

Radiotelephony

§ 5-1 Modulation

The carrier — The steady radio-frequency power generated by transmitting circuits cannot alone result in the transmission of an intelligible message to a receiving point. The continuous wave from the transmitter itself serves only as a "carrier" for the message; the intelligence is conveyed by *modulation* (a change) of the carrier. In radiotelephony, this modulation reproduces electrically the sounds it is intended to convey.

Sound and alternating currents — Sounds are caused by vibrations of air particles. The pitch of the sound depends upon the rate of vibration; the more rapid the vibration, the higher the pitch. Most sounds consist of complex combinations of vibrations of differing rates or frequencies; the human voice, for instance, generates frequencies from about 100 cycles per second to several thousand per second. The problem of transmitting speech by radio therefore is one of varying the r.f. carrier in a way which corresponds to the air-particle vibrations. The first step in doing this is to change the sound vibrations into alternating electrical currents of the same frequency and relative intensity; the electromechanical device which achieves this translation is the *microphone*. These currents then may be amplified and used to modulate the normally steady r.f. output of the transmitter.

Methods of modulation — The carrier may be made to vary in accordance with the speech current by using the current to change the phase (§ 2-7), frequency or amplitude of the carrier. *Amplitude modulation* is by far the most common system, and is used exclusively on all frequencies below the very-high-frequency region (§ 2-7). *Frequency modulation*, which has special characteristics which make its use desirable under certain conditions, is used to a considerable extent on the very-high-frequencies. *Phase modulation*, which is closely related to frequency modulation, has had little or no direct application in practical communication.

§ 5-2 Amplitude Modulation

Carrier requirements — For proper amplitude modulation, the carrier should be completely free from inherent amplitude variations such as might be caused by insufficient filtering of a rectified-a.c. power supply (§ 8-4). It is also essential that the carrier frequency be entirely unaffected by the application of modulation. If modulating the amplitude of

the carrier also causes a change in the carrier frequency the signal wobbles back and forth with the modulation, introducing distortion and widening the channel taken by the signal. This causes unnecessary interference to other transmissions. In practice, this undesirable frequency modulation is prevented by applying the modulation to an r.f. amplifier stage which is isolated from the frequency-controlling oscillator by a "buffer" amplifier. Amplitude modulation of an oscillator almost always is accompanied by frequency modulation. It is permitted therefore only on frequencies above 112 Mc., because the problem of interference is less acute in this region than on lower frequencies.

Percentage of modulation — In the amplitude-modulation system the audible output at the receiver depends entirely upon the amount of variation — termed *depth of modulation* — in the carrier wave, and not upon the strength of the carrier alone. It is desirable therefore to obtain the largest permissible variations in the carrier wave. This condition

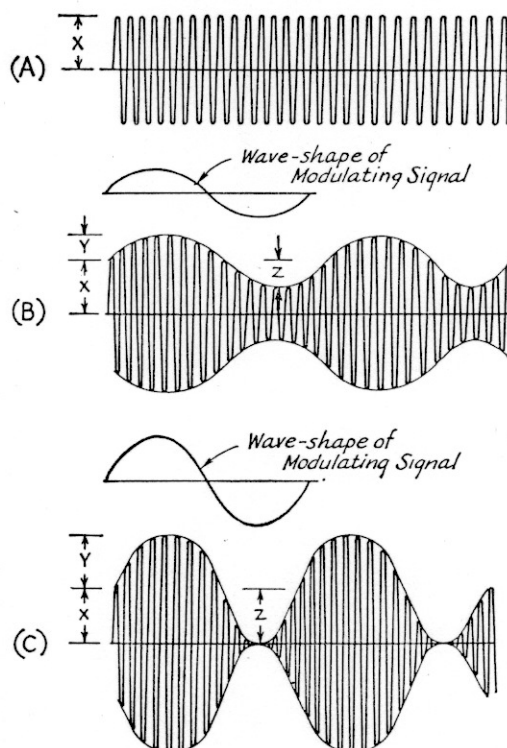


Fig. 501 — Graphical representation of (A) unmodulated carrier, (B) modulated 50%, (C) modulated 100%.

is reached when the carrier amplitude during modulation is at times reduced to zero and at other times increased to twice its unmodulated value. Such a wave is said to be *fully modulated*, or *100 per cent modulated*. Any desired degree of modulation can be expressed as a percentage, using the unmodulated carrier as a base. Fig. 501 shows, at A, an unmodulated carrier wave; at B, the same wave modulated 50 per cent, and at C, the wave with 100 per cent modulation, using a sine-wave (§2-7) modulating signal. The outline of the modulated r.f. wave is called the *modulation envelope*.

The percentage modulation can be found by dividing either *Y* or *Z* by *X* and multiplying the result by 100. If the modulating signal is not symmetrical, the larger of the two (*Y* or *Z*) should be used.

Power in modulated wave — The amplitude values correspond to current or voltage, so that the drawings may be taken to represent instantaneous values of either. Since power varies as the square of either the current or voltage (so long as the resistance in the circuit is unchanged), at the peak of the modulation up-swing the instantaneous power in the wave of Fig. 501-C is four times the unmodulated carrier power. At the peak of the down-swing the power is zero, since the amplitude is zero. With a sine-wave modulating signal, the *average* power in a 100 per cent modulated wave is one and one-half times the unmodulated carrier power; that is, the power output of the transmitter increases 50 per cent with 100 per cent modulation.

Linearity — Up to the limit of 100 per cent modulation, the amplitude of the carrier should follow faithfully the amplitude variations of the modulating signal. When the modulated r.f. amplifier is incapable of meeting this condition, it is said to be *non-linear*. The amplifier may not, for instance, be capable of quadrupling its power output at the peak of 100 per cent modulation. A non-linear modulated amplifier causes distortion of the modulation envelope.

Modulation characteristic — A graph showing the relationship between r.f. amplitude and instantaneous modulating voltage is called the *modulation characteristic* of the modulated amplifier. This graph should be a straight line (linear) between the limits of zero and twice carrier amplitude. Curvature of the line between these limits indicates non-linearity in the amplifier.

Modulation capability — The *modulation capability* of the transmitter is the maximum percentage of modulation that is possible without objectionable distortion from non-linearity. The maximum capability is, of course, 100 per cent. The modulation capability should be as high as possible, so that the most effective signal can be transmitted for a given carrier power.

Overmodulation — If the carrier is modulated more than 100 per cent, a condition such

as is shown in Fig. 502 occurs. Not only does the peak amplitude exceed twice the carrier amplitude, but actually there may be a considerable period during which the output is entirely cut off. The modulated wave is therefore distorted (§3-3), with the result that harmonics of the audio modulating frequency appear. The carrier should never be modulated more than 100 per cent.

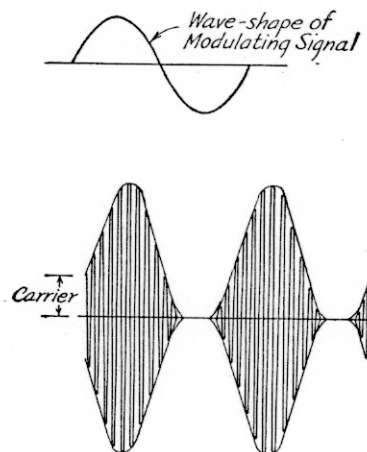


Fig. 502 — An overmodulated carrier wave.

Sidebands — The combining of the audio frequency with the r.f. carrier is essentially a heterodyne process, and therefore gives rise to beat frequencies equal to the sum and difference of the a.f. and r.f. frequencies involved (§2-13). Therefore, for each audio frequency appearing in the modulating signal, two new radio frequencies appear, one equal to the carrier frequency plus the audio frequency, the other equal to the carrier minus the audio frequency. These new frequencies are called *side frequencies*, since they appear on each side of the carrier, and the groups of side frequencies representing a band or group of modulation frequencies are called *sidebands*. Hence a modulated signal occupies a group of radio frequencies, or *channel*, rather than a single frequency as in the case of the unmodulated carrier. The *channel width* is twice the highest modulation frequency. To accommodate the largest number of transmitters in a given part of the r.f. spectrum it is apparent that the channel width should be as small as possible, but on the other hand it is necessary, for speech of reasonably good quality, to use modulating frequencies up to about 3000 or 4000 cycles. This calls for a channel width of 6 to 8 kilocycles.

Spurious sidebands — Besides the normal sidebands required by speech frequencies, unwanted sidebands may be generated by the transmitter. These usually lie outside the normally required channel, and hence cause it to be wider without increasing the useful modulation. By increasing the channel width, these spurious sidebands cause unnecessary

interference to other transmitters. The quality of transmission also is adversely affected when spurious sidebands are generated.

The chief causes of spurious sidebands are harmonic distortion in the audio system, over-modulation, unnecessary frequency modulation, and lack of linearity in the modulated r.f. system.

Types of amplitude modulation—The most widely used type of amplitude-modulation system is that in which the modulating signal is applied in the plate circuit of a radio-frequency power amplifier (*plate modulation*). In a second type the audio signal is applied to a control-grid circuit (*grid-bias modulation*). A third system involves variation of both plate voltage and grid bias, and is called *cathode modulation*.

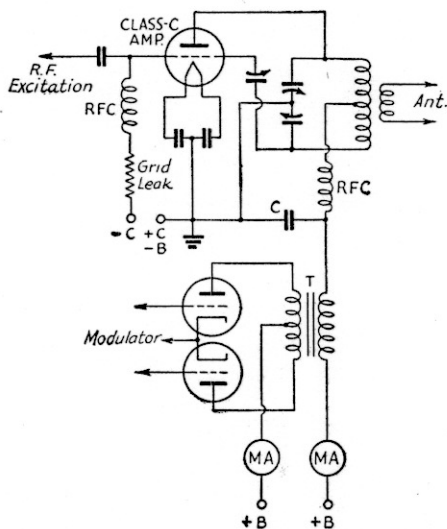


Fig. 503—Plate modulation of a Class-C r.f. amplifier. The r.f. plate by-pass condenser, C , in the amplifier stage should have high reactance at audio frequencies. A capacity of 0.002 $\mu\text{fd.}$ or less usually is satisfactory.

5-3 Plate Modulation

Transformer coupling—In Fig. 503 is shown the most widely used system of plate modulation. A balanced (push-pull Class-A, Class-AB or Class-B) modulator is transformer-coupled to the plate circuit of the modulated r.f. amplifier. The audio-frequency power generated in the modulator plate circuit is combined with the d.c. power in the modulated-amplifier plate circuit by transfer through the coupling transformer, T . For 100 per cent modulation the audio-frequency output of the modulator and the turns ratio of the coupling transformer must be such that the voltage at the plate of the modulated amplifier varies between zero and twice the d.c. operating plate voltage, thus causing corresponding variations in the amplitude of the r.f. output.

Modulator power—The average power output of the modulated stage must increase 50 per cent for 100 per cent modulation (§ 5-2), so that the modulator must supply to the mod-

ulated r.f. stage audio power equal to 50 per cent of the d.c. plate input. For example, if the d.c. plate power input to the r.f. stage is 100 watts, the sine-wave audio power output of the modulator must be 50 watts.

Modulating impedance, linearity—The *modulating impedance*, or load resistance presented to the modulator by the modulated r.f. amplifier, is equal to

$$\frac{E_b}{I_p} \times 1000$$

where E_b is the d.c. plate voltage and I_p the d.c. plate current in milliamperes, both measured without modulation.

Since the power output of the r.f. amplifier must vary as the square of the plate voltage (r.f. voltage proportional to applied plate voltage) in order for the modulation to be linear, the amplifier must operate Class-C (§ 3-4). The linearity depends upon having sufficient grid excitation and proper bias, and the adjustment of circuit constants to the proper values (§ 4-8).

Power in speech waves—The complex waveform of a speech sound translated into alternating current does not contain as much power, on the average, as there is in a pure tone or sine wave of the same peak (§ 2-7) amplitude. That is, with speech waveforms the ratio of peak to average amplitude is higher than in the sine wave. For this reason, the previous statement that the power output of the transmitter increases 50 per cent with 100 per cent modulation, while true for tone modulation, is not true for speech. On the average, speech waveforms will contain only about half as much power as a sine wave, both having the same peak amplitude. The average power output of the transmitter therefore increases only about 25 per cent with 100 per cent speech modulation. However, the *instantaneous* power output must quadruple on the peak of 100 per cent modulation (§ 5-2) regardless of the modulating waveform. Therefore, the peak capacity of the transmitter must be the same for any type of modulating signal.

