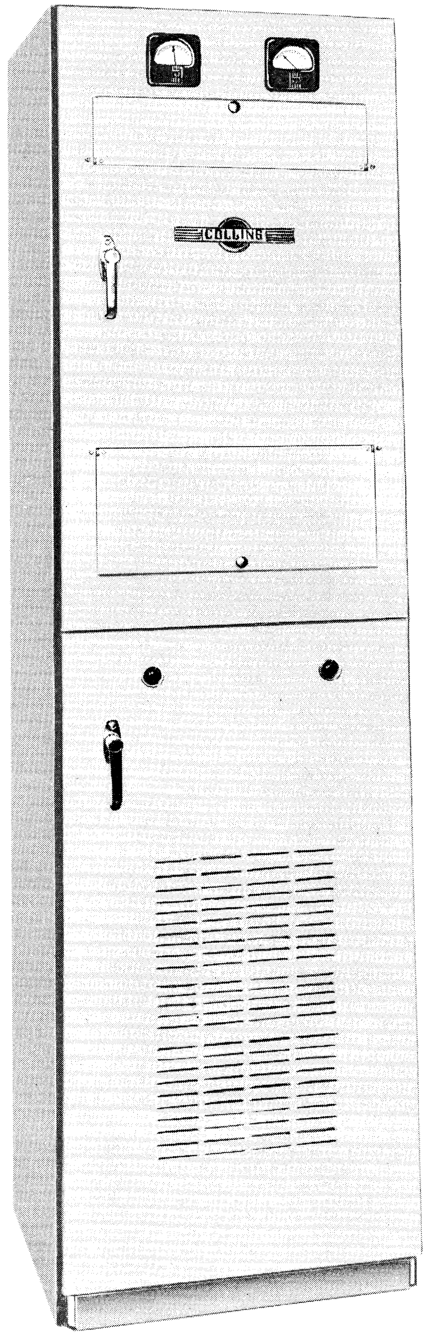

Collins 204F Power Amplifier, a Three Stage Linear Amplifier with an Output of 2.5 Kw PEP

CHAPTER 7
R-F LINEAR POWER AMPLIFIERS

1. INTRODUCTION

The r-f power amplifier of the SSB transmitter receives a low power level, radio-frequency SSB signal from the exciter. The function of the power amplifier is to raise the power level of the input signal without changing the signal. That is, the envelope of the output signal must be a replica of the envelope of the input signal. A power amplifier which will perform this function is, by definition, a linear power amplifier.

2. POWER AMPLIFIER CLASSIFICATION

Radio-frequency amplifiers are classified A, B, and C according to the angle of plate current flow; that is, the number of degrees of plate current flow during a 360° r-f cycle. Class A amplifiers have a continuous plate current flow and operate over a small portion of the plate current range of the tube, as shown in figure 7-1. This class amplifier is used for amplification of small signals for low distortion. Its efficiency in converting d-c plate power input into r-f power output is quite low, usually less than 35 per cent, but this is seldom of major importance where small signals are amplified.

Class B amplifiers have their grids biased to near plate current cutoff so that plate current flows for approximately 180° of the r-f cycle, as shown in figure 7-2. Amplifiers operated with appreciably more than 180° of plate current flow but less than 360° are called class AB amplifiers. Both class AB and class B operation is used in the high-power stages of r-f linear amplifiers to achieve higher efficiency and maximum output power with low distortion. Plate efficiency depends upon the tube used and the operating conditions selected, with efficiencies in the range of 50 to 70 per cent obtainable. The distinction between class B and class AB is somewhat arbitrary since both operate over more than 180° but less than 360°. However, the class AB amplifier draws appreciably more static plate current than the class B amplifier, which draws only a small static plate current.

