep distortion of intelligence to a minimum. One of the arguments in favor of DSB over SSB is the distortion caused by the phase shift inherent in SSB due to the loss of the opposing phase shift of the other sideband. This shift can be minimized by maintaining a sufficiently high level of carrier insertion at the receiver. This phase shift has little effect on voice transmissions but pulse and data transmissions may be seriously affected. In a DSB system the effects of this phase shift are greatly minimized since the phase shift of one sideband tends to oppose the phase shift of the other sideband. The DSB system, however, requires that the locally inserted carrier be of the same phase relationship as the original modulation at the transmitter. This is accomplished by the use of a phase-locked oscillator to generate the carrier to be reinserted in the receiver. Another advantage seen in DSB transmission over SSB is the possibility of greater reliability of reception under varying conditions of fading. Under such conditions one sideband may be phased out by multi-path fading while the other sideband may not be excessively attenuated. By definition, selective fading results when the various frequency components of a transmission are not received exactly as transmitted with respect to power levels and phase relationships. The adverse effects of this condition on full carrier AM is distortion of received intelligence, and decreased receiver output. It can then be said that SSB is not subject to selective fading since only one sideband is transmitted. However, if propagation conditions are such that the frequency of the sideband being transmitted is excessively attenuated the receiver output is likewise decreased, whereas a DSB system operating at the same frequency will probably maintain satisfactory communications since the other sideband will probably be unaffected. Another advantage of DSB over SSB is the simplicity of the DSB transmitter. To convert a conventional full carrier AM transmitter to a DSB suppressed carrier transmitter only the power amplifier must be modified. The modified DSB power amplifier closely resembles the balanced modulators used in SSB transmitters. The DSB power amplifier discussed here consists of two push-pull connected triodes operating class C with r-f carrier applied to the control grids of both tubes in parallel (in-phase), and the audio modulating signal applied to the control grids in push-pull (180° out-of-phase). In push-pull amplifier circuits a push-pull input is required to produce an output and an in-phase input cancels in the output. The r-f carrier and the audio modulation present simultaneously on the control grids of the tubes beat together, and four basic frequencies are present in the plate circuit of the modulator tubes. These frequencies are the original r-f carrier, the original audio modulation and sum-difference frequencies generated as a result of heterodyning. Heterodyning results when two or more frequencies are applied to any element of a nonlinear resistance such as an electron tube or a transistor. If the reader desires detailed information on heterodyning he may find it in the introduction to chapter 13 of this Handbook. The r-f carrier frequency present in the plate circuit is canceled out by push-pull action in the output transformer (the r-f carrier is applied to the push-pull amplifier in parallel) and the output transformer presents a very low impedance to audio frequencies. Therefore, the original audio modulating signal is not developed in the output. The generated sidebands, which are a product of the in-phase r-f carrier input and the out-of-phase audio modulation input are therefore, out-of-phase at the plates of the tubes and add in the output transformer, rather than cancel as in-phase signals do, and they are inductively coupled to the antenna circuit through the output transformer. The power amplifier described here uses two power triodes, however, the use of power tetrodes may be encountered.

Circuit Operation. The following schematic diagram illustrates a final power amplifier designed to suppress or eliminate the r-f carrier and produce a double sideband output.



Double Sideband Generator

Transformer T1 couples the audio modulation from the modulator to the grids of the power amplifier. Capacitor C1 places the centertap of T1 at a-f ground potential so that 180° out-of-phase audio voltages are developed across the top and bottom halves of the secondary of T1, and are felt on the grids of power amplifier tubes V1 and V2. Coupling capacitor C2 couples the r-f carrier from the preceding stages to the slider of carrier balance potentiometer R1, which provides a means of varying the amplitude of the r-f carrier coupled to the grids of V1 and V2 with respect to each other. Capacitors C3 and C4 couple the r-f carrier from carrier balance potentiometer R1 to the grids of V1 and V2, respectively. Power triodes V1 and V2 are the nonlinear devices used to generate upper and lower sidebands at high power levels. Resistor R2 which is shunted by inductor L1, and resistor R3 which is shunted by inductor L2 form parasitic suppressor networks intended to decrease the tendency for parasitic r-f oscillations to develop. Center-tapped transformer T2 serves as the push-pull output transformer for the power amplifier and capacitors C5 and C6 form a split-stator type of tank capacitor used to resonate T2 to the output frequency. Radio frequency choke RFC1 together with bypass capacitor C8 prevent r-f energy from entering the power supply. Tapped inductor L3, whose inductance can be varied by switch S1, together with variable capacitor C7 couple the transmitter output to a coaxial transmission line which transmits the sideband r-f energy to the antenna. Since triodes are used the circuit must be neutralized or the relatively high value of grid to plate capacitance of the triodes would provide a feedback path and the amplifier would break into self oscillations. Capacitor C9 and C10 couple r-f energy from the plate of one tube to the grid of the other and cancel or "neutralize" the effects of grid to plate capacitance and thus prevent self oscillations.

To more easily examine the operation of the DSB power amplifier assume first that only the r-f carrier is applied.

The r-f carrier is coupled from the preceding driver stage through coupling capacitor C2 to the slider of carrier balance potentiometer R1. The r-f carrier appears at both ends of R1 and is coupled in-phase through capacitors C3 and C4 to the grids of V1 and V2. The amplitude of the r-f carrier at the grid of each tube is controlled by the adjustment of half cycle, both plates draw an increasing amount of plate current (the input is in phase) and the voltage drop across each half of the tapped primary of the output transformer T2 is negative going, so that opposing voltages are developed in the transformer primary which cancel, and no output is produced. If the circuit is properly balanced by the adjustment of R1, these opposing signals are equal in amplitude and the carrier is effectively suppressed. Since the amplifier is operated with class C bias (approximately twice cut-off) only the peaks of the positive half cycle of the r-f input have an effect on conduction. Neither tube conducts during the negative half cycle of r-f carrier input and again no output is produced. Therefore, an output is not produced by the DSB power amplifier when only the r-f carrier is applied. When audio modulation is applied in addition to the r-f carrier, upper and lower sidebands are generated and are coupled through the output circuit to the antenna.

Audio modulation is applied to the primary of T1 and since the center tap of the secondary of T1 is placed at a-f ground potential by capacitor C1, audio modulation signal voltages are developed across each half of the winding, which are 180° out-of-phase with each other. This modulation signal is applied directly to the grids of V1 and V2. Capacitors C3 and C4 are of such a value that they present a high impedance to audio frequencies and, thus, prevent the out-of-phase audio modulation from crossing over from one grid to the other and canceling each other out. During the period when both tubes are driven into conduction by the positive half cycle of r-f carrier input, the audio modulation and the r-f carrier beat together, and sum and difference frequencies (sidebands) are generated as the result of heterodyning. Actually there are four basic frequencies present in the plate circuit of V1 and V2. There are the original r-f carrier, the original audio modulating signal, and the upper and the lower sideband. Other higher order harmonics are also present but are of little consequence. Of the frequencies present only the sidebands are developed in the output circuit since the r-f carrier cancels in the push-pull output transformer, as explained previously. The audio modulating frequency is not developed because of the low value of impedance offered by the r-f output transformer. The sideband frequencies, being a product of the out-of-phase modulating signal, are developed across the primary, of the output transformer and are inductively coupled through the secondary of T2 to the output circuit. The even order harmonics present in the plate circuit are cancelled through push-pull action and the odd order harmonics are shunted around the primary of T2 to ground by capacitors C5 and C6. The sidebands are coupled through inductor L3, whose inductance can be varied by switch S1, and variable capacitor C7 to the coaxial transmission line. L3, S1, and C7 match the impedance of the power amplifier output to the impedance of the coaxial line so that maximum power is transferred to the antenna and minimum power is reflected.

FAILURE ANALYSIS.

No Output. Dangerous high voltages are present in the power amplifier and all applicable safety precautions should be taken when working with the power amplifier. Since each branch of the power amplifier performs essentially the same function, failure of one branch is not likely to cause a no-output condition to exist. Failure of the power supplies or failure of the input or output circuits are likely causes of output. If the power amplifier is at fault, make resistance checks with the equipment denergized, and pay particular attention to the resistances measured from the plates to ground; since components having high voltages applied to them are more likely to breakdown and short than components having lower voltages applied to them. Capacitors C5, C6 and C8 would short the high voltage to ground if they broke down, and capacitors C9 and C10 would short the high voltage supply to the bias supply if either capacitor broke down. Capacitor C1 would short the bias supply to ground if it failed. Transformer T2, inductors L1 or L2 or RFC1 could become shorted to ground. This would also short the HV power supply to ground as well as a possible shorted tube. Insulation breakdown on any of the wires carrying high voltage could also be the cause of a shorted power supply.

If the no-output condition does not manifest itself in the form of blown H.V. fuses, lack of high voltage at the plates of V1 and V2 could be the trouble. Observing all applicable safety precautions, measure the plate voltage of the power amplifiers with the transmitter keyed. If there is no plate voltage on either tube, the power supply is defective or RFC1 is open. If proper plate voltage is applied but there is no output, failure of either the r-f carrier, or modulation, to reach the grids of V1 and V2 could be the cause of no output, since the DSB power amplifier, like the SSB balanced modulator, produces an output only when both inputs are present simultaneously at the grids. Presense of these signals can easily be determined by observing, with an oscilloscope, the waveform present at the grids of V1 and V2. If either input signal is missing, signal trace from the grids of V1 and V2 to the preceding stage to determine the defective component. Failure of T1 is a likely cause for no modulation drive to V1 and V2. Resistance checks of transformer windings and leakage checks to ground should reveal any defects that may exist in T1. Failure of R1, or an open C2, could prevent the r-f carrier from reaching the grids of V1 and V2, hence, no output would result. Failure of output transformer T2 could also result in a no-output condition. Resistance checks of transformer windings and checks for leakage to ground, and leakage between windings should reveal any defects existing in T2.

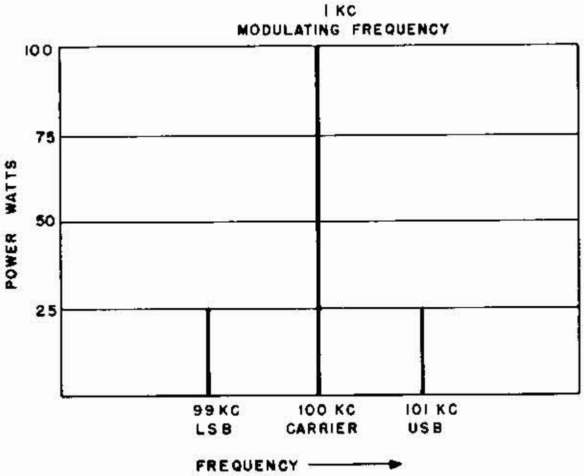
Low Output. A low output condition can be caused by defective tubes, improper power supply voltages, low amplitude inputs, or improper tuning of the output circuit. Observe all applicable safety precautions and check the high voltage applied to the plates of the power amplifier. Also check the bias voltage applied to the grids V1 and V2. If the tubes are good and the power supply voltages are correct, low output could be caused by insufficient r-f carrier, or modulation drive applied to the power amplifier. This condition can be checked by observing with an oscilloscope, the amplitude of the r-f carrier and the modulating signal on the grids of V1 and V2. If either input signal is weak on the grids of V1 and V2, check the amplitude of that signal at the point where it enters the power amplifier, in order to determine whether the defect exists in the power amplifier, or in the preceding stages. A defect in T1 such as a partially shorted winding or excessive leakage to ground could result in a decreased amplitude modulating signal on the grids of V1 and V2, and a partial failure of C2 or R1 could result in decreased amplitude r-f carrier on the grids of V1 and V2. Both situations could result in a low output. Likewise, if one of the input signals is unable to reach the grid of either V1 or V2 that branch of the power amplifier would be inoperative, since both modulating signal and r-f carrier must be present at the grid simultaneously to produce an output, and low output would result. If C3 or C4 opened, or R1 opened, the r-f carrier would not be coupled to the grid of either V1 and V2. Likewise, a similar situation would arise if either the top or bottom half of the tapped secondary of T1 become shorted. In this case the audio modulation signal would not be coupled to the grid of one of the tubes and low output could, again, result. Another possible cause of low output is a defect in the parasitic suppressors networks L1-R2 and L2-R3. If the resistor in either network opened, a decreased output could result since much of the sideband voltage would be dropped across the inductor shunting the open resistor.

Distorted Output. A distorted output condition may be caused by defective tubes, improper power supply voltages, excessive input drive, or a distorted input. Check the power supply voltages taking care to observe all safety precautions and make any required adjustments, if necessary. If the output is still distorted it would be wise at this point to observe, with an oscilloscope, the amplitude and waveshape of the input signals. It should be noted that if the input signals are excessive or distorted the fault lies in the stages preceding the power amplifier.

It would be wise at this point to observe, with an oscilloscope, the amplitude and waveshape of the input signals. It should be noted that if the input signals are excessive or distorted the fault lies in the stages preceding the power amplifier.

SINGLE SIDEBAND MODULATORS (SSB)

An amplitude modulated r-f signal can be separated into three different frequencies. They are, the carrier frequency, the upper sideband frequency (USB) and the lower sideband frequency (LSB). A 100-percent modulated A-M signal utilizes two thirds of its total power in the carrier. The following diagram illustrates the frequency verses power relationships of a fully modulated AM envelope.

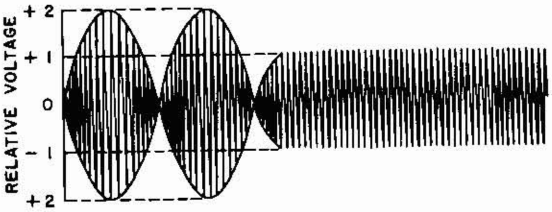


100% Modulated A-M Signal (100 Watt Carrier Power)

An understanding of the principles of Amplitude Modulation is essential to the understanding of SSB modulation, since SSB is basically a form of AM. A brief review of the principles of amplitude modulation as discussed in Section 14 of this Handbook will greatly facilitate the understanding of SSB modulation for the reader who is not throughly familiar with A-M.

Since only the AM sidebands carry all of the intelligence (modulation) the carrier can be eliminated, and the available transmitter power utilized to a much greater advantage. Both upper and lower sidebands are identical in waveform except for a difference in frequency. Therefore if one of the sidebands along with the carrier is suppressed or eliminated leaving only a single sideband, an even greater efficiency may be obtained.

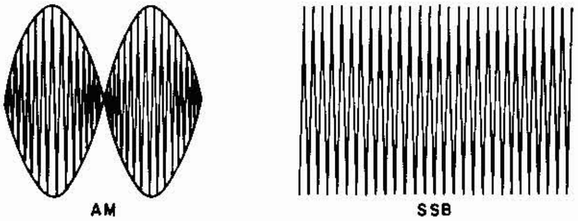
Normally, an effective 6 db power gain can be obtained from a r-f power amplifier, capable of dissipating say 400 watts of peak power, by using SSB instead of conventional DSB AM. For comparison purposes we shall use a 100 watt rated carrier power AM signal and a 400 watt peak envelope power (abbreviated PEP) SSB signal. Note that the 100 watt rated carrier A-M signal also dissipates 400 watts on audio peaks when fully modulated as illustrated below.



100% Modulated AM Envelope

As can be seen from the illustration, the peak to peak voltage of a fully modulated A-M envelope is twice that of the unmodulated carrier. Peak power is four times carrier power, since $P = E^2/R$.

The following illustration compares a fully modulated 100 watt rated carrier power envelope to a 400 watt PEP single sideband envelope for a single sustained tone.

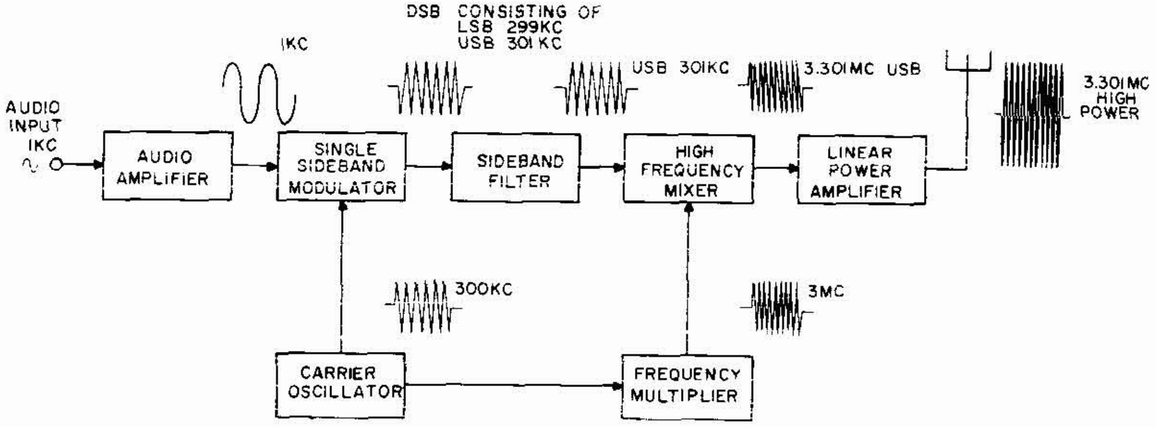


Comparison of A-M and SSB Modulation Envelopes

Note that while the peak power ratings of both signals are identical, the conventional AM modulated signal only reaches full peak power at the instant of 100 percent modulation. On the other hand, the single-sideband signal operates constantly at full peak power. Assuming that the AM envelope consists of a 100 kc carrier modulated by a 1 kc audio tone, an upper sideband at 101 kc and a lower sideband at 99 kc are produced, along with the 100 kc basic carrier in the r-f envelope. Thus, the average sideband power is only 50 watts (25 watts in each sideband). On the other hand the 400 watt single sideband r-f envelope is either the upper sideband or the lower sideband (depending upon which sideband is selected to be transmitted), and there is no carrier frequency present. Hence all 400 watts of PEP is usable power. Consequently, there is an apparent 8-fold (9 db) increase in usable power of SSB over conventional DSB AM. Actually this only amounts to a 6 db gain is useful power, since a conventional DSB AM signal containing 50 watts of total sideband power produces twice the receiver output that a 50 watt PEP SSB signal produces. This is because the upper and lower sidebands of the DSB AM signal combine in the receiver detector circuit, and produce an audio voltage which is proportional to double the amplitude of each sideband. The loss of one sideband reduces the apparent 9 DB gain of the SSB transmission over conventional AM to an actual 6 db advantage.

Up to this point we have only discussed the power advantages gained through the use of single sideband in the transmitting system. Another important advantage realized through the use of SSB is that of frequency spectrum conservation. For good intelligibility modulating frequencies up to 3 kc are required for voice transmissions. A conventional DSB AM contains the carrier frequency and sideband frequencies deviating 3 kc on both sides of the carrier frequency, when the carrier frequency is modulated by a 3 kc tone. Thus the total bandwidth of this signal is 6 kc. With the same modulating frequency the bandwidth of the SSB system is only 3 kc, since only one sideband is transmitted. It is apparent that a SSB system will provide twice the number of channels of a comparable conventional DSB A-M system. Still another advantage of SSB operation is reduced receiver noise, since the required bandwidth of the receiver is halved due to the reduced bandwidth of the transmitted signal. Since noise power is directly proportional to bandwidth, a 3 db gain in signal-to-noise ratio results because of the increased selectivity. From the above discussion, it can be seen that the SSB system provides an effective 9 db overall improvement (6 db in the transmitter, and 3 db in the receiver) over the conventional DSB AM system. The power comparison between SSB and AM stated previously is also based on ideal propagation conditions. Over long distance transmission paths, AM is subject to selective fading, which causes severe distortion and sometimes a weaker received signal. Only the A-M transmission is subject to this type of deterioration under poor propagation conditions, because the upper sideband, the lower sideband, and the carrier must both be received exactly as transmitted to realize full fidelity, and the full theoretical power from the signal. If one, or both, of the transmitted sidebands is attenuated more than the carrier, a loss of received signal results. The most serious and most common result is selective fading which occurs when the carrier is attenuated more than the sidebands. The effect of this type of selective fading is severe distortion of the received intelligence. Selective fading can also cause a phase shift between the relative phase positions of the carrier and sidebands. This condition also results in distortion of intelligence. On the other hand, a SSB signal is not subject to selective fading, which varies the amplitude or phase relationship between the sidebands and the carrier, since only one sideband and no carrier is transmitted.

The following block diagram illustrates a simple SSB transmitter arrangement.



Single Conversion SSB Transmitter

The audio amplifier stage increases the speech input voltage to a level sufficient to drive the SSB modulator. An extremely stable r-f signal is provided for use in generating the desired r-f sidebands by the carrier oscillator. The SSB modulator generates both upper and lower sidebands when both audio modulation and r-f carrier are applied simultaneously. The sideband filter stage passes the selected sideband and rejects the undesired sideband. The frequency multiplier stage multiplies the r-f carrier generated in the carrier oscillator to a higher frequency for use in the high frequency mixer stage, where this multiplied frequency heterodynes with the sideband frequency from the sideband filter, and produces the desired transmitter output frequency. The linear power amplifier stage is used to amplify the signal from the HF mixer stage to a power level suitable for transmission. Since very stable oscillators and very sharp filters are much easier to produce for low frequency applications, SSB generation is made to occur at relatively low radio frequencies. The generated sideband frequency is brought to the desired high r-f output frequency by frequency conversion. Although the simple single sideband transmitter discussed above uses single conversion for ease of understanding, it is normal practice to use double conversion to obtain the desired high frequency output.

The single sideband modulator is used to generate amplitude modulated upper and lower sidebands, meanwhile suppressing or cancelling the r-f carrier which was used to generate the sidebands. By beating the audio modulation against the unused carrier frequency, sum and difference frequencies are produced to provide the actual sideband frequencies. It is also important to note that the carrier frequency does not appear in the output of the modulator because circuit elements are arranged to produce this effect. All types of single sideband modulators such as the balanced modulator, the balanced-bridge rectifier-type modulator, and the product modulator produce the same end result. They differ, however, in the manner in which they achieve carrier suppression and generate sidebands. Each of these circuits is discussed in detail in the following paragraphs.

BALANCED (PUSH-PULL CARRIER INPUT) MODULATOR.

APPLICATION.

The balanced (push-pull carrier input) modulator is used to produce amplitude modulated upper and lower sidebands for use in single sideband transmitters.

CHARACTERISTICS.

Operates class C with push-push output.

Both r-f carrier and audio modulation are applied to the modulator in push-pull.

Generates upper and lower sidebands while suppressing the r-f carrier.

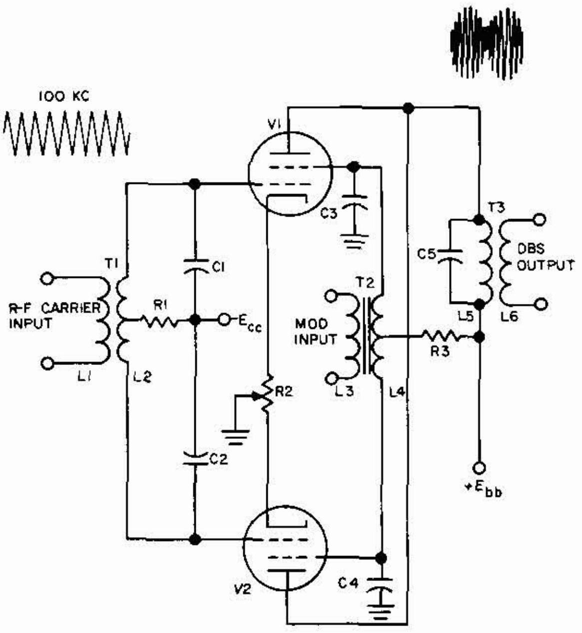
Utilizes two tetrodes with their plates connected in parallel.

CIRCUIT ANALYSIS.

General. While all modulators have the characteristic of producing sidebands the balanced modulator is unique in that it produces only upper and lower sidebands and suppresses, or cancels the r-f carrier in the output. Different types of balanced modulators differ in the manner in which they achieve carrier suppression. This discussion concerns the manner in which the balanced (push-pull carrier input) modulator achieves carrier suppression. The balanced modulator discussed here utilizes two tetrodes with their plates connected in parallel, and operated class C. The r-f carrier is applied to the modulator control grids in push-pull (out of phase) while the modulating signal is applied to the screen grids in push pull, also out of phase. The r-f carrier signal is cancelled in the output tank circuit and upper and lower sidebands are generated. It is important to consider that carrier suppression occurs in the output tank circuit and not in the plate circuit. The parallel-plate connected modulator tubes are operated with Class C bias, and conduct only on positive-going input signals. Since the r-f carrier input is applied to the modulator control grids push pull, the modulator tubes conduct and produce an r-f output on alternate half cycles of the r-f input. Since only one tube is conducting at a given instant, the r-f pulses appearing in the plate circuit of each tube are not affected by the other tube. In the tank circuit, however, the r-f pulses occur at a rate which tends to cancel rather than reinforce tank circuit oscillations. The generated sidebands do not cancel in the output, since the output tank is resonant to only the carrier frequency. The audio modulation signal is not developed in the output due to the low impedance presented to audio frequencies by the r-f output transformer. This discussion concerns the use of tetrodes in the push-pull carrier input balanced modulator. Triodes or pentodes may be used in place of tetrodes, the need being determined by system requirements.