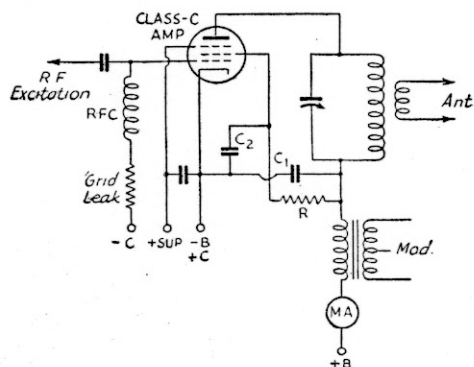


Fig. 504—Plate and screen modulation of a Class-C r.f. amplifier using a pentode tube. The plate and screen r.f. by-pass condensers, C_1 and C_2 , should have high reactance at all audio frequencies (0.002 $\mu\text{fd.}$ or less).

Adjustment of plate-modulated amplifiers — The general operating conditions for Class-C operation have been described (§ 3-4, 4-8). The grid bias and grid current required for plate modulation usually are given in the operating data supplied by the tube manufacturer; in general, the bias should be such as to give an operating angle (§ 4-8) of about 120 degrees at carrier plate voltage, and the excitation should be sufficient to maintain the plate efficiency constant when the plate voltage is varied over the range from zero to twice the d.c. plate voltage applied to the amplifier. For best linearity, the grid bias should be obtained partly from a fixed source of about the cut-off value, supplemented by grid-leak bias to supply the remainder of the required operating bias.

The maximum permissible d.c. plate power input for 100 per cent modulation is twice the sine-wave audio-frequency power output of the modulator. This input is obtained by varying the loading on the amplifier (keeping its tank circuit tuned to resonance) until the product of d.c. plate voltage and plate current is the desired power. The modulating impedance under these conditions will be the proper value for the modulator, if the proper output-transformer turns ratio (§ 2-9) is used.

Neutralization, when triodes are used, should be as nearly perfect as possible, since regeneration may cause non-linearity. The amplifier also should be free from parasitic oscillations (§ 4-10).

Although the *effective* value (§ 2-7) of power input increases with modulation, as described above, the *average* plate input to a plate-modulated amplifier does not change, since each increase in plate voltage and plate current is balanced by an equivalent decrease in voltage and current. Consequently, the d.c. plate current to a properly modulated amplifier is always constant, with or without modulation.

Screen-grid amplifiers — Screen-grid tubes of the pentode or beam tetrode type can be used as Class-C plate-modulated amplifiers provided the modulation is applied to both the plate and screen grid. The method of feeding the screen grid with the necessary d.c. and modulation voltage is shown in Fig. 504. The dropping resistor, R , should be of the proper value to apply normal d.c. voltage to the screen under steady carrier conditions. Its value can be calculated by taking the difference between plate and screen voltages and dividing it by the rated screen current.

The modulating impedance is found by dividing the d.c. plate voltage by the sum of the plate and screen currents. The plate voltage multiplied by the sum of the two currents is the power-input figure which is used as the basis for determining the audio power required from the modulator.

Choke coupling — In Fig. 505 is shown the circuit of the choke-coupled system of plate

modulation. The plate power for the modulator tube and modulated amplifier is furnished from a common source through the modulation choke, L , which has high impedance for audio frequencies. The modulator operates as a power amplifier with the plate circuit of the r.f.

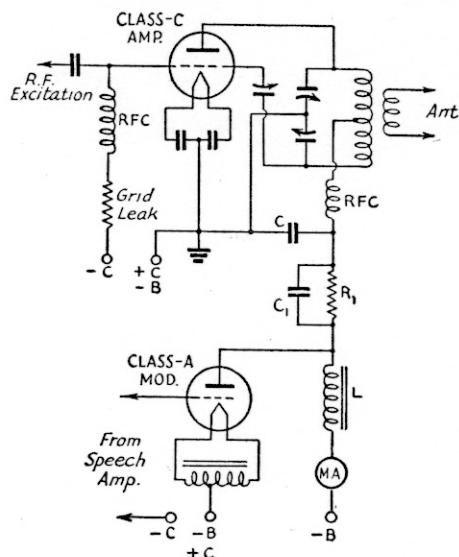


Fig. 505 — Choke-coupled plate modulation.

amplifier as its load, the audio output of the modulator being superimposed on the d.c. power supplied to the amplifier. For 100 per cent modulation, the audio voltage applied to the r.f. amplifier plate circuit across the choke, L , must have a peak value equal to the d.c. voltage on the modulated amplifier. To obtain this without distortion the r.f. amplifier must be operated at a d.c. plate voltage less than the modulator plate voltage, the extent of the voltage difference being determined by the type of modulator tube used. The necessary drop in voltage is provided by the resistor, R_1 , which is by-passed for audio frequencies by the by-pass condenser, C_1 .

This type of modulation seldom is used except in very low-power portable sets, because a single-tube Class-A (§ 3-4) modulator is required. The output of a Class-A modulator is very low compared to that obtainable from a pair of tubes of the same size operated Class B, hence only a small amount of r.f. power can be modulated.

§ 5-4 Grid-Bias Modulation

Circuit — Fig. 506 is the diagram of a typical arrangement for grid-bias modulation. In this system, the secondary of an audio-frequency output transformer, the primary of which is connected in the plate circuit of the modulator tube, is connected in series with the grid-bias supply for the modulated amplifier. The audio voltage thus introduced varies the grid bias, and thus the power output of the r.f. stage, when suitable operating condi-

tions are chosen. The r.f. stage is operated as a Class-C amplifier, with the d.c. grid bias considerably beyond cut-off.

Operating principles — In this system the plate voltage is constant, and the increase in power output with modulation is obtained by making the plate current and plate efficiency vary with the modulating signal. For 100 per

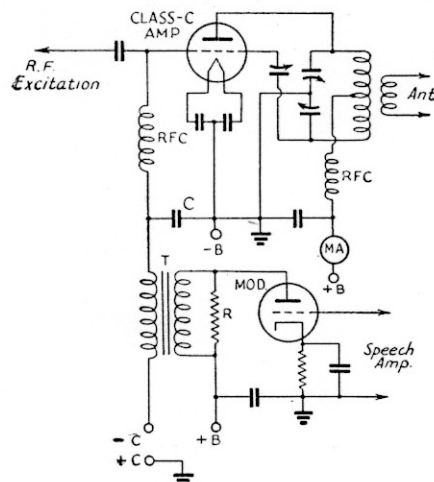


Fig. 506 — Grid-bias modulation of a Class-C amplifier. The r.f. grid by-pass condenser, *C*, should have high reactance at audio frequencies (0.002 μ fd. or less).

cent modulation, both plate current and efficiency must, at the peak of the modulation upswing, be twice their carrier values, so that the peak power will be four times the carrier power. Since the peak efficiency in practicable circuits is of the order of 70 to 80 per cent, the carrier efficiency ordinarily cannot exceed about 35 to 40 per cent. For a given size of r.f. tube, the carrier output is about one-fourth the power obtainable from the same tube plate-modulated. The grid bias, r.f. excitation, plate loading and audio voltage in series with the grid must be adjusted to give a linear modulation characteristic.

Modulator power — Since the increase in average carrier power with modulation is secured by varying the plate efficiency and d.c. plate input of the amplifier, the modulator need supply only such power losses as may be occasioned by connecting it in the grid circuit. These are quite small, hence a modulator capable of only a few watts output will suffice for transmitters of considerable power. The load on the modulator varies over the audio-frequency cycle as the rectified grid current of the modulated amplifier changes, hence the modulator should have good voltage regulation (§ 5-6).

Grid-bias source — The change in bias voltage with modulation causes the rectified grid current of the amplifier also to vary, the r.f. excitation being fixed. If the bias source has appreciable resistance, the change in grid current also will cause a change in bias

in a direction opposite to that caused by the modulation. It is necessary, therefore, to use a grid-bias source having low resistance, so that these bias variations will be negligible. Battery bias is satisfactory. If a rectified a.c. bias supply is used, the type having regulated output (§ 8-9) should be chosen. Grid-leak bias for a grid-modulated amplifier is unsatisfactory, and its use should not be attempted.

Driver regulation — The load on the driving stage varies with modulation, and a linear modulation characteristic may not be obtained if the r.f. voltage from the driver does not stay constant with changes in load. Driver regulation (ability to maintain constant output voltage with changes in load) may be improved by using a driving stage having two or three times the power output necessary for excitation of the amplifier (this is somewhat less than the power required for ordinary Class-C operation), and by dissipating the extra power in a constant load such as a resistor. The load variations are thereby reduced in proportion to the total load.

Adjustment of grid-bias modulated amplifiers — This type of amplifier should be adjusted with the aid of an oscilloscope, to obtain optimum operating conditions. The oscilloscope should be connected as described in § 5-10, the wedge pattern being preferable. A tone source for modulating the transmitter will be convenient. The fixed grid bias should be two or three times the cut-off value (§ 3-2). The d.c. input to the amplifier, assuming 33 per cent carrier efficiency, will be $1\frac{1}{2}$ times the plate dissipation rating of the tube or tubes used in the modulated stage. The plate current for this input (in milliamperes, $1000 P/E$, where P is the power and E the d.c. plate voltage) must be determined. Apply r.f. excitation and, without modulation, adjust the plate loading to give the required plate current (keeping the plate tank circuit tuned to resonance). Next, apply modulation and increase the modulating signal until the modulation characteristic shows curvature (§ 5-10). This probably will occur well below 100 per cent modulation, indicating that the plate efficiency is too high. Increase the plate loading and reduce the excitation to maintain the same plate current; then apply modulation and check the characteristic again. Continue this process until the characteristic is linear from the axis to twice the carrier amplitude. It is advantageous to use the maximum permissible plate voltage on the tube, since it is usually easier to obtain a more linear characteristic with high plate voltage and low current (carrier conditions) than with relatively low plate voltage and high plate current.

The amplifier can be adjusted without an oscilloscope by determining the plate current as described above, then setting the bias to the cut-off value (or slightly beyond) for the d.c. plate voltage used and applying maximum excitation. Adjust the plate loading, keeping

the tank circuit at resonance, until the amplifier draws twice the carrier plate current, and note the antenna current. Decrease the excitation until the output and plate current just start to drop. Then increase the bias, leaving the excitation and plate loading unchanged, until the plate current drops to the proper carrier value. The antenna current should be just half the previous value; if it is larger, try somewhat more loading and less excitation; if smaller, less loading and more excitation. Repeat until the antenna current drops to half its maximum value when the plate current is biased down to the carrier value. Under these conditions the amplifier should modulate properly, provided the plate supply has good voltage regulation (§ 8-1) so that the plate voltage is practically the same at both values of plate current during the initial testing.

The d.c. plate current should be substantially constant both with and without modulation (§ 5-3).

Suppressor modulation — The circuit arrangement for suppressor-grid modulation of a pentode tube is shown in Fig. 507. The operating principles are the same as for grid-bias modulation. However, the r.f. excitation and modulating signals are applied to separate grids, which gives the system a simpler operating technique since best adjustment for proper excitation requirements and proper modulating circuit requirements are more or less independent. The carrier plate efficiency is approximately the same as for grid-bias modulation, and the modulator power requirements are similarly small. With tubes having suitable suppressor-grid characteristics, linear modulation up to practically 100 per cent can be obtained with negligible distortion.