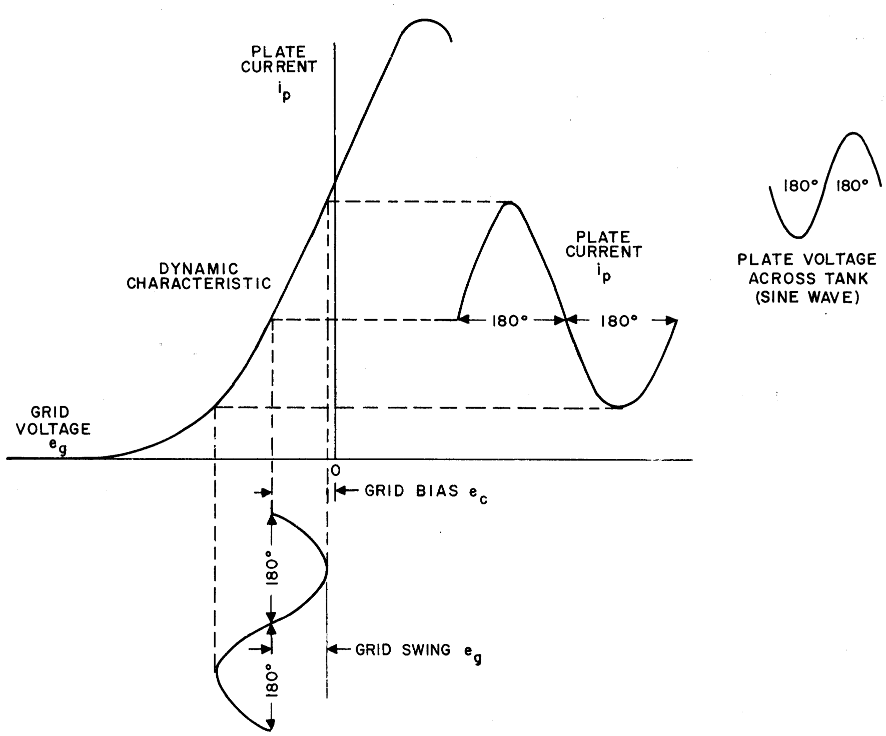

Figure 7-1. Class A Tube Operation

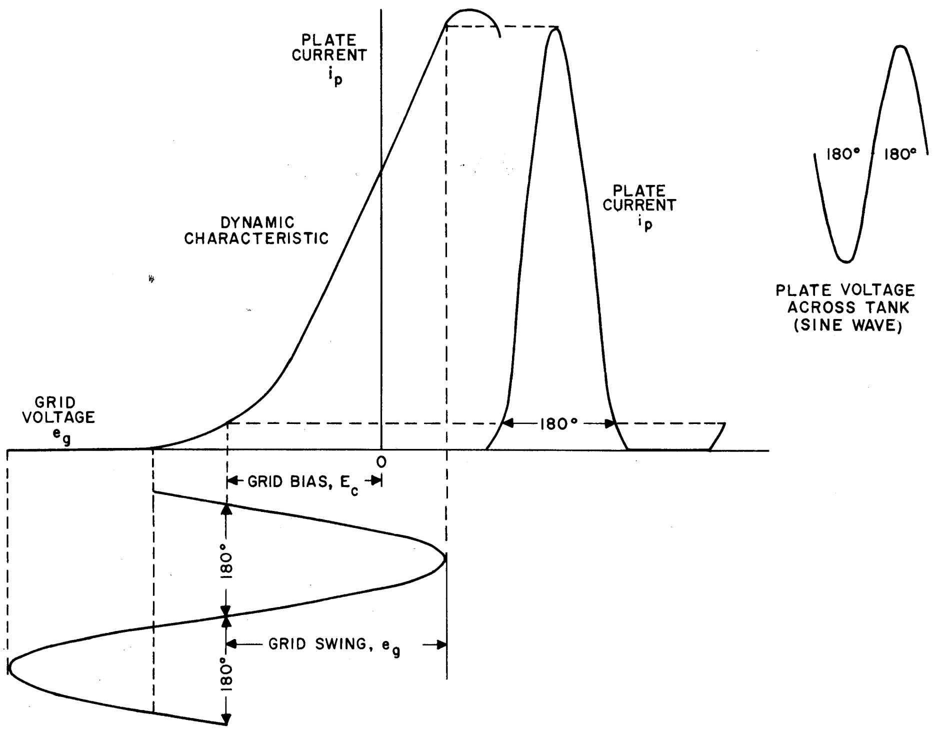

Figure 7-2. Class B Tube Operation

The class C amplifier, as shown in figure 7-3, is biased well beyond cutoff so that plate current flows less than 180° of the r-f cycle. The principal advantage of the class C amplifier is high plate efficiency, from 65 to 85 per cent, but class C amplifiers are not suited for SSB use because they are not linear amplifiers and will not respond to low-level input signals.

A subscript number is commonly added to the amplifier class designator to indicate whether or not the tube is operated in the positive grid region over part of the cycle. For example, class AB_1 indicates that the grid never goes positive so that no grid current is drawn. Class AB_2 indicates that the grid does go positive so that grid current is drawn. Because class A amplifiers are nearly always operated without grid current, and because class C amplifiers are nearly always operated with grid current, subscript designators are omitted unless they are operated to the contrary of the usual practice.

3. R-F POWER AMPLIFIER TUBES

Conventional grid-controlled power amplifier tubes are classified according to the number of elements they have. Until fairly recently, the triode which has a control grid in addition to the cathode and anode was the only transmitting-type tube available in the medium and high power sizes. (The cathode is sometimes called the filament because the cathode is usually directly heated in high power tubes, and the anode is often called the plate.) Tetrodes, which have a screen grid between the control grid and plate, have recently become available. The screen grid provides an accelerating potential to the electron stream and also provides an electrostatic shield between the anode and the control grid. The two grids of most transmitting-type tetrodes provide a beaming action to the electron stream which improves the tube characteristics. This beaming action reduces the d-c screen current and increases the control of the control grid. Power pentodes up to 1 kw have an additional grid, a suppressor grid, located between the screen and the anode. In some beam power tubes this element may consist of beam forming plates which, in general, give an improved plate characteristic when the plate voltage swings below or in the region of the d-c screen voltage.

Triode power amplifier tubes have the advantage of simplicity, low cost, and availability in all sizes. In general, they require a large amount of driving power. Also, since their grid is exposed directly to the plate, there is considerable capacitive coupling from the plate to the grid within the tube. This plate-to-grid capacitance must be accurately neutralized in r-f linear power amplifiers. The amplification factor of triode tubes ranges from 4 to 5 for low mu tubes, to twenty for medium mu tubes to fifty for high

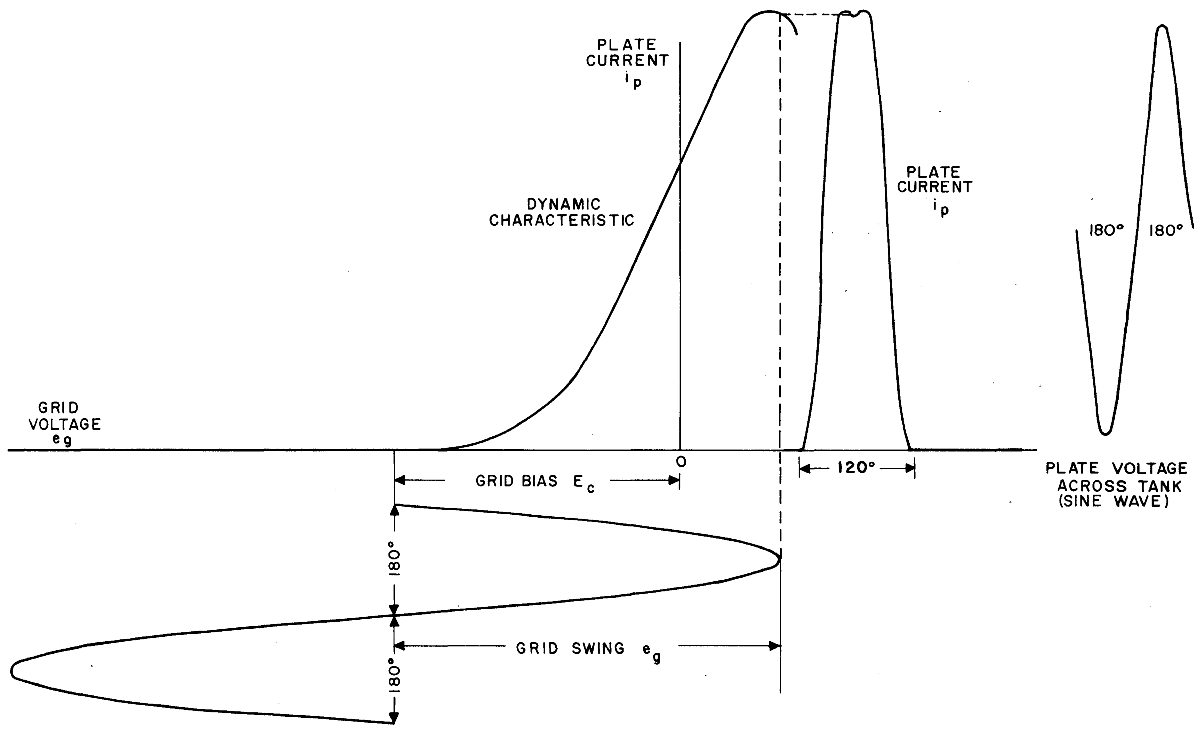

Figure 7-3. Class C Tube Operation

mu tubes. Generally only the low and medium mu triodes can be used for linear power amplifier circuits. Therefore, a large grid swing is required to obtain the power amplification available from the tube.