Circuit Operation. The following schematic diagram illustrates a typical balanced (push-pull carrier input) modulator.

Transformer T1 couples the r-f carrier signal from the carrier oscillator to the control grids of balanced modulators V1 and V2. Secondary L2 of T1 is effectively centertapped by R1 and capacitors C1 and C2. Resistor R1 also permits fixed bias insertion for V1 and V2, and serves as a bias decoupling resistor. Potentiometer R2 provides a means for electrically balancing the circuit by varying the cathode resistance of V1 and V2. V1 and V2 are the nonlinear devices used to generate the upper and lower sidebands. Transformer T2 couples the audio modulation to the screen grids of V1 and V2. The secondary of T2 is center-tapped to form a push-pull screen circuit so that the induced audio frequency voltages will be 180 degrees out of phase at the screen grids of the modulator tubes. The audio frequencies do not appear in the output since the output transformer, T3, presents a low impedance to audio frequencies. Capacitors C3 and C4 are screen grid r-f bypass capacitors preventing r-f from entering the screen supply. Resistor R3 is a screen voltage dropping resistor intended to keep screen voltage



Push-Pull Carrier Input Balanced Modulator

always lower than the plate voltage, so that the negative resistance effects inherent in the tetrode are not encountered. Transformer T3 serves as the tuned output transformer. The primary L5 of T3 together with capacitor C5 form a parallel resonant tank circuit which is sharply tuned to the carrier frequency.

To more easily understand the operation of the balanced (push-pull carrier input) modulator assume first that only the r-f carrier is applied. Assume that the first half cycle of r-f carrier drives the grid of V1 positive and the grid of V2 negative. Since V2 is cutoff due to class C bias, the negative signal on the grid of V2 has no effect on V2. On V1, however, the positive half cycle of r-f drives the tube into conduction and a negative going r-f signal appears in the plate circuit. Capacitor C5 charges during the period of increasing plate current. When plate current starts to decrease C5 discharges building a magnetic field around L5. When plate current ceases the magnetic field around L5 would normally collapse and charge C5 in the opposite direction. This is normal tank circuit oscillation sometimes called, "flywheel action".

At this time, however, the next half cycle of r-f input drives V2 into conduction and a negative going r-f pulse appears in the plate circuit. Capacitor C5 charges and prevents the magnetic field around L5 from collapsing. When plate current starts to decrease C5 discharges and maintains constant current through L5. With constant current through L5 the magnetic field around L5 remain unchanged, and an output is not inductively coupled to the following stages. In effect, the r-f output pulse from V2 cancels the r-f output pulse from V1. The amplitude of these pulses should be approximately equal, considering the losses in the tank circuit, for the r-f carrier signal to be effectively canceled. The relative amplitude of the r-f carrier pulses can be varied by the adjustment of potentiometer R2.

Under actual operating conditions with both the r-f carrier and the audio modulation applied, upper and lower sidebands are produced through the beating of the r-f carrier and the audio modulating signal in the non-linearly operated modulator tubes. It is important to note that the sideband frequencies, unlike the carrier frequency, are not canceled in the output tank circuit. This is because the output tank circuit is sharply tuned to the carrier frequency and the sideband frequencies will deviate sufficiently from the carrier frequency for the output tank circuit to appear non-resonant to these frequencies. Hence no sideband energy will be stored in the tank circuit from one half cycle of r-f input to the next and cancellation of the sidebands will not occur.

FAILURE ANALYSIS.

No Output. Failure of one of the modulator tubes is not likely to cause a no-output condition to exist. Failure of the power supply or a circuit component common to both branches of the balanced modulator is a much more likely cause of no output. Voltage checks of V1 and V2 with a voltmeter would reveal a defective component that could be the cause of no output. Power supply voltages should be checked and adjusted if necessary. Any discrepancies found during voltage checks can be followed up, with the equipment deenergized, with resistance checks of associated circuit components to reveal the component at fault. Since both r-f carrier and modulation inputs are required to produce a sideband output, lack of either signal could be a cause of no output. Presence of these input signals can be readily determined with an oscilloscope. The r-f carrier should be present on the control grids of both tubes and should have sufficient amplitude to drive the tubes above cutoff. If the r-f carrier is not present on the grids of the modulator tubes, check for presence of the r-f carrier on the primary of T1. If no signal is present on the primary of T1 the fault likely lies in the stage, or stages, preceding the balanced modulator. If a signal is present on the primary of T1 but absent on the control grids of V1 and V2 the fault likely lies in transformer T1. If the audio modulating signal is not present on the screen grids of the modulating tubes, check for presence of the modulation signal on the primary of T2. If modulation is present on the primary of T2 but absent on the screen grids of V1 and V2, transformer T2 is defective. If the modulation signal is absent at the primary of T2 the fault likely lies in the preceding stages.

Low Output. A common cause of low output is decreased emission of the modulator tubes. The power supply voltages should be checked and corrected if necessary. Voltage checks of V1 and V2 would reveal if a defective circuit component is the cause of low output. Should a discrepancy be found during voltage checks a resistive analysis of cicuit components would reveal the component at fault. Another possible cause of low output could be decreased amplitude r-f carrier input or decreased amplitude modulation input. The existance of this condition can be determined by observing with an oscilloscope the amplitude of the r-f carrier signal on the control grids, and the amplitude of the modulating signal on the screen grids of V1 and V2.

Distorted Output. Distortion of intelligence in SSB systems will occur if the transmitter and receiver are not exactly on frequency. Distortion in SSB transmitter is usually caused by improper operation of the linear power amplifier or by operating any stage in the transmitter beyond its capabilities. If the balanced modulator is determined to be the cause of distortion a possible cause could be defective tubes. Check the power supply voltages with a voltmeter. If the tubes are good and the power supply voltages are correct, a resistive analysis of circuit components with the equipment deenergized would reveal a component failure that could be a cause of distorted output. Do not overlook the possibility that the audio modulation is distorted before it reaches the balanced modulator. The existance of this condition can be determined by observing, with an oscilloscope, the quality of the modulation signal on the screen grids of V1 and V2 with an audio tone from an audio signal generator applied to the transmitter.

BALANCED (PARALLEL CARRIER INPUT) MODULATOR.

APPLICATION

The parallel carrier input balanced modulator is used to produce amplitude modulated upper and lower sideband frequencies for use in suppressed-carrier, single sideband transmitters, commonly abbreviated as SSSC.

CHARACTERISTICS.

Utilizes nonlinear characteristics of electron tubes to produce sidebands.

Produces amplitude modulated upper and lower sidebands while suppressing the r-f carrier.

No output is produced unless both r-f carrier and modulation are present.

Modulation is accomplished at low power levels, therefore, no large modulator power supply and transformers are needed.

Uses push-pull output and parallel input to cancel out the carrier.

Can provide conversion gain i.e. Sideband output greater than modulation input.

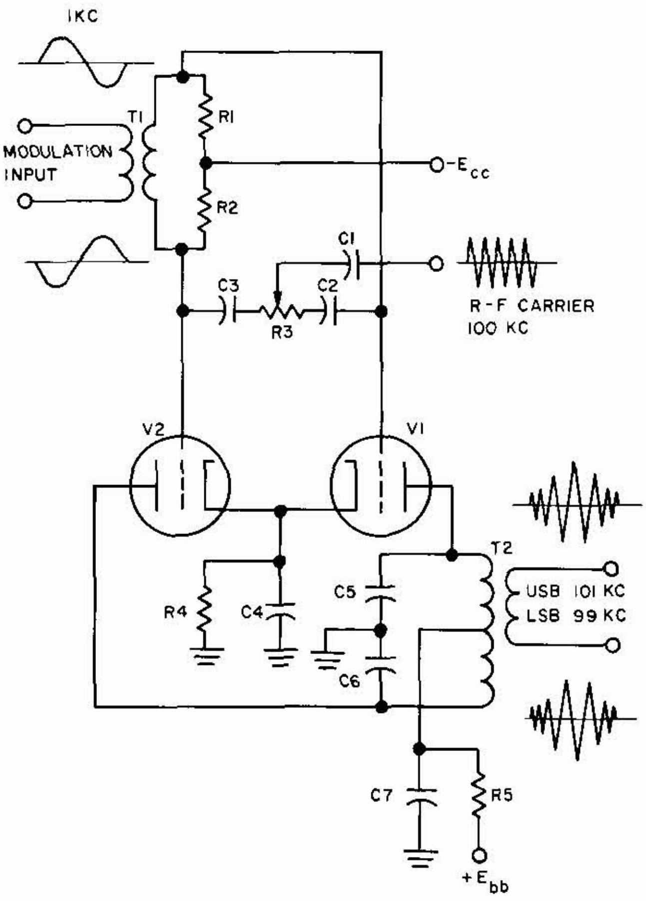
CIRCUIT ANALYSIS.

General. The parallel carrier-input balanced modulator produces amplitude modulated sidebands and suppresses the r-f carrier. This is achieved by coupling the r-f carrier, in-phase, to the grids of two tubes whose output is connected in push pull (out-of-phase). The r-f carrier signal voltage is kept 8 to 10 times as large as the modulating voltage to keep distortion to a minimum. In push pull amplifiers an input signal inserted in-phase on the grids (in parallel) will cancel in the output. The modulating signal is applied in series to the grids of the balanced modulator through a transformer. This transformer is effectively centertapped by a resistance network connected across the secondary winding for bias insertion. The center tap arrangement produces a 180 degree phase different between the audio modulation signal voltages on the grids of the modulating tubes. When both r-f carrier and modulating audio signal are applied to the grids of the balanced modulators, sum and difference frequencies (sideband) are produced by the modulating frequencies beating against the carrier, since any amplitude modulation process is essentially the same as heterodyning. As in a frequency converter, any modulation which exists on one of the mixing frequencies is linearly transposed to the resultant sum and difference frequencies. The plate circuit contains the upper and lower sidebands, which are the sum and difference frequencies, respectively, the r-f carrier, and the audio modulation. The carrier is cancelled out by push-pull action in the output transformer and the output transformer also presents a low impedance to the audio modulating signal. Therefore, the original modulating signal is not developed in the output. The generated sidebands are out-of-phase with each other at the plates of the tubes, since the modulating signal is out-of-phase at the grids. These out of phase signals add in the output rather than cancel as in-phase signals do, and they are inductively coupled to the following stages through the output transformer. Tetrodes and pentodes may be used with equal or greater effectiveness, their use being determined by system requirements.

Circuit Operation. The accompanying diagram illustrates a typical parallel carrier-input balanced modulator.

Transformer T1 couples the audio modulation to the grids of balanced modulator tubes V1 and V2. Resistors R1 and R2 provide grid bias and an effective centertap for T1. Capacitor C1 couples the r-f carrier from the carrier oscillator to carrier balance potentiometer R3. Carrier balance potentiometer R3 is adjusted to vary the relative amplitude of the carrier signal on the grids of V1 and V2, so that the circuit may be completely balanced and the carrier suppressed in the output. Capacitors C2 and C3 couple the r-f carrier from balance potentiometer R3 to the grids of V1 and V2. Modulator tubes V1 and V2 are the nonlinear devices used for developing the modulation. Resistor R4, which is bypassed by C4, provides cathode bias for both tubes. Center-tapped plate transformer T2 provides a push-pull plate load for the modulators. Capacitors C5 and C6 bypass any higher order harmonics that might be generated in the plate circuit to ground. Resistor R5 is a plate voltage dropping resistor, while C7 bypasses any unwanted signals to ground, and places the center tap of T2 at ground potential.

The operation of the parallel carrier-input balanced modulator can be more easily examined by first applying only the r-f carrier. The r-f carrier generated in the carrier oscillator is coupled through C1 to the slider of variable resistor R3. Thus the carrier signal appears at both ends of R3 and is coupled through C2 and C3 to the grids of V1 and V2. The carrier signal voltage is inserted in-phase on the grids of V1 and V2, and the amplitude, at each tube is controlled by adjusting R3. Assuming that the r-f input is



Parallel Carrier Input Balanced Modulator

operating on the positive half-cycle, both plates draw an increasing plate current (the grid input is in-phase), and the voltage drop across each half of the transformer winding is negative going, so that equal and opposing voltages are developed in the transformer primary which cancel, and no output is obtained from the secondary. Likewise, on the negative half-cycle less plate current is drawn and the drop across the transformer is positive going, and equal and opposing voltages are developed in the primary and also cancel out, so no carrier again is produced. If the circuit is properly balanced by the adjustment of R3, these opposing signals are equal in amplitude and the carrier is effectively suppressed.

The amount of carrier suppression obtained depends upon the degree of balance between the two legs of the balanced modulator circuit. When two tubes of the same type are used in a balanced modulator circuit (without any balancing adjustment) carrier suppression of 10 to 15 DB generally results. Since carrier suppression of at least 35 DB is usually required in suppressed-carrier, single-sideband systems it can be seen that some type of fine balancing adjustment is required. In this circuit R3 is used for carrier balancing, but other methods (such as varying the bias or plate voltage on the modulator tubes) may be encountered in other circuits.

When audio modulation also is applied, a different situation arises. The audio modulation is applied through transformer T1. Since the secondary of T1 is effectively center tapped by resistors R1 and R2 modulation signal voltages will be developed across each half of the winding which are out of phase with each other. This modulating signal is applied directly to the grids of V1 and V2. Capacitors C2 and C3 are of such a value that they present a high impedance to audio frequencies and prevent any audio modulation from crossing over, from one grid to the other, and canceling each other out. The audio modulating signal modulates the r-f carrier and produces upper and lower sidebands in the plate circuit of the modulator tubes. These sidebands are produced by mixing the r-f carrier frequency and the modulation signal across a nonlinear device. To illustrate the operation of the parallel carrier-input balanced modulator with both r-f carrier and modulating signal applied assume that the first half cycle of the modulating voltage applied to the grid of V1 is positive and the first half cycle of the modulating signal applied to the grid of V2 is negative. It can readily be seen that conduction of V1 will increase with negative going sideband frequencies being generated across the top half of the output transformer. At the same time, the negative half cycle of audio modulation applied to the grid of V2 decreases conduction of V2, causing positive going sideband frequencies to be developed across the bottom half of the output transformer. Push pull action thus occurs and the sideband frequencies add to each other, causing both upper and lower sidebands to be developed and inductively coupled to the secondary of T2. The r-f carrier is suppressed, as explained earlier, and the original audio modulating signal is not developed due to the low reactance of T2 to the basic audio modulation frequencies. Therefore, only the upper and lower amplitude modulated sidebands are produced by the balanced modulator.

FAILURE ANALYSIS.

No Output. Since both modulator tubes perform the same function it is unlikely that failure of one tube or associated circuit would cause a no-output condition. A much more likely cause of no output would be failure of something common to both tubes such as the power supply, the cathode resistor or the circuits associated with the r-f carrier input or modulation input. Voltage checks on V1 and V2 with a voltmeter would reveal a defective component that could cause no output. Should all the voltages check good the cause of no output could be the lack of either r-f carrier or modulating signal. This can be easily checked with an oscilloscope. Check the grids for presence of both signals with the carrier oscillator operating and modulation applied. If the modulating signal is not present on the grids, check for presence of the modulation signal on the primary of T1. This will determine whether T1 or the preceding audio stages are at fault. Should the r-f carrier be missing check the output of the carrier oscillator. If there is an output from the carrier oscillator, signal trace the components linking the carrier oscillator to the grids of the modulator tubes. Should all the conditions necessary for proper operation be met, i.e. proper voltages on the tube elements, proper carrier and modulation inputs, and there is still no output, transformer T2 could be defective. Check all windings of T2 for proper resistance and check all windings for leakage to ground.

Low Output. Low output can be caused by a defective tube or tubes, improper power supply voltages or by a defective circuit component. Low output could also be caused by decreased amplitude of the r-f carrier signal voltage or possibly by decreased amplitude of the modulating signal. Check the power supply voltages. If the power supply voltages are good, voltage checks of the tube elements would reveal whether or not a defective circuit component was the cause of low output. Should these voltage checks reveal a discrepancy, resistance checks, with the circuit deenergized, would reveal the component at fault. The possibility of decreased amplitude r-f carrier signal or modulating signal input can be checked by observing these signals on an oscilloscope. If all the conditions necessary for proper operation are met, i.e. good tubes, proper power supply voltages, and good circuit components, poor operation could be the result of a defective output transformer. Since the resistance of the output transformers windings are relatively low a shorted winding could easily be overlooked when making resistance checks. Check the resistance of each half of the primary winding, each half should be equal, and check the resistance of the secondary winding. With the centertap disconnected check the windings for leakage to ground.

Distorted Output. It should be noted that distortion of intelligence will occur if the single sideband transmitter and receiver are not exactly on frequency. Distortion in single sideband transmitters is frequently caused by improper operation of the linear amplifiers, or by operating any stage beyond its capabilities. If system distortion is determined to be caused by the balanced modulator a likely cause could be improper voltages applied to the tubes, or defective tube or tubes, or failure of some circuit component. Check the power supply voltages, if they are good, voltage checks of the tube elements would indicate whether or not a defective circuit component is the cause of distorted output. Incorrect voltages found to be present on tube elements can be traced to the component at fault with resistance checks of associated circuit components. The possibility of a distorted audio input or possibly a distorted r-f carrier should not be overlooked. The existance of these conditions can be determined by observing these signals on an oscilloscope.

BALANCED BRIDGE MODULATOR.

APPLICATION.

The balanced bridge modulator is used in single sideband generators to produce amplitude modulated upper and lower sidebands while suppressing the r-f carrier.

CHARACTERISTICS.

Produces upper and lower sidebands while suppressing the r-f carrier.

Utilizes four diodes connected in a bridge configuration.

Produces sidebands by heterodyning action produced by nonlinear diodes.

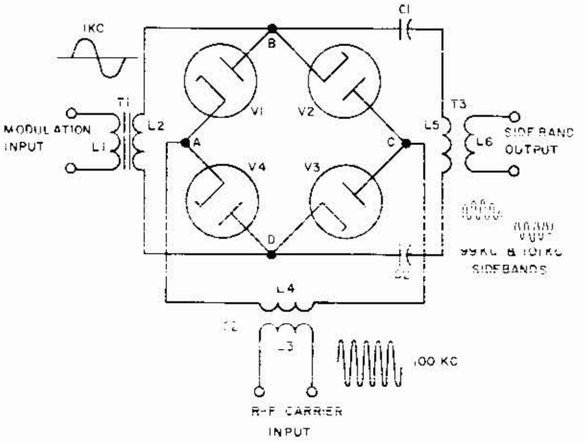
Requires both an r-f carrier and modulation applied simultaneously to produce an output.

CIRCUIT ANALYSIS.

General. The purpose of the balanced bridge balanced modulator is to produce amplitude modulated upper and lower sidebands and suppress the r-f carrier. Basically this is achieved in the balanced bridge modulator by arranging the circuit elements so that a balanced condition exists between the two legs of the bridge when only an r-f carrier is applied. This balanced condition will prevent an r-f output from being produced. Modulation is applied so that the bridge becomes unbalanced, that is, more current flows through one leg than the other. This causes current to flow through the output transformer, and an output is produced. The current flowing through the output transformer is the upper and lower sidebands generated by the heterodyning of the r-f carrier and modulating signal within the non-linear diodes.

Carrier suppression is achieved because the current through one leg represents the carrier and sideband currents plus the modulating signal current, while current through the other leg consists of only the carrier current. The overall effect is to cancel the r-f carrier currents. The audio frequency component is blocked from the output by capacitors whose reactance is high to audio frequencies. Only the sidebands are present in the output.

Circuit Operation. The accompanying diagram illustrates a typical balanced bridge modulator utilizing electron tube diodes.

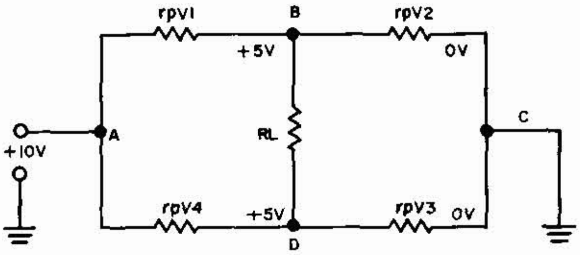


Balanced Bridge Modulator

Transformer T1 couples the modulation signal to the balanced bridge, and Transformer T2 couples the r-f carrier from the carrier oscillator to the balanced bridge. Diodes V1, V2, V3, and V4, form the balanced bridge. Capacitors C1 and C2 block audio frequencies, thereby preventing the primary of T3 from shunting the secondary of T2. This is necessary since T3 is an r-f transformer and would present a very low impedance to audio frequencies. Transformer T3 serves as an output transformer. Designations at points A, B, C, and D are used only to illustrate circuit operation.

To more easily analyze the operation of the balanced bridge modulator, assume first that only the r-f carrier is applied. Assume that during the first half-cycle of r-f, point A is positive with respect to point C. This back biases the diodes and no current flows, hence no output results, since the bridge appears as an open circuit.

When the negative half-cycle appears point A becomes negative with respect to point C. This forward biases the diodes and current flows from point A through V1 and V2 to point C. An equal current will flow from point A through V4 and V3 to point C. When the current through leg V1, V2 is equal to the current through leg V4, V3, a state of balance exists and no current will flow through winding L5 of the output transformer, T3. The accompanying illustration shows the equivalent circuit of the bridge in a balanced state.



Equivalent Circuit of Balanced Bridge Modulator With Only r-f Carrier Applied

The resistances represent the plate resistance of the diodes. Since the diodes are all of the same type and have the same characteristics, their conduction and plate resistances are the same. Resistor RL represents the load presented by the output transformer. There is no difference in potential between points B and D, and no current flows through the output transformer. Thus there is no output from the balanced bridge modulator when only the r-f carrier is applied.

When only the modulation signal is applied, circuit operation is as follows. Assume first that a positive half-cycle of modulating voltage is applied; causing point B to be more positive than point D. It can be seen that the instantaneous potential created by the positive half-cycle of modulation signal will cause current to flow from point D through V3 to point C. Since the plate of V2 is connected to point C, current will not flow through V2. Current will, however, flow from point C through the secondary, L4, of T2 to point A, and through V1 to point B. Current also will not flow through V4 since V4 like V2 is back-biased to current flow in this direction. The return path for current flow is through secondary L2, of T1. The primary, L5, of T3 does not effect the modulation signal since C1 and C2 offer a high impedance to the relatively low modulating frequency and prevent any shunting effects of L5 on L2. When the polarity of the modulating signal reverses, current flows from point B through V2 to point C. From point C current flows through the secondary, L4, of T2 to point A and then through V4 to point D. The return path is through the secondary, L2, of T1.

Under actual operating conditions with both r-f carrier and signal applied, the balance between the upper and lower legs of the bridge caused by the equal r-f carrier currents through each leg is disrupted by the modulating signal and a sideband output results.

To examine the circuit under actual operating conditions, consider first that r-f carrier current is flowing in equal amounts through the upper and lower legs, V1 and V2, and V4 and V3 respectively. When a positive going cycle of audio modulating signal is applied to T1, modulation signal current flows from point D through V3 to secondary L4 of T2 and to point A, and then through V1 to point B and back to secondary L2 of T1. Since the diode is a nonlinear device, mixing, or heterodyning, takes place between the r-f carrier currents and the modulating signal currents flowing through V1 and V3, and both upper and lower sidebands are produced. These sideband currents follow the same path as the modulating signal except that they flow through the output transformer T3 instead of the secondary L2 of T1. This is because transformer T1 offers a high impedance to the relatively high sideband frequencies. The sidebands are inductively coupled through T3 to the following stages. The overall effect is the same for a negative half-cycle of modulation except that sideband current flow is through V2 and V4 and the flow is through the output transformer in the opposite direction.

FAILURE ANALYSIS.

No Output. A no-output condition could be caused by an open or shorted winding on any of the three transformers. With the equipment de-energized, a resistance check of the transformer windings will indicate an open or partially shorted winding. Failure of one of the diodes will not be likely to cause no-output, however if the diode filaments are connected in series an open filament could cause the other diodes to be in operative. A visual check with the equipment energized will reveal whether or not any filament failures occur. Since a balanced modulator does not produce an output unless both r-f carrier and modulation signals are present, lack of either these signals could be a cause of no output. Presence of these signals can be determined with an oscilloscope. To check for the presence of the modulating signal, observe the waveform present at points B and D. If the modulating signal is not present at these points check for modulating signal on L1 the primary of T1. If the modulating signal is present here, but is absent at points B and D the fault most likely lies in transformer T1. If there is no signal present on the primary of T1 the trouble is likely to be in the preceding stages. The presence of the r-f carrier can be determined in the same manner by observing the waveform present at points A and C. If the r-f carrier is not present at A and C the trouble can be localized by signal tracing with an oscilloscope through T2.