The method of adjustment is essentially the same as that described in the preceding paragraph. Apply normal excitation and bias to the control grid and, with the suppressor bias at zero or the positive value recommended for c.w. telegraph operation with the particular tube used, adjust the plate loading to obtain twice the carrier plate current (on the basis of 33 per cent carrier efficiency). Then apply suf-

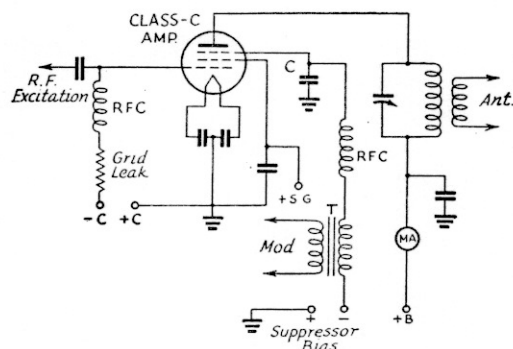


Fig. 507 — Suppressor-grid modulation of an r.f. amplifier using a pentode tube. The suppressor-grid r.f. by-pass condenser, C, should be 0.002 μ fd. or less.

ficient negative bias to the suppressor to bring the plate current to the carrier value, leaving the loading unchanged. Simultaneously, the antenna current also should drop to half its maximum value. The amplifier is then ready for modulation. Should the plate current not follow the antenna current in the same proportion when the suppressor bias is made negative, the loading and excitation should be readjusted to make them coincide.

5-5 Cathode Modulation

Circuit — The fundamental circuit for cathode or "center-tap" modulation is shown in Fig. 508. This type of modulation is a combination of the plate and grid-bias methods, and permits a carrier efficiency midway between the two. The audio power is introduced

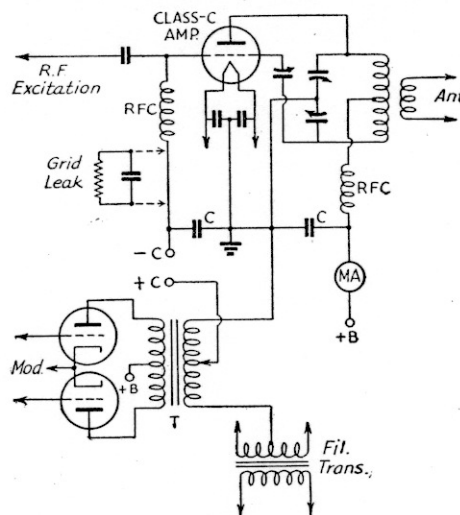


Fig. 508 — Cathode modulation of a Class-C r.f. amplifier. The grid and plate r.f. by-pass condensers, C, should be 0.002 μ fd. or less (for high a.f. reactance).

in the cathode circuit, and both grid bias and plate voltage vary during modulation.

The cathode circuit of the modulated stage must be independent of other stages in the transmitter; that is, when filament-type tubes are modulated they must be supplied from a separate filament transformer. The filament by-pass condensers should not be larger than about 0.002 μ fd., to avoid by-passing the audio-frequency modulation.

Operating principles — Because part of the modulation is by the grid-bias method, the plate efficiency of the modulated amplifier must vary during modulation. The carrier efficiency therefore must be lower than the efficiency at the modulation peak. The required reduction in carrier efficiency depends upon the proportion of grid modulation to plate modulation; the higher the percentage of plate modulation, the higher the permissible carrier efficiency, and vice versa. The audio power required from the modulator also varies with the percentage of plate modulation, being greater as this percentage is increased.

The way in which the various quantities vary is illustrated by the curves of Fig. 509. In these curves the performance of the cathode-modulated r.f. amplifier is plotted in terms of the tube ratings for plate-modulated telephony, with the percentage of plate modulation as a base. As the percentage of plate modulation is decreased, it is assumed that the grid-bias modulation is increased to make the over-all percentage of modulation reach 100 per cent. The limiting condition, 100 per cent plate modulation and no grid-bias modulation, is at the right (A); pure grid-bias modulation is represented by the left-hand ordinate (B and C).

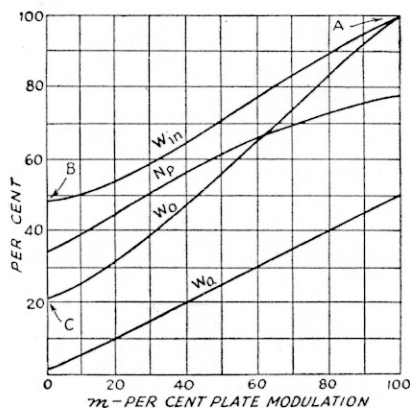


Fig. 509 — Cathode-modulation performance curves, in terms of percentage of plate modulation plotted against percentage of Class-C telephony tube ratings. W_{in} — D.c. plate input watts in terms of percentage of plate-modulation rating. W_o — Carrier output watts in per cent of plate-modulation rating (based on plate efficiency of 77.5%). W_a — Audio power in per cent of d.c. watts input. N_p — Plate efficiency of the amplifier in percentage.

As an example, assume that 40 per cent plate modulation is to be used. Then the modulated r.f. amplifier must be adjusted for a carrier plate efficiency of 56 per cent, the permissible plate input will be 65 per cent of the ratings of the same tube with pure plate modulation, the power output will be 48 per cent of the rated output of the tube with plate modulation, and the audio power required from the modulator will be 20 per cent of the d.c. input to the modulated amplifier.

Modulating impedance — The modulating impedance of a cathode-modulated amplifier is approximately equal to

$$m \frac{E_b}{I_b}$$

where m is the percentage of plate modulation expressed as a decimal, E_b is the plate voltage and I_b the plate current of the modulated r.f. amplifier. This figure for the modulating impedance is used in the same way as the corresponding

figure for pure plate modulation, in determining the proper modulator operating conditions (§ 5-6).

Conditions for linearity — R.f. excitation requirements for the cathode-modulated amplifier are midway between those for plate modulation and grid-bias modulation. More excitation is required as the percentage of plate modulation is increased. Grid bias should be considerably beyond cut-off; fixed bias from a supply having good voltage regulation (§ 8-9) is preferred, especially when the percentage of plate modulation is small and the amplifier is operating more nearly like a grid-bias modulated stage. At the higher percentages of plate modulation a combination of fixed and grid-leak bias can be used, since the variation in rectified grid current is smaller. The grid-leak should be by-passed for audio frequencies. The percentage of grid modulation may be regulated by choice of a suitable tap on the modulation transformer secondary.

Adjustment of cathode-modulated amplifiers — In most respects, the adjustment procedure is similar to that for grid-bias modulation (§ 5-4). The critical adjustments are those of antenna loading, grid bias, and excitation. The proportion of grid-bias to plate modulation will determine the operating conditions.

Adjustments should be made with the aid of an oscilloscope (§ 5-10). With proper antenna loading and excitation, the normal wedge-shaped pattern will be obtained at 100 per cent modulation. As in the case of grid-bias modulation, too-light antenna loading will cause flattening of the up-peaks of modulation (downward modulation), as also will too-high excitation (§ 5-10). The cathode current will be practically constant with or without modulation when the proper operating conditions are reached (§ 5-3).

§ 5-6 Class-B Modulators

Modulator tubes — In the case of plate modulation, the relatively large audio power needed (§ 5-3) practically dictates the use of a Class-B (§ 3-4) modulator, since the power can be obtained most economically with this type of amplifier. A typical circuit is given in Fig. 510. A pair of tubes must be chosen which is capable of delivering sine-wave audio power

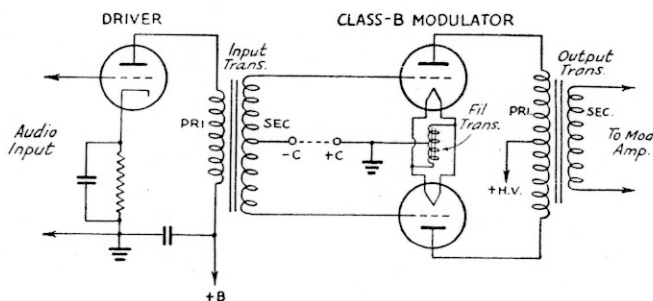


Fig. 510 — A typical Class-B audio modulator and driver circuit.

equal to half the d.c. input to the modulated Class-C amplifier. It is sometimes convenient to use tubes which will operate at the same plate voltage as that applied to the Class-C stage, since one power supply of adequate current capacity may then suffice for both stages. Available components do not always permit this, however, and better over-all performance and economy may result from the use of separate power supplies.

Matching to load—In giving Class-B ratings on power tubes, manufacturers specify the plate-to-plate load impedance (§ 3-3) into which the tubes must operate to deliver the rated audio power output. This load impedance seldom is the same as the modulating impedance (§ 5-3) of the Class-C r.f. stage, so that a match must be brought about by adjusting the turns ratio of the coupling transformer. The required turns ratio, primary to secondary, is

$$\sqrt{\frac{Z_p}{Z_m}}$$

where Z_m is the Class-C modulating impedance and Z_p is the plate-to-plate load impedance specified for the Class-B tubes.

Commercial Class-B output transformers usually are rated to work between specified primary and secondary impedances and are designed for specific Class-B tubes. In such a case, the turns ratio can be found by substituting the given impedances in the formula above. Many transformers are provided with primary and secondary taps, so that various turns ratios can be obtained to meet the requirements of a large number of tube combinations.

Driving power—Class-B amplifiers are driven into the grid-current region, so that power is consumed in the grid circuit (§ 3-3). The preceding stage (*driver*) must be capable of supplying this power at the required peak audio-frequency grid-to-grid voltage. Both of these quantities are given in the manufacturer's tube ratings. The grids of the Class-B tubes represent a variable load resistance over the audio-frequency cycle, since the grid current does not increase directly with the grid voltage. To prevent distortion, therefore, it is necessary to have a driving source which has good *regulation*—that is, which will maintain the waveform of the signal without distortion even though the load varies. This can be brought about by using a driver capable of delivering two or three times the actual power consumed by the Class-B grids, and by using an input coupling transformer having a turns ratio giving the largest step-down in the voltage between the driver plate or plates and the Class-B grids that will permit obtaining the specified grid-to-grid a.f. voltage.

Driver coupling—A Class-A or Class-AB (§ 3-4) driver is used to excite a Class-B stage. Tubes for the driver preferably should

be triodes having low plate resistance, since these will have the best regulation. Having chosen a tube or tubes capable of ample power output from tube data sheets, the peak output voltage will be, approximately,

$$E_o = 1.4 \sqrt{PR}$$

where P is the power output and R the load resistance. The input transformer ratio, primary to secondary, will be

$$\frac{E_o}{E_g}$$

where E_o is as given above and E_g is the peak grid-to-grid voltage required by the modulator tubes.

Commercial transformers usually are designed for specific driver-modulator combinations, and usually are adjusted to give as good driver regulation as the conditions will permit.

Grid bias—Modern Class-B audio tubes are intended for operation without fixed bias. This lessens the variable grid-circuit loading effect and eliminates the need for a grid-bias supply.

When a grid-bias supply is required, it must have low internal resistance so that the flow of grid current with excitation of the Class-B tubes does not cause a continual shift in the actual grid bias and thus cause distortion. Batteries or a regulated bias supply (§ 8-9) should be used.

Plate supply—The plate supply for a Class-B modulator should be sufficiently well filtered (§ 8-3) to prevent hum modulation of the r.f. stage (§ 5-2). An additional requirement is that the output condenser of the supply should have low reactance (§ 2-8) at 100 cycles or less compared to the load into which each tube is working, which is one-fourth the plate-to-plate load resistance. A 4- μ f. output condenser with a 1000-volt supply, or a 2- μ f. condenser with a 2000-volt supply, usually will be satisfactory. With other plate voltages, condenser values should be in inverse proportion to the plate voltage.

Overexcitation—When a Class-B amplifier is overdriven in an attempt to secure more than the rated power, distortion in the output waveshape increases rapidly. The high-frequency harmonics which result from the distortion (§ 3-3) modulate the transmitter, producing spurious sidebands (§ 5-2) which readily can cause serious interference over a band of frequencies several times the channel width required for speech. This may happen even though the transmitter is not being overmodulated, as in the case where the modulator is incapable of delivering the power required to modulate the transmitter fully, or when the Class-C amplifier is not adjusted to give the proper modulating impedance (§ 5-3).