In tetrode power amplifier tubes, the screen grid acts as an electrostatic shield between the plate and control grid which reduces the plate-to-grid capacitance. This reduces the neutralization required to as little as one-hundredth of that required for a triode. However, since the gain of the tetrode tube is so much higher than that of the triode, neutralization of the small residual plate-to-grid capacitance of the tetrode is still required for the best, high-gain linear performance. Because of the high gain of the tetrode, the tube requires relatively low drive to obtain high power output. This advantage allows fewer stages to be used to obtain a given power output.

Pentode construction is used in most small receiving size power tubes and in some cases in power tubes up to 1 kw output. In small tubes, pentodes provide good performance with low plate voltage, and in larger tubes, pentodes give improved efficiency because the r-f plate swing can be increased some. The pentode has disadvantages in that it is more complex than the tetrode, is more expensive, and requires extra circuitry for the suppressor grid. These disadvantages have limited the development of the pentode power tubes. At the present time, the pentode has little advantage over the well designed tetrode.

For r-f linear amplifier operation, the following features are desirable in the power amplifier tubes:

(1) High gain

(2) Low plate-to-grid capacitance

(3) Good efficiency

(4) Linear characteristics which are maintained without degradation at all frequencies in the desired operating range

The needs for power amplifier tubes in the vhf and uhf ranges have spurred development of tubes suitable for operation at those frequencies. This has resulted in tubes with better performance in the h-f (3 to 30 mc) range. A typical comparison can be made between the type 813 tube and the type 4X250B tube which are in the same power class. The small compact design of the 4X250B tube results in short lead lengths, better screening, closer element spacing and much higher performance which can be maintained easily over the h-f range. The ceramic construction, rather than glass, of an increasing number of new tubes promises to result in a more rugged and longer lifed tube. Ceramic sealed tubes which are now available include the RCA-6118 which is smaller than the 4X150A, the Eimac 4CX300A which has characteristics similar to the 4X250B, an all ceramic version of the

4X250B, the Eimac 4CX5000A which is capable of 10 kw of r-f output, and an RCA super-power, shielded-grid tube that will deliver 500 kw of r-f output. Tube manufacturers have additional types of power amplifier tubes under development which promise better performing tubes for the near future.

The Collins Radio Company has chosen to use high gain tubes of those types considered to be the best compromise of desired characteristics. At low signal levels, such as exist in exciters, conventional receiver-type r-f amplifier tubes are used. For delivering .1 watt output from exciters, the type 6CL6, which is a miniature 9-pin tube, is generally used. The 6CL6 is also frequently used to excite type 4X250B power amplifier tubes. The 4X250B tube is used in small, compact equipment for power levels of 1 kw by paralleling three, and for power levels of 500 watts by paralleling two. The type 4CX5000A is used for power levels of from 5 kw to 10 kw. This tube is used to obtain power levels up to 45 kw by paralleling four of them.

4. BASIC LINEAR POWER AMPLIFIER CIRCUITS

a. GENERAL

For linear operation, r-f power amplifiers may be operated class A or class AB. The amplifiers used are quite conventional, being either grid driven or cathode driven (grounded grid) type amplifiers. However, the design considerations are extremely stringent to produce maximum linearity for a given tube in a given circuit. The tube operating point must be discreetly chosen and precisely maintained, neutralization must be as effective as possible, r-f feedback circuits are often used, and input and output impedances must be held as constant as possible. Generally class A pentode power amplifiers are employed in low-level power stages to preserve linearity in these stages while producing enough power to drive the higher level stages. Class AB_1 or AB_2, triode or tetrode power amplifiers are employed in the high-level power stages to obtain the desired power output.

b. GRID DRIVEN TRIODE POWER AMPLIFIER

Figure 7-4 is a simplified schematic of a typical grid driven triode power amplifier. This amplifier, operating class AB_1, produces up to 2.5 kw using the type 3X3000A-1 triode. The triode tube, having a large plate-to-grid interelectrode capacitance, always requires neutralization to prevent oscillation when used in the grid-driven circuit. The only types of triodes capable of class AB_1 operation are the low amplification factor types, such as the 3X3000A-1. Due to the low amplification factor, very high r-f grid excitation voltage is required, on the order of 1000 volts for the 3X3000A-1. A similar tube suitable for class AB_2 operation is the 3X2500A-3 which has an

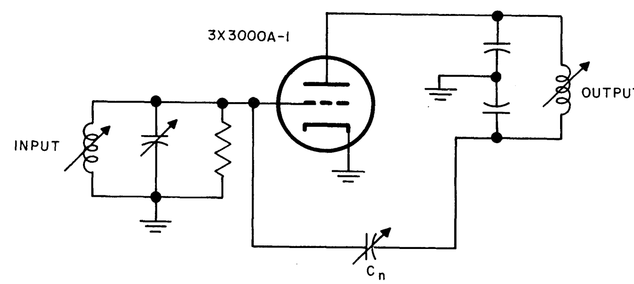

Figure 7-4. Grid Driven, Plate Neutralized Triode Power Amplifier

amplification factor of 20. This medium-mu triode requires less grid swing, but it requires grid driving power for class AB_2 operation. Neutralization, of course, is still required.

A swamping resistor is used in the grid circuit to maintain a constant input impedance to the stage and for stability. When the stage is operated class AB_2, the grid current represents a varying load to the driving source. By adding the swamping resistor, the grid current drawn represents only a small portion of the total grid load so that the driver load impedance is relatively constant. The swamping resistor does increase the required driving power. The swamping resistor also improves stability by affording a low impedance to ground for regenerative feedback through the plate-to-grid capacitance.

c. CATHODE DRIVEN TRIODE POWER AMPLIFIER

Figure 7-5 is a simplified schematic of a typical cathode driven (grounded grid) triode power amplifier. This amplifier, operating class AB_2 produces 4 to 5 kw using the type 3X2500A triode. In the cathode driven amplifier, the control grid is at r-f ground and the signal is fed to the cathode. The main advantage

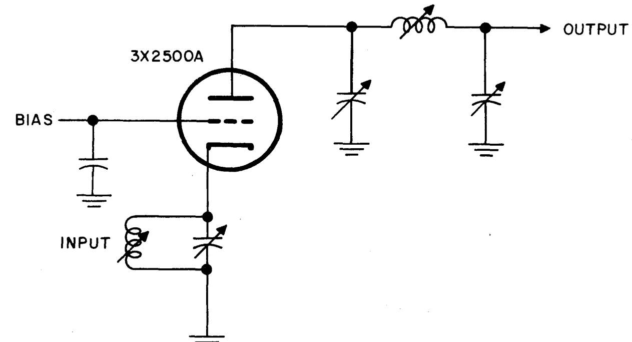

Figure 7-5. Cathode Driven Triode Power Amplifier

of operating the triode in this manner is that the control grid becomes an effective screen between the plate and the cathode making neutralization seldom necessary. The small values of plate-to-cathode capacity have very little effect on the input signal because the input circuit impedance is usually quite low. Since neutralization is not required, triodes with an amplification factor of 20, such as the 3X2500A, can be used. Another advantage of the cathode driven power amplifier is that the feedthrough power is an effective load across the input circuit, making swamping resistors unnecessary. The main disadvantages of this circuit are that a large driving power is required and that power gains of from six to ten are all that can be realized. Most of the power required for driving, however, feeds through the stage and appears in the plate circuit so that it is not lost. The cathode driven circuit is a convenient circuit to use when high power has already been developed and needs another step up.