Low Output. A common cause of low output can be from decreased emission of one or more of the diodes. If any tubes are replaced it would be good procedure to check **all** the tubes on a tube checker and use only tubes which have approximately the same emission. This is particularly advisable if a high degree of balance is desired within the bridge of diodes. If the tubes are good, another possible cause of low output could be insufficient modulation input or insufficient r-f carrier input. This condition can be checked by observing the amplitude of the waveforms present at the modulation inputs to the bridge, and at the r-f carrier inputs to the bridge. If one of the inputs are low the cause can be determined by signal tracing with an oscilloscope and noting any excessive attenuation through the input transformers. If the amplitude of either signal is proper on the primary of the respective input transformer but low on the secondary, the transformer is defective. If the amplitude of the input signal is low on the primary of the respective input transformer the trouble likely lies in the stages preceding the balanced modulator.

Distorted Output. Distortion could be caused by a defective tube. Another cause of distortion might be a low r-f carrier input. The r-f carrier should be 8 to 10 times the amplitude of the modulating signal for distortion to be at a minimum. Do not overlook the possibility that the modulation input is distorted before it reaches the balanced modulator. Analysis of the modulation input with an oscilloscope would reveal if this condition existed.

PRODUCT MODULATOR.

APPLICATION.

The product modulator is used in single sideband transmitters to produce amplitude modulated upper and lower sidebands while suppressing the r-f carrier.

CHARACTERISTICS.

The output of a product modulator is proportional to the product of the amplitudes of the input signals.

Does not require input transformers.

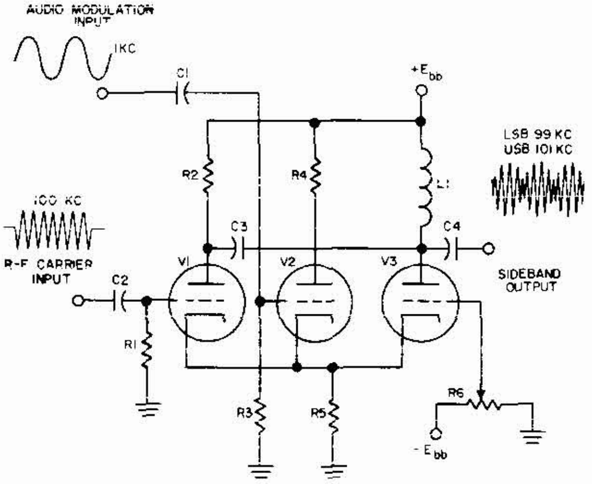
Utilizes three triodes with two of them operated as cathode followers.

Operates with class A bias.

CIRCUIT ANALYSIS.

General. The product modulator in single sideband applications produces amplitude modulated upper and lower sidebands while suppressing, or cancelling the r-f carrier. The single sideband product modulator utilizes three triodes with two of them operated as cathode followers. It is interesting to note that all three triodes have a common cathode resistor. The r-f carrier and the audio modulation are impressed on the grids of cathode followers, and r-f carrier and audio modulation are developed across the common cathode resistor. Since the modulator tube also uses the same cathode resistor, audio modulation and r-f carrier signal voltage appear on the cathode of the modulator tube. The r-f carrier and audio modulation beat together in the modulator tube and upper and lower sidebands are generated. Carrier suppression is achieved by coupling the r-f carrier signal developed at the plate of V1 to the plate of V3. Since there is 180° phase difference between the r-f carrier signal developed at the plate of V1 and at the plate of V3, the r-f carrier is effectively canceled. The product modulator when used in single sideband applications produces a sideband output only when both the r-f carrier and the audio modulator are applied simultaneously. The use of cathode followers eliminates the need for r-f carrier and audio modulation input transformers, since the cathode followers provide the necessary impedance match between the r-f carrier oscillator and the product modulator, and also between the audio amplifying circuits and the product modulator. The cathode followers also provide isolation between the r-f carrier oscillator and the audio circuits. By eliminating the carrier suppression provision the product modulator can also be used as a low distortion A-M modulator.

The following circuit diagram illustrates a typical product modulator for use in single sideband systems.



Product Modulator

Circuit Operation. Capacitor C1 couples the audio modulation to the grid of V2 and capacitor C2 couples the r-f carrier to the grid of V1. Resistor R1 and R3 are grid resistor for V1 and V2, respectively. Capacitor C3 couples the r-f carrier signal voltage from the plate of V1 to the plate of V3 for the purpose of carrier cancellation. Resistor R2 and R4 are plate dropping resistors and load for V1 and V2, respectively. Resistor R5 is a common cathode resistor for all three tubes and potentiometer R6 provides a carrier balance control by varying the fixed bias on V3. V1 and V2 which serve as cathode followers couple the r-f carrier input and the audio modulation input to the cathode of V3 which serves as the modulator tube. Inductor L1 is the plate load for V3, and C4 capacitively couples the generated sidebands to the following stages.

To more easily examine the operation of the single sideband product modulator, first assume that only the r-f carrier is applied to the modulator.

During the positive half cycle of r-f carrier input the conduction of V1 increase and the voltage drop across plate resistor R2 increase causing a negative going r-f carrier pulse to appear at the plate of V1, and the voltage drop across common cathode resistor R5 increases, causing a positive going r-f carrier pulse to appear at the cathode of V1. Since the cathode of V3 is directly connected to the cathode of V1, the positive r-f pulse appears on the cathode of V3 and decreases the conductor of V3 causing a positive going r-f pulse to appear at the plate of V3. The negative r-f pulse on the plate of V1, is coupled through capacitor C3 to the plate of V3. If the r-f pulses from V1 are equal in amplitude to the r-f pulses from V3 there will be complete cancellation, and the r-f carrier will not appear in the output. The relative amplitude of these r-f pulses may be varied by the adjustment of R6 which varies the gain of V3. The positive half cycle of r-f input was used only to illustrate circuit operation. Circuit operation is the same for a negative half cycle of r-f input.

Thus with only the r-f carrier applied there will be no output from the product modulator.

When audio modulation is applied in addition to the r-f carrier upper and lower sidebands are generated. Audio modulation is coupled through coupling capacitor C1 to the grid of cathode follower V2. Audio frequency voltage are developed across common cathode resistor R5 and are directly coupled to the cathode of V3. The r-f carrier and audio modulation beat together in V3 and four basic frequencies appear in the plate circuit of V3. These frequencies are the original audio modulation, the original r-f carrier, and newly generated sum and difference frequencies. The r-f carrier frequency present in the plate circuit of V3 will be canceled by the 180° out-of-phase r-f carrier signal coupled to V3 from V1, as explained in the previous paragraph. The audio modulator present in the plate circuit of V3 is not developed in the output since inductor L1 presents a low impedance to audio frequencies. The generated sideband frequencies, referred to earlier as sum and difference frequencies are developed across inductor L1 and capacitively coupled through C4 to the following stages.

FAILURE ANALYSIS.

No Output. Failure of almost any component could be a cause of no output in the product modulator. Check the power supply voltages to make certain that a defective power supply is not the cause of no-output. Voltage checks of tube elements will reveal if a component failure is the cause of no-output. Any discrepancies found during voltage checks can be followed up, with the equipment de-energized, by a resistive analysis of circuit components to reveal the component at fault. It should be noted that the product modulator will produce an output only when both r-f carrier and audio modulation are present on the cathode of V3. Presence of the r-f carrier and the audio modulation can be determined by observing the waveform with a oscilloscope on the cathode of V3 with modulation applied to the transmitter and the carrier oscillator operating. If either signal is missing the trouble can be localized by signal tracing from the signal source, either the carrier oscillator, or the audio amplifying circuits, to the cathode of V3.

Low Output. A likely cause of low output in the product modulator is decreased emission of the electron tubes. If proper operation is not restored, a defective circuit component could be the cause of low output. A resistive analysis of circuit components with the equipment de-energized would reveal a defective component that could be the cause of low output.

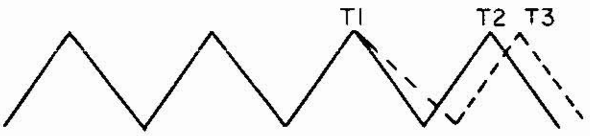
Another possible cause of low output is decreased amplitude r-f carrier input or decreased amplitude audio modulation input. The existence of this condition can be readily determined by observing the amplitude of the r-f carrier signal and audio modulation present on the cathode of V3, with an oscilloscope.

Distorted Output. It should be noted that distortion will occur in SSB systems if the transmitter and receiver are not exactly on frequency. Distortion in SSB transmitters usually results from improper operation of the linear power amplifiers or by operating any stage beyond its capabilities.

If the modulator is determined to be the cause of distortion a likely cause of distortion would be defective tubes or a defective circuit component. The tubes can easily checked by exchanging them with tubes known to be good. Resistance checks of circuit components would reveal if a defective circuit component is the cause of distorted output. Power supply voltages should be checked and adjusted if necessary to make certain that a defective power supply is not the cause of distorted output. Don't overlook the possibility that the audio modulation may be distorted before it reaches the product modulator. To check for this condition observe with an oscilloscope, the quality of the audio modulation present on the grid of V2, with a audio tone from a audio signal generator applied to the modulation input of the transmitter.

PHASE MODULATORS (PM).

In phase modulation, sometimes referred to as indirect frequency modulation, the audio signal is used to shift the phase and the frequency of the carrier frequency, resulting in a frequency variation in the output. The amount of phase deviation is directly proportional to the amplitude of the audio signal, and the amount of frequency deviation is proportional to the frequency of the audio signal. An illustration of phase modulation is shown below.



Result of Phase Modulation.

The solid line represents the carrier frequency. If an audio signal is introduced at the beginning of time T1, the next positive peak occurs, for example, at time T3, shown in dotted lines, instead of at a time T2, where it would normally occur. Since the peak following T1 now occurs at a later time, the phase of the output is now lagging the carrier. By the same token, the phase can be changed to a leading one by the applications of a signal of opposite polarity. Thus the amount and direction of phase shift varies in accordance with the amplitude and polarity of the audio input. A frequency variation also occurs in the output, because the frequency of the modulating signal determines the rate at which the phase of the carrier deviates, and thus determines the amount of frequency deviation.

The frequency of the carrier before a phase shift occurs is called the center frequency, and is generated by a crystal controlled oscillator, which accounts for the excellent frequency stability of the phase modulator.

The phase variations, or modulation, are not applied until after the carrier frequency is generated and it is this peculiarity which allows the use of a crystal oscillator. With no audio signal applied, only the carrier frequency, is transmitted.

Since random noise usually consists of higher frequencies, the signal to noise ratio at the higher audio frequencies may be lower. It is for this reason that the audio modulation is coupled through a pre-emphasis network before being applied to the modulator circuit. The pre-emphasis network increases the relative strength of the higher frequency components of the audio signal, and thereby compensates for any decrease in signal-to-noise ratio as caused by random high frequency noise. This creates a state of unbalance between the amplitudes of the high and low frequency components, but it is compensated for in the receiver by the use of a de-emphasis circuit, which performs the opposite function of pre-emphasis.

The greatest advantage of the phase modulator is, as previously mentioned, its excellent frequency stability, which results from the use of a crystal oscillator.

The advantage of this type of modulation over a-m is its noise reducing capabilities. Most noise signals produce amplitude modulation of the carrier, or the carrier-plus-modulation signal, which is applied to the demodulating circuit in the receiver. If the receiver is responsive to amplitude variations, as in a-m receivers, this random noise is detected and amplified. If the receiver is responsive only to changes in frequency, as in an f-m receiver, phase modulation makes possible a considerable increase in the signal-to-noise ratio. Actually, phase modulation is a form of f-m, the difference being that whereas f-m is responsive only to changes in amplitude, p-m is responsive to both the amplitude and the frequency of the audio modulation.

A better understanding of phase modulation can be obtained from the following descriptions of specific phase modulator circuits.

BASIC PHASE MODULATOR.

APPLICATION.

The phase modulator is used in transmitters to vary the frequency of an r-f signal in accordance with the intelligence to be transmitted.

CHARACTERISTICS.

Carrier frequency is supplied by a crystal controlled oscillator.

Frequency stability is excellent.

Has a high signal-to-noise ratio.

Operates over the linear portion of the Eg - Ip curve.

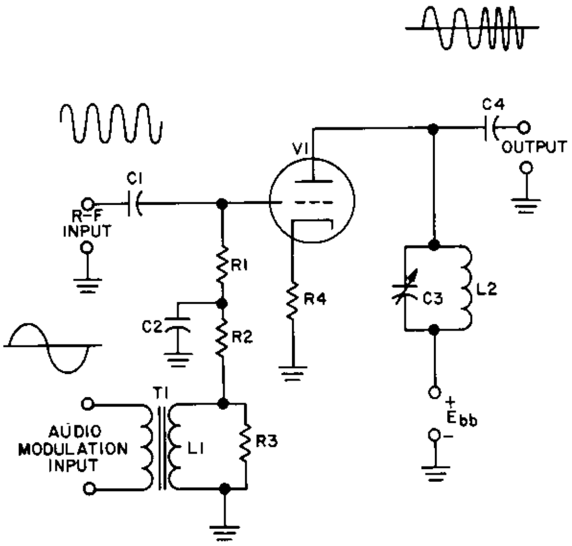
CIRCUIT ANALYSIS.

General. The purpose of the modulator stage is to convert an audio signal into a radio frequency containing the audio intelligence.

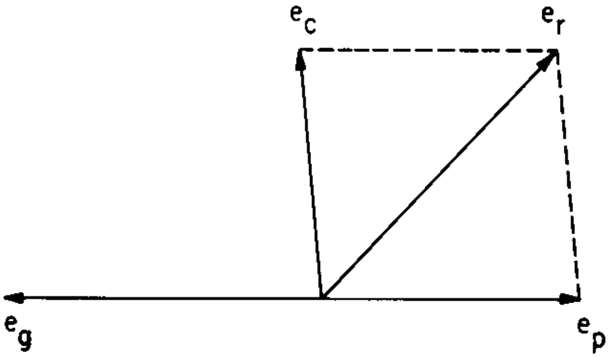
In the basic phase modulator, a crystal controlled oscillator supplies the desired basic frequency to the grid of a triode. A modulating (audio) signal is also applied to the grid of this modulator tube, and a phase shift occurs in the r-f output. The amount and direction of the phase shift is proportional to the amplitude and polarity as well as the frequency of the audio modulating signal.

Circuit Operation. A basic phase modulator is shown in the accompanying schematic diagram.

The crystal oscillator r-f output is coupled through coupling capacitor C1 to the grid of V1, and it is this crystal oscillator frequency which is the center frequency of the phase modulated output. Resistors R1, R2, and R3 form a voltage divider, across which both the oscillator r-f signal



Basic Phase Modulator



Vector Diagram Showing Effect of Modulation

and the audio modulation is applied. R2, in conjunction with C2, also performs the function of a decoupling network, which bypasses the lower end of R1 to ground and prevents the r-f carrier frequency component from feeding back into the audio circuits through T1. In effect, it isolates the r-f from the audio, despite the apparent common connection. The audio modulation is applied through transformer T1 and through R2 and R1 to the grid of V1. Cathode resistor R4 provides degenerative feedback, and the plate tank circuit, consisting of L2 and C3, is tuned to a frequency below the lowest output r-f frequency. Because R4 is unbypassed and causes degenerative feedback, the tube gain is relatively low.

The r-f signal (the carrier) is of constant amplitude and frequency, and with both positive and negative cycles equal in amplitude, no bias change is produced on V1 grid. Thus an amplified r-f carrier appears as the reproduced output, with the normal 180 degree grid to plate phase shift. The audio modulation, however, applied through transformer T1, provides, in effect a changing bias on V1 grid as it varies in amplitude and polarity. As a result, the gain of the tube is varied in accordance with the audio signal bias. The manner in which this variation in the gain of the triode is converted into a phase shift of the carrier, can be better understood through the use of vector diagrams.

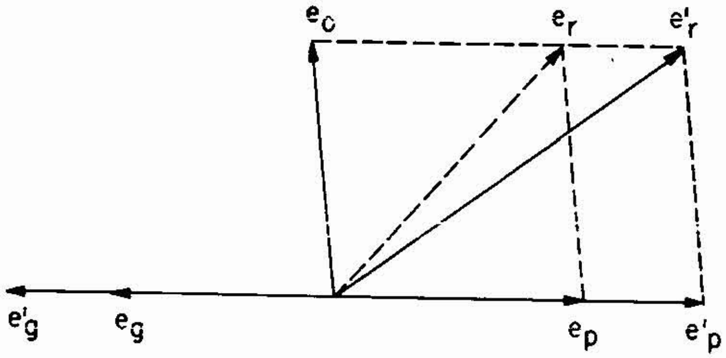
The voltage produced by normal amplifier action is represented as e_p. Another r-f voltage is produced by the grid to plate capacitance of the tube, and is represented as e_c, and the result of these two r-f plate voltages, which is the instantaneous plate voltage, is represented as e_r. Due to normal amplifier action, e_p is 180 degrees out of phase with e_g, the grid voltage and its amplitude is relatively low because of the degenerative effect of the unbypassed cathode resistor, R4. Since e_c lags e_g by some amount, e_r, which is the vector result of e_c and e_p it falls somewhere between these two voltages, as illustrated in the above diagram.

When the signal on the grid increases in a positive direction, the amplitude of the plate signal also increases, with the following result. The vectors which change as a result of this increase in grid signal are designated as e'_g, e'_r, and e'_p. Voltages e_g, e_r, and e_p are shown in order to compare this example with the previous one. It can be seen therefore, that with a larger signal on the grid (e'_g), the closer e'_p and e'_r become in phase.

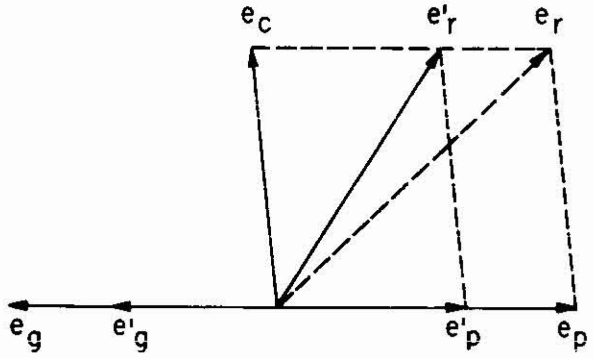
Conversely, when the grid signal (e'_g) decreases in amplitude, the plate signal, e'_p decreases, as illustrated below.

As a result, the vector e_r shifts further out of phase with e_p (to e'_r) than it was under the first condition illustrated. By comparing these three illustrated circumstances, it can be seen that the phase relationship between e_r and e_g constantly changes in phase as e_g varies in amplitude and polarity.

The overall effect is that the amplitude of the modulating signal determines the amount and direction of phase deviation of the carrier in the output. The frequency of the modulating signal determines the rate at which the phase of the carrier deviates, and thus determines the amount of frequency deviation. This effect can be more clearing seen by referring to the accompanying illustration showing the different frequencies produced by adding F1 and F2, and F1 and F3.

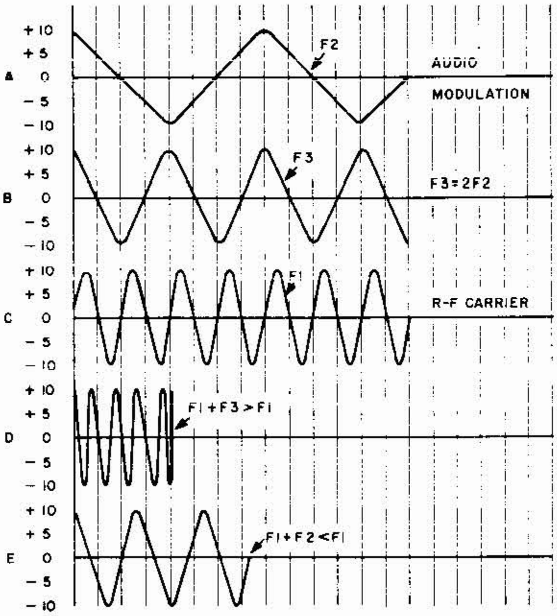


Vector Diagram For Increasing Grid Voltage



Vector Diagram For Decreasing Grid Voltage

The carrier (oscillator) frequency is represented by F1 in part C of the figure. F2 (shown in part A of the figure) represents the modulation frequency, and the result of adding or combining $F_1 + F_2$ is shown in part E of the figure. As shown in the figure F_2 starts at 10-volts positive and assume for ease of explanation that this positive 10-volts modulation causes a full 90 degree phase shift in the carrier. Now,



Effect of Frequency and Amplitude Changes of Modulating Signal

since the carrier frequency F_1 is at 0 at the same instant, the sum value (F1 + F2) is at +10 volts and by assumption leads F_1 by 90 degrees. As the modulation voltage (F2) decreases to +5 volts, the phase shift is reduced to one-half maximum or 45 degrees. At this point, F1 has completed 180 degrees of its cycle and is at 0 voltage, except that the 45 degree advance makes the sum of F_1 and F_2 a minus 5-volts instead, as shown in part E of the figure. As modulation Voltage F_2 continues to decrease and reaches 0 voltage no further phase shift occurs and the carrier and modulator voltages are again in-phase (at this point F1 has just completed 360 degrees of its cycle and by coincidence happens to be at 0 voltage also). The negative modulation cycle now continues, and, when F2 reaches −5 volts it also causes a 45 degrees phase shift, but this time the shift is in a lagging direction. Therefore, although F1 is actually at 0 the lagging sum produces a +5 volts combined signal as shown at E. In this manner, the phase shift follows the modulating voltage, leading on the positive half cycle of modulation and lagging over the negative half cycle, with the amount of phase shift being proportional to the instantaneous amplitude of the modulating signal.

By following the relationship between F_1 and F_3 (part B of the figure) in the same manner as for F_1 and F_2 as just explained, we see that when a modulation frequency twice that of F_2 is used, the sum shown in part D of the figure is an increasing frequency. Since frequency deviation increases with an increase in the modulation frequency, this is the result to be expected and proves our previous assumptions to be correct.

FAILURE ANALYSIS.

No Output. A defect in nearly any component in the circuit can cause a no output condition to exist. Check with an oscilloscope to make sure that both the oscillator and the audio modulation are present at the inputs to the circuit. If either one is missing, the modulator is probably not defective, and the output will probably be restored with the restoration of the missing input. If both inputs are present, disable the oscillator, and check for the modulation input of the grid. If not present, check transformer T1 for continuity with an ohmmeter. Check R1, R2 and R3 for a change in value, and C2 for a short. Disable the audio input, and check for the presence of oscillator frequency on the grid. If absent, check C1 for an open. If both signals are present on the grid, check R4 for value, and L2 for continuity. Check for the presence of plate voltage with an voltmeter. Check C3 for a short, and C4 for an open. If a no-output condition still exists, check all capacitors with an in-circuit capacitor checker.

Low or Distorted Output. A low or distorted output can also be caused by a defect in nearly any component in the circuit. Check for the proper amplitude of each input signal on the grid of tube V1 with an oscilloscope. If low, determine whether it is low due to a defective oscillator or audio stage, or if it is a defect in the modulator circuit itself. If localized to the modulator, check transformer T1 continuity and resistors R1 and R3 with an ohmmeter. Check C2 for proper value with an in-circuit capacitor checker. Check R4 for value. Check plate voltage and determine whether or not the power supply is defective. Check C3 and C4 with an in-circuit capacitor checker, and check the continuity of L2 with an ohmmeter.

PHASITRON MODULATOR.

APPLICATION.

The phasitron is used in transmitters to vary the frequency of an r-f signal in accordance with the intelligence to be transmitted.

CHARACTERISTICS.

Utilizes a special phasitron tube.

Carrier frequency is supplied by a crystal controlled oscillator.

Has a high signal-to-noise ratio.

Operates Class "A".

