Efficiency Modulation in Simple Terms

By J. N. A. Hawkins, W6AAR

The whole subject of efficiency modulation seems to be rather hazy in the mind of the average phone man. The advantages of class BC operation over the older class B system of efficiency modulation are becoming more widely appreciated. Several new ideas are presented herewith, and although ordinary linear amplification will probably be succeeded by the new expanding linear amplifier described in this issue, a thorough understanding of the principles of grid modulation is essential in order to get the idea behind the new expanding amplifier. Inasmuch as this article was prepared several months ago it includes nothing on dynamic shift amplification, and perhaps a general qualification should be made to the effect that the statements made in this article apply only to steady-state or constant-axis amplifiers and the limits of efficiency and output do not apply to dynamic shift or expanding amplifiers.

"Grid Modulation"

All low-level modulation systems can well be classified under the general heading of *grid modulation.* Suppressor grid modulation of a pentode is obviously grid modulation as is the system known as grid bias modulation. The operation of a radio frequency amplifier as a class B or BC linear amplifier also is a form of grid modulation. Perhaps it best could be termed *grid excitation modulation.* As far as the operation of the amplifier tube is concerned there is practically no difference between grid bias modulation and grid excitation modulation. In the grid bias modulated amplifier the grid excitation is held constant while the d.c. bias voltage is varied by the audio signal. See figure 2. In grid excitation modulation, or linear r.f. amplification, the d.c. grid bias is held constant and the amplitude of the grid excitation is varied by the audio signal. See figure 3. The result, as far as the amplifier grid and plate circuits are concerned, is the same in either case.

There is very little difference in cost, linearity, or adjustment between grid bias and grid excitation modulation, but what difference there is seems to favor grid excitation modulation, or the linear amplifier system, at the present time.

Amplitude Modulation

Amplitude modulation of any wave involves a variation in the peak amplitude of the carrier wave so that the envelope of the resultant modulated wave is similar to the waveform of the audio, or modulating, signal. When a carrier wave is completely modulated (100% modulated) the unmodulated amplitude of the wave is alternately doubled and then reduced to zero. The amplitude of a wave corresponds to the r.f.

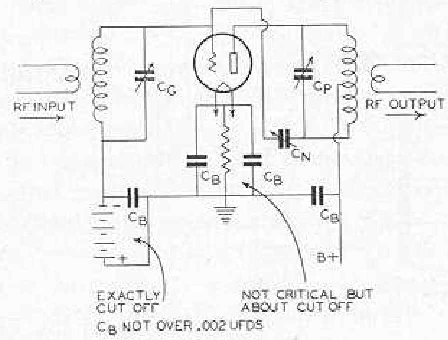

Figure 1
Class BC linear amplifier. The cathode bypass resistors must not be over .002 µfd.

voltage across the antenna that is radiating the wave. Thus when the amplitude of the carrier wave is doubled the r.f. voltage across the transmitting antenna is also doubled. As an antenna is effectively a pure resistance, doubling the voltage across it also doubles the current flowing through it (by Ohm's law). When the voltage and current in any resistive circuit both double, the *power* in that circuit has quadrupled. Thus complete modulation of a carrier wave causes the *instantaneous* power in the antenna (or output circuit) to vary between the limits of zero power and *four times* the normal unmodulated carrier power. Note the word *instantaneous*; it must be carefully distinguished from *effective* power. By integrating out the instantaneous variations in carrier power caused by 100% modulation it is found that the effective power (averaged over one audio, or modulating cycle) has been increased exactly 50% over the power in the unmodulated carrier. A 50% increase in average power output equals a 22% increase in effective antenna current. (Note that for the purposes of this discussion pure, sine-wave modulation is assumed.)

It is this 50% increase in average carrier power that is supplied by the output of the audio modulators in a plate-modulated phone transmitter. In a high level modulation system this is done by increasing the plate input to the class C modulated amplifier 50%, which increases the r.f. output in the same degree due to the fact that the conversion, or plate efficiency, of a class C stage is relatively independent of plate input, when operating properly. Thus the audio modulators in a plate-modulated transmitter are really modulating the plate power supply of the class C stage, and not the class C stage itself. Thus plate modulation is often called *power modulation.*

Grid, or Efficiency Modulation

It is a fundamental of grid modulation that the *average* plate input (as indicated on a d.c. plate meter) to the modulated amplifier must not vary during modulation. Thus if the average plate input remains constant and independent of modulation, the 50% increase in average power output of the modulated amplifier which occurs during complete sine-wave modulation can only be obtained by *increasing the average plate efficiency of the grid modulated amplifier 50%*. Thus all grid modulation systems are *efficiency* modulation systems. The average plate input to the modulated amplifier remains constant, but the efficiency of conversion of that input into r.f. power output is varied at an audio frequency rate by the modulating voltage applied to the grid bias supply in grid bias modulation, or to the preceding amplifier in grid excitation modulation.