d. GRID DRIVEN TETRODE POWER AMPLIFIER

Figure 7-6 is a simplified schematic of a grid driven tetrode power amplifier. This amplifier, operating class AB_1 produces 250 watts per tube using the type 4X250B tetrode. In general, the same design considerations exist for tetrode amplifiers as for triode amplifiers. That is, grid circuit swamping is required to hold the input impedance constant if the tetrode is driven into the grid current region, and neutralization is generally required if the tube is to operate over the entire high-frequency range. However, since the plate-to-grid capacitance is small in the tetrode, neutralization is much simpler. The tetrode amplifier, being a high gain tube, requires relatively little driving power and a relatively small grid swing for operation. This permits the paralleling of tubes with a common input network and a common output network which reduces the number of stages and simplifies tuning. In the tetrode power amplifier, the screen voltage has a very pronounced effect on the dynamic characteristic of the tube. By lowering the screen voltage, the static current required for optimum linearity is lowered. This permits greater plate r-f voltage swing which improves efficiency. The use of lower screen voltage has the adverse effect of increasing the grid drive for class AB_2 operation and lowering the power output for class AB_1 operation. The tetrode tube can be used in the cathode driven circuit and can be so used without neutralization in the high-frequency range.

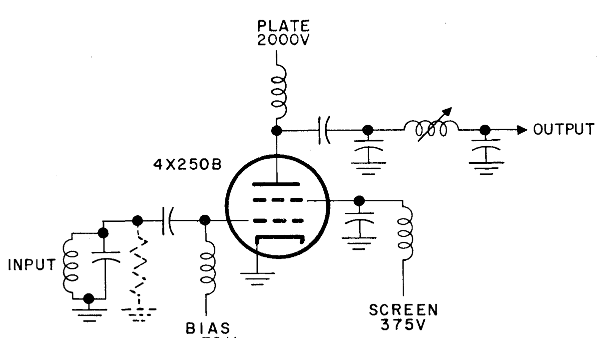

Figure 7-6. Grid Driven Tetrode Power Amplifier

5. POWER AMPLIFIER OUTPUT NETWORKS

a. TANK CIRCUIT CONSIDERATIONS

The plate tank circuit of an r-f power amplifier must perform four basic functions:

(1) It must maintain a sine wave r-f voltage on the plate of the tube.

(2) It must provide a low impedance path from plate to cathode for harmonic components of the plate current pulses.

(3) It must provide part or all of the necessary attenuation of harmonics and other spurious frequencies.

(4) It must provide part or all of the impedance matching from the tube plate to the antenna.

In addition, for many uses the output circuit should be single ended so that it will feed into a 52 ohm coaxial transmission line. A 52 ohm coaxial transmission line is desirable because it prevents stray r-f radiation near the transmitter; it is convenient for coaxial r-f switching; it is a convenient impedance for additional r-f filtering, and because it is ideal for directional wattmeter installation. For simplicity of operation, the output circuit should require a minimum of tuning controls. A direct-coupled network, such as the Pi-L network, is the most suitable network to meet these requirements.

The Q of the plate circuit, of which the tank is a part, must be sufficient to keep the r-f plate voltage close to a sine wave shape. This is often referred to as the "flywheel effect." If the plate circuit Q is insufficient, the r-f waveform may be distorted which will result in low plate efficiency. This loss of efficiency is seldom noticed unless the plate circuit Q is less than 5. A plate circuit Q of at least 10 is known to be sufficient for linear operation and is a recommended minimum.

A power amplifier operating either class AB, B, or C delivers power to the tank circuit by plate current pulses. The harmonic content of these pulses is determined primarily by the angle of plate current flow, the harmonics being greater with a smaller angle of plate current flow. In a linear power amplifier, the second harmonic component can be as great as 6 db below the fundamental at full peak envelope power. The higher order harmonic components drop off rapidly but their magnitude varies greatly, depending upon the pulse shape. These harmonics must be attenuated in the output network so that they are 50 db, 80 db, or even further, below the fundamental component. The Pi-L network will attenuate the second harmonic to about 50 db below the fundamental, which is from 10 db to 15 db more attenuation than can be obtained from the simple Pi network. Where more attenuation is required, external filters of either the low-pass or band rejection type are added. Increasing plate circuit Q increases harmonic attenuation, but since doubling the Q results in only about 6 db more second harmonic attenuation, Q's above 20 are seldom used below 30 mc.

The Pi-L output network is ideally suited to matching a tube load to a 52-ohm coaxial transmission line. Loads with a standing wave ratio as high as 4 to 1 can be matched easily. This can be done with any value of tube load impedance, whereas the simple Pi network has difficulty matching to low load impedance when the tube plate load resistance is high.

The Pi-L network has only four variable elements, and they can be ganged to have only a tuning control and a loading control, as shown in figure 7-7. Since in the Pi-L network, C_2 and L_2 affect loading in the same direction, the extra capacity and inductance range of the elements required to extend the loading range of the circuit is relatively small. For example, the loading control varies about ±25 per cent to match a 52 ohm load with a 4:1 swr. The tuning control varies about ±10 per cent.

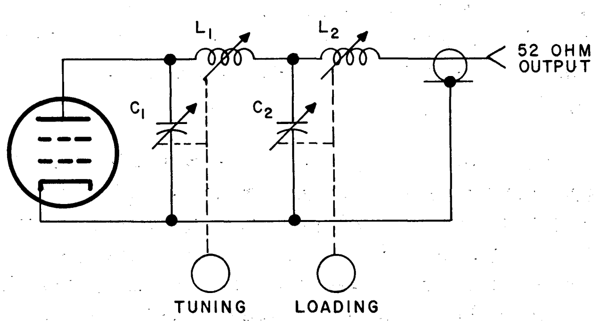

Figure 7-7. Tuning Controls for Pi-L Output Network

b. CIRCUIT LOSSES

Nearly all of the tank circuit loss occurs in the coils. These losses are closely related to the ratio of plate circuit Q to coil Q, but other design considerations enter in. These circuit losses are shown in figure 7-8 for a Pi-L network, which has lower losses than other networks for 50 db of second harmonic attenuation. Resistances r_1 and r_2 represent the equivalent series resistance of the coils determined from coil Q and reactance. Resistance r_q is the equivalent load resistance in series with L_1 and is determined from the relationship