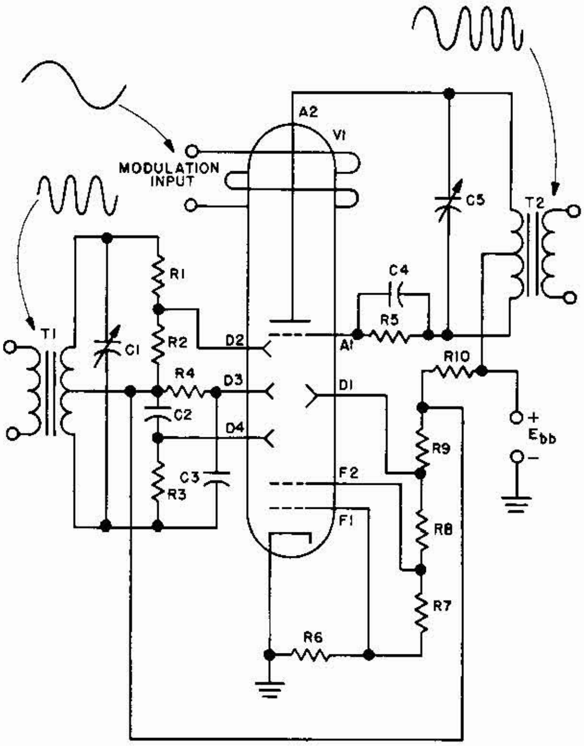
Frequency stability is excellent.

Output modulation proportional to both amplitude and the frequency of the audio modulation.

CIRCUIT ANALYSIS.

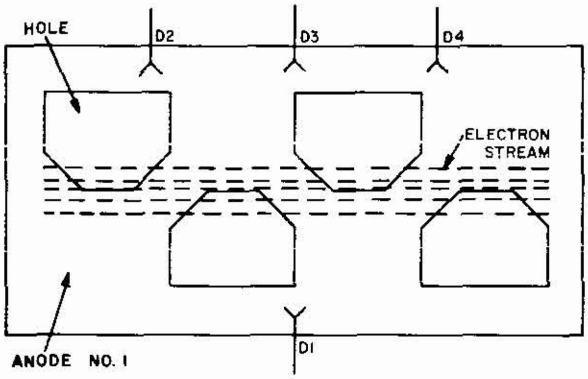
General. The phasitron performs the function of a phase modulator through the use of a special tube, called the phasitron tube. The carrier frequency is generated by a crystal controlled oscillator, and coupled through a phase splitting network to the tube. The modulation is applied inductively to the tube through a coil arranged around the outside of the tube, and the result in the output is a phase and frequency modulated carrier.

Circuit Operation. A schematic diagram of a Phasitron is illustrated below.



Phasitron Modulator.

Before attempting to understand the operation of the phasitron circuit, a basic understanding of the special tube utilized is essential. The illustration below shows the basic configuration of the structure of anode number 1, the four deflection grids, D1, D2, D3, D4, and the electron stream, with no potential applied to the deflection plates.

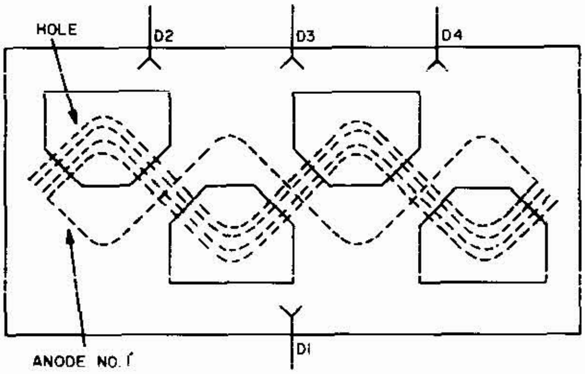


Phasitron Anode Structure and Electron-Beam Configuration with no Potential Applied to Deflector Grids

Anode number 1 has holes punched at regular intervals above and below a dividing line. The two focusing grids, F1 and F2, are such that it shapes the electron stream into a flat disc, which strikes anode number 1 as shown. Behind anode number 1 is another anode, which receives the electrons which are permitted to pass through the holes in anode number 1. Thus, with no potential applied to the deflector grids, nearly equal current flows in each plate.

In operation, however, potentials are applied to these deflector grids, and they are each 120 degrees out of phase with each other. Upon re-examining the electron disc, but this time with the potentials applied to the deflector plates, the result is illustrated below.

Now a greater portion of the stream passes through the holes in the first anode, and strike the second anode. Hence the plate current in anode number 2 is now greater than that of anode number 1. Since the potentials on D2, D3, and D4 are constantly changing (though always 120 degrees apart), the shape of the disc is also constantly changing, and shortly the disc is as shown by the dotted lines, resulting in maximum plate current in anode number 1, and minimum current in anode number 2. For any phase between these two extremes, each anode receives correspondingly more or less current. The modulation is applied to the coil around the outside of the tube, and the magnetic fields developed around this coil tends to increase or decrease the speed of rotation of the electron disc. By increasing or decreasing the speed of rotation, the frequency at which the anode current increases or decreases changes, and the output frequency is either increased or decreased.



Phasitron Anode Structure and Electron-Beam Configuration with Potential Applied to Deflector Grids.

In actual circuit operation, the carrier frequency is applied through transformer T1. The secondary of T1, together with C1, form a tank circuit tuned to this carrier frequency. Resistors R1, R2, R3, and R4, together with capacitors C2 and C3, form a phase splitting network, and the result is that the signals applied to D2, D3, and D4 are 120 degrees out of phase with each other. Also applied to the phase shifting network is a constant potential, tapped from the common point of R9 and R10. Resistors R6, R7, R8, R9, and R10 perform the function of voltage dividers in order to apply the proper voltages to the respective elements of the tube. R5 is a voltage dropping resistor, and C4 is an a-c bypass. The primary of T2, together with C5, form a tank circuit, tuned to the center frequency.

Referring to the construction of the first anode and the shape of the electron stream, it can be seen that there is a time during which all of the electrons strike the first anode, but never a time at which all of the electrons strike the second anode. This characteristic is overcome with R5, which causes a lower potential to be applied to the first anode than to the second anode. This same resistor would also cause degeneration of the a-c component of plate current however, and for this reason C4, an a-c bypass, is placed in parallel with R5. The over-all effect, with no modulation applied is that the plate current is constantly alternating between the two anodes in such a way that when one is maximum, the other is minimum, and conversely. The rate at which these currents rotate is equal to the crystal oscillator frequency, and it is to this frequency that the plate tank circuit is tuned.

When modulation is applied to the coil surrounding the tube, a magnetic field is developed, and this field advances or delays the rate of phase change of the electron stream. Thus the phase of the output leads or lags the oscillator frequency by an amount which is proportional to the amplitude and polarity of the modulation. The frequency of the modulation determines the rate at which the electron disc rotates. When the speed of disc rotation is increased, the output tank excitation frequency is higher, and when the speed of the disc rotation is decreased, the output frequency is lower.

The overall result in the output is therefore a signal which changes in phase and frequency as the audio modulation varies in amplitude and frequency.

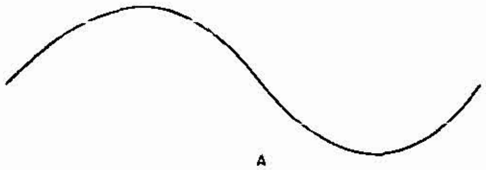
FAILURE ANALYSIS.

No Output. A no output condition can be caused by a defective V1, and open R5, a shorted C1 or C5, a defective T1 or T2, or a loss of the plate supply voltage. Check for the proper plate supply voltage with a voltmeter. Check both transformers with an ohmmeter. Check R5 for value, and C1 and C5 for a possible short with an in-circuit capacitor checker. Do not overlook the possibility of either of the tank circuits being misaligned.

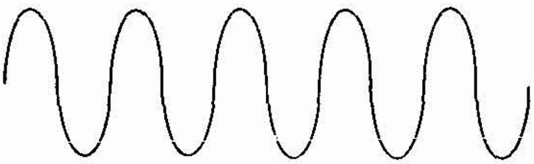
Low or Distorted Output. A low or distorted output can be caused by a defect in any component in the circuit. Check for the proper value of plate supply voltage with a voltmeter. With an oscilloscope, check the presence of both the carrier and modulation inputs on their respective elements of the tube, as the absence of either input will produce a distorted output. Check the alignment of both tank circuits. With an in-circuit capacitor checker, check the value of all capacitors, especially for a distorted output condition. Check all resistors with an ohmmeter for proper value, and the transformer for partial shorts.

FREQUENCY MODULATORS (FM).

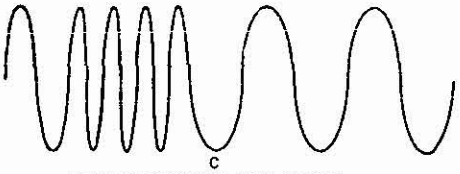
In frequency modulation, an audio signal is used to shift the frequency of an oscillator at an audio rate. The rate at which the oscillator changes its frequency depends upon the frequency of the modulating signal, and the deviation (the amount that the frequency shifts from the center frequency) depends upon the amplitude of the modulating signal, as illustrated below.



A
MODULATING SIGNAL



B
CARRIER WAVE



C
FREQUENCY-MODULATED SIGNAL

Frequency Modulation Waveforms

The frequency of the carrier is called the center frequency. When this carrier is modulated by a positive signal, its frequency changes; for example, it may become higher in frequency, proportional to the amount that the signal goes positive. Conversely, when the signal goes negative, the frequency becomes lower. Thus, when the sine wave shown in part A of the illustration is applied to a carrier, shown in part B, the carrier frequency changes from the normal center frequency to higher frequency, back to normal, to a lower frequency, and back to normal again as shown in part C. This variation is in direct accordance with the polarity and amplitude of the voltage of the sine wave. The maximum frequency change from center frequency, which depends upon the amplitude of the signal, is called the deviation. Note, in part C of the figure, that the amplitude of the modulated carrier is constant. As a result, frequency modulation is not so susceptible to static as in amplitude modulation, and it is for this reason that it is used for high-quality transmission of sound, such as for music.

Since random noise usually consists of higher frequencies, the signal-to-noise ratio at the higher frequencies may be lower. It is for this reason that the audio modulator is coupled through a pre-emphasis network before being applied to the modulator circuit. The pre-emphasis network increases the relative signal strength of the higher frequency components of the audio signal, and thereby compensates for any decrease in signal-to-noise ratio as caused by random high frequency noise. This creates a state of unbalance between the amplitudes of the high and low frequency components, but it is compensated for in the receiver by the use of a de-emphasis circuit, which performs the opposite function of pre-emphasis.

The primary difference between f-m and a-m is that the amplitude of the f-m signal is constant, while a-m depends upon amplitude variations for the transmission of intelligence.

The advantage of this type of modulation over a-m is its noise reducing capabilities. Most noise signals produce amplitude modulation of the carrier, or the carrier-plus-modulation signal, which is applied to the demodulating circuit in the receiver. If the receiver is responsive to amplitude variations, as in a-m receivers, this random noise is detected and amplified. If the receiver is responsive only to changes in frequency, as in f-m receivers, frequency modulation makes possible a considerable increase in the signal-to-noise ratio.

BASIC REACTANCE-TUBE MODULATOR.

APPLICATION.

The frequency modulator is used in fm transmitters to vary the frequency of an r-f signal in accordance with the intelligence to be transmitted.

CHARACTERISTICS.

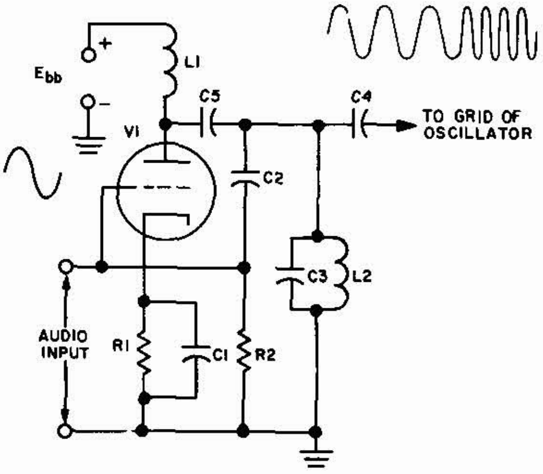
Output is used to change the frequency of an oscillator.
Has a high signal-to-noise ratio.
Output frequency is independent of modulating frequency.
Has relatively low harmonic distortion.

CIRCUIT ANALYSIS.

General. The purpose of the modulator stage is to convert an audio signal into a radio frequency containing the audio intelligence.

In the basic reactance tube modulator, a tube is used to change the resonant frequency of an oscillator by an amount proportional to the amplitude of the modulating signal. The polarity of the modulation determines the direction of the frequency shift; for example, an increase in oscillator frequency for a positive polarity, and a decrease in frequency for a negative polarity. The rate at which this frequency deviation occurs is determined by the frequency of the audio modulation.

Circuit Operation. A schematic diagram of a basic reactance tube modulator is illustrated below.

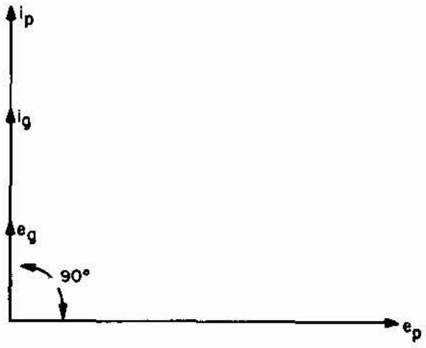


Basic Reactance Tube Modulator

V1 performs the function of the reactance tube, using cathode bias, supplied by R1 and C1. L1 is an r-f choke which acts as the plate load, and keeps the a-c component of plate current out of the power supply. Capacitor C2 and resistor R2, in parallel with the oscillator tank circuit consisting of C3 and L2, performs the function of a variable reactance. C4 and C5 are grid and plate coupling capacitors, respectively.

With no audio signal applied to the grid of V1, the only voltage present across the C2, R2, network is the voltage across the oscillator tank circuit, C3 and L2. The values of C2 and R2 are chosen so that the reactance of C2 is large *in comparison to the resistance of R2. This factor permits* the capacitive reactance to be the current controlling component, and causes the voltage across it to lag the current through it by approximately 90 degrees. This same current flows through R2 and another voltage drop is produced which leads the applied voltage by 90 degrees. Actually, the current and voltage at the resistor are in phase, but since the current through the resistor leads the applied voltage (because of the capacitive reactance of C2), the voltage developed by this current also leads the applied voltage by the same amount. The reactance tube is effectively in shunt with the oscillator tank (C3 and L2) and the phase shift network (C2 and R2). Capacitor C5 allows the a-c component of current to pass through it, and at the same time, blocks the d-c plate voltage from the phase-shift circuit and the tank.

The relationship of the currents and the voltages in the circuit can be best *explained through the use of a vector* diagram, as illustrated below.



Relationships of Currents and Voltage with no Modulation Inputs

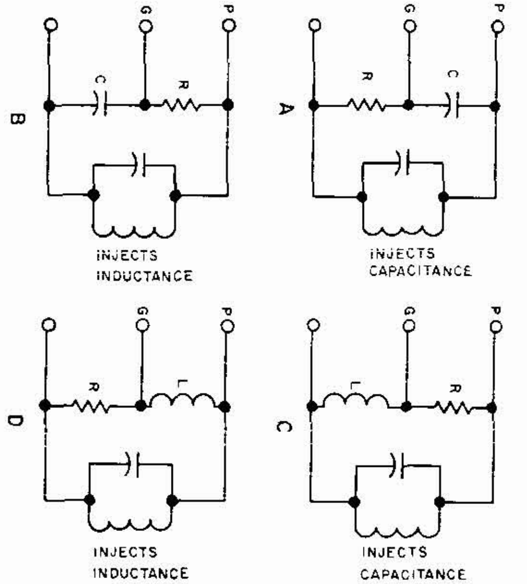
Voltage e_p is the alternating component of the plate to ground voltage which appears simultaneously across the reactance tube, the phase-shift network, and the oscillator tank circuit. The reactance tube receives its a-c grid-input voltage, e_g, across R2. This voltage is the voltage drop across R, and is in phase with the plate current i_p and the grid current, i_g. This relationship is characteristic of amplifier tubes.

Since both i_p and i_g are in phase with e_g, and since e_g leads e_p by approximately 90 degrees, i_p and i_g also lead e_p by 90 degrees. Both of these currents are supplied by the oscillator tank circuit, and since they lead the tank voltage, they act *like the current in a capacitor.* Thus the injection of these currents into the tank circuit accomplishes the same effect as placing a capacitor across the oscillator tank circuit. The frequency of the tank in this case is, therefore, decreased. With no audio modulation input, this frequency is the operating, or center frequency of the modulator.

Consider now the application of audio modulation to the grid of the tube. It is important to keep in mind that we are not speaking of actual capacitive reactance or capacitance changes. Our concern here is an **effective** capacitance *produced by the leading currents in the R2, C2, com*bination. If the signal applied on the grid of V1 increases in a positive direction, the plate current of V1 also increases, and since this current is an effective capacitance shunt across the oscillator tank circuit, the frequency of the oscillator is decreased. Conversely, when the grid signal shifts in a negative direction under audio modulation, V1 plate current decreases, and since this current is an effective reduction in capacitance across (shunting) the oscillator tank circuit, the frequency of the oscillator is increased.

The frequency of the audio modulation does not actually affect the frequency of the output. Its only effect is that it determines the number of times per second that the oscillator changes its frequency. The amount and direction of the frequency change is determined solely by the amplitude and the polarity of the modulation input. That is, a positive signal causes an increase of frequency, while a negative signal causes a decrease in frequency. Likewise, a larger amplitude signal causes a greater frequency change than a smaller amplitude signal.

Circuit Variations. There are several circuit variations of the basic reactance tube modulator, but most of these variations are only differences in the arrangement of the phase shifting circuit (the R2, C2, combination in the previous example). The illustration below shows how the circuit variations cause the phase shift to be either inductive or capacitive. There is no particular advantage to any one of them over any of the others.



Circuit Variations

Part A of the figure has been explained in the previous discussion. In part B of the figure, R and C are connected in the opposite manner, and the reactance values are chosen so that the resistance of R is large in comparison to the reactance of C. Since the resistive component is so much larger, the r-f voltage applied to the plate load by the tank circuit causes the current to be in phase with the r-f voltage. The current through C, however, leads the applied voltage by 90 degrees. The voltage across C, therefore, lags both the current and the applied voltage by 90 degrees. This voltage is coupled to the grid of the reactance tube, and causes an r-f variation in the plate current that is in phase with the grid voltage. This r-f current is coupled to the oscillator tank and since it is in phase with the grid voltage, it must lag the current in the tank by 90 degrees. This produces the same result as injecting inductance into the tank circuit.

By substituting a small inductor in the place of C in part C of the figure, it is also possible to inject an effective capacitance into the tank circuit. The oscillator voltage applied across the plate load of the reactance tube causes a current to flow whose phase is controlled by the large resistance of R. This current is in phase with the applied voltage, since R is large with respect to L. Since the voltage across L leads the current through it by 90 degrees, this voltage also leads the applied voltage by 90 degrees. This voltage is coupled to the grid of the reactance tube, and r-f plate current flows which is in phase with the grid voltage and 90 degrees leading in respect to the oscillator tank voltage. The effect is, therefore, the same as injecting capacitance into the tank circuit, and the frequency is decreased.

By the same token, the reversing of R and L produces the same result as injecting inductance into the tank circuit as shown in part D of the figure. The inductive reactance of L, of course, must be large in comparison to the resistance of R. The r-f voltage from the oscillator tank circuit causes a current to flow through the plate load which lags the applied voltage by 90 degrees. This voltage then is applied to the grid of the reactance tube, producing an r-f plate current which is lagging the current in the tank circuit by 90 degrees, producing the effect of injecting inductance into the tank circuit.

FAILURE ANALYSIS.

No Output. An open or shorted L2, an open or shorted C3, or an open C4 are the only components that can cause a no output condition to exist. Check L2 for continuity and C3 and C4 for value with an in-circuit capacitor checker.

Unmodulated Output. The absence of plate voltage, an open L1, and open C5, an open R1, an open C2 or R2, or a defective V1, can cause an unmodulated output condition to exist. Check for the presence of plate voltage with a voltmeter. Check L1 for continuity and C5 for an open or short with an ohmmeter. Also check R1 and R2 for proper value, and C2 for an open or short with an ohmmeter. If a modulated output is not restored, check all capacitors with an in-circuit capacitor checker.

BALANCED REACTANCE-TUBE MODULATOR

APPLICATION.

The balanced reactance tube modulator is used in fm transmitters to vary the frequency of an r-f signal in accordance with the intelligence to be transmitted.

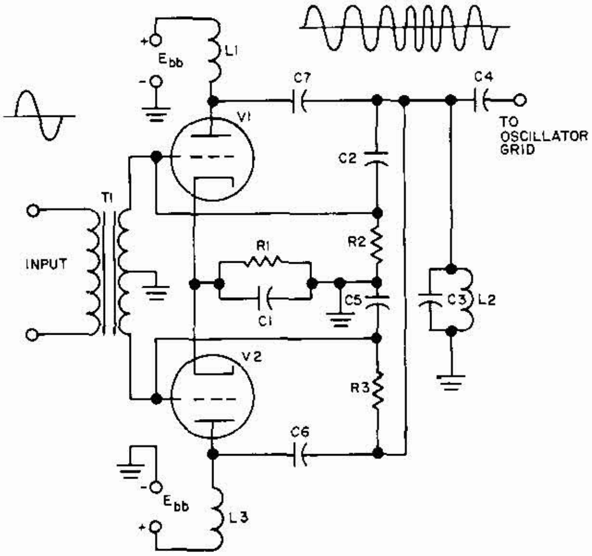
CHARACTERISTICS.

Has relatively high degree of frequency shift.
Has low inherent distortion.
Has high signal-to-noise ratio.

CIRCUIT ANALYSIS.

General. The purpose of the modulator stage is to convert an audio signal into a radio frequency containing the audio intelligence. *In the balanced reactance tube modulator,* two tubes are used to change the resonant frequency of an oscillator by an amount proportional to the amplitude of the modulating signal. The polarity of the modulation determines the direction of the frequency shift, for example, an increase in oscillator frequency for a positive polarity, and a decrease in frequency for a negative polarity. The rate at which this frequency deviation occurs is determined by the frequency of the audio modulation.

Circuit Operation. A schematic diagram of a balanced reactance tube modulator is shown in the accompanying illustration.



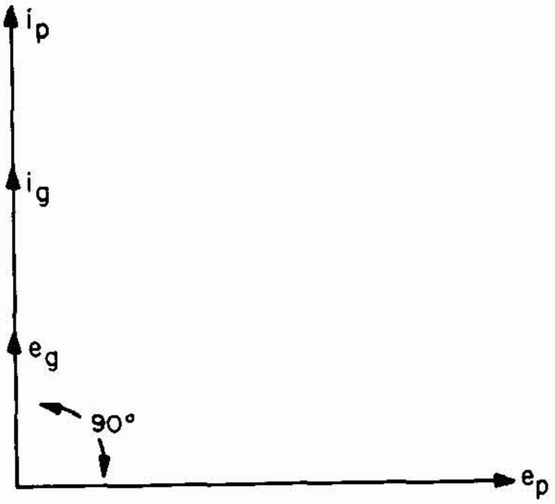
Balanced Reactance Tube Modulator.

V1 performs the function of one of the reactance tubes, and operates in conjuction with V2, in a push-pull manner. C1 and R1 form a cathode bias circuit, which is common to both of the tubes. L1 and L3 are r-f chokes which act as plate loads for the tubes, and keeps the a-c component of plate current out of the power supply. The C2-R2 combination, together with the C5-R3 combination, both in parallel with the oscillator tank circuit, made up of L2 and C3, perform the function of a variable reactance. C4, C6, and C7, are grid and plate coupling capacitors, respectively.

Circuit operation can be easiest understood, if analyzed and discussed as two separate circuits. One circuit, consists of V1, L1, C7, C2, and R2, while the other circuit consists of V2, L3, C6, R3, and C5. The remaining components are common to both of the circuits.

We shall first consider the operation of the circuit consisting of V1 and its associated components. With no audio signal applied to the grid of V1, the only voltage present across the C2-R2 network is the voltage across the oscillator tank circuit. The values of C2 and R2 are chosen so that the reactance of C2 is large in comparison to the resistance of R2. This factor permits the capacitive reactance to be the *current controlling component*, and causes the voltage across it to lag the current through it by approximately 90 degrees. This same current flows through R2 and another voltage drop is produced which leads the applied voltage by 90 degrees. Actually, the current and voltage at the resistor are in phase, but since the current through the resistor leads the applied voltage (because of the capacitive reactance of C2), the voltage developed by this current also leads the applied voltage by the same amount. The reactance tube, V1, is effectively in shunt with the oscillator tank and the phase shift network. Capacitor C7 allows the a-c component of current to pass through it, and at the same time, blocks the d-c plate voltage from the phase-shift circuit and the tank.

The relationship of the currents and the voltages in the *circuit can* be best explained through the use of a vector diagram, as illustrated below.