So far the grid modulated amplifier has been analyzed only from the standpoint of *average* variations in plate efficiency and power output that occur during modulation. The instantaneous power output of the grid modulated amplifier must swing up to *four* times the unmodulated carrier, then down to *zero* power, then back to the unmodulated value, during periods of 100% modulation. This quadrupling of instantaneous power output results from two separate causes. First, the *instantaneous* plate efficiency varies, during complete modulation, from the normal unmodulated value up to twice normal, then down to zero efficiency and then back to normal.

The variation in plate efficiency accounts only for a doubling in instantaneous power output during complete modulation. The rest of the increase in the power output comes from the fact that the *instantaneous* plate current is also varying at an audio frequency rate between the limits of twice normal and zero current. As the plate voltage is constant the instantaneous plate power input varies exactly with the plate current so that doubling the instantaneous current doubles the instantaneous power input. The

Instead of presenting a table showing operating constants for all tube types and at all possible plate voltages (which would be awkward), the following formulae may be used to derive all the unknown constants for class BC operation from the factors that are generally known in advance, such as maximum allowable plate dissipation, μ of the tube to be used, and available plate voltage. From these factors may be determined the unknown factors such as d.c. battery bias, resistance of the cathode bias resistor, optimum d.c. plate current, and carrier power output.

Unknown Factors:

W_{IN} = d.c. plate input power, in watts.
W_{OUT} — r.f. unmodulated carrier power, in watts.
I_P = average d.c. plate current, in amperes.
E_{CCO} = negative battery bias equal to theoretical cut-off, in volts (½ total bias).
R_K = cathode bias resistance, in ohms.

Known Factors:

E_B = d.c. plate supply voltage, in volts.
W_{PL} = rated plate loss, in watts.
μ = amplification factor of tube used.

Formulae:

$$W_{IN} = 1.66\ W_{PL}$$

$$W_{OUT} = .66\ W_{PL}$$

$$I_P = \frac{1.66\ W_{PL}\ (1 + \mu)}{\mu\ E_B}$$

$$E_{CCO} = \frac{E_B}{1 + \mu}$$

$$R_K = \frac{E_B^2\ \mu}{1.66\ W_{PL}\ (1 + \mu)^2}$$

instantaneous plate current varies directly with the instantaneous plate efficiency and when both have been doubled (during 100% modulation) the r.f. power output has been quadrupled. It should be noted that the variation in plate current between zero and twice normal occurs at an audio frequency rate, not a syllabic rate, and thus good voltage regulation in the plate power supply is not necessary. When the plate current drops to zero, energy is stored in the last filter condenser. When the plate current doubles, this stored energy is given up again and as the plate voltage is constant, this variation in