$$r_q = \frac{R_L}{Q^2 + 1} = \frac{R_L}{(R_L/X_C)^2 + 1}$$

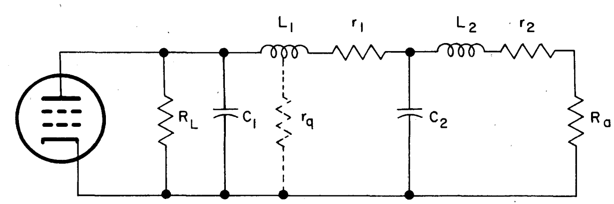

Figure 7-8. Circuit Losses in Pi-L Network

Resistance R_a is the series resistive component of the load. The Pi-L network loss is given by the equation:

$$\text{Per cent loss} = \left(\frac{r_1}{r_q + r_1} + \frac{r_2}{R_a + r_q}\right) 100$$

c. TANK COIL AND CAPACITOR REQUIREMENTS

The frequency range and method of tuning are major factors in determining tank circuit components. Continuously variable coils and capacitors which will cover the entire frequency range without any band switching are the most desirable. However, this is not practical in Autotune transmitters because of the limited torque available to drive the tuning elements and the often short repositioning time specified. With these limitations, bandswitching is almost essential. Where instantaneous frequency change is specified, it is common to switch from one pretuned r-f unit to another and manually tuned circuits are suitable for this purpose. Servo control of the tuning elements permits incorporation of various automatic tuning or prepositioning circuits and is well suited for driving continuously variable elements. A practical way to design a transmitter is to use continuously variable elements that can be operated either manually or by an accessory servo system.

The use of continuously variable elements has the following advantages:

(1) The circuit Q can be kept more uniform across the frequency range.

(2) The circuit losses can be kept to a minimum.

(3) The range of variable coils and capacitors can be less.

(4) A maximum amount of harmonic attenuation is more easily maintained across the frequency range.

Variable vacuum capacitors are widely used in transmitters with power levels of 1 kw and higher. Their added expense is often justified by the added capacity range, small size, and low series inductance, especially where voltages above 2500 volts are employed. Variable tank coils are usually constructed with a rotary coil and either a sliding or rolling contact that traverses the length of the coil as it is rotated. The unused turns are shorted out to keep high voltages from developing in them. The series self-resonant frequency of the shorted-out section must not be near the operating frequency or high circulating currents will develop and cause, appreciable power dissipation.

6. NEUTRALIZATION

a. EFFECTS OF PLATE-TO-GRID CAPACITANCE

The purpose of neutralization is to balance out the effect of plate-to-grid capacitive coupling in a tuned r-f amplifier.

In a conventional tuned r-f amplifier using a tetrode tube, the effective input capacity of the tube is given by the following equation:

$$\text{Input capacitance} = C_{in} + C_{gp}\,(1 + A \cos \Theta)$$

where C_{in} is tube input capacitance

C_{gp} is plate-to-grid capacitance

A is voltage amplification from grid to plate

Θ is phase angle of plate load.

In an unneutralized, 4-1000A tetrode amplifier with a gain of 33, the input capacity of the tube with the plate circuit in resonance is increased 8.1 uuf due to the unneutralized plate-to-grid capacity. This small increase in capacitance is not particularly important in amplifiers where the gain remains constant, but if the gain does vary, serious detuning and r-f phase shift can result. The gain of a tetrode or pentode r-f amplifier operating below plate saturation does vary with loading so that if it drives a following stage into grid current, the loading increases and the gain falls off.

The input resistance of the grid is also affected by the plate-to-grid capacitance. The input resistance is given by the following equation:

$$\text{Input resistance} = \frac{1}{2\pi f\, C_{gp}\,(A \sin \Theta)}$$

This input resistance is in parallel with the grid current loading, grid tank circuit losses, and driving source impedance. When the plate circuit is tuned to the inductive side of resonance, energy is transferred from the plate to the grid circuit through the plate-to-grid capacitance (positive feedback). This introduces negative resistance in the grid circuit. When this shunt negative resistance across the grid circuit is lower than the equivalent positive resistance of the grid loading, circuit losses, and driving source impedance, the amplifier will oscillate. As the plate circuit is tuned to the capacitive side of resonance, the input resistance becomes positive and power is transferred from the grid-to-the-plate circuit. This is why the grid current in an unneutralized tetrode r-f amplifier varies from a low value to a high value as the tank circuit is varied from below to above resonance. If the amplifier is overneutralized, the effect reverses. This effect can be observed in a pentode or tetrode amplifier operating class A or AB_1 by placing an r-f voltmeter across the grid circuit and tuning the plate circuit through resonance.

b. NEUTRALIZING CIRCUITS

Most of the neutralizing circuits developed for use with triodes may be used equally successfully with tetrodes. However, those circuits which require balanced tank circuits for neutralizing purposes only, are undesirable because the trend in r-f power amplifier design is toward single-ended stages.

A conventional grid neutralized amplifier is shown in figure 7-9. Capacitor C_3 balances the grid-to-filament capacity to keep the grid circuit in balance. When $C_1 = C_2$ and $C_n = C_{gp}$, it is readily seen that a signal introduced into the grid circuit will not appear across the plate circuit because the coupling through C_n is equal and opposite to the coupling through C_{gp}.

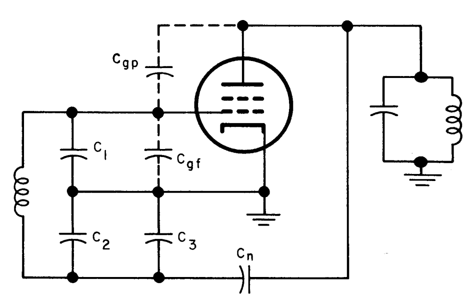

Figure 7-9. Conventional Grid-Neutralized Amplifier

The relationship for no coupling from the grid circuit to the plate circuit is given by the relationship

$$\frac{C_1}{C_2} = \frac{C_{gp}}{C_n}$$

This indicates that the grid tank circuit need not be balanced to ground. If C_2 is made larger, then C_n must be made correspondingly larger. In a tetrode amplifier, C_{gp} is very small (approximately .1 uuf) so that practical values, 5 uuf, can be used for C_n when C_2 is very much larger than C_1.

By placing most of the grid tuning capacitance across the grid tank coil, using the bypass capacitor C from the bottom end of the grid tank circuit to ground for C_2, and using the grid-to-filament capacity for C_1, the modified grid neutralized circuit shown in figure 7-10 results. The relationship for neutralization of this circuit is given by the relationship

$$\frac{C_n}{C} = \frac{C_{gp}}{C_{gf}}$$

This relationship assumes perfect screen and filament bypassing and negligible effect from stray inductance and capacity. This modified grid neutralizing circuit is very effective for neutralizing tetrode power amplifiers and is accomplished with single-ended tuning elements.