The tubes used in the Class-B modulator should be capable of somewhat more than the power output nominally required (50 per cent of the d.c. input to the modulated amplifier) to

take care of losses in the output transformer. These usually run from 10 per cent to 20 per cent of the tube output. In addition, the Class-C amplifier should be adjusted to give the proper modulating impedance and the correct output transformer turns ratio should be used. Such high-frequency harmonics as may be generated in these circumstances can be reduced by connecting condensers across the primary and secondary of the output transformer (about 0.002 μ fd. in the average case), to form, with the transformer leakage inductance (§ 2-9) a low-pass filter (§ 2-11) which cuts off just above the maximum audio frequency required for speech transmission (about 4000 cycles). The condenser voltage ratings should be adequate for the peak a.f. voltages appearing across them.

Operation without load — Excitation should never be applied to a Class-B modulator until after the Class-C amplifier is turned on and is drawing the value of plate current required to present the rated load to the modulator. With no load to absorb the power, the primary impedance of the transformer rises to a high value and excessive audio voltages are developed across it — frequently high enough to break down the transformer insulation. If the modulator is to be tested separately from the transmitter, a load resistance of the same value as the modulating impedance, and capable of dissipating the full power output of the modulator, should be connected across the transformer secondary.

5-7 Low-Level Modulators

Selection of tubes — Modulators for grid-bias and suppressor modulation can be small audio power tubes, since the audio power required usually is small. A triode such as the 2A3 is preferable because of its low plate resistance, but pentodes will work satisfactorily.

Matching to load — Since the ordinary Class-A receiving power tube will develop about 200 to 250 peak volts in its plate circuit, which is ample for most low-level modulator applications, a 1:1 coupling transformer is generally used. If more voltage is required, a step-up ratio must be provided in the transformer. It is usual practice to load the primary of the output-coupling transformer with a resistance equal to or slightly higher than the rated load resistance for the tube, to stabilize the voltage output and thus improve the regulation. This is indicated in Figs. 506 and 507.

5-8 Microphones

Sensitivity — The level of a microphone is its electrical output for a given speech intensity input. Level varies greatly with microphones of different basic types, and also varies between different models of the same type. The output is also greatly dependent on the character of the individual voice (that is, the audio frequencies present in the voice) and the distance of the speaker's lips from the micro-

phone, decreasing approximately as the square of the distance. Hence, only approximate values based on averages of "normal" speaking voices can be attempted. The values given in the following paragraphs are based on close talking; that is, with the microphone less than an inch from the speaker's lips.

Frequency response — The frequency response or fidelity of a microphone is its relative ability to convert sounds of different frequencies into alternating current. With fixed sound intensity at the microphone, the electrical output may vary considerably as the sound frequency is varied. For understandable speech transmission only a limited frequency range is necessary, and natural-sounding speech can be obtained if the output of the microphone does not vary more than a few decibels (§ 3-3) at any frequency within a range of about 200 cycles to 4000 cycles. When the variation expressed in terms of decibels is small between two frequency limits, the microphone is said to be flat between those limits.

Carbon microphones — Fig. 511 shows connections for single- and double-button carbon microphones, with a rheostat included in each circuit for adjusting the button current to the correct value as specified with each microphone. The single-button microphone consists of a metal diaphragm placed against an insulating cup containing loosely packed carbon granules (*microphone button*). Current from a battery flows through the granules, the diaphragm being one connection and the metal back-plate the other. The primary of a transformer is connected in series with the battery and microphone. As the diaphragm vibrates its pressure on the granules alternately increases and decreases, causing a corresponding increase and decrease of current flow through the circuit, since the pressure changes the resistance of the mass of granules. The resulting change in the current flowing through the transformer primary causes an alternating voltage, of corresponding frequency and intensity, to be set up in the transformer secondary (§ 2-9). The double-button type is similar, but with two buttons in push-pull.

Good quality single-button carbon microphones give outputs ranging from 0.1 to 0.3 volt across 50 to 100 ohms; that is, across the primary winding of the microphone transformer. With the step-up of the transformer, a peak voltage of between 3 and 10 volts across 100,000 ohms or so can be assumed available at the grid of the first tube. The usual button current is 50 to 100 ma.

The level of good-quality double-button microphones is considerably less, ranging from 0.02 volt to 0.07 volt across 200 ohms. With this type of microphone and the usual push-pull input transformer, a peak voltage of 0.4 to 0.5 across 100,000 ohms or so can be assumed available at the first speech-amplifier grid. The button current with this type of microphone ranges from 5 to 50 ma. per button.

Crystal microphones — The input circuit for a piezoelectric or crystal type of microphone is shown in Fig. 511-E. The element in this type consists of a pair of Rochelle salts crystals cemented together, with plated electrodes. In the more sensitive types, the crystal is mechanically coupled to a diaphragm. Sound waves actuating the diaphragm cause the crystal to vibrate mechanically and, by piezoelectric action (§ 2-10), to generate a corresponding alternating voltage between the electrodes, which are connected to the grid circuit of a vacuum-tube amplifier, as shown. The crystal type requires no separate source of current or voltage.

Although the level of crystal microphones varies with different models, an output of 0.01 to 0.03 volt is representative for communication types. The level is affected by the length of the cable connecting the microphone to the first amplifier stage; the above figure is for lengths of 6 or 7 feet. The frequency characteristic is unaffected by the cable, but the load resistance (amplifier grid resistor) does affect it, the lower frequencies being attenuated as the shunt resistance becomes less. A grid-resistor value of 1 megohm or more should be used for reasonably flat response, 5 megohms being a customary figure.

Condenser microphones — The condenser microphone of Fig. 511-C consists of a two-plate capacity, with one plate stationary. The other, which is separated from the first by about a thousandth of an inch, is a thin metal membrane serving as a diaphragm. This condenser is connected in series with a resistor and a d.c. voltage source. When the diaphragm vibrates, the change in capacity causes a small charging current to flow through the circuit. The resulting audio voltage, which appears across the resistor is fed to the grid of the tube through the coupling condenser.

The output of condenser microphones varies with different models, the high-quality type being about one-hundredth to one-fiftieth as sensitive as the double-button carbon microphone. The first speech-amplifier stage must be built into the microphone, since the capacity of a connecting cable would impair both output and frequency range.

Velocity and dynamic microphones — In a velocity or "ribbon" microphone, the element acted upon by the sound waves is a thin corrugated metallic ribbon suspended between the poles of a magnet. When vibrating, the ribbon cuts the lines of force between the poles, first in one direction and then the other, thus generating an alternating voltage. The movement of the ribbon is proportional to the velocity of the sound-energized air particles. Velocity microphones are built in two types, high impedance and low impedance, the former being used in most applications. A high-impedance microphone can be directly connected to the grid of an amplifier tube, shunted by a resistance of 0.5 to 5 megohms. Low-impedance microphones are used when a long connecting cable (75 feet or more) must be employed. In such case the output of the microphone is coupled to the first amplifier stage through a suitable step-up transformer.

The level of the velocity microphone is about 0.03 to 0.05 volt. This figure applies directly to the high-impedance type, and to the low-impedance type when the voltage is measured across the coupling transformer secondary.

The dynamic microphone somewhat resembles a dynamic loud speaker in principle. A light-weight voice coil is rigidly attached to a diaphragm, the coil being placed between the poles of a permanent magnet. Sound causes the diaphragm to vibrate, thus moving the coil back and forth between the magnet poles and generating an alternating voltage the

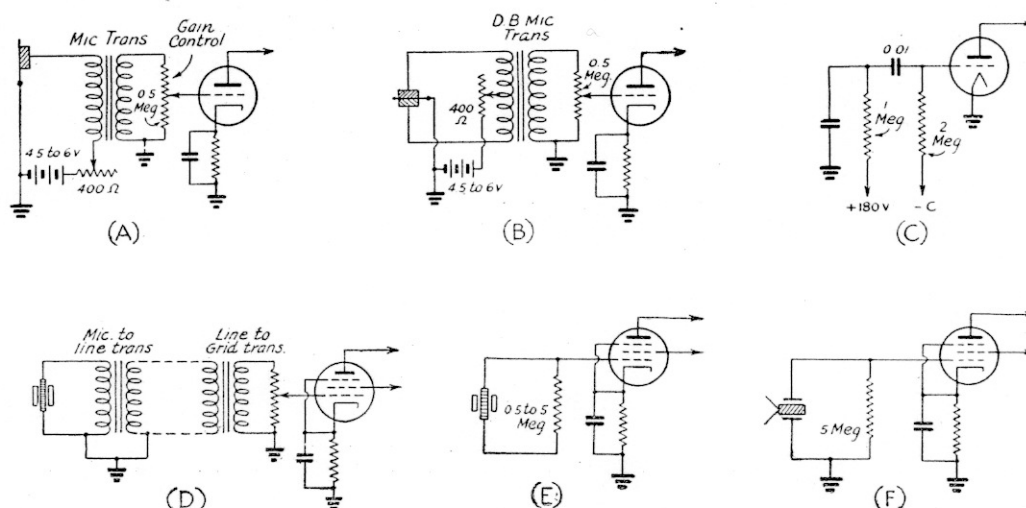


Fig. 511 — Speech input circuits of five commonly used types of microphones. A, single-button carbon; B, double-button carbon; C, condenser; D, low-impedance velocity; E, high-impedance velocity; F, crystal.

frequency of which is proportional to the frequency of the impinging sound and the amplitude proportional to the sound pressure. The dynamic microphone usually is built with high-impedance output, suitable for working directly into the grid of an amplifier tube. If the connecting cable must be unusually long a low-impedance type should be used, with a step-up transformer at the end of the cable. A small permanent-magnet speaker can be used as a dynamic microphone, although the fidelity is not as good as is obtainable with a properly designed microphone.

§ 5-9 The Speech Amplifier

Description — The function of the speech amplifier is to build up the weak microphone voltage to a value sufficient to excite the modulator to the required output. It may have from one to several stages. The last stage nearly always must deliver a certain amount of audio power, especially when it is used to excite a Class-B modulator. Speech amplifiers for grid-bias modulation usually end in a power stage which also functions as the modulator.

The speech amplifier frequently is built as a unit separate from the modulator, and in such a case may be provided with a step-down transformer designed to work into a low impedance, such as 200 or 500 ohms (tube-to-line transformer). When this is done, a step-up input transformer intended to work between the same impedance and the modulator grids (line-to-grid transformer) is provided in the modulator circuit. The line which connects the two transformers may be made of any convenient length.

General design considerations — The last stage of the speech amplifier must be selected on the basis of the power output required from it; for instance, the power necessary to drive a Class-B modulator (§ 5-6). It may be either single-ended or push-pull (§ 3-3), the latter generally being preferable because of the higher power output and lower harmonic distortion. Push-pull amplifiers may be either Class A, Class AB₁ or Class AB₂ (§ 3-4), as the power requirements dictate. If a Class-A or AB₁ amplifier is used, the preceding stages all may be voltage amplifiers, but when a Class-AB₂ amplifier is used the stage immediately preceding it must be capable of furnishing the power consumed by its grids at full output. The requirements in this case are much the same as those which must be met by a driver for a Class-B stage (§ 5-6), but the actual power needed is considerably smaller and usually can be supplied by one or two small receiving triodes. Any lower-level speech amplifier stages invariably are worked purely as voltage amplifiers.

The minimum amplification which must be provided ahead of the last stage is equal to the peak audio-frequency grid voltage required by the last stage for full output (peak grid-to-grid voltage in the case of a push-pull

stage), divided by the output voltage of the microphone or secondary of the microphone transformer if one is used (§ 5-8). The peak a.f. grid voltage required by the output tube or tubes is equal to the d.c. grid bias in the case of a single-tube Class-A amplifier, and approximately twice the grid bias for a push-pull Class-A stage. The requisite information for Class-AB₁ and AB₂ amplifiers can be obtained from the manufacturer's data on the type considered. If the gain is not obtainable in one stage, several stages must be used in cascade. When the output stage is operated Class AB₂, due allowance must be made for the fact that the next-to-the-last stage must deliver power as well as voltage. In such cases, suitable driver combinations usually are recommended by manufacturers of tubes and inter-stage transformers. The coupling transformer must be designed especially for the purpose.

The total gain provided by a multi-stage amplifier is equal to the product of the individual stage gains. For example, when three stages are used, the first having a gain of 100, the second 20 and the third 15, the total gain is $100 \times 20 \times 15$, or 30,000. It is good practice to provide two or three times the minimum required gain in designing the speech amplifier. This will insure having ample gain available to cope with varying conditions.