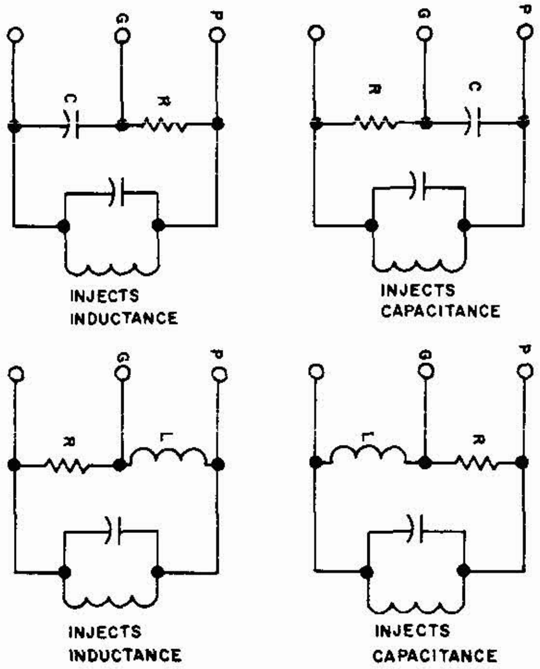
Relationship of Currents and voltages with no Modulation Input.

Voltage e_p is the alternating component of the plate to ground voltage which appears simultaneously across the reactance tube, the phase-shift network, and the oscillator tank circuit. The reactance tube receives its a-c grid-input voltage, e_g, across R_g. This voltage is the voltage drop across R_g and is in phase with the plate current i_p and the grid current, i_g. This relationship is characteristic of amplifier tubes.

Since both i_p and i_g are in phase with e_g, and since e_g leads e_p by approximately 90 degrees, i_p and i_g also lead e_p by 90 degrees. Both of these currents are supplied by the oscillator tank circuit, and since they lead the tank voltage, they are acting like the current in a capacitor. Thus the injection of these currents into the tank circuit accomplishes the same effect as placing a capacitor across the oscillator tank circuit. The frequency of the tank in this case is therefore decreased. With no audio modulation input, this frequency is the operating, or center frequency of the modulator.

Consider now the application of audio modulation to the grid of the tube. It is important to keep in mind that we are not speaking of actual capacitive reactance or capacitance changes. Our concern here is an **effective** capacitance produces by the leading currents in the R2-C2 combination. If the signal applied on the grid of V1 increases in a positive direction, the plate current of V1 also increases, and since this current is an effective capacitance shunt across the oscillator tank circuit, the frequency of the oscillator is decreased. Conversely, when the grid signal shifts in a negative direction under audio modulation, V1 plate current decreases, and since this current is an effective capacitance across (shunting) the oscillator tank circuit, the frequency of the oscillator is increased.

Before attempting to explain the operation of the circuit made up of V2, it should be pointed out that there are several minor circuit variations of the previously discussed circuit. Most of these variations concern differences in the phase shifting circuit (the R2-C2 combination in the previous example). The illustration below shows the variations which cause the phase shift to be either inductive or capacitive. There is no particular advantage to any one of them over any of the others.



Circuit Variations

Part A of the figure has been explained in the previous discussion. In part B of the figure, R and C are connected in the opposite manner, and the reactance values are chosen so that the resistance of R is large in comparison to the reactance of C. (This is the manner in which operation of V2 yet to be explained is connected.) Since the resistive component is so much larger, the r-f voltage applied to the plate load by the tank circuit causes the current to be in phase with the r-f voltage. The current through C, however, leads the applied voltage by 90 degrees. The voltage across C, therefore, lags both the current and the applied voltage by 90 degrees. This voltage is coupled to the grid of the reactance tube, and causes an r-f variation in the plate current that is in phase with the grid voltage. This r-f current is coupled to the oscillator tank and since it is in phase with the grid voltage, it must lag the current in the tank by 90 degrees. This produces the same result as injecting inductance into the tank circuit.

By substituting a small inductor in the place of capacitor C in part C of the figure, it is also possible to inject an effective capacitance into the tank circuit. The oscillator voltage applied across the plate load of the reactance tube causes a current flow whose phase is controlled by the large resistance of R. This current is in phase with the applied voltage, since R is large with respect to L. Since the voltage across L leads the current through it by 90 degree, this voltage also leads the applied voltage by 90 degrees. This voltage is coupled to the grid of the reactance tube, and an r-f plate current flows which is in phase with the grid voltage and 90 degrees leading in respect to the oscillator tank voltage. The effect is, therefore, the same as injecting capacitance into the tank circuit, and the frequency is decreased.

By the same token, the reversing of R and L produces the same result as injecting inductance into the tank circuit, as shown in part D of the figure. The inductive reactance of L, of course, must be large in comparison to the resistance of R. The r-f voltage from the oscillator tank circuit causes a current to flow through the plate load which lags the applied voltage by 90 degrees. This voltage is then applied to the grid of the reactance tube, producing an r-f plate current which is lagging the current in the tank circuit by 90 degrees, producing the effect of injecting inductance into the tank circuit.

The V2 circuit operates in the same manner as the V1 circuit, only instead of injecting a capacitive reactance into the oscillator tank, it injects an inductive reactance. Upon close examination of the V2 circuit, it can be seen that the phase shifting circuit, R3 and C5, are connected in the opposite manner to the R2-C2 combination in the first example.

By referring to the illustration of circuit variations, it can be seen that this type of connection (Part B of the figure) produces the effect of inductance in parallel with the tank circuit. It should be noted here that an increase in plate current in the first example caused an increase in the capacitive reactance injected into the tank, and hence the oscillator frequency decreased. In the V2 circuit, the inductive reactance is decreased with an increase in plate current, and thus produces an increase in the oscillator frequency. Now let us see what occurs when both circuits are connected as shown, and an audio signal is applied to the transformer T1.

When the input signal is such that the grid of V1 is positive, and the grid of V2 is negative, the following action results. The negative signal on the grid of V2 drives V2 into cut-off, and a further negative increase produces no further change. V1, however, conducts a greater as the signal on the grid becomes more positive, and thus additional capacitive reactance is injected into the oscillator tank circuit, resulting in a decreasing frequency. As the signal on the grid reaches its positive peak, and begins decreasing towards zero, the oscillator frequency begins increasing, and when the grid is returned to zero, the oscillator is again at the center frequency. The signal now continues in a negative direction and V1 is driven into cut-off. V2, the grid of which is connected to the opposite end of T1, is now brought into conduction, and begins to inject an inductive reactance into the tank circuit, resulting in an increasing frequency. As the signal on the grid reaches its positive peak, and begins decreasing towards zero, the oscillator frequency begins decreasing and as the signal reaches zero the oscillator is again at the center frequency. The overall result of one cycle of audio modulation is illustrated below.

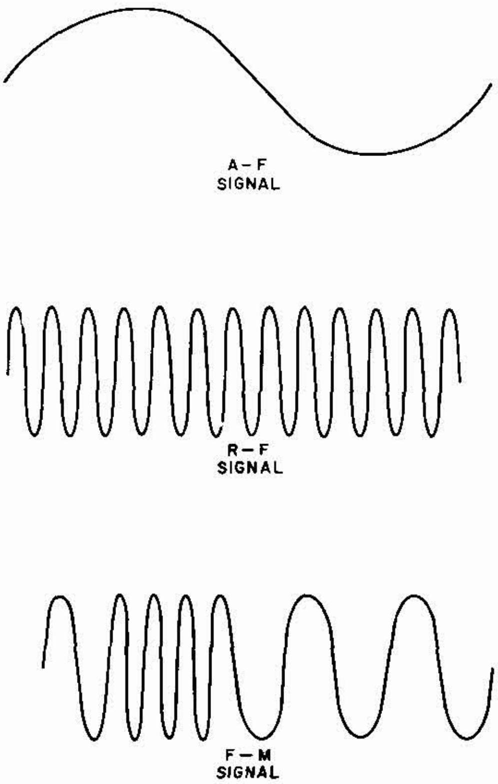
Thus, it can be seen that the frequency of the audio modulation does not actually have an effect on the frequency of the output. The only effect is that it determines the number of times per second that the oscillator changes its frequency. The amount and direction of the frequency change is determined by the amplitude and the polarity of the modulation input.

FAILURE ANALYSIS.

No Output. An open or shorted L2, an open or shorted C3, or an open C4 are the only components that can cause a no-output condition to exist. Check L2 for continuity and C3 and C4 for value with an in-circuit capacitor checker.

Distorted or Unmodulated Output. A defective V1 or V2, a defective T1, an open or shorted L1 or L3, an open or shorted C2 or C5, or an open R2 or R3 can cause a distorted output condition to exist. With an ohmmeter, check the continuity of L1 and L3, and check R2 and R3 for proper value. Also check C2, C5, C6, and C7 for opens or shorts with an ohmmeter. Check transformer T1 for continuity, as one half of the secondary may be open. If a distorted output still exists, check all capacitors with an in-circuit capacitor checker.

An unmodulated output can be caused by a defective T1, an open or shorted R1, or an open or shorted C1. With an ohmmeter, check the continuity of T1 and the value of R1. Check C1 for an open or short with an ohmmeter. An unmodulated output may also be caused by components being defective in pairs, that is, V1 and V2, L1 and L3, C6 and C7, etc. Check all components in this case, in the manner described in the preceding paragraph.



Effect of Modulation

PULSE MODULATORS.

Radio frequency energy in radar is transmitted in short pulses whose time duration may vary from 1 to 50 microseconds or more. If the transmitter is turned off before the reflected energy returns from the target, the receiver can distinguish between the transmitted pulse and the reflected pulse. After all reflections have returned, the transmitter can again be turned on and the process repeated. The receiver output is applied to an indicator which measures the time interval between the transmission of energy and its return as a reflection. Since the energy travels at a constant velocity, the time interval becomes a measure of the distance traveled (range). Since this method does not depend on the relative frequency of the returned signal or on the motion of the target, difficulties experienced in cw and fm methods are not encountered. The pulse modulation method is used in practically all military and naval applications.

Since most radar oscillators operate at pulse voltages between 5 Kv and 20 Kv, and require currents of several amperes during the pulse, the requirements of the modulator are quite severe. The function of the high-vacuum tube modulator is to act as a switch to turn a pulse on and off at the transmitter in response to a control signal. The best device for this purpose is one which requires the least signal power for control and which allows the transfer of power from the transmitter power source to the oscillator with the least loss. The pulse modulator circuits discussed in this section are typical pulse modulators used in radar equipments.

SPARK GAP MODULATOR.

APPLICATION.

The spark gap modulator is used in radar equipments to generate the pulse which controls the operation of the transmitter.

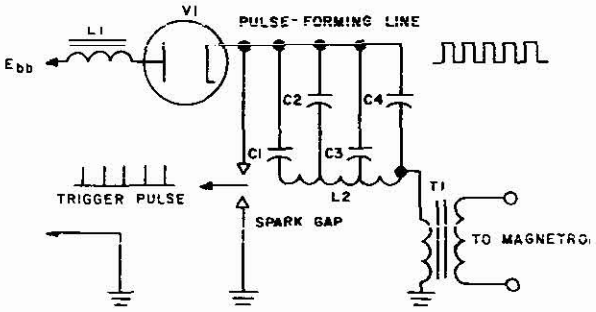
CHARACTERISTICS.

Capable of handling high peak current and voltage.
Generated pulses have high peak power.
Generated pulses have low average power.
Generated pulses have a specific repetition rate.
Generated pulses have controlled duration and shape
Output pulse is somewhat erratic in timing

CIRCUIT ANALYSIS.

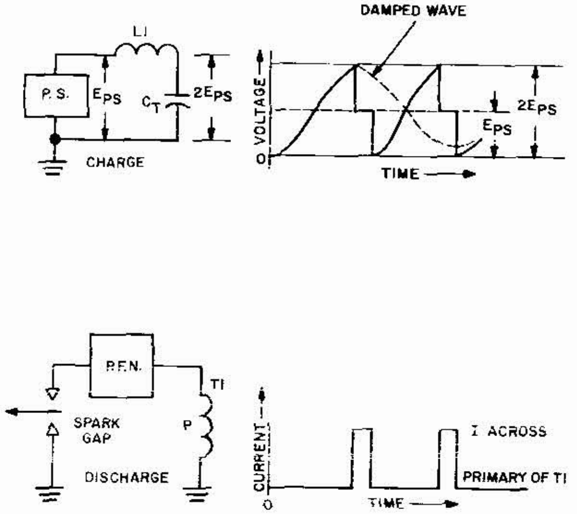
General. Different types of pulse modulators are used for triggering radar transmitters, depending on the particular requirements of the system. Each type contains a circuit for storing energy, a circuit for rapidly discharging the storage circuit, a pulse transformer, and an a-c power source. The circuit for storing energy is essentially a short section of artificial transmission line which is known as the pulse forming line. In the spark gap modulator, the pulse forming line is discharged by a spark gap. Two types of spark gaps are in use: fixed gaps and rotary gaps. The fixed gap, discussed in this section, uses a trigger pulse to ionize the air between the contacts of the spark gap and initiate the discharge of the pulse forming line. The rotary gap is similar to a mechanically driven switch.

Circuit Operation. A typical fixed spark gap modulator circuit is shown in the accompanying illustration.



Fixed Spark Gap Modulator Circuit

Between trigger pulses the spark gap is an open circuit, and current flows through the pulse transformer T1, the pulse forming line L2, the diode V1, and inductor L1 to the plate supply voltage Ebb. These components form the charging circuit for the pulse forming line, and the entire circuit may be reduced to a series resonant circuit as shown in the accompanying illustration.



Equivalent Pulse-Modulator Circuits, With Waveforms

The impedance of the primary of T1 is negligible as far as the charging circuit is concerned, the inductance of the pulse forming line may be considered to be short circuited because of the slow charging rate, and the diode, when conducting, is effectively a short circuit; therefore, these components are omitted from the figure. In effect, then, the total capacitance (Ct) of the pulse forming line is in series with the inductor L1 across the power supply. Assuming that diode V1 and the spark gap were not present, this circuit when shock-excited by the sudden application of voltage would produce a damped-wave oscillation. On the first peak, the voltage across the entire pulse forming line approaches twice the value of the supply voltage as shown in the illustration, and at this time the current in the inductor L1 is zero since the diode stops conducting at full charge. As the peak voltage is reached, the spark gap is triggered by a synchronous separate trigger placing the pulse-forming network in series with the primary of T1 to ground. At this time approximately half the voltage (Eps) appears across the pulse-forming network (PFN) and the other half appears across T1, since the network impedance is equal to that of T1 in this instance because of the rapidity of discharge. The action of the pulse-forming line is such as to cause voltage Eps to continue at the same amplitude until the complete discharge of the circuit by a time interval depending upon twice its delay period. The waveforms and time relationships of the circuit action are shown in the illustration. The pulse waveform is coupled through transformer T1 to the magnetron.

The spark gap is actually triggered (ionized) by the combined action of the charging voltage across the pulse-forming line and the trigger pulse. The air between the trigger-pulse injection point and ground is ionized by the trigger voltage, and this in turn initiates the ionization of the complete gap by the charging voltage.

Coincidence between the peak of the voltage swing across Ct and the trigger pulse used to fire the spark gap is required, in order that maximum power output may be obtained from the circuit. In order to ensure correct timing diode V1 is used and the design of the charging circuit is such that its resonant frequency is higher than half the repetition rate of the spark-gap trigger pulse. Since the diode is nonconductive when maximum charge is reached on Ct, the maximum charge is retained until the spark gap is triggered.

Inductor L1 prevents current surge through V1 when the spark gap is triggered. Where humidity or pressure may affect the ionization of the spark gap, it is enclosed in a sealed container.

In some circuits a resistor and capacitor in series are connected across the primary of T1. The function of these components is to eliminate the spike (sometimes encountered on the magnetron pulse) which is caused by delay between the time the pulse is presented to the magnetron and the time the magnetron conducts.

FAILURE ANALYSIS.

No Output. A no output condition can be caused by one of the following; an open L1, a defective V1, an open L2, or a defective T1. Determine that the plate supply voltage (Ebb) and the trigger pulse are present. If they are not present, the trouble is in the preceding stages and the circuit is probably not at fault. If the plate supply voltage is not present on the anode of V1, L1 is defective. If plate voltage is present on the anode of V1 and no output appears, the tube is defective. Check L2 and the windings of T1 with an ohmmeter for an open or short.

Low Output. A low output can be caused by a low plate supply voltage, a weak V1, leaky or shorted capacitors, shorted windings on L1, L2, or transformer T1. Check the plate supply voltage with a VTVM, if it is not the proper value the trouble is in the preceding stages and the modulator circuit is probably not at fault. Check the capacitors in the circuit with an in-circuit capacitor checker. Inductors L1 and L2 and transformer T1 can be checked with an ohmmeter for shorted turns.

Distorted Output. A distorted output could occur if the pulse-forming line had shorted or leaky capacitors or if the inductor windings became shorted or open. Check the capacitors with a capacitance cheker and the inductor for continuity with an ohmmeter.

THYRATRON (GAS-TUBE) MODULATOR.

APPLICATION.

The thyratron modulator is used in radar equipment to generate the pulse which controls the operation of the transmitter.

CHARACTERISTICS.

Possesses heavy current handling capacity.

Is relatively independent of ambient temperatures.

Has positive grid control.

Has stable timing.

Can be triggered with a low amplitude pulse.

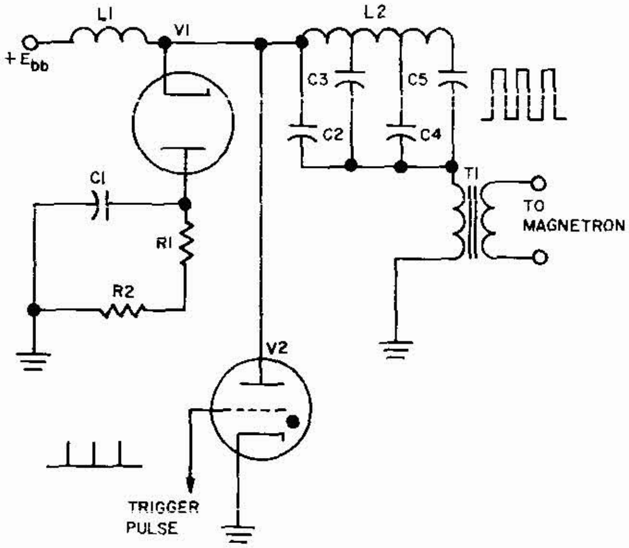
Operates over a wide range of anode voltages without readjustment.

CIRCUIT ANALYSIS.

General. The hydrogen thyratron is a versatile electronic switch which requires a positive trigger of only 150 volts rising at the rate of 100 volts per microsecond. In contrast to spark devices, the hydrogen thyratron operates over a wide range of anode voltages and repetition rates. Its grid has complete control of initiation of cathode emission over a wide range of voltages. The anode is completely shielded from the cathode by the grid. Thus, effective grid action results in very smooth firing over a wide range of anode voltages and repetition frequencies. Unlike most other thyratrons, the positive grid control characteristic ensures stable operation. In addition, the deionization time is reduced by using the hydrogen filled tube. This makes the performance of the tube relatively independent of ambient temperature so false triggering is avoided.

The hydrogen thyratron modulator provides improved timing because the synchronized trigger pulse is applied to the control grid of the thyratron and instantaneous firing is obtained. In addition, only one gas tube is required to discharge the pulse forming line, and a low amplitude trigger pulse is sufficient to initiate discharge. A damping diode is used to prevent breakdown of the thyratron by reverse voltage transients. The thyratron requires, for a driver pulse, a sharp leading edge and depends on a sudden drop in anode voltage (controlled by the pulse-forming line) to terminate the pulse and turn off the tube.

Circuit Operation. The schematic of a typical thyratron gas tube modulator circuit is shown in the accompanying illustration.



Typical Thyratron Gas Tube Modulator Circuit

L1 is a charging inductance. The damping circuit consists of damping diode V1, current limiting resistors R1 and R2, together with r-f bypass capacitor C1, which hold the plate of V2 at ground level during each negative half cycle of operation, thus eliminating the possibility of a negative overshoot and the production of damped oscillations. Inductor L2 with capacitors C2, C3, C4 and C5 form the pulse-forming line which develops and shapes the output pulse. Transformer T1 couples the shaped pulse output of the circuit inductively to the magnetron.

With no trigger pulse applied, as the circuit is turned on, the pulse forming line charges through the primary of T1, the pulse forming line, charging inductor L1, and the power supply to ground. When the pulse-forming line reaches maximum charge, a synchronized trigger pulse is applied to the grid of thyratron V2, ionizing the tube (which acts like a closed switch) and provides a discharge path for the primary of T1 and the pulse-forming network to discharge to ground, through V2. As the voltage across the pulse forming network discharges and falls below the ionization level of the thyratron tube, the tube shuts off like opening a switch. However, there is a tendency for the positive discharge voltage to swing negative as it is abruptly stopped and cause negative overshoot because of the inductive properties of the discharging circuit. This negative overshoot is prevented from affecting the output of the circuit by the insertion of damping diode V1 and the damping circuit consisting of R1, R2, and C1. This damping circuit provides a path for the overshoot transient through V1, and it is dissipated by R1, and R2. C1 is a high frequency bypass to ground to preserve the sharp leading and trailing edge of the rectangularly shaped pulse.

FAILURE ANALYSIS.

No Output. The following defects can cause a no-output condition. Low plate supply voltage, an open charging choke L1, or pulse-forming line choke L2, the windings of T1 being shorted or open, a defective tube V2, or a trigger pulse of insufficient voltage to ionize V2.

Check the plate supply voltage, if it is not normal, the trouble is probably in the power supply and the modulator circuit is probably not at fault. If plate voltage is normal, check the voltage on the cathode of V1. If no voltage is present, L1 is open.

If no voltage is present on the primary of T1, pulse-forming line inductor L2 is open.

Make a point to point check with d-c voltmeter (make certain you observe all high-voltage safety regulations) for the proper voltages in the charging circuit. Should no voltage be present at any of the points, the component or components associated with that portion of the circuit is defective; check the inductors with an ohmmeter (be careful to use a shorting stick to make certain the line is discharged) and the capacitors with an in-circuit capacitor checker. With an oscilloscope, check for the proper trigger pulse (both amplitude and repetition rate).

Low Output. Insufficient plate voltage, an improper trigger pulse, a defective pulse-forming network, or a defective magnatron transformer, T1, can cause a low output. Use an ohmmeter for checking the inductors and transformer T1 (make certain the pulse network is discharged first), and an in-circuit capacitor checker for checking the capacitors in the pulse-forming line.

Distorted Output. With the proper trigger signal and plate supply voltage, a distorted output can be caused by shorted turns on inductors L1, and L2 or on the windings of T1. Use an ohmmeter to check for proper values. The pulse-forming line components, if defective, can also cause the output to become distorted. These can be roughly checked with an ohmmeter and an in-circuit capacitor checker.

HARD-TUBE MODULATOR.

APPLICATION.

The hard-tube pulse modulator is used in radar equipments to develop the pulse which controls the operation of the transmitter.

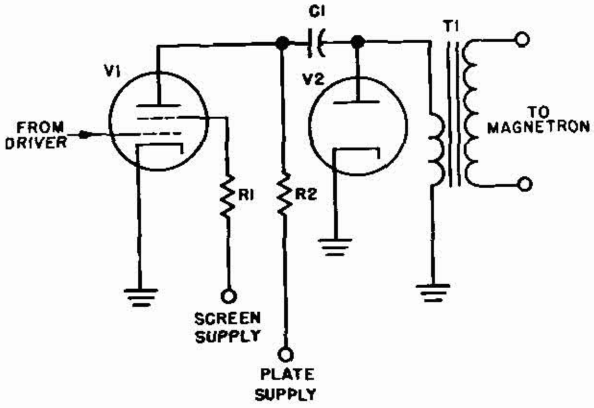
CHARACTERISTICS.

Needs a shaped high-voltage pulse for operation.
Biased to cutoff.
Has gain of about 10.

CIRCUIT ANALYSIS.

General. The hard-tube pulse modulator operates as an amplifier tube with a gain of about 10. The modulator tube is normally biased to cutoff. The application of a positive pulse of about 1300 volts to the grid is necessary to overcome the bias, causing V1 to conduct and dropping the plate-to-cathode potential from the plate supply value established by the cutoff condition. Because of the large resistance of the plate load resistor, the negative voltage pulse developed by this action is effectively applied to the output transformer and the modulator tube in series. Since the impedance of the modulator tube is about one-tenth that of the output transformer, about nine-tenths of the voltage pulse appears across the output transformer. The time between pulses is known as the charging time. A damping diode is in the circuit to damp out the oscillations produced by a negative overshoot when the positive pulse applied to the grid of the modulator is terminated. The damping is accomplished on the first oscillatory swing by shorting it to ground (the negative pulse on the cathode causes the diode to conduct).