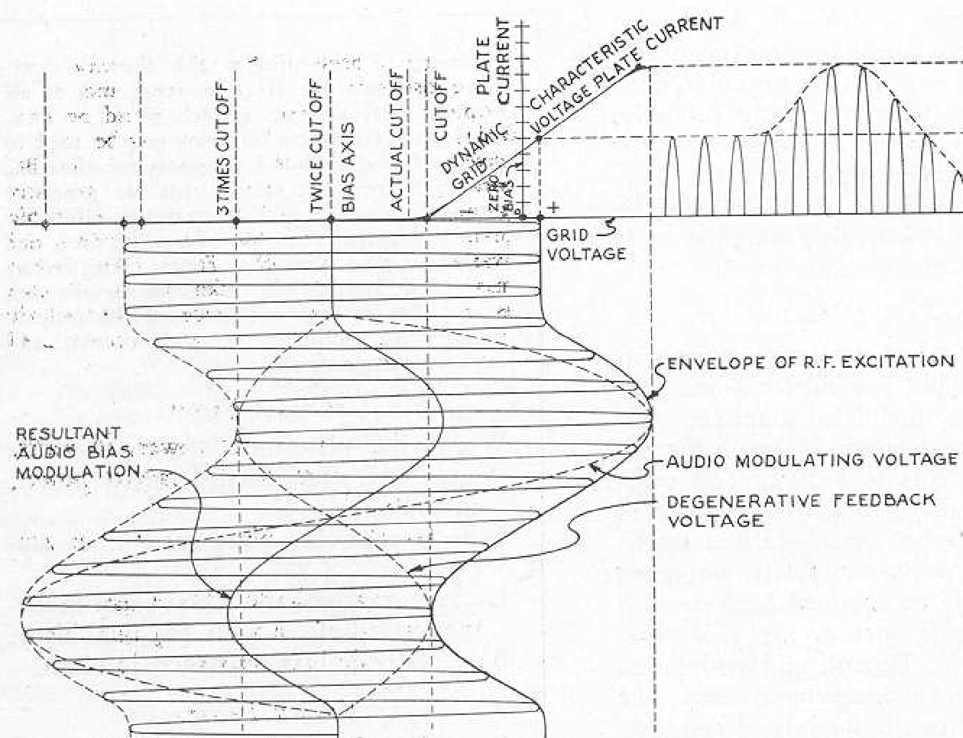

Figure 2

Class BC bias modulation (no audio bypass on cathode resistor). Note the two forces working on the grid bias voltage: the audio modulation voltage and the degenerative feedback voltage, working in opposite directions. The degree of degenerative feedback is dependent on the value of unbypassed resistance in the cathode circuit.

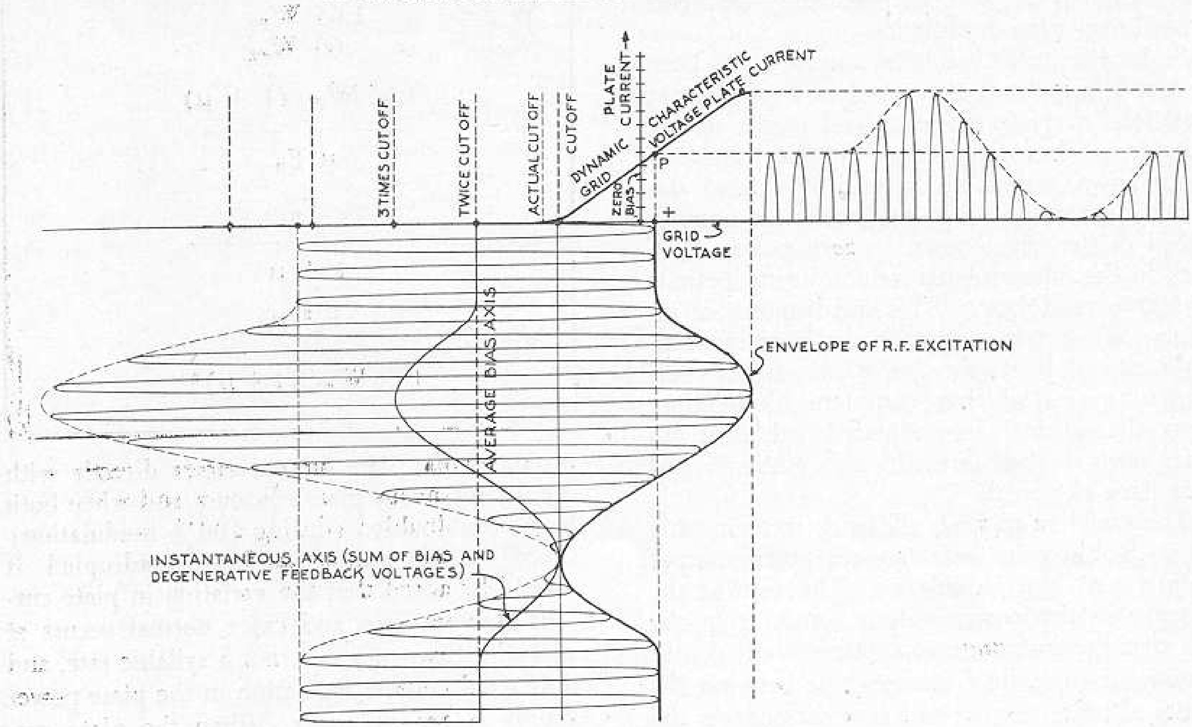

Figure 3

Class BC linear or excitation modulation. Here there is only one force working on the bias: the a.f. variation in current through the unbypassed cathode resistor (degenerative feedback). Contrary to widespread belief, there is no "modulation gain" in a class BC linear amplifier. This should be apparent from study of the above curves.