When the gain must be fairly high, as when a crystal microphone is used, the speech amplifier frequently has four stages, including the power output stage. The first generally is a pentode, because of the high gain attainable with this type of tube. The second and third stages usually are triodes, the third frequently having two tubes in push-pull when it drives a Class-AB₂ output stage. Two pentode stages seldom are used consecutively, because of the difficulty of getting stable operation when the gain per stage is very high. With carbon microphones less amplification is needed and hence the pentode first stage usually is omitted, one or two triode stages being ample to obtain full output from the power stage.

Stage gain and voltage output — In voltage amplifiers, the *stage gain* is the ratio of a.c. output voltage to a.c. voltage applied to the grid. It will vary with the applied audio frequency, but for speech work the variation should be small over the range 100-4000 cycles. This condition is easily met in practice.

The output voltage is the maximum value which can be taken from the plate circuit without distortion. It is usually expressed in terms of the peak value of the a.c. wave (§ 2-7), since this value is independent of the waveform. The peak output voltage usually is of interest only when the stage drives a power amplifier, since only in this case is the stage called upon to work near its maximum capabilities. Low-level stages very seldom are worked near their full capacity, hence harmonic distortion is negligible and the voltage gain of the stage is the primary consideration.

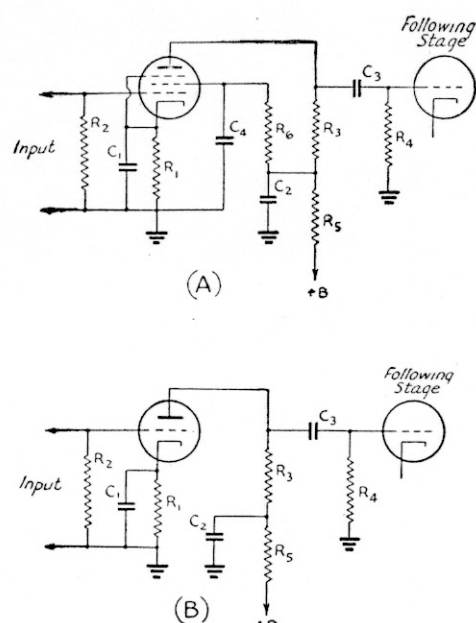


Fig. 512 — Resistance-coupled voltage amplifier circuits. A, pentode; B, triode. Designations are as follows:

- C₁ — Cathode by-pass condenser.
- C₂ — Plate by-pass condenser.
- C₃ — Output coupling condenser (blocking condenser).
- C₄ — Screen by-pass condenser.
- R₁ — Cathode resistor.
- R₂ — Grid resistor.
- R₃ — Plate resistor.
- R₄ — Next-stage grid resistor.
- R₅ — Plate decoupling resistor.
- R₆ — Screen resistor.

Values for commonly used tubes are given in Table I.

Resistance coupling — Resistance coupling generally is used in voltage amplifier stages. It is relatively inexpensive, good frequency response can be secured, and there is little danger of hum pick-up from stray magnetic fields associated with heater wiring. It is the only type of coupling suitable for the output circuits of pentodes and high- μ triodes, since with audio-frequency transformers a sufficiently high load impedance (§ 3-3) cannot be obtained without considerable frequency distortion. Typical circuits are given in Fig. 512.

The frequency response of the amplifier will be determined by the circuit constants, particularly C_3R_4 , the coupling condenser and resistor to the following stage, and C_1R_1 , the cathode bias resistor and by-pass condenser. For adequate amplification at low frequencies, the time constant (§ 2-6) of both these CR combinations should be large. Depending upon the type of tube used in the next stage, R_4 may vary from 50,000 ohms (with power tubes such as the 2A3 or 6F6) to 1 megohm; it is advantageous to use the highest value recommended for the type of tube used, since this gives greatest low-frequency response with a given size of coupling condenser, C_3 . A capacity of 0.1 μ fd. at C_3 will provide ample coupling at low frequencies with any ordina-

rially used tube, if the values shown in Table I for load resistance (R_3) and next-stage grid resistance (R_4) are used.

The reactance (§ 2-8) of C_1 must be small compared to the resistance of R_1 , for good low-frequency response. While with values of R_1 in the vicinity of 10,000 ohms, more or less, a condenser of 1 μ fd. will suffice, it is more common practice to use 5- or 10- μ fd. low-voltage electrolytic condensers for the purpose, since they are inexpensive and provide ample by-passing. A capacity of 10 μ fd. usually is sufficient with values of R_1 as low as 500 ohms.

For maximum voltage gain, the resistance at R_3 should be as high as possible without causing too great a drop in voltage at the plate of the tube. Values range from 50,000 ohms to 0.5 megohm, the smaller figure being used with triodes having comparatively low plate resistance. The value of R_1 depends upon R_3 , which principally determines the plate current; in general, the grid bias is somewhat smaller than in circuits having low-resistance output devices (such as a transformer) because of the lower voltage effective at the plate of the tube. This is true also of the screen voltage, for similar reasons, and values for the screen resistor, R_6 , may vary from 0.25 to 2 megohms. A screen by-pass (C_4) of 0.1 μ fd. will be adequate in all cases.

Table I shows typical values for some of the more popular tube types used in speech amplifiers. The stage gain and peak undistorted output voltage also are given. Other operating conditions are, of course, possible. The value of the grid resistor, R_2 , does not affect any of these quantities, but it should not exceed the maximum value recommended by the manufacturer for the particular tube used.

The resistance-capacity filter (§ 2-11) formed by C_2R_5 is a *decoupling circuit* which isolates the stage from the power supply, so that unwanted coupling between it and other stages through the output impedance of the power supply is eliminated. Such coupling is a cause of low-frequency oscillation (*motorboating*) in multi-stage resistance-coupled amplifiers.

TABLE I — TYPICAL VOLTAGE AMPLIFIER DATA

Tube Type	R_3 (megohms)	R_6 (megohms)	R_1 (ohms)	Peak Output Volts	Voltage Gain
6C5	0.1	—	6000	88	13
6J5	0.1	—	3000	64	14
6F5, 6SF5	0.25	—	3000	54	63
6J7	0.25	1.2	1200	104	140
6SJ7	0.25	1.0	900	88	167
	0.5	2.0	1300	64	200

Other values (Fig. 512): C_1 , 10 μ fd. (low-voltage electrolytic); C_2 , 8- μ fd. electrolytic; C_3 , C_4 , 0.1- μ fd. paper; R_2 , 0.1 to 1 megohm; R_4 , 0.5 megohm; R_5 , 10,000 to 50,000 ohms. Data are based on a plate-supply voltage of 300; lower values will reduce the undistorted peak output voltage in proportion, but will not materially affect the voltage gain.

Transformer coupling — Transformer coupling between stages ordinarily is used only when power is to be transferred (in such a case resistance coupling is very inefficient), or when it is necessary to couple between a single-ended and a push-pull stage. Triodes having an amplification factor of 20 or less are used in transformer-coupled voltage amplifiers.

Representative circuits for coupling single-ended to push-pull stages are shown in Fig. 513. That at A uses a combination of resistance and transformer coupling, and may be used for exciting the grids of a Class-A or AB₁ following stage. The resistance coupling is used to keep the d.c. plate current from flowing through the transformer primary, thereby preventing a reduction in primary inductance below its no-current value (§ 8-4). This improves the low-frequency response. With the triodes ordinarily used (6C5, 6J5, etc.), the gain is equal to that with resistance coupling (typical values in Table I) multiplied by the secondary-to-primary turns ratio of the transformer. This ratio generally is 2:1.

In B the transformer primary is in series with the plate of the tube, and thus must carry the tube plate current. When the following amplifier operates without grid current, the voltage gain of the stage is practically equal to the μ of the tube multiplied by the transformer ratio. This circuit also is suitable for transferring power (within the capabilities of the tube) as in the case of a following Class-AB₂ stage used as a driver for a Class-B modulator.

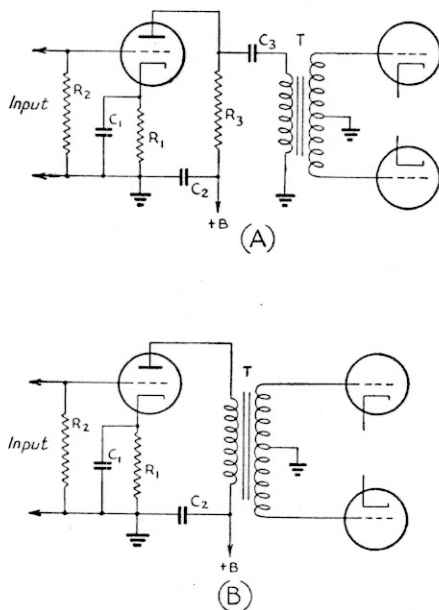


Fig. 513 — Transformer-coupled amplifier circuits for driving a push-pull amplifier. A is for resistance-transformer coupling; B, for transformer coupling. Designations correspond to those in Fig. 512. In A, values can be taken from Table I. In B, the cathode resistor is calculated from the rated plate current and grid bias as given for the particular type of tube used (§ 3-6).

Gain control — The overall gain of the amplifier may be changed to suit the output level of the microphone, which will vary with voice intensity and distance of the speaker from the microphone, by varying the proportion of a.c. voltage applied to the grid of one of the stages. This is done by means of an adjustable voltage divider (§ 2-6), commonly called a "potentiometer" or "volume control," as shown in Fig. 514. The actual voltage applied between

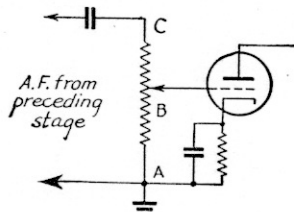


Fig. 514 — Audio gain control circuit.

grid and cathode will be very nearly equal to the ratio of the resistance between AB to the total resistance, AC, multiplied by the a.c. input voltage appearing across AC. The gain control is usually also the grid resistor for the amplifier stage with which it is associated.

The gain-control potentiometer should be near the input end of the amplifier, so that there will be no danger of overloading the stages ahead of the gain control. With carbon microphones the gain control may be placed directly across the microphone transformer secondary, but with other types the gain control usually will affect the frequency response of the microphone when connected directly across it. The control therefore usually is placed in the grid circuit of the second stage.

Phase inversion — Push-pull output may be secured with resistance coupling by using an extra tube, as shown in Fig. 515. There is a phase shift of 180 degrees through any normally operating resistance-coupled stage (§ 3-3), and the extra tube is used purely to provide this phase shift without additional gain. The outputs of the two tubes are then added to give push-pull excitation to the next amplifier.

In Fig. 515, V_1 is the regular amplifier, connected in normal fashion to the grid of one of the push-pull tubes. The next-stage grid resistor is tapped, so that part of the output voltage is fed to the grid of the phase inverter, V_2 . This tube then amplifies the signal and applies it in reverse phase to the grid of the second push-pull tube. Two similar tubes should be used at V_1 and V_2 , with identical plate resistors and output-coupling condensers. The tap on R_4 is adjusted to make V_1 and V_2 give equal voltage outputs, so that balanced excitation is applied to the grids of the following stage.

The cathode resistor, R_6 , commonly is left unby-passed, since this tends to help balance the circuit. For convenience, double-triode tubes frequently are used as phase inverters.

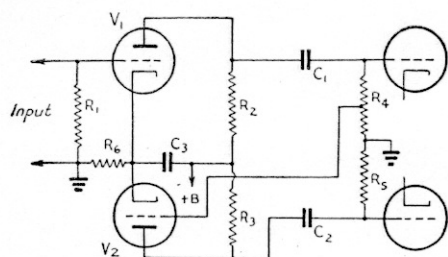


Fig. 515 — Phase-inverter circuit for resistance-coupled push-pull output. With a double-triode tube (such as the 6N7) the following values are typical: R_1, R_4, R_5 — 0.5 megohm. R_2, R_3 — 0.1 megohm. R_6 — 1500 ohms. C_1, C_2 — 0.1 μ fd. R_4 should be tapped as described in the text. The voltage gain of a stage using these constants is 22.