Circuit Operation. The schematic of a typical hard-tube modulator is shown in the accompanying illustration.



Typical Hard-Tube Pulse Modulator

V1 is the modulator tube, R1 is the screen voltage dropping resistor, and R2 is the plate load resistor for V1. Capacitor C1 couples the output of the modulator to output transformer T1. Tube V2 is the damping diode, and T1 is the step-up output (magnetron) transformer.

With no trigger pulse applied from the driver, coupling capacitor C1 charges to the plate supply voltage through the primary of T1, R2, the power supply and ground. Tube V1 is biased at cutoff and the plate-to-cathode potential is established by the cutoff condition. A synchronized trigger pulse from the driver circuit is applied to the grid of V1 taking the tube out of cutoff and causing it to conduct. This is similar to closing a switch, and provides a path for C1 to discharge through both the primary of T1 and V1 to ground. This discharge occurs only for the duration of the trigger pulse applied to the grid of V1. When the trigger pulse terminates, the modulator is again cutoff and the magnetic field in the primary of T1 collapses, causing a reverse flow of electrons in the circuit. This reverse flow of electrons is prevented from causing negative oscillations by diode V2, which conducts as soon as the plate goes in a positive direction (when a negative pulse appears on the cathode). Thus, diode V2 dampens any oscillations which would effect the output pulse of the modulator circuit.

FAILURE ANALYSIS.

No Output. Should plate load resistor R2 open, coupling capacitor C1 open, damping diode V2 short, or the windings of transformer T1 be open or shorted, no output would appear on the secondary winding of T1. First check for plate supply voltage at the source. If the supply voltage is present, a drop should appear across R1. At the junction of R2, C1, if no voltage is present, R2 is open. Check the windings of T1 for continuity or a short, with an ohmmeter.

Low Output. An incorrect plate or screen supply voltage, a weak V1, shorted turns on transformer T1, or any of the components in the circuit changing value could cause a low output. Check all supply voltages and the trigger voltage from the driver. If any of these voltages are incorrect, the trouble is in that stage and the modulator circuit is probably not at fault. Check screen and plate load resistors R1 and R2, respectively, with an ohmmeter. Check coupling capacitor C1 with an in-circuit capacitor checker, and transformer T1 with an ohmmeter.

Distorted Output. Distortion can occur from any of the following: an improper trigger pulse, a change in screen or plate supply voltage, a defective V1 or T1, a leaky coupling capacitor C1, or load resistors R1 or R2 changing value. If the driver output pulse applied to the grid of the modulator is not the proper pulse repetition rate or amplitude, the trouble is in the preceeding stages and the modulator is probably not at fault. If the screen and plate voltages are correct, and the output is still distorted, determine that C1 is not leaky by using an in-circuit capacitor checker. Determine that load resistors R1 and R2 are the correct value and that output transformer T1 has no shorted windings.

PART B. SEMICONDUCTOR CIRCUITS

AMPLITUDE MODULATION (AM).

Modulation, in general, is the process by which the amplitude, phase, or frequency of a carrier is modified in accordance with the characteristics of another signal. Only amplitude-modulation circuits will be discussed here. Frequency-modulation and phase-modulation circuits will be discussed later in this section. Amplitude modulation is defined as the process whereby the **amplitude of the carrier** is modified in accordance with the characteristics of another signal. It is essentially a **heterodyning** process, with the resultant modulated waveshape containing both the original carrier frequency, the modulation frequencies, and their sum and difference frequencies (the sidebands). Since the carrier component undergoes no change, the modulated wave contains more power than before and the intelligence is contained in the sidebands. Since the carrier contains no intelligence, suppressed-carrier modulation is possible. This is the form of modulation used for single-sideband operation, which will also be discussed separately later in this section.

The discussion of amplitude modulation under Part A, Electron Tubes, in this section is generally applicable to the semiconductor modulator circuit. However, although the same general conditions must be fulfilled to achieve amplitude modulation, the semiconductor operates at a much lower power level than the electron tube; also since it is a low-impedance device, it operates on the principle of current gain or variation. Thus, instead of speaking of varying the voltage from zero to twice normal to achieve 100-percent modulation, the general practice is to speak of varying the **transistor gain** to achieve modulation. (This is similar to control grid modulation.)

Since the gain of a transistor is dependent upon the voltages applied to its electrodes, it is evident that changing the d-c bias or the a-c signal to any one of its three terminals will produce a corresponding change in gain. Therefore, it is possible to produce AM modulation of a transistor by any of three basic methods, namely, base injection, emitter injection, or collector injection. Each of these basic circuits are discussed separately later in this section.

At present, semiconductor modulators operate over a relatively low power range as compared with that of electron-tube modulators. In the majority of applications they are operated over a range of milliwatts, with the range of from 1 to 100 watts representing special and high-power applications. As high-powered r-f and audio transistors are developed, this power range will be extended so that it will be more comparable to that of the electron tube.

Although it operates at low power levels, the performance of the transistor modulator is approximately equal to that of the vacuum-tube modulator as far as fidelity and efficiency are concerned. Their small size, ruggedness, and economy of power comsumption make them particularly useful as low-power modulators for small portable and mobile equipments.

BASE-INJECTION MODULATOR.

APPLICATION.

The base-injection modulator is used to produce low-level modulation in equipment operating at very low power levels. It is particularly well suited for small portable transmitters, such as walkie-talkies, and for test equipment.

CHARACTERISTICS.

Operates by varying the base bias at the modulating frequency.

Is restricted to low-level, small-signal operation.

Uses common emitter configuration.

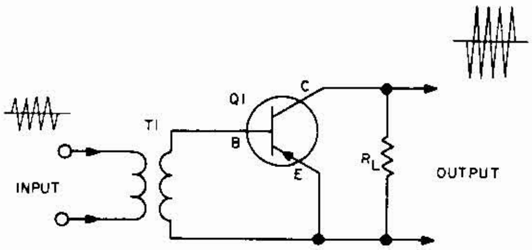
Modulating signal amplitude is limited to less than that of the base bias voltage.

CIRCUIT ANALYSIS.

General. The base-injection semiconductor modulator is analogous to the control-grid modulator in electron-tube circuits. The operating conditions, however, are entirely different. For example, since the semiconductor operates as a true low-level device under **small-signal** conditions, the voltage required to produce the modulation is also very small. This means that very little modulator power is required, much less than for comparable vacuum-tube operation. Likewise, since the transistor is operating under small-signal conditions, the r-f input (drive) is also small. Under these conditions, operation is usually class A or class AB. If operation is extended into the class B or C regions, it becomes large-signal operation. When operated large-signal fashion, the rectified r-f drive signal determines the operating bias and considerable distortion is produced by the non-linear transistor response characteristic for large signals. Because of these conditions such operation is seldom used, except for special applications; therefore, it will not be further discussed in this technical manual.

Base injection can be accomplished by a number of different methods. For example, it may be accomplished by feeding the signal either in series with the base-emitter circuit or in parallel with it, and can be accomplished by capacitive coupling or through means of transformers. Each of these methods will be considered in the following discussion.

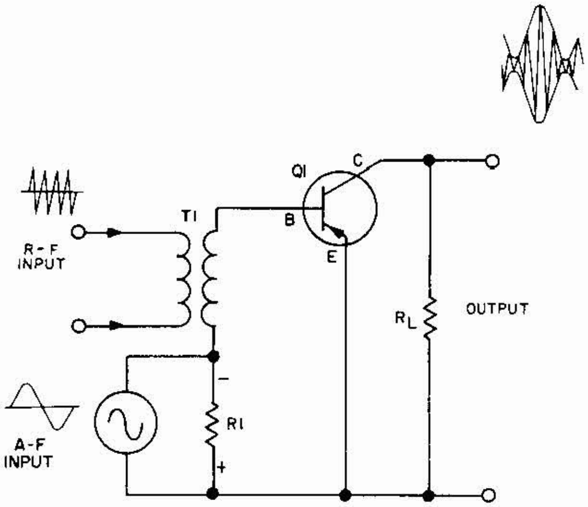
Circuit Operation. Amplitude modulation by base injection (or emitter injection) depends upon a widely separated r-f frequency and modulation (audio) frequency. There are two basic circuits involved, namely, the r-f amplifier circuit and the gain control (bias) circuit. A simplified schematic of the basic r-f amplifier is shown in the accompanying figure. For simplicity, the r-f amplifier circuit is shown without bias supplies, and with a resistive load in place of the tank circuit. It is assumed that normal forward bias is applied to the base-emitter junction, and that a reverse bias is applied to the collector junction. The secondary of T1 is effectively connected across the base-emitter junction, and the load is connected between emitter and collector as shown. With normal class A bias applied, the r-f signal will vary the base voltage equally above and below the operating point (assuming a sine-wave signal), and a corresponding base current will flow. A similar but



Simplified R-F Amplifier Circuit

larger (amplified) collector current will flow through the load resistor, developing an oppositely polarized output voltage. This is the action of a conventional r-f amplifier circuit.

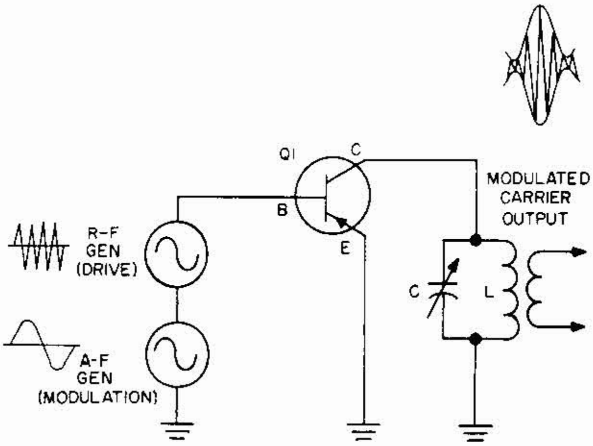
Consider now the method by which modulation is accomplished in the bias circuit, using the accompanying simplified schematic. For simplicity this circuit is also shown without bias supplies and with a load resistor in place of the tank circuit. It is assumed that normal forward bias is supplied to the base-emitter junction, and that a reverse bias is applied to the collector junction. The modulation is injected across R1, which is also the bias resistor, having a fixed d-c forward bias placed across it. Since the modulation signal is effectively connected in series with the base-emitter circuit, it adds to the bias when of the same polarity. When these voltages are of opposite polarity they cancel and reduce the total effective bias. Thus the bias on the transistor is made to vary instantaneously above and below the fixed d-c bias level in accordance with the modulation signal.



Simplified Modulator Circuit

Assuming a sinusoidal modulating signal, it is evident that the instantaneous bias will also vary sinusoidally. Since a change in bias will produce a change in gain, the instantaneous gain will also vary similarly. Consequently, the instantaneous amplification of the r-f carrier signal will vary in accordance with the modulation, but in an opposite direction. (The common-emitter output polarity is opposite the input polarity.) For maximum modulation the a-f signal must be slightly greater than the r-f carrier input signal. To prevent distortion produced by driving the transistor to cutoff or into saturation, the modulation signal amplitude must never exceed the d-c bias value.

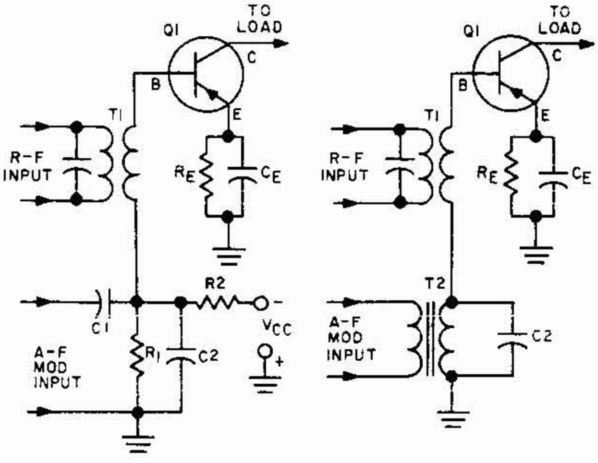
A simplified schematic of the series-feed method of base injection is shown in the accompanying figure. For simplicity, the inputs are shown as r-f and a-f generators, and biasing voltages are not shown. As can be seen, the r-f driver signal is connected in series with the a-f modulating signal between base and ground. The d-c bias (not shown) is such as to bias the transistor for class A operation. The bias value is chosen so that the quiescent collector current is set for half the maximum value. When the r-f input is applied, it adds to the base bias on the negative excursions and reduces the base bias on the positive excursions. The collector current follows these sinusoidal variations of bias, producing a voltage drop across the tuned tank (LC) in series with the collector. The tank is tuned to the driver frequency and is inductively coupled to the next r-f amplifier (or output circuit). Because of the gain through the transistor, the r-f drive signal is amplified. When the a-f modulating signal is applied, it alternately adds to and subtracts from the r-f drive signal applied to the base circuit (both r-f and a-f generators are series connected). The result of combining the r-f signal with the audio modulation signal has the total effect of increasing and decreasing the bias in accordance with the modulation signal amplitude. The changing bias varies the **transistor gain** in accordance with the modulation signal, and an amplified and modulated r-f output signal is obtained. This signal appears in the output as an r-f carrier with an



Series Injection

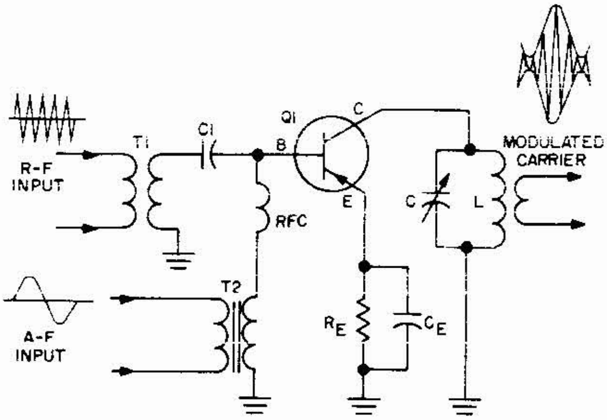
envelope which is a replica of the original modulation signal.

While either capacitance coupling or transformer coupling may be used to inject the modulation signal, there is essentially no difference between them in the manner in which this base injection circuit operates. In the capacitance-coupling method the modulator is isolated by the capacitor (C1) from the d-c biasing circuit as shown in the following figure, and the modulation is applied across the base bias resistor (R1) which also acts as the modulator load. R1 is bypassed for r-f by C2. With transformer coupling either internal (contact) or emitter bias, or a combination of both are used. Whereas with capacitive coupling fixed (voltage divider) bias is usually used. In either case C2 bypasses the r-f around the audio, completing the emitter-base circuit for r-f. The two methods of coupling are illustrated below. Although not very prevalent, the parallel (shunt)-feed method of base injection may also be used; it is shown below in simplified form. Blocking capacitor C1 is used to prevent r-f transformer T1 secondary from shorting the base bias and modulation signal to ground, through its very low secondary resistance. Likewise, the RFC is used to prevent the low-impedance secondary of modulation transformer T2 from shunting the r-f carrier signal to ground. Emitter bias and swamping are employed, using R_E and C_E. The collector circuit is identical with the series injection circuit; it contains the tank and ouput coupling circuit.



CAPACITANCE TRANSFORMER

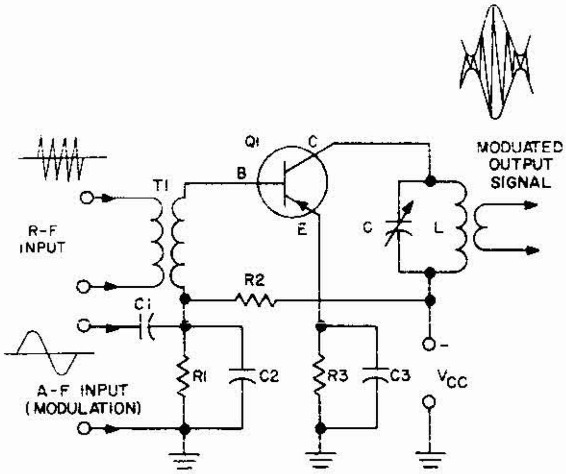
Coupling Methods



Parallel (Shunt) Injection

In the parallel-feed circuit, the bias is also caused to vary at the modulation rate. The difference is that since the two inputs are in parallel with each other, more modulation signal is required for full modulation. At low percentages of modulation (very small modulator inputs), a larger signal is also required in the parallel-feed circuit to produce the same effect as in the series-feed circuit. The addition of the r-f choke also presents an additional problem, that is, avoiding unwanted resonances in equipment operating over a large range of frequencies. Therefore, shunt injection is not very popular with designers.

The circuit of a typical capacitance-coupled series-feed base-injection modulator is shown in the following illustration. The r-f input is applied to the base of Q1 through r-f transformer T1, which is shown untuned for simplicity. Assuming normal bias and operation as a conventional class A amplifier, the r-f drive signal is amplified by Q1, and appears as a larger-amplitude r-f output in r-f transformer T2. Transformer T2 has a tuned primary with L and C acting as the conventional tank circuit across which the output signal is developed. The secondary of T2 is connected to the next amplifier stage or to a load (an antenna in special cases). Conventional emitter swamping is employed, with resistor R3 serving as the swamping resistor, bypassed by capacitor C3. Capacitor C3 is large enough to offer a low reactance to the lowest modulation frequency employed. Thus, both rf and af are bypassed around R3, so that no degeneration is produced.

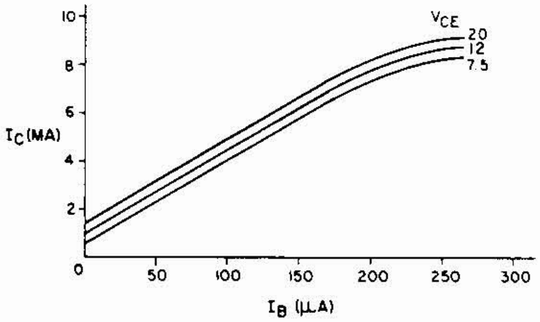


Base-Injection Modulator

Only very slowly varying temperature changes produce a voltage change across R3. (See section 3, paragraph 3.4.2, BIAS STABILIZATION, for a discussion of the function of R3 and C3.)

Consider now the base bias circuit consisting of R1 and R2. This is fixed bias with the resistors forming a voltage divider across the supply. (Refer to section 3, paragraph 3.4.1, BIAS CIRCUITS, for a discussion of this form of biasing.) The voltage appearing across R1 is the effective bias applied to the base of Q1 through the secondary of r-f transformer T1. Thus, the r-f input is applied in series with the d-c bias provided by R1. However, capacitor C2 bypasses R1 to ground for rf and, together with C3, effectively connects the secondary of T1 from base to emitter. As the r-f signal varies between positive and negative alternations, the emitter current varies similarly but oppositely (decreases on positive part of cycle and increases on negative part of cycle). The pulses of emitter current applied across the tank load (LC) produce an amplified sine wave of rf at the same frequency as the input.

Consider now the effect of the modulating signal. Since the modulating signal is coupled through capacitor C1, it appears as a varying a-f voltage across R1. While C2 bypasses R1 for rf, it is not large enough to bypass the a-f modulation. Therefore, since the a-f voltage is applied across R1, between the bottom of the T1 secondary and ground, it is also effectively in series with the d-c bias voltage, and the bias is caused to vary at the modulation rate. As the bias changes under control of the modulating signal, the gain of the transistor is varied likewise. Since the transistor is not exactly linear in its base-collector relationship, the carrier envelope will not be a linear replica of the modulation. It will be similar in shape, with the peaks and troughs occurring at the same time, but somewhat distorted. A typical forward-transfer characteristic curve for the common-emitter circuit is shown in the following figure. Because of the rounding off at the higher currents, the effective limits of modulation are for values between zero and about 92-percent modulation. Above this range the distortion tends to become excessive. Therefore, applications requiring full 100-percent modulation generally employ the collector-injection circuit, which will be discussed later in this section.



Typical Forward-Transfer Characteristic

While a resistive collector load has been assumed for ease of explanation in the simplified circuit discussions, in practice a tuned (L-C) tank circuit is necessary to select the proper output frequency. In every modulator there are sum and difference frequencies, and spurious frequencies are generated by the nonlinearity of the modulator (even in so-called linear modulators). Therefore, it is necessary to select the desired output frequency. In this case it is the frequency of the r-f carrier plus the sidebands generated in the modulation process.

FAILURE ANALYSIS.

No Output. A defective transistor or open base circuit caused by a defective transformer or an open bias resistor, will prevent operation. Also, an open bias capacitor can produce cutoff bias through degeneration if the r-f drive and the resistance in the circuit are sufficient to block operation. Either of these conditions can be detected by means of a resistance or continuity check with an ohmmeter. An open-circuited emitter, possibly caused by a defective swamping resistor, (R_E) will stop operation. An open-circuited collector will also stop operation; this condition can result from an open tank coil or a defective soldered joint, causing an extremely high resistance. Checking the collector voltage to ground will determine whether this circuit is open. Improper supply polarity will reverse the bias, stop operation, and most likely ruin the transistor. In most cases a simple resistance and continuity check combined with a voltage analysis, using a high-impedance voltohmmeter, will locate any of the no-output troubles.

Low Output. Too low or too high a bias will cause clipping of the output signal, resulting in low output and distortion. For maximum modulation, the a-f signal must be slightly greater than the r-f carrier input signal. Therefore, lack of audio gain, a defective coupling capacitor (C1), or shorting of the a-f signal to ground through a shorted bypass capacitor (C2) can cause loss of or low audio, and produce a low-output indication. The use of an oscilloscope to check the waveform will indicate the point in the circuit where the waveform amplitude changes or is lost. Lack of sufficient r-f drive will also produce a low-output condition since the a-f functions merely to modulate the r-f carrier. A defective or mistuned tank circuit can cause a low-output condition since the maximum output is developed at the same frequency as that of the input (carrier).

Where the modulation is present but r-f drive is lacking, no output will appear with normal a-f drive, since the collector load impedance (tank circuit) is too low to develop any audio voltage across it as it is tuned to the r-f signal.

Distorted or Incorrect Output. Distortion will be caused by improper bias and collector voltage, or by excessive input signals. Collector voltage and bias can be checked with a high resistance voltmeter. The r-f signal must not exceed the d-c bias; otherwise, rectification of the rf will occur and change the bias, and, as a result, clipping will occur on the peaks of modulation. If the a-f modulation is not of sufficient amplitude, the peaks of modulation will also be lost and distortion will occur. In a similar manner, too great an a-f drive will send the collector current into the saturation region, the troughs (negative peaks) will be cut off, and distortion will result. The use of an oscilloscope will permit waveform distortion to be observed and located. In the case of failure of the a-f modulation, an unmodulated r-f output will be obtained. Under special circumstances with high a-f drive and no r-f drive, it is possible that the audio waveform may be observed on an oscilloscope (because of capacitive leakage across the transistor); however, this is a rather remote possibility. In any event, the proper method of determining whether distortion exists and of locating the origin of distortion are to use an oscilloscope to observe the waveform, to make a resistance and voltage analysis to check the components, and to determine that the values of the element voltages are correct for normal operation.

If the tank circuit is too sharp (that is, has too high a Q), sideband clipping will result and the higher modulation frequencies will be lost. However, this is only of academic interest since such a condition could result only from an unauthorized modification of Navy equipment.

EMITTER-INJECTION MODULATOR.

APPLICATION.

The emitter-injection modulator is used to produce low level modulation in equipment operating at very low power levels. It is particularly well suited for small portable transmitters, such as walkie talkies, and for test equipment.

CHARACTERISTICS.

Operates by varying the emitter bias at the modulating frequency.

Is restricted to low-level, small signal operation.

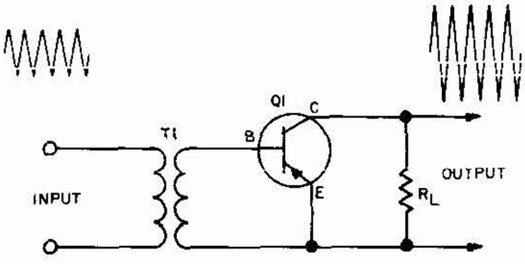
Uses common-emitter configuration.

Modulating signal amplitude is limited to less than that of the emitter bias voltage.

CIRCUIT ANALYSIS.

General. Emitter injection is very similar to base injection, since both methods vary the emitter-base bias. The carrier signal input is coupled to the base region of the transistor, while the modulating signal is applied across the emitter swamping resistor to regulate the gain of the transistor in accordance with the modulation. Consequently very little modulator power is required. Much less than that required for electron tube cathode modulation which is the electron tube counterpart of this circuit. Since the transistor is operating under small-signal conditions, the r-f carrier input (drive) is also small. Under these conditions the transistor is operated either Class A or Class AB. Injection of the modulation in the emitter circuit may be made by either the shunt or series method. In the series method a transformer is used in series with the emitter. Either method, however, operates similarly.