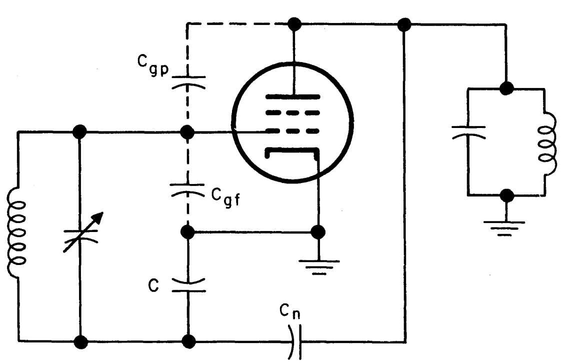

Figure 7-10. Modified Grid-Neutralized Amplifier

c. TESTING FOR PROPER NEUTRALIZATION

When a power amplifier stage is properly neutralized, the power output peaks at the same time the plate current dips. An indication of this simultaneous peak and dip is often the most convenient way of testing for proper neutralization. To perform such a test, the d-c cathode current, or plate current, of the neutralized stage is used to obtain an indication of plate current dip. The power output from the same stage or the grid drive to any succeeding stage is used to obtain an indication of power output. A power amplifier is usually checked for proper neutralization near the high-frequency end of its range where neutralization is more critical.

When the drive to a neutralized stage is so low that a plate current dip is not present, the best way to test for proper neutralization is by injecting a test signal into one circuit and checking for coupling of the signal into another circuit. In the modified grid neutralized circuit shown in figure 7-10, proper neutralization balances out coupling between the input tank circuit and the output tank circuit, but it does not remove all coupling between the plate circuit and the grid-to-cathode circuit. Therefore, a test signal injected into the plate circuit will result in grid-to-cathode signal even with proper neutralization. However, a test signal injected into the plate circuit will not result in a signal in the grid coil with proper neutralization. The presence of a signal in the grid coil can be detected by using an inductive coupling loop. This circuit can also be neutralized by inductively coupling an input signal into the input circuit and adjusting the neutralizing capacitor for minimum signal on the plate circuit.

7. R-F FEEDBACK CIRCUITS

a. INTRODUCTION

An r-f feedback is a very effective means of reducing distortion in a linear power amplifier. Twelve decibels of r-f feedback produces nearly twelve decibels of distortion reduction, and this distortion reduction is realized at all signal levels. However, voltage gain per stage is reduced by the amount of feedback employed, so that with 12 db of feedback the gain is reduced to one-quarter.

b. FEEDBACK AROUND ONE STAGE

Figure 7-11 shows a negative feedback circuit around a one-stage r-f amplifier. The voltage

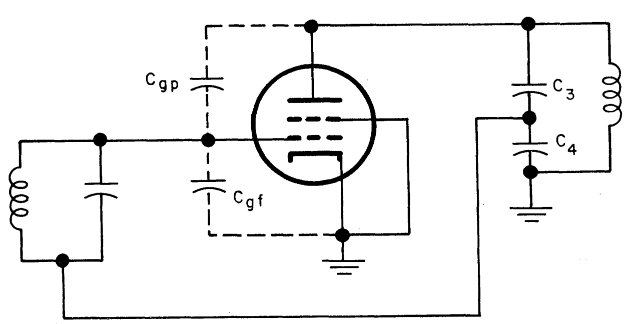

Figure 7-11. One-Stage Feedback with Neutralization

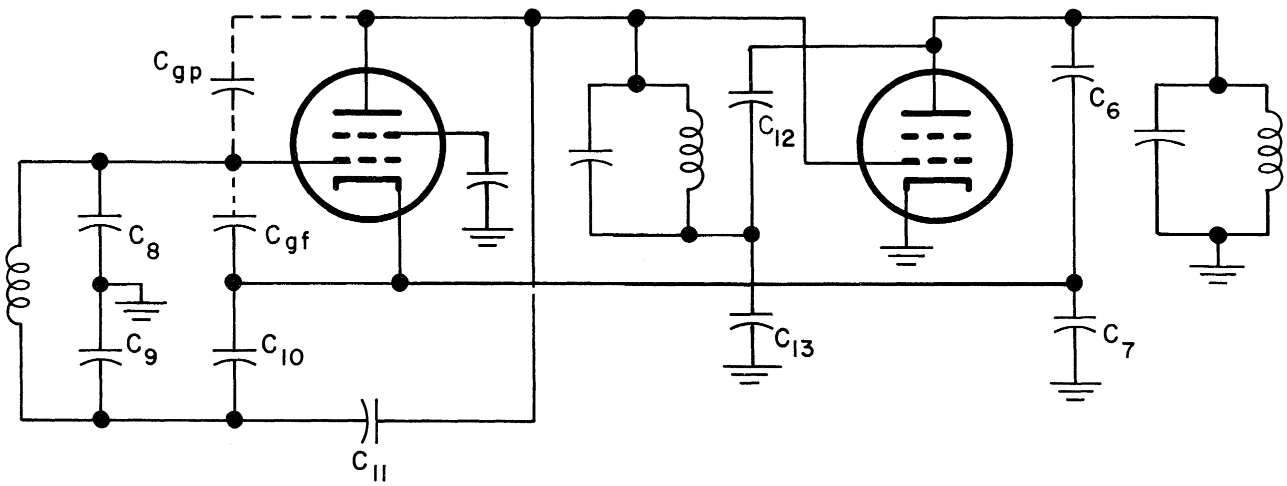

Figure 7-12. Two-Stage Feedback with Neutralization

developed across C_4 is introduced in series with the voltage developed across the grid tank circuit and is in phase opposition to it. The feedback obtainable with this circuit can be varied between zero and 100 per cent by properly choosing the values of C_3 and C_4. It is necessary to neutralize this feedback amplifier, the neutralization requirements being

$$\frac{C_{gp}}{C_{gf}} = \frac{C_3}{C_4}$$

To satisfy the neutralization requirement, it is usually necessary to add capacity from the plate to the grid.

Using this circuit presents a problem in coupling into the grid circuit. Inductive coupling is ideal, but the extra tank circuit complicates the tuning of the power amplifier if several cascaded amplifiers are used with feedback around each. The grid can be capacity coupled to a driver with a high source impedance, such as a tetrode or pentode. However, if this is done, feedback can not be used in the driver because it would cause the source impedance to be low.

c. FEEDBACK AROUND TWO STAGES

Feedback around two r-f stages has the advantage that more of the tube gain can be realized while nearly as much distortion reduction can be obtained. For instance, 12 db feedback around two stages provides about the same distortion reduction as 12 db around each of two stages separately. Figure 7-12 shows a negative feedback circuit around a two stage amplifier with each stage neutralized. The small feedback voltage required is obtained from the voltage divider C_6 and C_7. This feedback voltage is applied to the cathode of the first stage. The feedback divider can be left fixed for a wide frequency range since C_6 is only a few micromicrofarads. For example, if the combined tube gain is 160 and 12 db of feedback is desired, the ratio of C_7 to C_6 may be 400 uuf to 2.5 uuf. Either inductive input coupling or direct capacitive coupling may be used with this circuit, and any form of output coupling can be used.