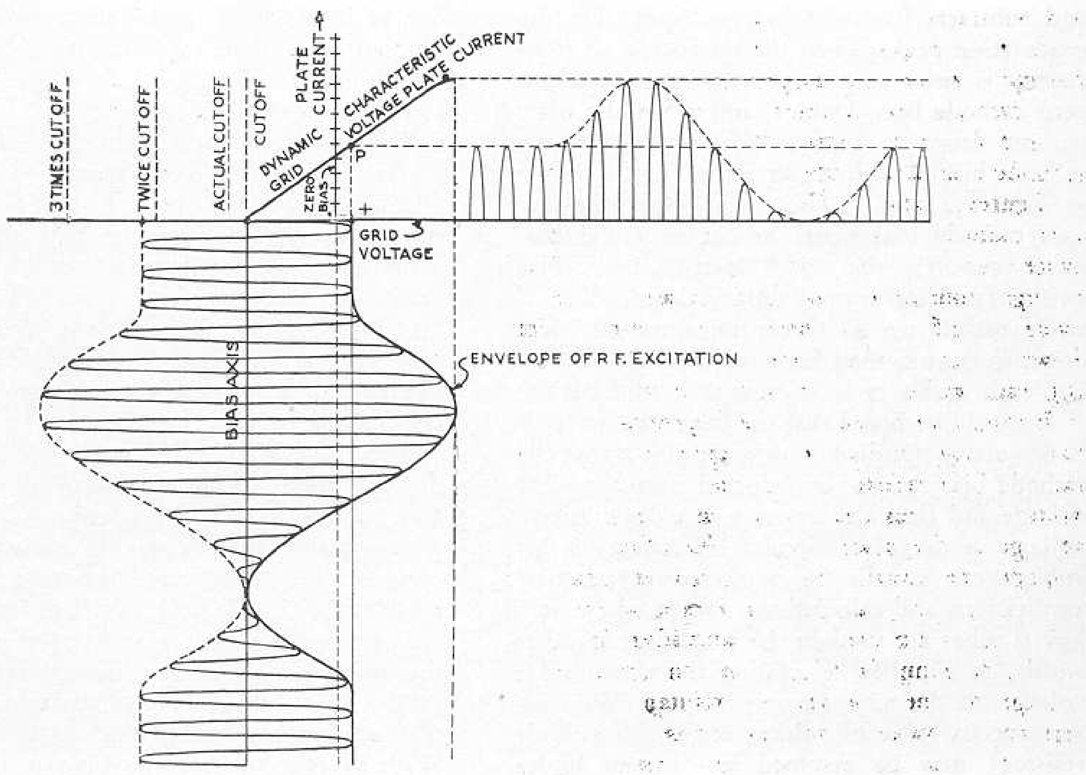

Figure 4
Conventional Class B Linear Amplifier Curves, Shown for Comparison.

plate current causes no variation in the *average* power drawn from the plate power supply, although the *instantaneous* plate input alternately doubles and drops to zero. This explains how the instantaneous power output of a 200 watt grid modulated amplifier can swing up to 800 watts on the *instantaneous* (audio) peaks although the average d.c. plate input is only 500 watts. It must be noted that the last filter condenser in the plate supply hum filter should be large enough to take care of the audio frequencies that pass through it.

In pure class B operation of a linear amplifier the bias is made equal to theoretical cut-off, or d.c. plate voltage divided by the μ of the tube used in the amplifier. The plate current is not actually cut-off when a tube is biased to this point, as no practical vacuum tube has a constant μ clear out to the cut-off point. However, only a small amount of plate current flows at theoretical, or projected, cut-off and for most purposes it can be assumed that actual and theoretical cut-off coincide.