Output limiting — It is desirable to modulate as heavily as possible without overmodulating, yet it is difficult to speak into the microphone at a constant intensity. To maintain reasonably constant output from the modulator in spite of variations in speech intensity, it is possible to use automatic gain control which follows the *average* (not instantaneous) variations in speech amplitude. This is accomplished by rectifying and filtering (§ 8-2, 8-3) some of the audio output and applying the rectified and filtered d.c. to a control electrode in an early stage in the amplifier.

A practical circuit for this purpose is shown in Fig. 516. The rectifier must be connected, through the transformer, to a tube capable of

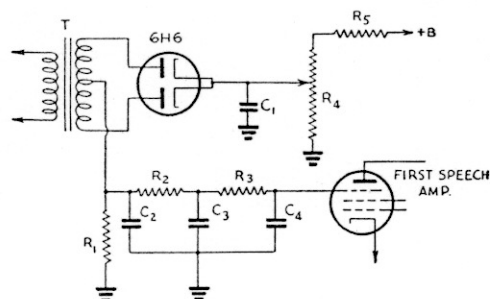


Fig. 516 — Speech amplifier output-limiting circuit. C_1, C_2, C_3, C_4 — 0.1- μ fd. R_1, R_2, R_3 — 0.25 megohm. R_4 — 25,000- Ω hm pot. R_5 — 0.1 megohm. T — See text.

delivering some power output (a small part of the output of the power stage may be used) or else a separate amplifier for the rectifier circuit alone may have its grid connected in parallel with that of the last voltage amplifier. Resistor R_4 in series with R_5 across the plate supply provides variable bias on the rectifier plates, so that the limiting action can be delayed until a desired microphone input level is reached. R_2, R_3, C_2, C_3 , and C_4 form the filter (§ 2-11), and the output of the rectifier is connected to the suppressor grid of the pentode first stage of the speech amplifier.

A step-down transformer with a turns ratio such as to give about 50 volts when its primary is connected to the output circuit of the power

stage should be used. A half-wave rectifier may be used instead of the full-wave circuit shown, although satisfactory filtering will be more difficult to achieve.

Noise — It is important that the noise level in a speech amplifier be low compared to the level of the desired signal. Noise in the speech amplifier is caused chiefly by hum, which may be the result of insufficient power-supply filtering or may be introduced into the grid circuit of a tube by magnetic or electrostatic means from heater wiring. The plate voltage for the amplifier should be free from ripple (§ 8-4), particularly the voltage applied to the low-level stages. A two-section condenser-input filter (§ 8-5) usually is satisfactory. The decoupling circuits mentioned in the preceding paragraphs also are helpful in reducing plate-supply hum.

Hum from heater wiring may be reduced by keeping the wiring well away from ungrounded components or wiring, particularly in the vicinity of the grid of the first tube. Complete shielding of the microphone jack is advisable, and when tubes with grid caps instead of the single-ended types are used the caps and the exposed wiring to them should be shielded. Heater wiring preferably should run in the corners of a metal chassis, to reduce the magnetic field. A ground should be made either on one side of the heater circuit or to the center-tap of the heater winding. The shells of metal tubes should be grounded; glass tubes require separate shields, especially when used in low-level stages. Heater connections to the tube sockets should be kept as far as possible from the plate and grid prongs, and the heater wiring to the sockets should be kept close to the chassis. A connection to a good ground (such as a cold water pipe) also is advisable. The speech amplifier always should be constructed on a metal chassis, with all ground connections made directly to the metal chassis.

When the power supply is mounted on the same chassis with the speech amplifier, the power transformer and filter chokes should be well separated from audio transformers in the amplifier proper to reduce magnetic coupling, which would cause hum and raise the residual noise level.

5-10 Checking 'Phone Transmitter Operation

Modulation percentage — The most reliable method of determining percentage of modulation is by means of the cathode-ray oscilloscope (§ 3-9). The oscilloscope gives a direct picture of the modulated output of the transmitter, and by its use the waveform errors inherent in other types of measurements are eliminated.

Two types of oscilloscope patterns may be obtained, known as the "wave envelope" and "trapezoid." The former shows the shape of the modulation envelope (§ 5-2) directly, while

the latter in effect plots the modulation characteristic (§ 5-2) of the modulated stage on the cathode-ray tube screen. To obtain the wave-envelope pattern, the oscilloscope must have a horizontal sweep circuit. The trapezoidal pattern requires only the oscilloscope, the sweep circuit being supplied by the transmitter itself. Fig. 517 shows methods of connecting the oscilloscope to the transmitter for both types of patterns. The oscilloscope connections for the wave-envelope pattern, Fig. 517-A, are usually simpler than those for the trapezoidal figure. The vertical-deflection plates are coupled to the amplifier tank coil or an antenna coil by means of a pick-up coil of a few turns connected to the oscilloscope through a twisted-pair line. The position of the pick-up coil is varied until a carrier pattern, Fig. 518-B, of suitable height is obtained. The sweep voltage should be adjusted to make the width of the pattern somewhat more than half the diameter of the screen. It is frequently helpful in eliminating r.f. harmonics from the pattern to connect a resonant circuit, tuned to the operating frequency, between the vertical deflection plates, using link coupling between this circuit and the transmitter tank circuit.

With the application of voice modulation, a rapidly changing pattern of varying height will be obtained. When the maximum height of this pattern is just twice that of the carrier alone, the wave is being modulated 100 per cent (§ 5-2). This is illustrated by Fig. 518-D, where the point X represents the sweep line

(reference line) alone, YZ is the carrier height, and PQ is the maximum height of the modulated wave. If the height is greater than the distance PQ , as illustrated in *E*, the wave is overmodulated in the upward direction. Overmodulation in the downward direction is indicated by a gap in the pattern at the reference axis, where a single bright line appears on the screen. Overmodulation in either direction may take place even when the modulation in the other direction is less than 100 per cent. Assuming that the modulation is symmetrical, however, any modulation percentage can be measured directly from the screen by measuring the maximum height with modulation and the height of the carrier alone; calling these two heights h_1 and h_2 respectively, the modulation percentage is

$$\frac{h_1 - h_2}{h_2} \times 100$$

Connections for the trapezoidal pattern are shown in Fig. 517-B. The vertical plates are similarly coupled to the transmitter tank circuit through a pick-up loop; the tuned input circuit to the oscilloscope may also be used. The horizontal plates are coupled to the output of the modulator through a voltage divider (§ 2-6), R_1R_2 , the resistance of R_2 being variable to permit adjustment of the audio voltage to a suitable value to give a satisfactory horizontal sweep on the screen. R_2 may be a 0.25-megohm volume control resistor. The value of R_1 will depend upon the audio output voltage of the modulator. This voltage is equal to $\sqrt{PR}$, where P is the audio power output of the modulator and R is the modulating impedance of the modulated r.f. amplifier. In the case of grid-bias modulation with a 1:1 output transformer, it will be satisfactory to assume that the a.c. output voltage of the modulator is equal to $0.7E$ for a single tube or $1.4E$ for a push-pull stage, where E is the d.c. plate voltage on the modulator. If the transformer ratio is other than 1:1, the voltage so calculated should be multiplied by the actual secondary-to-primary turns ratio. The total resistance of R_1 and R_2 in series should be 0.25 megohm for every 150 volts of modulator output; for example, if the modulator output voltage is 600, the total resistance should be four $(600/150)$ times 0.25 megohm, or 1 megohm. Then, with 0.25 megohm at R_2 , R_1 should be 0.75 megohm. The blocking condenser, C , should be 0.1 μ fd or more, and its voltage rating should be greater than the maximum voltage appearing in the circuit. With plate modulation, this is twice the d.c. voltage applied to the plate of the modulated amplifier.

The trapezoidal patterns are shown in Fig. 518 at F to J, each alongside the corresponding wave-envelope pattern. With no signal, only the cathode-ray spot appears on the screen. When the unmodulated carrier is applied, a vertical line appears; the length of the line

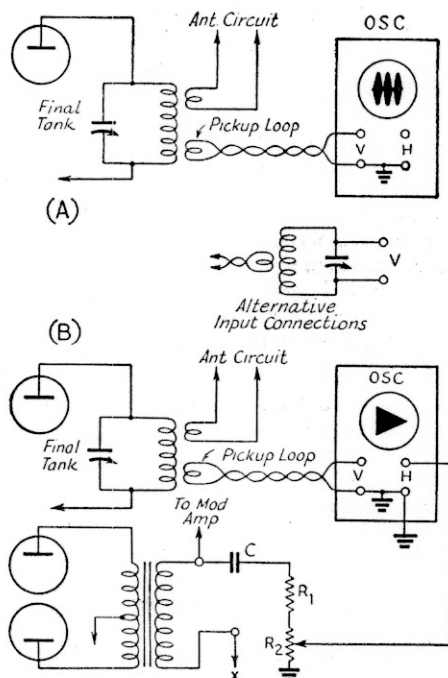


Fig. 517—Methods of connecting an oscilloscope to the modulated r.f. amplifier for checking modulation.

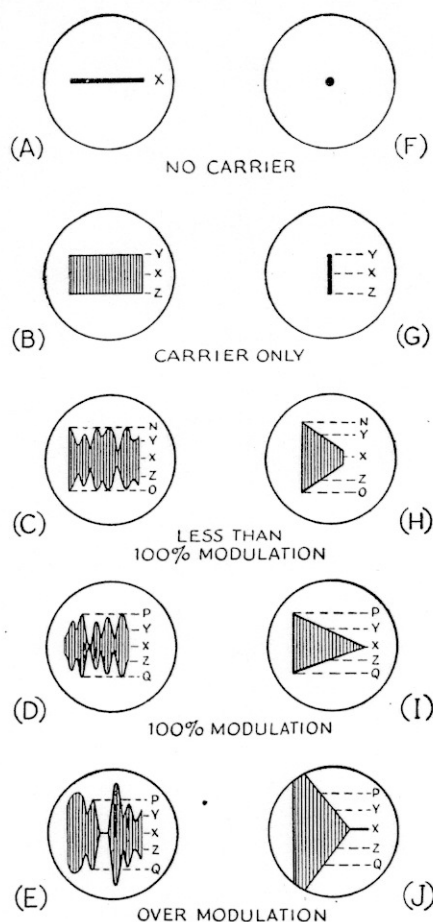


Fig. 518 — Wave-envelope and trapezoidal patterns encountered under different conditions of modulation.

should be adjusted, by means of the pick-up coil coupling, to a convenient value. When the carrier is modulated, the wedge-shaped pattern appears; the higher the modulation percentage, the wider and more pointed the wedge becomes. At 100 per cent modulation it just makes a point on the axis, A, at one end, and the height, PQ, at the other end is equal to twice the carrier height, YZ. Overmodulation in the upward direction is indicated by increased height over PQ, and in the downward direction by an extension along the axis X at the pointed end. The modulation percentage may be found by measuring the modulated and unmodulated carrier heights, in the same way as with the wave-envelope pattern.

Non-symmetrical waveforms — In voice waveforms the average maximum amplitude in one direction from the axis frequently is greater than in the other direction, although the average energy on both sides is the same. For this reason the percentage of modulation in the "up" direction frequently differs from that in the "down" direction. With a given voice and microphone, this difference in modulation percentage is usually always in the same

direction. Since overmodulation in the downward direction causes more out-of-channel interference than overmodulation upward because of the steeper wavefront (§ 6-1), it is advisable to "phase" the modulation so that the side of the voice waveform having the larger excursions causes the instantaneous carrier power to increase and the smaller excursions to cause a power decrease. This reduces the likelihood of overmodulation on the "down" peak. The direction of the larger excursions can readily be found by careful observation of the oscilloscope pattern. The phase can be reversed by reversing the connections of one winding of any transformer in the speech amplifier or modulator.

Modulation monitoring — While it is desirable to modulate as fully as possible, 100 per cent modulation should not be exceeded, particularly in the downward direction, because harmonic distortion will be introduced and the channel width increased (§ 5-2), thus causing unnecessary interference to other stations. The oscilloscope may be used to provide a continuous check on the modulation, but simpler indicators may be used for the purpose, once calibrated. A convenient indicator, when a Class-B modulator (§ 5-6) is used, is the plate milliammeter in the Class-B stage, since plate current fluctuates with the voice intensity. Using the oscilloscope, determine the gain-control setting and voice intensity which gives 100 per cent modulation on voice peaks, and simultaneously observe the maximum Class-B plate-milliammeter reading on the peaks. When this maximum reading is obtained, it will suffice in regular operation to adjust the gain so that it is not exceeded.