It is necessary to neutralize the cathode-to-grid capacity of the first tube in the two stage feedback circuit to prevent undesirable feedback coupling to the input grid circuit. The relationship for the circuit which accomplishes this cathode-to-grid neutralization is

$$\frac{C_8}{C_9} = \frac{C_{gf}}{C_{10}}$$

To reduce the voltage across the input tank coil and minimize the power dissipated by the coil, the input circuit can be unbalanced by making C_9 up to five times C_8, as long as C_{10} is increased accordingly. The cathode-to-grid capacity of the first tube can be neutralized by injecting a test signal into the cathode of the tube. The neutralizing bridge is then adjusted for minimum signal as indicated by a detector which is inductively coupled into the input coil.

Except for tubes with very small plate-to-grid capacity, it is necessary to neutralize C_{gp} in both tubes. This neutralization for the second tube is realized by choosing C_{12} and C_{13} so that the ratio C_{12}/C_{13} equals the ratio C_{gp}/C_{gf} in the second tube.

If neutralization of C_{gp} is necessary for the first tube, it is obtained by satisfying the relationship

$$\frac{C_{gp}}{C_{11}} = \frac{C_{gf}}{C_{10}} = \frac{C_8}{C_9}$$

The screen and suppressor of the first stage should be grounded to keep the tank output capacity directly across the interstage circuit. This avoids common coupling between the feedback on the cathode and the interstage circuit.

In a two stage feedback amplifier, the voltage fed back to the cathode of the first stage must be in phase with the grid input signal, measured from grid to ground. If the feedback voltage is not in phase with the grid input signal, the resultant grid-to-cathode voltage increases as shown in figure 7-13. When the output circuit is properly tuned, the resulting grid-to-cathode voltage on the first tube is minimum which will make the voltage across the interstage tank circuit minimum also.

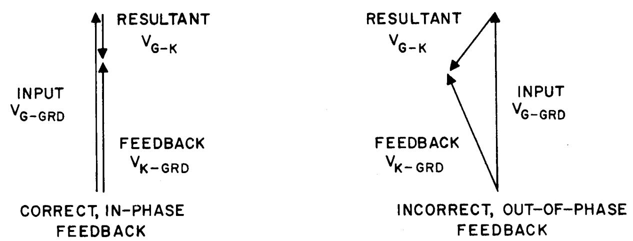

Figure 7-13. Vector Relationship of Voltages for Two-Stage Feedback

8. AUTOMATIC LOAD CONTROL

Automatic load control is a means of keeping the signal level adjusted so that the power amplifier works near its maximum power capability without being overdriven on signal peaks. In AM. systems, it is common to use speech compressors and speech clipping to perform this function. However, in an SSB system these methods are not equally useful because the peaks of the SSB signal do not necessarily correspond with the peaks of the audio signal. Therefore, the most effective means of control is obtained by a circuit which receives its input from the envelope peaks in the power amplifier and uses its output to control the gain of the exciting signal. Such a circuit is an automatic load control (alc) circuit.

Figure 7-14 is a simplified schematic of an alc circuit. This circuit uses two variable gain stages of remote cutoff tubes, such as a 6BA6, operating very similarly to the i-f stages of a receiver with automatic volume control. The grid bias voltage of the variable gain amplifiers is obtained from the alc rectifier connected to the power amplifier plate circuit. The capacity voltage divider steps down the r-f voltage from the power amplifier plate to about 50 volts for the rectifier. A large delay bias is used on the rectifier so that no reduction of gain takes place until the signal level is nearly up to full power capability of the power amplifier. The output of the alc rectifier passes through RC networks to obtain the

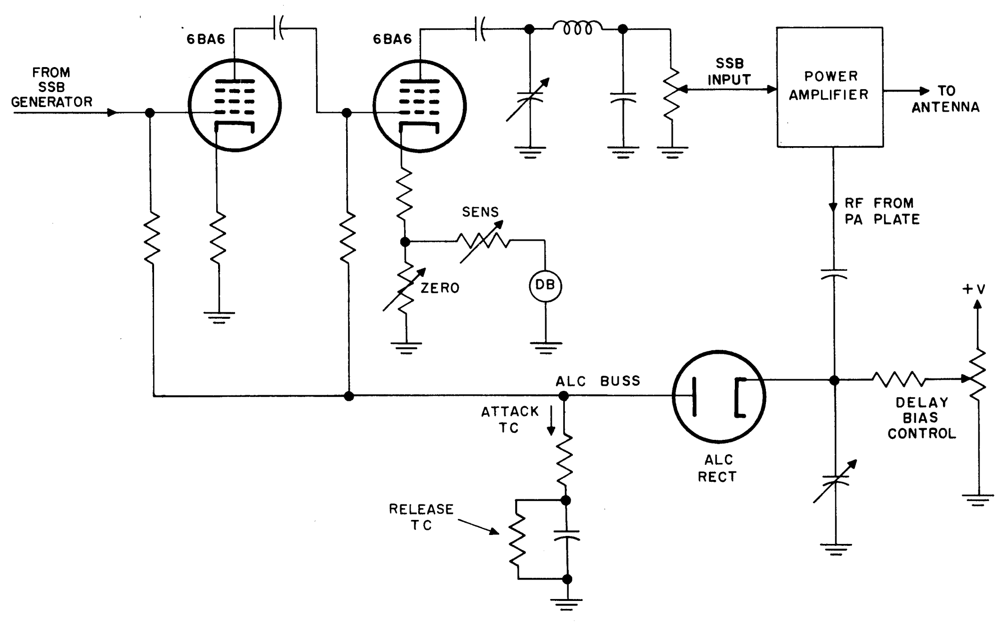

Figure 7-14. Automatic Load Control Circuit

desired attack and release times. Usually a fast attack time, about two milliseconds, is used for voice signals so that the gain is reduced rapidly to remove the overload from the power amplifier. After a signal peak passes, a release time of about one-tenth second returns the gain to normal. A meter calibrated in decibels of compression is used to adjust the gain for the desired amount of load control.

In single channel speech transmission, the alc circuit performs the function of a speech compressor. To do this a range of 12 db is usually provided with control maintained on input peaks as high as 20 db above the threshold of compression. Since the signal level should be fairly constant through the preceding SSB generator, it is unlikely that more than a 12 db range of the alc would be useful. If the signal level varies more than 12 db for the SSB generator, a speech compressor in the input audio amplifier is usually used to limit the range of the signal fed into the SSB generator.