In the class BC amplifier fixed bias equal to cut-off is used, and in addition, there is a cathode bias resistor used which supplies additional bias. The additional bias supplied by the cathode bias resistor is not critical and can be almost anything from half cut-off to several times cut-off. However, the best compromise value for the medium μ tubes (μ between 8 and 16) seems to be about cut-off. Thus the total bias (fixed plus cathode) should equal about twice cut-off. The *fixed* bias should be well bypassed to audio frequencies and the bias source should have good voltage regulation, particularly if the amplifier is to be driven hard into the positive grid region. The fixed bias is rather critical for minimum amplitude distortion, and once set it should be left alone. If it is desired to experiment with bias, vary the cathode bias but leave the fixed bias alone once it has been set for a given plate voltage. There is one very important thing about the cathode bias that must not be overlooked. The cathode bias resistor *must not be bypassed* for the audio frequencies. A radio frequency bypass across the resistor may be used but it should not be over .002 μfds. Placing an audio bypass across the cathode resistor short circuits the degenerative audio feedback voltage which appears across the cathode resistor. This degenerative feedback voltage is what keeps the amplifier linear even though the average total bias exceeds cut-off. This feedback voltage varies directly with the plate current. It alternately adds to and subtracts from the bias voltage. On the modulation peaks, when the instantaneous plate current is twice its average value the instantaneous cathode bias doubles, and when the plate current drops to zero a half cycle later, the cathode bias also drops to zero. This is shown in figures 2 and 3. Thus if a given amplifier uses cathode bias equal to cut-off (total bias twice cut-off) the total instantaneous bias swings from its normal unmodulated value of twice cut-off up to three times cut-off, then down to cut-off, then back to twice cut-off during each audio cycle of complete modulation.

It should be noted that the degenerative feedback voltage (audio) which appears across the cathode bias resistor is deducted from the plate voltage and thus also appears as a degenerative voltage in the plate circuit. The effect of this voltage can usually be neglected in practical applications and calculations, except where very low μ tubes are used in the amplifier. In other words, to simplify calculation the actual plate voltage on the tube (supply voltage minus instantaneous value of voltage across the cathode resistor) may be assumed as constant under modulation, though it is not strictly so.

The use of degenerative feedback in the class BC amplifier allows high peak and unmodulated plate efficiency to be obtained and even improves the linearity of the amplifier over the conventional class B amplifier. The power gain through the class BC amplifier is somewhat less than through a comparable class B amplifier but the reduction in overall power gain is slight and the increase in output, efficiency and linearity is well worth the slight loss in gain.

It should be mentioned that there is no modulation gain through a class BC linear amplifier. No matter what the total unmodulated bias may be, if the fixed bias is equal to cut-off, the preceding stage must be completely modulated if the class BC amplifier output is to be completely modulated.

Due to the fact that the d.c. grid current flows through the cathode bias resistor of a class BC amplifier it is desirable to keep both the cathode bias resistance and the d.c. grid current low in order to avoid audio distortion arising from changes in bias with grid current flow. To keep this distortion low it is desiraable, therefore, to use a tube with the highest possible transconductance, as cathode bias resistance and d.c. grid current both vary inversely with the transconductance of the tube used.

As the instantaneous peak plate efficiency must be able to double in order for the amplifier to have 100% modulation capability, the unmodulated plate efficiency must be adjusted to *not more than one half* of the maximum attainable peak plate efficiency.

The theoretical maximum peak efficiency of a class B amplifier (one biased to cut-off) is 79%, as the angle of plate current flow remains constant at 180°. Thus one half of this peak value equals 39%. Practical class B amplifiers rarely exceed about 66% peak efficiency, and 50 to 60% peak plate efficiency is more common in practice. Thus the unmodulated plate efficiency of a practical class B amplifier ranges from about 25%to 33%.

The class BC amplifier can have almost any desired angle of plate current flow between 180° and 0° merely by increasing the degenerative cathode bias. Therefore, like a class C amplifier the theoretical maximum peak plate efficiency is 100%.

For reasons of driver and power supply cost the peak plate efficiency is usually held at about 80%, which allows a maximum unmodulated plate efficiency of half this value, or about 40%. With average tubes of medium μ (between 8 and 16) this requires a total bias equal to between two and two and a half times cut-off.

The variations in plate efficiency and plate current that must occur during modulation are caused by superimposing the audio frequency modulating voltage on the d.c. grid bias voltage, or on the r.f. excitation voltage. See figures 2 and 3. As the grid must be allowed to swing somewhat positive (with respect to the filament) at least during modulation, it will intercept electrons from the filament, causing d.c. grid current to flow. If the power output is to be free from distortion this flow of grid current must not be allowed to change the negative bias on the tube. This necessitates a very low resistance d.c. grid return to ground.

The r.f. driver is best stabilized by connecting a tungsten filament lamp across either part of the driver plate tank or else across the low impedance coupling link which transfers energy from the driver plate tank to the grid tank of the modulated amplifier. Of course, a resistor of any convenient value up to about 5000 ohms could be used in place of the tungsten filament lamp, but the lamp is usually more convenient as well as self-adjusting due to the temperature-resistance characteristic of a tungsten filament.

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W1CAV has been using the same S-tube rectifiers in his transmitter since 1923!