Circuit Operation. Amplitude modulation by emitter injection depends upon a widely separated r-f frequency and modulation (audio) frequency. There are two basic circuits involved, namely, the r-f amplifier and the modulating (bias gain control) circuit. A simplified schematic of the basic r-f amplifier is shown in the accompanying figure. For simplicity, the r-f circuit is shown without bias supplies and a resistive load in place of the tank circuit. It is assumed that normal forward bias is applied the emitter-base junction, and that a reverse bias is applied the collector junction. The secondary of T1 is effectively connected across the emitter-base junction, and the load is connected between emitter and collector as shown.

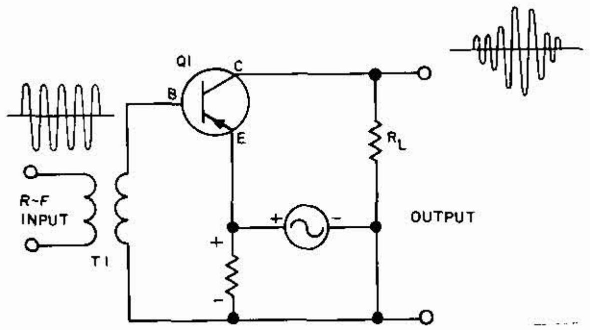


Simplified R F Amplifier Circuit

With normal Class A bias applied, the r-f signal will vary the base voltage equally above and below the operating point (assuming a sine-wave signal), and a corresponding base current will flow. A similar but larger (amplified) collector current will flow through the load resistor, developing an oppositely polarized output voltage. This is the action of a conventional r-f amplifier.

Consider now the method by which modulation is accomplished in the bias circuit, using the accompanying schematic. For simplicity, the modulator circuit is also shown without bias supplies and a load resistor in place of the tank circuit. It is assumed that normal bias is applied the emitter-base junction, and that a reverse bias is applied to the collector junction. The modulation is injected across the emitter swamping resistor. Since the modulating signal is effectively connected in series with the emitter circuit it adds to the emitter bias when of the same polarity. When this voltage is opposite in polarity to the emitter bias it partially cancels and reduces the total emitter bias.

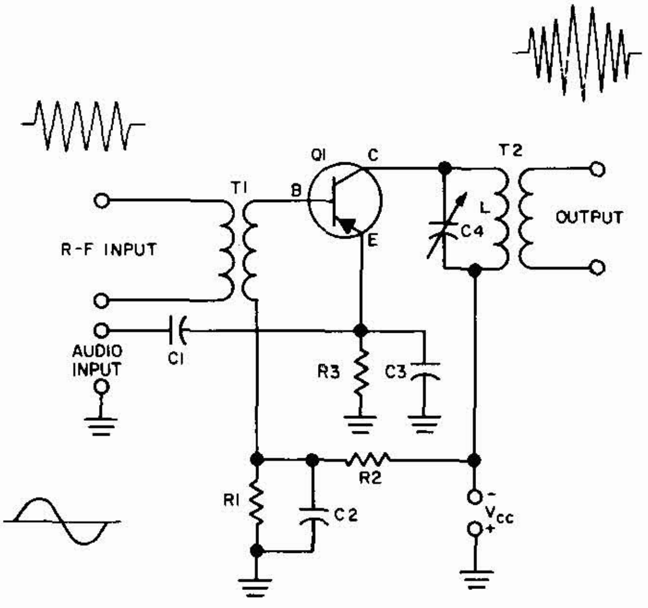
Thus the bias on the transistor is made to vary instantaneously above and below the fixed emitter bias level in accordance with the modulating signal. Assuming a sinusoidal modulating signal, it is evident that the instantaneous bias will also vary sinusoidally. Since a change in bias will produce a change in gain, the instantaneous gain will also vary similarly. Consequently, the instantaneous amplification of the r-f carrier signal will also vary in accordance with the modulation, but in a different and opposite direction. (Common-emitter output polarity is opposite the input polarity.) For maximum modulation the a-f signal must be slightly greater than the



Simplified Modulator Circuit

r-f carrier input signal. To prevent distortion produced by driving the transistor into cutoff or into saturation, the *modulation signal voltage must never exceed the d-c bias* value.

The circuit of a typical capacitance-coupled emitter injection modulator is shown in the following illustration.



Emitter-Injection Modulator

The r-f input is applied to the base of Q1 through r-f transformer T1 shown untuned for simplicity. Resistor R1 and R2 form a base bias voltage divider from the supply to ground, which places a fixed forward bias on Q1. *Capacitor C2 bypasses the divider to ground to prevent r-f* feedback into the bias supply. Resistor R3 and capacitor C3 form a conventional emitter swamping resistor bypassed to prevent degeneration. Only very slowly varying temperature changes produce a voltage across R3. (See section 3, paragraph 3.4.1 for an explanation of BIAS CIRCUITS and paragraph 3.4.2 for an explanation of BIAS STABILIZATION for more detailed information on this portion of the circuit, if desired). Transformer T2 is the collector output transformer with tuned primary L and C4 acting as a conventional tank circuit across which the output signal is developed. The secondary of T2 is connected to the next amplifier stage, or to a load (an antenna in special cases).

The bias voltage appearing across R1 is the effective bias applied to the base of Q1 through the secondary of r-f transformer T1. Thus the r-f input voltage is applied in series with the d-c bias provided by R1. However, capacitor *C2 bypasses R1 to ground for rf and together with C3* effectively connects the secondary of T1 from base to emitter. As the input signal varies between positive and negative alternations, the emitter current varies similarly but oppositely (decreases on the positive part of the cycle and increases on the negative part of the cycle). The pulses of collector current applied across the tank load C4 and L produce an amplified sine wave of r-f of the same frequency as the input.

Consider now the effect of the modulating signal. Since the modulating signal is coupled through capacitor C1, it appears as a varying af voltage across R3. While C3 bypasses R3 for rf, it is not large enough to bypass the a-f modulation. Thus the emitter voltage is alternately increased and decreased by the modulation which changes the base bias accordingly, so that the bias varies at the modulation rate. Consequently, the gain of the transistor is also changed at the modulation rate. The transistor is not exactly linear in its emitter-collector relationships, but is more linear than the base-collector relationship. While the output is not an exact replica of the input modulation, it will be similar in shape with troughs and valleys occurring at the same time but slightly distorted. Modulation is effectively linear from about zero to 96 per cent before the transfer characteristic rounds off. Above this range the distortion tends to become excessive. Therefore, applications requiring full 100 per cent modulation generally employ the collector injection circuit, which will be discussed later in this section.

While a resistive collector load has been assumed for ease of explanation in the simplified circuit discussions, *in practice a tuned (LC) tank is necessary to select the* proper output frequency. In every modulator, there are sum and difference frequencies, and spurious frequencies are also generated (even in so-called linear modulators). Therefore, it is necessary to select the desired output frequency. *In this case it is the frequency of the r-f carrier plus the* sidebands generated in the modulation process.

FAILURE ANALYSIS.

General. When making voltage checks use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low voltage ranges of conventional voltohmmeters. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A defective transistor or open base circuit caused by a defective input transformer, or an open bias resistor will prevent operation. An open bias capacitor also can produce cutoff bias through degeneration if the r-f drive and the resistance in the circuit are sufficient to block operation. Either of these conditions can be checked by means of a resistance or a continuity check with an ohmmeter. An open-circuited emitter, possibly caused by a defective swamping resistor, R3, will also stop operation. An open circuited collector will also stop operation; this condition can result from an open tank coil or a defective soldered joint, causing an extremely high resistance. Checking the collector voltage to ground will determine if this circuit is open. Improper supply polarity will reverse the bias, stop operation, and most likely ruin the transistor. In most cases, a simple resistance and continuity check combined with a voltage analysis, using a high impedance voltmeter, will locate any of the no-output troubles.

Low Output. Too low or too high a bias will cause clipping of the output signal, resulting in a low output with distortion. For maximum modulation, the a-f signal must be slightly greater than the r-f carrier input signal. Therefore, lack of audio gain, a defective coupling capacitor (C1), or shorting the a-f signal to ground by a defective bypass capacitor (C3) can cause loss of or low audio, and produce a low output condition. The use of an oscilloscope to check the waveform will permit the point in the circuit where the waveform is changed or lost to be observed. Lack of sufficient r-f drive will also produce a low-output condition, since the a-f functions merely to modulate the r-f carrier. A defective or mistuned tank circuit can also cause a low output condition, since the maximum output is developed on the same frequency as that of the input (carrier). Where the modulation is present but r-f drive is lacking no output will appear with normal af drive, since the collector load impedance (tank circuit) is too low to develop any voltage across it since it is tuned to the r-f signal.

Distorted or Incorrect Output. Distortion will be caused by improper bias and collector voltage, or by excessive input signals. Check the collector bias and voltage with a high resistance voltmeter. The r-f signal must not exceed to d-c bias; otherwise, rectification of the rf will occur, and change the bias, and, as a result, produce clipping on the modulation peaks. If the a-f modulation is not of sufficient amplitude the peaks of modulation will also be lost and distortion will occur. In a similar manner, too great an a-f drive will send the collector current into the saturation region, and the troughs (negative peaks) will be cutoff, and distortion will result. The use of an oscilloscope permits waveform distortion to be observed and located. In the case of failure of the a-f modulation an unmodulated r-f output will be obtained.

If the tank circuit is too sharp (that is has too high a Q), sideband clipping will also result and the higher modulation frequencies will be lost. However, such a condition is not likely to be found in military equipment that meets specifications.

COLLECTOR-INJECTION MODULATOR.

APPLICATION.

The collector-injection modulator is used to produce modulation at either low or relatively high levels, and up to a maximum of 100 per cent for semiconductor transmitting equipment.

CHARACTERISTIC.

Is operable under either small signal or large signal conditions.

Uses fixed bias.

Is capable of full 100 per cent modulation.

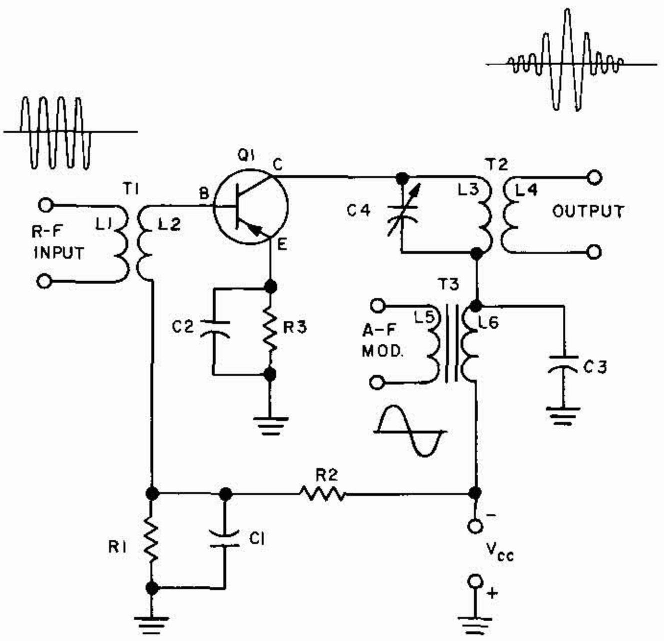
CIRCUIT ANALYSIS.

General. Collector-injection is the semiconductor counterpart of electron tube plate modulation. While plate modulation is usually always at a high level, collector-injection can be at very low levels. In fact, at the present state of the art, linear modulation for high frequency transistors is limited to a maximum change of one tenth of a volt or less which is a very low level of operation. In addition, the transistor ratings must be such that normal d-c collector voltage does not exceed one half of the collector breakdown rating, otherwise the peak swing on large signal operation may cause breakdown. When inputs larger than the emitter bias are applied, rectification occurs in the base circuit and causes an increase of bias. However, this slight bias shift does not create as much distortion when collector-injection is used as it would if either base-or-emitter injection were used.

Circuit Operation. The accompanying illustration is a schematic of a typical collector-injection modulator circuit.

The r-f drive voltage is applied to the base of Q1, through r-f transformer T1, inductively from primary L1 to secondary L2. The base is held at a fixed forward bias by bias voltage divider R1 and R2. C1 is the r-f bypass for R1, preventing feedback of r-f into the bias supply and possible regeneration. Emitter resistor R3 provides thermal compensation and is bypassed by C2 to prevent degeneration. With the emitter at ground potential, only slowly varying d-c current changes caused by a temperature change will bias off the emitter and counteract the tendency of increased current flow with increasing temperature.

The audio modulation is inserted in series with the collector of Q1 through audio transformer T3 by connecting secondary L6 between the collector supply and the output tank. The secondary of T3 is also bypassed for r-f by C3 to prevent r-f squeal in the audio circuits caused by feed back. Output transformer T2 has its primary tuned, with L3 and C4 forming the tank, which is inductively coupled



Collector-Injection Modulator

to secondary L4 providing a modulated output.

The fixed negative base bias causes heavy forward conduction in Q1, and base current flows from the supply through R2, L2 secondary, and through Q1 emitter-base junction back to ground through emitter swamping resistor R3. Thus the base is held near cutoff for large signal operation (and is Class A biased for small signal operation). With only the r-f drive signal applied, collector current is decreased during the positive half-cycles and increased during the negative half-cycle. This is conventional r-f amplifier operation and provides the normal r-f carrier.

Assume now, that modulation is applied to the input of L5, The signal is transformer coupled into the secondary. Thus during the positive half-cycles of modulation (assuming an in-phase connection) the collector voltage is opposed *decreasing the effective collector voltage. On the negative* half-cycle the polarity of the modulation adds to the collector voltage, increasing it. Thus the transistor gain is alternately decreased or increased in accordance with the modulation swing. When the gain is increased a peak of *modulation occurs, when decreased a trough in the modu*lation occurs. If the transistor gain varies linearly, 100 percent modulation is achieved when the collector voltage is doubled on the negative half-cycle. Although secondary L6 of T3 is bypassed by C3, the bypassing is effective for rf only and the af signal remains effective in changing the instantaneous collector voltage. The output tank circuit *varies in accordance with the modulation and inductively* couples the output to L4 secondary of T2. In small-signal, Class A operation the tank circuit determines the output frequency. In large-signal, Class B or C operation, the tank supplies the missing half cycle which is lost during cutoff, and also determines the output frequency. Thus distortion is kept to a minimum for either small-or large-signal operation.

FAILURE ANALYSIS.

General. When making voltage checks use a vacuum tube voltmeter to avoid the low values of shunting resistance employed on the low voltage ranges of conventional voltmeters. Be careful, also, to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A defective transistor, open base, emitter, or collector circuit, or a loss of bias will prevent operation. An open base circuit can be caused by lack of continuity in the windings of T1. Check L1 and L2 for continuity with an ohmmeter. Likewise, an open bias circuit may be caused by either R1 or R2 open. If R2 is open the operation is certain to cease, but with only R1 open some bias will be produced through R2 and the transistor, so complete output should not be lost. Check the values of R1 and R2 with an ohmmeter. An open circuited emitter, possibly caused by a defective swamping resistor R3, will also stop operation. Check the value of R3 using an ohmmeter. An open circuited collector will also stop operation; this can be caused by an open tank coil L3, a high resistance soldered joint, or by shorting of tank capacitor C4. An open modulation transformer will also prevent collector voltage from appearing if it is in the secondary of T3, as well as a short on C3. Use an ohmmeter to check the winding for continuity and an ohmmeter to check C3 for a short. *If all the circuits thus far are found to have con*tinuity and correct value there are still two possibilities. Transistor Q1 may be defective or output winding L4 of T2 may be open. Check L6 and L4 for continuity with an ohmmeter. Improper supply polarity will reverse the bias, *stop operation, and most likely ruin the transistor.* In most cases a continuity check combined with a voltage analysis, using a high impedance voltmeter, will locate any of the no-output troubles.

Low Output. Improper bias can result in a low output with distortion. Check R1 for proper value with an ohmmeter. Low output can also be caused by low collector voltage. First check the unmodulated value to be certain it is normal, and then check the instantaneous value with modulation using an oscilloscope. The modulation should be able to drive the collector from zero to twice normal voltage, less than this will produce less than 100 per cent modulation. Check the waveform with an oscilloscope. Lack of sufficient r-f drive will also produce a low-output condition, since the af merely functions to modulate the carrier. A defective or mistuned tank circuit can also cause a low-output condition, since the maximum output is developed on the same frequency as that of the input (carrier). With no a-f applied and low drive, the carrier amplitude will show on an oscilloscope as being less than normal or less than one-half the maximum possible amplitude at peak modulation. To determine if the tuning is correct adjust the tank for maximum r-f output (minimum current) if there is no sharp dip in current or pronounced peak output as the tuning capacitor is rotated, check the tuning capacitor for an open or short.

Distortion or Incorrect Output. Distortion will be caused by improper bias or collector voltage, and by excessive input signals. The r-f signal must not exceed the d-c bias; otherwise, rectification of the r-f will occur and change the bias, and, as a result, produce a slight modulation shift on peaks. This will not be as pronounced a distortion as if the injection were of base or emitter type, since only a small fraction of the signal is affected in collector modulation. Too great a modulation signal will cause peak clipping and distortion since the negative peaks will enter saturation and be lost. Use of an oscilloscope will permit this type of waveform distortion to be observed and located. It is also possible that excessive modulation peaks can exceed the maximum inverse voltage, and likewise cause peak clipping effects and possibly damage the transistor.

SINGLE SIDEBAND MODULATORS

Amplitude modulation is the process by which the amplitude of a signal called the carrier frequency (usually r-f), is varied by another signal (usually a-f). The resultant modulated r-f signal can be separated into three different frequencies. They are the original r-f carrier and the upper and lower sidebands. These sidebands are actually sum and difference frequencies generated through the process of frequency conversion. Two thirds of the average radiated power of a fully modulated AM transmission is contained in the r-f carrier. Since all of the intelligence contained in the modulating signal is transposed to the upper and lower sidebands, which are identical to each other, the carrier and one of the sidebands may be eliminated from the output without changing the remaining sideband. This allows the available transmitter power to be utilized to a much greater advantage in a single sideband. This type of transmission is generally known as suppressed carrier single sideband. The discussion of electron tube single sideband modulators in section 14.2 of this Handbook is generally applicable to semiconductor single sideband modulators. In general, semiconductor versions of electron tube single sideband modulators provide all the advantages one would expect to find in semiconductor circuits such as greater reliability, cooler operation, greater power efficiency and small size, in light-weight units.

In single sideband transmitters the carrier is usually suppressed or eliminated by the use of a balanced modulator. The basic principle of a balanced modulator is to introduce the r-f carrier to the balanced modulator in such a way that it does not appear in the output. There is only an output signal when both the audio modulation and the r-f carrier are present simultaneously at the modulator input. This output signal consists of only the upper and the lower sideband frequencies generated in the balanced modulator by the mixing of these two input signals across the nonlinear resistance of the transistor. The original audio modulation and the r-f carrier inputs are suppressed because of the operational characteristics of the circuit. All types of balanced modulator circuits function somewhat alike. Semiconductor balanced modulators are discussed in detail in the following paragraphs.

BASIC BALANCED MODULATOR.

APPLICATION.

The semiconductor basic balanced modulator is used to produce amplitude modulated upper and lower sideband frequencies for use in single sideband transmitters.

CHARACTERISTICS.

Utilizes nonlinear characteristics of transistors to produce sidebands.

Produces amplitude modulated upper and lower sidebands while suppressing the r-f carrier.

Uses push pull output and parallel input to cancel out the carrier.

Modulation is accomplished at low power levels; therefore, no large modulator power supplies and transformers are needed.

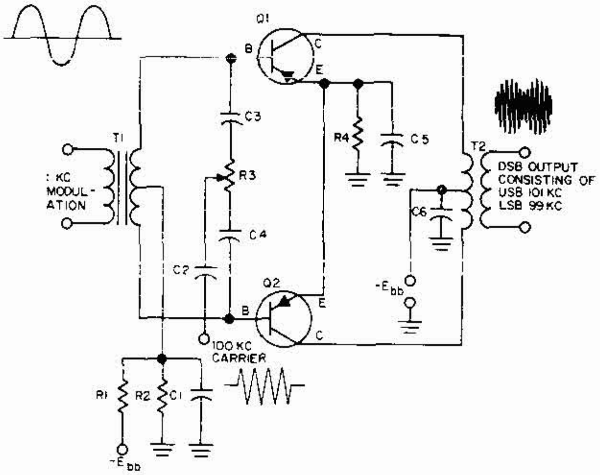
Can provide conversion gain, i.e., sideband output greater than modulation input.

CIRCUIT ANALYSIS.

General. The basic balanced modulator produces amplitude modulated upper and lower sidebands and suppresses the r-f carrier. This is achieved by coupling the r-f carrier, in-phase, to the bases of two transistors whose output is connected in push-pull, (out of phase). The r-f carrier is kept 8 to 10 times as large as the modulating voltage to keep distortion to a minimum. In push-pull amplifiers an input signal must be out of phase to produce an output since any in-phase inputs cancel in the output. The modulating signal is applied to the base of each transistor in push-pull (180 degrees out of phase) through a center tapped transformer. When both r-f carrier and audio modulating signals are applied simultaneously to the bases of the balanced modulators, sum and difference frequencies (sidebands) are produced by the modulating frequencies beating against the carrier, since any amplitude modulation process is essentially the same as heterodyning. As in a frequency converter, any modulation which exists on one of the mixing frequencies is linearly transposed to the resultant sum and difference frequencies. The collector circuit contains the upper and lower sidebands which are the sum and difference frequencies, respectively, the r-f carrier, and the audio modulation. The carrier is cancelled out by push-pull action in the output transformer, and the output transformer also presents a low impedance to the audio modulating signal. Therefore, the original modulating signal also is not developed in the output. The generated sidebands are out-of-phase with each other at the collectors of the transistors, since the modulating signal is out of phase at the bases. These out-of-phase signals add in the output transformer rather than cancel as in-phase signals do, and they are inductively coupled to the following stages through the output transformer.

Circuit Operation. The accompanying diagram illustrates a basic semiconductor balanced modulator.

Audio transformer T1 couples the audio modulation to the bases of transistors Q1 and Q2. Resistors R1 and R2 form a base bias voltage divider which provides the proper bias for the transistor. Capacitor C1 places the center tap of T1 at a-f ground potential to supply an out-of-phase (push-pull) input. Capacitor C2 couples the r-f carrier from the carrier oscillator to the slider of carrier balance potentiometer R3. Potentiometer R3 can be adjusted, to vary the relative amplitude of the r-f carrier signal voltage on the bases of Q1 and Q2, to provide a carrier balance control, so that the r-f carrier can be completely suppressed in the output. Capacitors C3 and C4 couple the r-f carrier from balance potentiometer R3 to the bases of Q1 and Q2, and also act as d-c bias blocking capacitors to prevent base shorting. Transistors Q1 and Q2 are the nonlinear devices used for generating the sidebands. Resistor R4,



Basic Balanced Modulator (Common Emitter).

which is bypassed by C5 is a conventional emitter stabilization resistor intended to prevent changes in temperature from altering transistor characteristics. Center-tapped output transformer T2 provides a push-pull collector load for the modulators. Capacitor C6 places the center-tap of the primary of T2 at r-f ground potential.

To more easily examine the operation of the basic balanced modulator, assume first that only the r-f carrier is applied. The r-f carrier generated in the carrier oscillator is coupled through C2 to the slider of potentiometer R3. Hence, the carrier signal appears at both ends of R3 and is coupled through capacitors C3 and C4 to the bases of Q1 and Q2, respectively. The carrier signal voltage is in-phase on the bases of Q1 and Q2 (they are parallel connected) and the amplitude of the carrier signal at the base of each transistor is controlled by the adjustment of R3. Assuming that the r-f input is operating on the negative half cycle, the negative forward base bias is increased and both collectors draw an increasing amount of collector current, (the base input is in phase). Thus, the voltage drop produced across each half of output transformer T2 is positive-going, and equal but opposing voltages are developed in each half of the transformer primary by current flowing in opposite directions which cancel, so that no output is obtained from the secondary winding. Likewise, on the positive half cycle of r-f input the forward bias is reduced and less collector current is drawn. Thus, the drop across transformer T2 primary windings is negative going and equal and opposing voltages are developed in the primary because the current flow through each primary is opposite. These voltages also cancel out (since they are out-of-phase) so no carrier again is developed in the output. If the circuit is properly balanced by the adjustment of R3, the opposing signals are exactly equal in amplitude and the carrier is completely suppressed. Thus, it can be seen that an output is not produced with only an r-f carrier input applied.