A sensitive rectifier-type voltmeter (copper-oxide type) also can be used for modulation monitoring. It should be connected across the output circuit of an audio driver stage where the power level is a few watts, and similarly calibrated against the oscilloscope to determine the reading which represents 100 per cent modulation.

The plate milliammeter of the modulated r.f. stage may also be used as an indicator of overmodulation. Since the average plate current is constant (§ 5-3, 5-4, 5-5) when the amplifier is linear, the reading will be the same with or without modulation. When the amplifier is overmodulated, especially in the downward direction, the operation is no longer linear and the average plate current will change. A flicker of the pointer may therefore be taken as an indication of overmodulation or non-linearity. However, it is possible that the average plate current will remain constant with considerable overmodulation under some operating conditions, so that an indicator of this type is not wholly reliable unless it has been checked previously against an oscilloscope.

Linearity — The linearity (§ 5-2) of a modulated amplifier may readily be checked with

the oscilloscope. The trapezoidal pattern is more easily interpreted than the wave envelope pattern, and less auxiliary equipment is required. The connections are the same as for measuring modulation percentage (Fig. 517). If the amplifier is perfectly linear, the sloping sides of the trapezoid will be perfectly straight from the point at the axis up to at least 100 per cent modulation in the upward direction. Non-linearity will be shown by curvature of the sides. Curvature near the point, extending the point farther along the axis than would occur with straight sides, indicates that the output power does not decrease rapidly enough in this region; it may also be caused by imperfect neutralization (a push-pull amplifier is recommended because better neutralization is possible than with single-ended amplifiers) or by r.f. leakage from the exciter through the final stage. The latter condition can be checked by removing the plate voltage from the modulated stage, when the carrier should disappear, leaving only the beam spot remaining on the screen (Fig. 518-F). If a small vertical line remains, the amplifier should be re-neutralized to eliminate it; if this does not suffice, it is an indication that r.f. is being picked up from lower-power stages, either by coupling through the final tank circuit or through the oscilloscope pick-up circuit.

Inward curvature at the large end of the pattern is caused by improper operating conditions of the modulated amplifier, usually improper bias or insufficient excitation, or both, with plate modulation. In grid-bias and cathode-modulated systems, the bias, excitation and plate loading are not correctly proportioned when such curvature occurs, usually because the amplifier has been adjusted to have too-high carrier efficiency without modulation (§ 5-4, 5-5).

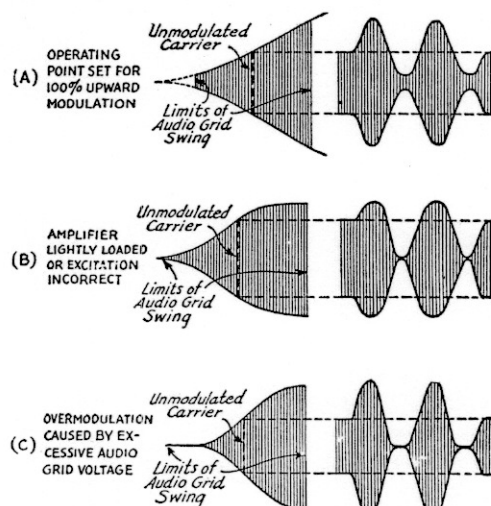


Fig. 519 — Oscilloscope patterns representing proper and improper adjustments for grid-bias or cathode modulation. The pattern obtained with a correctly adjusted amplifier is shown at A. The other drawings indicate non-linear modulation from typical causes.

For the wave-envelope pattern, it is necessary to have a linear horizontal-sweep circuit in the oscilloscope and a source of sine-wave audio signal voltage (such as an audio oscillator or signal generator) which can be synchronized with the sweep circuit. The linearity can be judged by comparing the wave envelope with a true sine wave. Distortion in the audio circuits will affect the pattern in this case (such distortion has no effect on the trapezoidal pattern, which shows the modulation characteristic of the r.f. amplifier alone), and it is also readily possible to misjudge the shape of the modulation envelope, so that the wave envelope is less useful than the trapezoid for checking linearity of the modulated amplifier.

Fig. 519 shows typical patterns of both types. The cause of the distortion is indicated for grid-bias and suppressor modulation. The patterns at A, although not truly linear, are representative of properly operated grid-bias modulation systems. Better linearity can be obtained with plate modulation of a Class-C amplifier.

Faulty patterns — The drawings of Figs. 518 and 519 show what is normally to be expected in the way of pattern shapes when the oscilloscope is used to check modulation. If the actual patterns differ considerably from those shown, it is probable that the pattern is faulty rather than the transmitter. It is important that only r.f. from the modulated stage be coupled to the oscilloscope, and then only to the vertical plates. The effect of stray r.f. from other stages in the transmitter has been mentioned in the preceding paragraph. If r.f. is present also on the horizontal plates, the pattern will lean to one side instead of being upright. If the oscilloscope cannot be moved to a spot where the unwanted pick-up disappears, a small by-pass condenser (10 μ fd.) should be connected across the horizontal plates as close to the cathode-ray tube as possible. An r.f. choke (2.5 mh. or smaller) may also be connected in series with the ungrounded horizontal plate.

"Folded" trapezoidal patterns occur when the audio sweep voltage is taken from some point in the audio system other than that where the a.f. power is applied to the modulated stage. Such patterns are caused by a phase difference between the sweep voltage and the modulating voltage. The connections should always be as shown in Fig. 517-B.

Plate-current shift — As mentioned above, the d.c. plate current of a modulated amplifier will be the same with and without modulation so long as the amplifier operation is perfectly linear and other conditions remain unchanged. This also assumes that the modulator is working within its capabilities. Because there is usually some curvature of the modulation characteristic with grid-bias modulation there is normally a slight upward change in plate current of a stage so modulated, but this occurs only at high modulation percentages and is

barely detectable under the usual conditions of voice modulation.

With plate modulation, a downward shift in plate current may indicate one or more of the following:

- 1) Insufficient excitation to the modulated r.f. amplifier.
- 2) Insufficient grid bias on the modulated stage.
- 3) Wrong load resistance for the Class-C r.f. amplifier.
- 4) Insufficient output capacity in the filter of the modulated-amplifier plate supply.
- 5) Heavy overloading of the Class-C r.f. amplifier tube or tubes.

Any of the following may cause an upward shift in plate current:

- 1) Overmodulation (excessive audio power, audio gain too great).
- 2) Incomplete neutralization of the modulated amplifier.
- 3) Parasitic oscillation in the modulated amplifier.

When a common plate supply is used for both a Class-B (or Class AB) modulator and a modulated r.f. amplifier, the plate current of the latter may "kick" downward because of poor power-supply voltage regulation (§ 8-1) with the varying additional load of the modulator on the supply. The same effect may occur with high-power transmitters because of poor regulation of the a.c. supply mains, even when a separate power-supply unit is used for the Class-B modulator. Either condition may be detected by measuring the plate voltage applied to the modulated stage; in addition, poor line regulation also may be detected by observing if there is any downward shift in filament or line voltage.

With grid-bias modulation, any of the following may be the cause of a plate current shift greater than the normal mentioned above:

Downward kick: Too much r.f. excitation; insufficient operating bias; distortion in modulator or speech amplifier; too-high resistance in bias supply; insufficient output capacity in plate-supply filter to modulated amplifier; amplifier plate circuit not loaded heavily enough; plate-circuit efficiency too high under carrier conditions.

Upward kick: Overmodulation (excessive audio voltage); distortion in audio system; regeneration because of incomplete neutralization; operating grid bias too high.

A downward kick in plate current will accompany an oscilloscope pattern like that of Fig. 519-B; the pattern with an upward kick will look like Fig. 519-A, with the shaded portion extending farther to the right and above the carrier, for the "wedge" pattern.

Noise and hum on carrier — These may be detected by listening to the signal on a receiver sufficiently removed from the transmitter to avoid overloading. The hum level should be

low compared to the voice at 100 per cent modulation. Hum may come either from the speech amplifier and modulator or from the r.f. section of the transmitter. Hum from the r.f. section can be detected by completely shutting off the modulator; if hum remains when this is done, the power-supply filters for one or more of the r.f. stages have insufficient smoothing (§ 8-4). With a hum-free carrier, hum introduced by the modulator can be checked by turning on the modulator but leaving the speech amplifier off; power-supply filtering is the likely source of such hum. If carrier and modulator are both clean, connect the speech amplifier and observe the increase in hum level. If the hum disappears with the gain control at minimum, the hum is being introduced in the stage or stages preceding the gain control. The microphone also may pick up hum, a condition which can be checked by removing the microphone from the circuit but leaving the first speech-amplifier grid circuit otherwise unchanged. A good ground on the microphone and speech system usually is essential to hum-free operation.

Hum can be checked with the oscilloscope, where it appears as modulation on the carrier in the same way as the normal modulation. While the percentage usually is rather small, if the carrier shows modulation with no speech input hum is the likely cause. The various parts of the transmitter may be checked through as described above.

Spurious sidebands — A superheterodyne receiver having a crystal filter (§ 7-8, 7-11) is needed for checking spurious sidebands outside the normal communication channel (§ 5-2). The r.f. input to the receiver must be kept low enough, by removing the antenna or by adequate separation from the transmitter, to avoid overloading and consequent spurious receiver responses (§ 7-8). With the crystal filter in its sharpest position and the beat oscillator turned on, tune through the region outside the normal channel limits (3 to 4 kilocycles each side of the carrier) while another person talks into the microphone. Spurious sidebands will be observed as intermittent beat notes coinciding with voice peaks, or, in bad cases of distortion or overmodulation, as "clicks" or crackles well away from the carrier frequency. Sidebands more than 4 kilocycles from the carrier should be of negligible strength in a properly modulated 'phone transmitter. The causes are overmodulation or non-linear operation (§ 5-3).

R.f. in speech amplifier — A small amount of r.f. current in the speech amplifier — particularly in the first stage, which is most susceptible to such r.f. pick-up — will cause overloading and distortion in the low-level stages. Frequently also there is a regenerative effect which causes an audio-frequency oscillation or "howl" to be set up in the audio system. In such cases the gain control cannot be advanced very far before the howl builds up,

even though the amplifier may be perfectly stable when the r.f. section of the transmitter is not turned on.

Complete shielding of the microphone, microphone cord, and speech amplifier are necessary to prevent r.f. pick-up, and a ground connection separate from that to which the transmitter is connected is advisable. Unsymmetrical or capacity coupling to the antenna (single-wire feed, feeders tapped on final tank circuit, etc.) may be responsible in that these systems sometimes cause the transmitter chassis to take an r.f. potential above ground. Inductive coupling to a two-wire transmission line is advisable. This antenna effect can be checked by disconnecting the antenna and dissipating the power in a dummy antenna (§ 4-9), when it usually will be found that the r.f. feed-back disappears. If it does not, the speech amplifier and microphone shielding are at fault.

§ 5-11 Frequency Modulation

Principles — In frequency modulation the carrier amplitude is constant and the output frequency of the transmitter is made to vary about the carrier or mean frequency at a rate corresponding to the audio frequencies of the speech currents. The extent to which the frequency changes in one direction from the unmodulated or carrier frequency is called the *frequency deviation*. It corresponds to the change of carrier amplitude in the amplitude-modulation system (§ 5-2). Deviation is usually expressed in kilocycles, and is equal to the difference between the carrier frequency and either the highest or lowest frequency reached by the carrier in its excursions with modulation. There is no modulation percentage, in the usual sense; with suitable circuit design the deviation may be made as large as desired without encountering any effect equivalent to overmodulation in the amplitude-modulated system.

Deviation ratio — The ratio of the maximum frequency deviation to the audio frequency of the modulation is called the *deviation ratio*. This ratio is also called the modulation index. Unless otherwise specified, it is taken as the ratio of the maximum frequency

deviation to the *highest* audio frequency to be transmitted.

Advantages of f.m. — The chief advantage of frequency modulation over amplitude modulation is noise reduction at the receiver. All electrical noises in the radio spectrum, including those originating in the receiver, are r.f. oscillations which vary in amplitude, this variation causing the noise response in amplitude-modulation receivers. If the receiver does not respond to amplitude variations but only to frequency changes, noise can affect it only by causing a phase shift which appears as frequency modulation on the signal. The effect of such frequency modulation by the noise can be made small by making the frequency change (deviation) in the signal large.

A second advantage is that the power required for modulation is inconsequential, since there is no power variation in the modulated output of the transmitter.

Triangular spectrum — The way in which noise is reduced by a large deviation ratio is illustrated by Fig. 520. In this figure the noise is assumed to be evenly distributed over the channel used, an assumption which is almost always true. It is also assumed that audio frequencies above 4000 cycles (4 kc.) are not necessary to voice communication, and that the audio system in the receiver has no response above this frequency. Then, if an amplitude modulation receiver is used and its selectivity is such that there is no attenuation of sidebands (§ 5-2) below 4000 cycles, the noise components of all frequencies within the channel will produce equal response when they beat with a carrier centered in the channel. The response under these conditions is shown by the line *DC*.

In the f.m. receiver the output amplitude is proportional to the frequency deviation, and noise components in the channel can be considered to frequency-modulate the steady carrier with a deviation proportional to the difference between the actual frequency of the component and the frequency of the carrier, and also to give an audio-frequency beat of the same frequency difference. This leads to a rising response characteristic, such as the line *OC*, where the noise amplitude is proportional to the audio beat frequency. The average noise power output is proportional to the square root of the sum of the squares of all the amplitude values (§ 2-7), so that the noise power with frequency modulation having a deviation ratio of 1 is only one-third that with amplitude modulation, or an improvement of 4.75 db.

If the deviation ratio is increased to 5, the noise response is represented by the line *OF*. Since only frequencies up to 4000 cycles are reproduced in the output, however, the audible noise is confined to the triangle *OAB*. These relations hold only when the carrier is strong compared to the noise. For reception of stations with weak signal strength, the signal-to-noise ratio is better with a deviation ratio of 1.

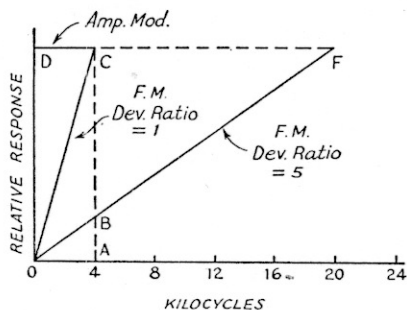


Fig. 520 — Triangular spectrum showing the noise response in an f.m. receiver compared with amplitude modulation. Deviation ratios of 1 and 5 are shown.

Linearity — A transmitter in which frequency deviation is directly proportional to the amplitude of the modulating signal is said to be *linear*. It is essential also that the carrier amplitude remain constant under modulation, which in turn requires that the transmitter tuned circuits be broad enough to handle without discrimination the range of frequencies transmitted. This requirement is easily met under ordinary conditions.

Sidebands — In frequency modulation there is a series of sidebands on either side of the carrier frequency for each audio-frequency component in the modulation. In addition to the usual sum and difference frequencies (§ 5-2) there are also beats at harmonics of the fundamental modulating frequency, even though the latter may be a pure tone. This occurs because of the necessity for maintaining the proper phase relationships between the carrier and sidebands to keep the power output constant. Hence a frequency-modulated signal inherently occupies a wider channel than an amplitude-modulated signal, and because of the necessity for conserving space in the usual communication spectrum the use of f.m. is confined to the very-high frequencies in the region above 28 Mc.

The number of sidebands for a single modulating frequency increases with the frequency deviation. When the deviation ratio is of the order of 5 the sidebands beyond the maximum frequency deviation are usually negligible, so that the channel required is approximately twice the frequency deviation.

5-12 Methods of Frequency Modulation

Requirements and methods — At present there are no fixed standards of frequency deviation in amateur work. Since a deviation ratio of 5 is considered high enough in any case, the maximum deviation necessary is 15 to 20 kc. for an upper audio-frequency limit of 3000 or 4000 cycles (§ 5-2), or a channel width of 30 to 40 kc. The permissible deviation is determined by the receiver (§ 7-18), since deviation beyond the limits of the receiver pass-band causes distortion. If the transmitter is designed to be linear (§ 5-11) with a deviation of about 15 kc., it can be used at a lower deviation ratio simply by reducing the gain in the speech amplifier. Thereby it can be made to conform to the requirements of the particular receiver in use.

The several possible methods of frequency modulation include mechanical modulation (for instance, varying condenser plate spacing in accordance with voice vibrations), initial phase modulation which later is transformed into frequency modulation, and direct frequency modulation of an oscillator by electrical means. The latter, in the form of the *reactance modulator*, is the simplest system.

The reactance modulator — The reactance modulator is a vacuum-tube amplifier con-

nected to the r.f. tank circuit of an oscillator in such a way as to act as a variable inductance or capacity, of a value dependent upon the instantaneous a.f. voltage applied to its grid. Fig. 521 is a representative circuit. The control

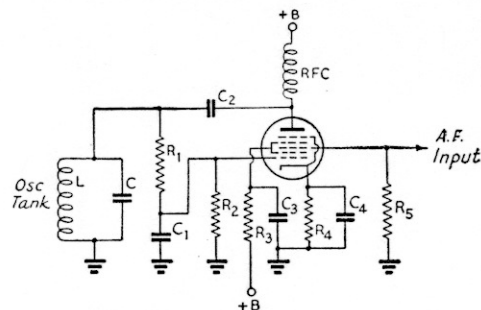


Fig. 521 — Reactance modulator circuit using a 6L7 tube. C — Tank capacity. C₁ — 3–10 μ fd. C₂ — 250 μ fd. C₃ — 8- μ fd. electrolytic (a.f. by-pass) in parallel with 0.01- μ fd. paper (r.f. by-pass). C₄ — 0.01 μ fd. L — Oscillator tank inductance. R₁ — 50,000 ohms. R₂, R₅ — 0.5 megohm. R₃ — 30,000 ohms. R₄ — 300 ohms.

grid circuit of the 6L7 tube is connected across the small capacity, C₁, which is in series with the resistor, R₁, across the oscillator tank circuit. Any type of oscillator circuit (§ 3-7) may be used. R₁ is large compared to the reactance (§ 2-8) of C₁, so the r.f. current through R₁C₁ will be practically in phase (§ 2-7) with the r.f. voltage appearing at the terminals of the tank circuit. However, the voltage across C₁ will lag the current by 90 degrees (§ 2-8). The r.f. current in the plate circuit of the 6L7 will be in phase with the grid voltage (§ 3-3), and consequently is 90 degrees behind the current through C₁, or 90 degrees behind the r.f. tank voltage. This lagging current is drawn through the oscillator tank, giving the same effect as though an inductance were connected across the tank (in an inductance the current lags the voltage by 90 degrees — § 2-8). The frequency is therefore increased in proportion to the lagging plate current of the modulator. This, in turn, is determined by the a.f. voltage applied to the No. 3 grid of the 6L7; hence the oscillator frequency varies with the audio signal voltage.

Other circuit arrangements to produce the same effect can be used. It is convenient to use a tube (such as the 6L7) in which the r.f. and a.f. voltages can be applied to separate control grids; however, both voltages may be applied to the same grid provided suitable precautions are taken to prevent r.f. from flowing in the external audio circuit, and vice versa (§ 2-13).

The modulated oscillator usually is operated on a relatively low frequency, so that a high order of carrier stability can be secured. Frequency multipliers are used to raise the frequency to the final frequency desired. The frequency deviation increases with the number of times the initial frequency is multiplied;

for instance, if the oscillator is operated on 7 Mc. and the output frequency is to be 112 Mc., an oscillator frequency deviation of 1000 cycles will be raised to 16,000 cycles at the output frequency.

Design considerations — The sensitivity of the modulator (frequency change per unit change in grid voltage) increases when C_1 is made smaller, for a fixed value of R_1 , and also increases with an increase in L/C ratio in the oscillator tank circuit. Since the carrier stability of the oscillator depends on the L/C ratio (§ 3-7), it is desirable to use the highest tank capacity which will permit the desired deviation to be secured while keeping within the limits of linear operation. When the circuit of Fig. 521 is used in connection with a 7-Mc. oscillator, a linear deviation of 2000 cycles above and below the carrier frequency can be secured when the oscillator tank capacity is approximately 200 μfd . A peak a.f. input of two volts is required for full deviation. At 56 Mc. the maximum deviation would be 8×2000 , or 16 kc.

Since a change in any of the voltages on the modulator tube will cause a change in r.f. plate current, and consequently a frequency change, it is advisable to use a regulated plate supply for both modulator and oscillator. At the low voltages used (250 volts), the required stabilization can be secured by means of gaseous regulator tubes (§ 8-8).

Speech amplification — The speech amplifier preceding the modulator follows ordinary design (§ 5-9), except that no power is required from it and the a.f. voltage taken by the modulator grid usually is small — not more than 10 or 15 volts, even with large modulator tubes. Because of these modest requirements, only a few speech-amplifier stages are needed; a two-stage amplifier consisting of a pentode followed by a triode, both resistance-coupled, will suffice for crystal microphones (§ 5-8).

R.f. amplifier stages — The frequency multiplier and output stages following the modulated oscillator may be designed and adjusted in accordance with ordinary principles. No special excitation requirements are imposed, since the amplitude of the output is constant. Enough frequency multiplication must be used to give the desired maximum deviation at the final frequency; this depends upon the maximum linear deviation available from the modulator-oscillator. All stages in the transmitter should be tuned to resonance, and careful neutralization (§ 4-7) of any straight amplifier stages is necessary to prevent r.f. phase shifts which might cause distortion.

Checking operation — The two quantities to be checked in the f.m. transmitter are linearity and frequency deviation. With a modulator of the type shown in Fig. 521, both the r.f. and a.f. voltages are small enough to make the operation Class A (§ 3-4), so that the plate

current of the modulator is constant so long as operation is over the linear portions of the No. 1 and No. 3 grid characteristics. Hence, non-linearity will be indicated by a change in plate current as the a.f. modulating voltage is increased. The distortion will be within acceptable limits, with the tube and constants given for the circuit in Fig. 521, when the plate current does not change more than 5 per cent with signal.

Non-linearity is accompanied by a shift in the carrier frequency, so it also can be checked by means of a selective receiver such as one with a crystal filter (§ 7-11). A tone source is convenient for the test. Set the receiver for high selectivity, switch on the beat oscillator, and tune to the oscillator carrier frequency. (The check does not need to be made at the output frequency and the oscillator frequency usually is more convenient, since it will fall within the tuning range of a communications receiver.) Increase the modulating signal until a definite shift in carrier frequency is observed; this indicates the point at which non-linearity starts. The modulating signal should be kept below the level at which carrier shift is observed, for minimum distortion.

A selective receiver also can be used to check frequency deviation, again at the oscillator frequency. A source of tone of known frequency is required, preferably a continuously variable calibrated audio oscillator or signal generator. Tune in the carrier as described above, using the beat oscillator and high selectivity, and adjust the modulating signal to the maximum level at which linear operation is secured. Starting with the lowest frequency available, slowly raise the tone frequency while listening closely to the carrier beat note. As the tone frequency is raised the beat note first will decrease in intensity, then disappear entirely at a definite frequency, and finally come back and increase in intensity as the tone frequency is raised still more. The frequency at which the beat note disappears, multiplied by 2.4, is the frequency deviation at that level of modulating signal; for example, if the beat note disappears with an 800-cycle tone, the deviation is 2.4×800 , or 1920 cycles. The deviation at the output frequency is the oscillator deviation multiplied by the number of times the frequency is multiplied; in this example, if the oscillator is on 7 Mc. and the output on 56 Mc., the final deviation is 1920×8 , or 15.36 kc.

The output of the transmitter can be checked for amplitude modulation by observing the antenna current. It should not change from the unmodulated carrier value when the transmitter is modulated. Where there is no antenna ammeter in the transmitter, a flashlight lamp and loop can be coupled to the final tank coil to serve as a current indicator. If the amplitude is constant, the lamp brilliance will not change with modulation.