When audio modulation and the r-f carrier are both applied simulaneously, a different situation arises. The audio modulation is applied through transformer T1. Since the secondary of T1 is effectively center-tapped by C1, R2, and the bias supply, modulation signal voltages are developed across each half of the secondary winding of T1 which are out of phase with each other. The out-of-phase modulating signals are applied directly to the base of each transistor. Capacitors C3 and C4 are of such a value that they present a high reactive impedance to audio frequencies and thus prevent any audio modulation from feeding back from one base to the other and cancelling each other out. Meanwhile, the audio modulating signal modulates the inserted r-f carrier and produces upper and lower sidebands in the collector circuit of transistors Q1 and Q2. These sidebands are produced by mixing the r-f carrier frequency and the modulation signal together across a nonlinear device. (Detailed information concerning frequency conversion, (mixing or heterodyning), can be found in the introduction to Section 13 of this Handbook.) To better illustrate the operation of the basic balanced modulator with both r-f carrier and modulation applied, assume that the first half cycle of the modulating signal voltage applied to the base of Q1 is positive and the first half cycle of the modulating signal applied to the base of Q2 is negative.

The conduction of Q1 decreases as a result of the positive half cycle of modulation input opposing the forward bias of the emitter base junction. This results in negative going sideband frequencies being developed across the top half of the output transformer. At the same instant the conduction of Q2 increases as a result of the negative going half cycle of modulation input aiding the forward bias of the emitter base junction, and causing positive-going sideband voltages to be developed across the bottom half of the output transformer T2. Push-pull action occurs and the side band frequency signal voltages add to each other causing both upper and lower sidebands to be developed and inductively coupled to the secondary of T2. The r-f carrier is suppressed, as explained earlier, and the original audio modulating signal is not developed due to the low reactance of T2 to audio frequencies. Therefore, only the upper and lower sidebands are produced by the balanced modulator.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of multiplier resistance employed on the low-voltage ranges of the standard 20,000 ohms-per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low resistance reading.

No Output. Since each leg of the basic balanced modulator performs essentially the same function, failure of one leg of the balanced modulator is not likely to cause a no-output condition to exist, unless the failure occurred in a manner that would affect the power supply such as a shorted transistor or a shorted C6. Failure of the power supply itself is a likely cause of no output. If the power supply measures normal when checked separately and no collector voltage appears on Q1 or Q2, check T2 primary and C6 for a short or ground. An open or shorted R1 or R2 or a shorted C1 would remove the bias from transistors Q1 and Q2 and could also cause a no-output condition to exist. Since R4 is a common emitter resistor for both transistors a no-output condition would also result if R4 opened. Check for proper value with an ohmmeter. Since any balanced modulator produces an output only when both the r-f carrier and the modulating signal are present, absence of either of these signals on the base of each transistor would cause the balanced modulator to be inoperative. Presence of the input signals can readily be determined by observing, with an oscilloscope, the waveform present at these points with the carrier oscillator operating and with modulation applied to the transmitter. Absence of the audio modulation on the bases of the transistors could be caused by a defective audio input transformer, T1, or by failure of the audio stages preceding the balanced modulator. Presence of audio modulation on the primary of T1 indicates that the preceding audio stages are functioning properly. Should the modulation be present on the primary of T1 but absent on the bases of the transistors, T1 is most likely defective (check the primary and secondary for continuity with an ohmmeter). Presence of the r-f carrier at the input to coupling capacitor C2 indicates that the carrier oscillator is operating. In the event that the r-f carrier is present at the input of C2 but is absent on the bases the transistors, capacitor C2 or potentiometer R3 may be open. Check R3 for proper value and C2 for value with an in-circuit capacity meter. Failure of C3 or C4 would only disable one leg of the balanced modulator and an output would still result. Signal tracing from C2 to the bases of the transistors will reveal which component is at fault. Another possible cause of no output is a defect in output transformer T2. Continuity checks of the transformer windings and checks for leakage between the primary and secondary and between each winding and ground will reveal whether or not a defect exists in the transformer.

Low Output. A low output condition could be caused by a defective transistor, a faulty circuit component, a defective power supply, or by low amplitude r-f carrier or modulation input. Voltage checks should be made of the power supply voltage and of transistor elements to determine whether or not a defective power supply or a faulty component is the cause of low output. A change in value of resistors R1 or R2 or leakage in capacitor C1 would change the base bias of transistors Q1 and Q2 and could cause a low output condition. If C5 opens the resulting degeneration would lower the gain of the modulator circuits and could cause low output to result. Likewise, an increase in value of emitter stabilization resistor R4 would alter the operating bias of the transistors and could cause a decreased output. Check the value of R4 with an ohmmeter. The amplitude of the inputs to the balanced modulator can be checked by observing with an oscilloscope the waveform present at the base of each transistor. If either input signal is low in amplitude, the cause can be determined by signal tracing from the bases of the transistors to the stages preceding the balanced modulator. If either C3 or C4 opens, one leg of the balanced modulator would be inoperative and low output would result. Do not overlook the possibility that a defective output transformer can also cause low output. Check the resistance to ground with an ohmmeter.

Distorted Output. Distortion of intelligence will result in SSB systems if the receiver and transmitter are not exactly on frequency. Distortion in SSB transmitters is usually the result of improper operation of the linear power amplifier or of operating any stage beyond its capabilities. Should the distortion be determined to be caused by the balanced modulator, check the modulation level to make sure that the audio circuits are not overdriving the balanced modulator. If the modulation level is correct, distortion could still be caused by a defective transistor. If the transistors are determined to be good and distortion persists, voltage checks of transistor elements with a high resistance voltmeter would reveal whether or not a defective component or a defective power supply is the cause of distortion. Low amplitude r-f carrier input could also cause distortion. The r-f carrier input should be 8 to 10 times the amplitude of the modulating signal.

BALANCED COMPLEMENTARY SYMMETRY MODULATOR

APPLICATION.

The balanced complementary symmetry modulator is used in single sideband transmitters to produce amplitude modulated upper and lower sidebands.

CHARACTERISTICS.

Produces amplitude modulated upper and lower sidebands while suppressing the r-f carrier.

Utilizes a PNP and an NPN transistor connected in a complementary symmetry circuit.

Requires two collector power supplies (one positive and one negative supply).

Static current does not flow through the output transformer.

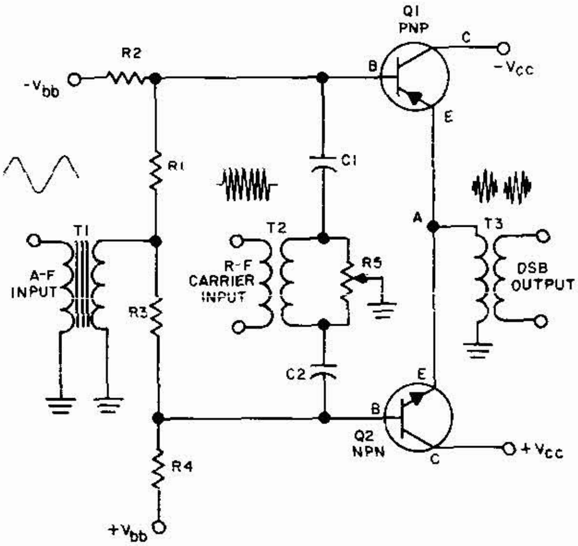
Utilizes the common collector configuration.

Requires two separate bias supplies.

CIRCUIT ANALYSIS.

General. The balanced complementary symmetry modulator produces amplitude modulated upper and lower sidebands and suppresses or cancels the r-f carrier, which is used to generate the sidebands. Basically this is achieved by coupling the audio modulation in parallel (in-phase) to the bases of two opposite polarity (PNP and NPN) transistors connected in a complementary symmetry configuration, and simultaneously coupling the r-f carrier in push pull (180° out-of-phase) to the bases of the transistors. It should be noted that, while the transistors are of opposite polarities, they have the same operational characteristics. The audio modulation and the r-f carrier beat together in the nonlinear resistance of the transistors, and sum and difference (sideband) frequencies are produced. The sideband frequencies are developed across the output transformer and are inductively coupled to the following stages. Circuit elements are arranged so that the r-f carrier and the original audio modulating signal do not appear in the output. For minimum distortion the r-f carrier is maintained at a level 8 to 10 times greater than the audio modulating signal.

Circuit Operation. The accompanying diagram illustrates a balanced complementary symmetry modulator.



Balanced Complementry Symmetry Modulator
(common collector configuration)

Audio transformer T1 couples the audio modulation from the preceding stages to the bases of Q1 and Q2 through bias resistors R1 and R3. R1 and R2 form a voltage divider network to bias transistor Q1 and resistors R3 and R4 form a voltage divider to bias transistor Q2. Transformer T2 couples the r-f carrier from the carrier oscillator to both sides of carrier balance potentiometer R5. Carrier balance potentiometer R5, which has its slider grounded, effectively centertaps the secondary of carrier input transformer T2, causing 180° out-of-phase r-f carrier signal voltages to be present at the top and bottom of T2. Coupling capacitors C1 and C2 couple the r-f carrier from transformer T2 to the base of each transistor and prevent a DC path from being formed from the base of each transistor to ground through carrier balance potentiometer R5. Transistors Q1 and Q2 are the nonlinear devices used to generate the sidebands, and transformer T3 serves as the output load for the balanced complementry symmetry modulator.

Since both transistors have the same operational characteristics both transistors conduct equally with no signal input, and thus both transistors have equal equivalent emitter-collector resistance. Thus, it can be seen that a balanced condition exists between Q1 and Q2, and the voltage drop across Q1 is equal to the voltage drop across Q2. Since the absolute value of voltage between each power supply and ground is the same and the voltage drop across the transistors is equal, there is no voltage between point A in the figure and ground, and thus no current flows through output transformer T3, and no output is produced.

When a push-pull (180° out-of-phase) input a signal is applied, in this case the r-f carrier, the following takes place. During the period of the input cycle when the base of Q1 is driven positive and the base of Q2 is driven negative, conduction of both Q1 and Q2 decreases. This is due to a reduction in forward bias applied to each transistor (PNP transistor Q1 normally has its base biased more negative than its emitter and NPN transistor Q2 normally has it base biased more positive than its emitter). This decrease in conduction of Q1 and Q2 is in effect an increase in equivalent emitter-collector resistance and, since both transistors have the same operational characteristics, both transistors decrease conduction in equal amounts. Although the equivalent emitter-collector resistance of both transistors increases, it increases equally in both transistors and, therefore, the voltage drop across Q1 remains equal to the voltage drop across Q2. Once again the balanced condition between Q1 and Q2 is maintained and no output is produced, since no current flows through output transformer T3. During the next half-cycle of r-f carrier input a negative-going half-cycle of r-f is coupled from transformer T2 to the base of Q1 and increases the forward bias on Q1 causing the conduction of Q1 to increase. Simultaneously, a positive half-cycle of r-f is applied to the base of Q2, where it again increases the forward bias on Q2, causing the conduction of Q2 to increase. Both transistors increase conduction at the same rate, and the equivalent emitter-collector resistance of both transistors decreases equally. Again the voltage drop across each transistor is equal and a balanced state is maintained. Hence no output is produced. In this manner the r-f carrier is effectively suppressed in the complementry symmetry balanced modulator. In actual practice, the slight differences in characteristic found between evenly matched pairs of transistors necessitates the use of some external method of balancing the circuit. The complementry symmetry balanced modulator achieves precise carrier balance by making it possible to vary the amplitude of the r-f carrier coupled to the base of Q1 with respect to the amplitude of the r-f carrier coupled to the base of Q2. This is achieved by effectively center-tapping the secondary of r-f carrier input transformer T2 by connecting both sides of potentiometer R5 across the secondary of T2. Varying the position of the grounded slider of R5 has the same effect as varying the position of the center-tap on a centertapped transformer.

When audio modulation in addition to the r-f carrier is applied simultaneously to the balanced modulator, upper and lower sidebands are generated as the result of the r-f carrier frequency and the audio modulating frequency beating together in the nonlinearly operated transistors. Four basic frequencies are present in the emitter circuit of the transistors. These frequencies are the original r-f carrier frequency, the original audio modulating frequency and the sum and difference frequencies (sidebands) resulting from heterodyning action. However, only the sideband frequencies are present in the output.

The audio modulation is applied to the base of each transistor in parallel (in phase) through transformer T1. During the positive half-cycle of modulation input the forward bias on Q1 is opposed by the modulating signal (Q1 is a PNP transistor) and conduction of Q1 decreases. At the same time, the positive half-cycle of modulating signal aids the forward bias on Q2 (Q2 is an NPN transistor) and conduction of Q2 increases. The balance between Q1 and Q2 is now upset since the equivalent emitter-collector resistance of Q1 increased causing an increased voltage drop across Q1, while the equivalent emitter collector resistance of Q2 decreased causing a decreased voltage drop across Q2. Point A in the figure is no longer at ground potential but at some positive voltage and current flows through output transformer T3 causing an output to be produced. The r-f carrier component of emitter current is cancelled as explained previously. The sideband component of emitter current and the original audio modulation component of emitter current flows through the primary of output transformer T3, but the output transformer presents a very low impedance to audio frequencies, therefore, audio frequency voltage is not developed across the primary of T3. Only the upper and lower sideband signal voltage is developed across the primary of output transformer T3 and is inductively coupled to the following stages. Overall circuit operation is the same for the negative half cycle of audio modulation input. That is, during the negative half-cycle of modulation input the forward bias on Q1 is increased and conduction of Q1 increases. At the same time, the negative half-cycle of modulation signal decreases the the forward bias on Q2 (an NPN transistor) and decreases conduction of Q2. The balance between Q1 and Q2 is now upset because the equivalent emitter-collector resistance of Q1 decreased, causing a decreased voltage drop across Q1, while the equivalent resistance of Q2 increased causing an increased voltage drop across Q2. Point A in the figure, is therefore, no longer at ground potential, but is at some negative voltage so that current flows through output transformer T3, causing an output to be produced. The r-f carrier component of emitter current is cancelled as explained previously. Although both the sideband component of emitter current and the original modulation component of emitter current both flow in the primary of T3, the low impedance offered to the audio modulation is insufficient to develop an audio frequency voltage across it. Therefore, only the upper and lower sidebands are inductively coupled to produce an output in the secondary of T3.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum tube voltmeter to avoid the low values of multiplier resistance employed on the low voltage range of the standard 20,000 ohms-per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low resistance reading.

No Output. Since transistor Q1 and its associated circuit performs essentially the same function as transistor Q2 and its associated circuit components, failure of either transistor or associated circuit components is not likely to cause a no-output condition to exist. Likewise, failure of either the positive or negative power supply is not likely to cause a no-output condition to exist, since each power supply serves only one branch of the modulator. Failure of a component, such as the audio modulation input transformer T1, the r-f carrier input transformer T2, or output transformer T3 all of which serve both branches of the modulator could be a cause of a no-output condition. Continuity checks of the transformer windings and resistance checks for shorts to ground or excessive leakage between windings will reveal a defect in either T1, T2, or T3 which could cause a no-output condition to exist. Failure of T1 or T2 could cause a no-output condition to exist by failing to couple either the audio modulation or the r-f carrier to the balanced modulator. Likewise, failure of the source of the signals (modulating signal or r-f carrier) would also create a no-output condition. To determine whether or not the signals are reaching the balanced modulator observe, with an oscilloscope, the waveform present on the primary of audio input transformer T1, and the waveform present on the primary of r-f carrier input transformer T2. Absence of either of these signals results in a no-output condition and indicates that the fault lies in the stage, or stages preceding the modulator.

Low Output. Failure of almost any component in the complementry symmetry balanced modulator could result in a decreased output. Failure of, or improper output from from either power supply could result in low output and the power supplies should be checked and repaired or adjusted, if necessary, before any component substitutions are attempted. Deterioration of either of the transistors could also be a cause of decreased output. A low output condition could also be due to improper base bias applied to either transistor. Check the voltage present on the base of Q1 and Q2 with a vacuum tube voltmeter. If a discrepancy is found the most likely cause is a change in value of voltage divider resistors R1 and R2 (for the base of Q1) or R3 and R4 (for the base of Q2). Improper base bias could also be caused by a short in coupling capacitor C1 or C2. If C1 or C2 opened, a low output condition would result since the r-f carrier would be unable to reach the base of either Q1 or Q2. A partial failure of transformers T1 or T2 could result in decreased amplitude audio modulation, or decreased amplitude r-f carrier, reaching the bases of the transistors. This condition would likely result in decreased output. Careful resistance and leakage checks, with an ohmmeter, would usually indicate a partial failure that could be the cause of low output. Likewise, decreased amplitude r-f carrier or audio modulation before it reaches the modulator could be the cause of low output. The existance of this condition can be determined by observing, with an oscilloscope, the amplitude of the input signals on the primary of the respective input transformer. Another possible cause of low output could be due to a defect in output transformer T3. Resistance and leakage checks of the transformer windings should indicate a possible defect.

Distorted Output. Distortion of intelligence will occur in single sideband systems when the transmitter and receiver are not exactly on frequency. Distortion in single sideband transmitters is usually the result of improper operation of the linear power amplifier, or of operating any stage beyond its rated capabilities. If system distortion is determined to be caused by the modulator, almost any component which could cause low output can also be suspected of causing a distorted output. The power supply voltages should be checked first and adjusted, if necessary. A check of base bias voltage of both transistors would reveal if a fault exists in voltage divider resistors R1, R2, R3, and R4. An open or shorted carrier balance potentiometer R5 could also cause a distorted output to result. excessive audio input could be the cause of distorted Since the r-f carrier input amplitude should, for good fidelity, be 8 to 10 times the amplitude of the audio modulating signal, a decrease in amplitude of the r-f carrier or excessive audio input could be the cause of distorted output. The amplitude of the r-f carrier input and the amplitude of the audio modulation input can be easily checked by observing, with an oscilloscope, the waveform present at the primary of the respective input transformer.

Do not overlook the possibility that the audio modulating signal is distorted before it reaches the modulator.

FREQUENCY MODULATORS (FM).

The semiconductor FM modulator varies the frequency of a carrier above and below the center frequency similarly to that of the vacuum tube. Frequency modulation is usually accomplished at very low levels as compared with tube operation. In many instances the modulation is accomplished with a low-frequency carrier and the modulated carrier is then frequency multiplied until the desired center frequency is reached. Since the input and output impedances of the transistor are functions of the operating point, the transistor may be used as a reactance modulator. Thus a transistor oscillator with a tank circuit may be used with the output side of the modulator connected across part of the tank coil. Thus voice variations of the modulation signal vary the reactive output impedance of the modulator and change the oscillator frequency accordingly. Another modulation method is to vary the operating point of the modulator by varying the bias. We find then, that the modulation can be inserted in either the emitter, base, or collector circuits. Since the reactance modulator is more efficient and provides large deviation it will be discussed in the following paragraphs.

BASIC REACTANCE MODULATOR.

APPLICATION.

The reactance modulator is used to frequency modulate low power semiconductor transmitters.

CHARACTERISTICS.

Uses collector to emitter output capacitance to provide reactive frequency control

Operates at relatively low power levels.

Shunts a portion of the oscillator tank coil.

Requires further limiting or clipping to eliminate a residual 10 to 15 percent amount of AM modulation.

Uses a single transistor to achieve full modulation.

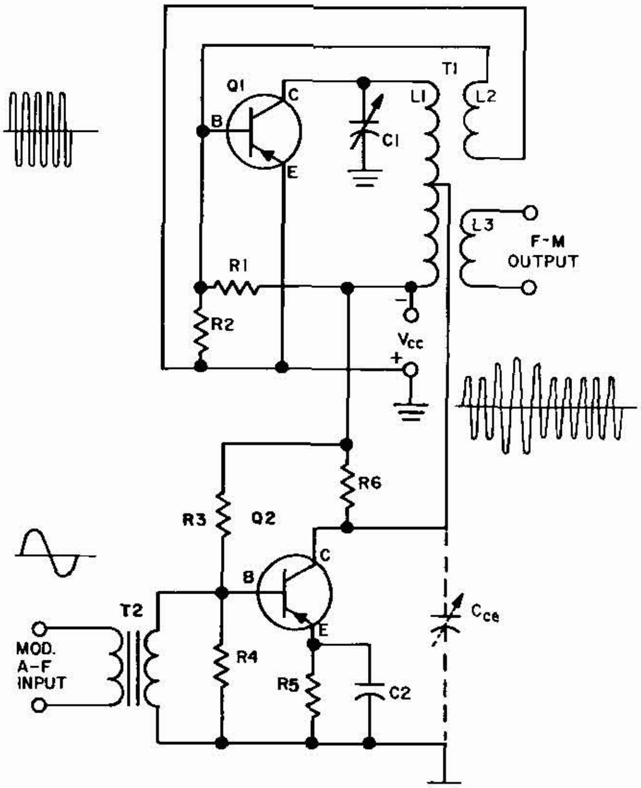
CIRCUIT ANALYSIS.

General. In an fm transistor, modulation is accomplished at the oscillator stage. The transitor oscillator is frequency modulated in the same manner as an electron tube oscillator, or by varying the gain at the modulating rate as is done with AM transistors. When the oscillator is fm modulated a slight amount of AM modulation is also inserted. Thus the modulated fm oscillator requires a limiter stage to remove the amplitude modulation before it is further amplified or multiplied in frequency. This is easily accomplished in a single stage.

Circuit Operation. The accompanying schematic shows the circuit of a typical frequency-modulated oscillator stage operated as a reactance modulator.

Transistor Q1 is the FM oscillator. Resistor R1 and R2 are base bias voltage dividers. Primary L1 of transformer T1 together with capacitor C1 form the tuned tank adjusted to the oscillator output frequency. R6 is the modulator load resistor. Secondary L2 of T1 is the collector to base feedback winding of the oscillator. Tertiary winding L3 is an inductively coupled output winding which couples the FM output signal to the next stage, or in special cases to an antenna. Transformer T2 is an audio transformer which inductively couples the modulation input to the base-emitter junction of Q2, the modulator stage. Resistors R3 and R4 are base bias voltage dividers, while R5 is an emitter swamping resistor bypassed by C2 for temperature stabilization. The output capacitance of Q2 shown dotted as C_{ce} shunts a portion of the r-f oscillator coil L1. As the modulator operates the output capacitance of Q2 is varied. Thus, the frequency of the oscillator is shifted in accordance with the modulation the same as if C1 were varied instead.

When the modulation is applied to the primary of T2 it is coupled into the base circuit. Thus the emitter-base bias changes constantly at the modulation rate. Since the bias is increasing and decreasing at the modulating rate, the collector voltage of Q2 also increases and decreases at



Reactance Modulator

the modulating rate. When the collector voltage increases, output capacitance Cce decreases, and conversely, when the collector voltage decreases. (An increase in voltage has the effect of spreading the capacitor plates further apart by increasing the width of the PN barrier. Conversely, the reduction of collector voltage reduces the width of the PN junction and has the same effect as pushing the capacitor plates together to provide more capacitance).

When the output capacitance of Cce decreases because of the increase in collector reverse bias, the resonant frequency of the Q1 oscillator tank circuit increases as if C1 were decreased, and produces a higher frequency r-f output. Conversely, when the output capacitance of Cce increases because of a decrease in collector reverse bias, the resonant frequency of Q1 oscillator tank circuit decreases and produces a lower frequency r-f output because of the shunting effect of Cce. Thus the resonant frequency of the oscillator tank circuit is increasing and decreasing at the modulating rate. Hence, the oscillator frequency is also increasing and decreasing at the modulation rate. The output of the oscillator, therefore, is a frequency modulated carrier signal. Since the audio modulation causes the collector voltage to increase and decrease, there is an AM component induced into the output. This produces both an FM and AM output. By placing a limiter stage after the reactance modulator, the amplitude variations are removed and only the frequency modulation remains, with a constant amplitude output. Frequency multipliers are then used to increase the oscillator frequency to the desired output frequency. For high power, linear r-f amplifiers are used to increase the steady amplitude signal to a particular level and power output. With the initial modulation occuring at low levels fm represents a saving in power as compared with conventional AM, with the FM noise reducing properties providing a better signal to noise ratio than is possible with AM.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low voltage ranges of conventional voltmeters. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low resistance reading.

No-Output. Open bias resistors, open collector resistor R6, or open windings on T1, can cause a no-output condition. Check the resistors for proper value with an ohmmeter and the transformer for continuity. If satisfactory indications are obtained but Q1 does not oscillate, the transistors may be defective. If Q1 operates but no modulation is obtained, Q2 is defective.

Low Output. Low collector voltage, low bias voltage, or a weak transistor may cause a low output. Check the supply voltage first to be certain it is normal, then check the collector voltage of both Q1 and Q2, and the base bias of Q1 and Q2 also, if the collector voltage is normal. Also check collector resistor R6 for proper value if the modulation appears weak. Low bias can be caused by a change in bias voltage dividers R1 and R2, and R3 and R4; check for proper resistance value with an ohmmeter. A high resistance connection in output winding L3 of T1 may also occur and course a reduced output.