Figure 7-15 shows the effectiveness of the alc circuit in limiting the output signal to the capabilities of the linear power amplifier. An adjustment of the delay bias will put the threshold of compression at the desired level.

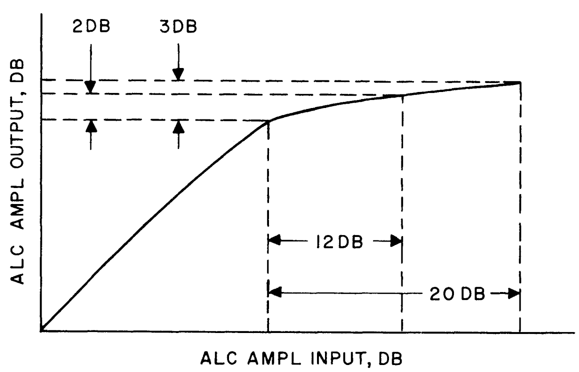

Figure 7-15. Automatic Load Control Performance Curve

9. LINEAR POWER AMPLIFIER TUNING

a. INTRODUCTION

When a power amplifier is operated class C, a pronounced plate current dip and grid current peak are fairly accurate indications of proper tuning. In a linear power amplifier, the use of these indications are limited. For instance, in a class A amplifier there will be no plate current dip; therefore, the class A amplifier output circuit must be tuned for an indication of maximum input to the next stage. In class AB amplifiers, the plate current dip is not always readily detected. This does not mean that conventional tuning procedures will not properly tune a linear amplifier, but tuning a linear amplifier with conventional procedures is much more exacting. One procedure commonly used is to increase the drive to a stage in order to obtain a good plate current dip indication.

In low Q tank circuits, the point of plate current dip is not a true indication of exact resonance because the plate current dip occurs at maximum impedance rather than when the tank circuit is pure resistive. This is especially true for Pi networks and Pi-L networks. For instance, in a network with a Q of ten, the phase angle at maximum impedance is about 17° from unity. Tuning this far from resonance in a linear amplifier with r-f feedback can be much more serious than in a class C amplifier because the phase angle of the feedback voltage is critical.

b. PHASE COMPARISON TUNING

Use of a phase comparator circuit to compare the phase of the input signal to the phase of the output signal affords the most sensitive means of tuning a linear power amplifier stage. This circuit employs a phase discriminator, such as shown in figure 7-16, for phase comparison. A balanced, push-pull voltage is obtained through a 90° phase-shifting network to provide the voltage $E_a + E_b$. In the figure shown, $E_a + E_b$ is in phase with the current in the inductive branch of the grid tank circuit. Since the current in the inductive branch is 90° out of phase with the voltage across the tank circuit, the induced voltage $E_a + E_b$ is also 90°

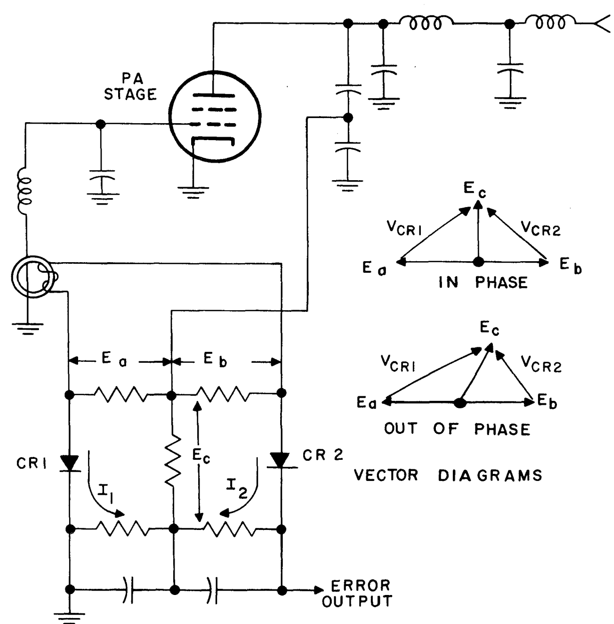

Figure 7-16. Phase Discriminator for PA Tuning

out of phase with the voltage across the tank circuit. From the output of the stage, E_c is obtained. When E_c is exactly 90° out of phase with E_a and E_b, the voltages across the two crystals, CR1 and CR2, are equal in magnitude. Then, the d-c currents in the diode loads are equal and flowing in opposite directions which produces zero output. When E_c is not exactly 90° out of phase with E_a and E_b, the voltages across the two crystals are unequal in magnitude. This will cause the d-c currents in the diode loads to be unequal which will produce an output. The error signal derived from this circuit can be used to operate a zero-center meter for manually tuning the output circuit. When tuned for zero meter indication, the output voltage is exactly 180° out of phase with the input voltage, the condition for true resonance.

The phase discriminator can also be used to obtain an error signal for servo tuning the stage. However, for servo tuning, coarse positioning information is necessary because the phase discriminator responds to harmonic tuning points and because there is insufficient output from the phase discriminator over much of the frequency range. This coarse positioning information can be provided with a coarse follow-up potentiometer which receives information from the exciter frequency control circuits. Such a system requires that the master potentiometer track the tuning curves of the amplifier tank circuits and that sequencing controls be used to initiate and halt coarse positioning at the proper times. Pretuning information can also be derived from the exciter r-f output signal by using a coarse discriminator circuit, such as is shown in figure 7-17. This circuit is a series RC network fed with r-f voltage from the exciter. A servo system then drives the capacitor in the RC bridge to produce zero error signal at the same time it positions a master potentiometer. A second, tuning servo then drives a follow-up potentiometer which is wound to cause the tuning servo to track the tuning curve of the amplifier tank circuit. To automatically tune the amplifier, the error signals from the phase discriminator and the course discriminator can be combined to operate a single servo. The servo system will then operate over the whole frequency range and have a precise zero error signal position, as shown in figure 7-18.

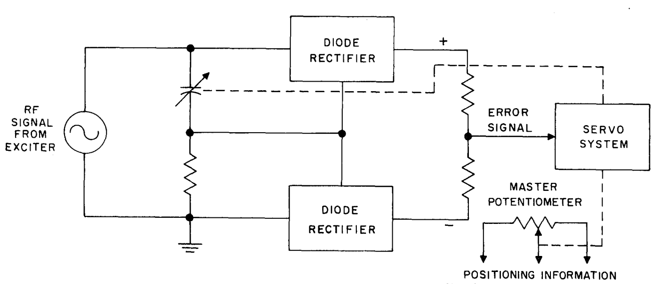

Figure 7-17. Coarse Discriminator for PA Tuning

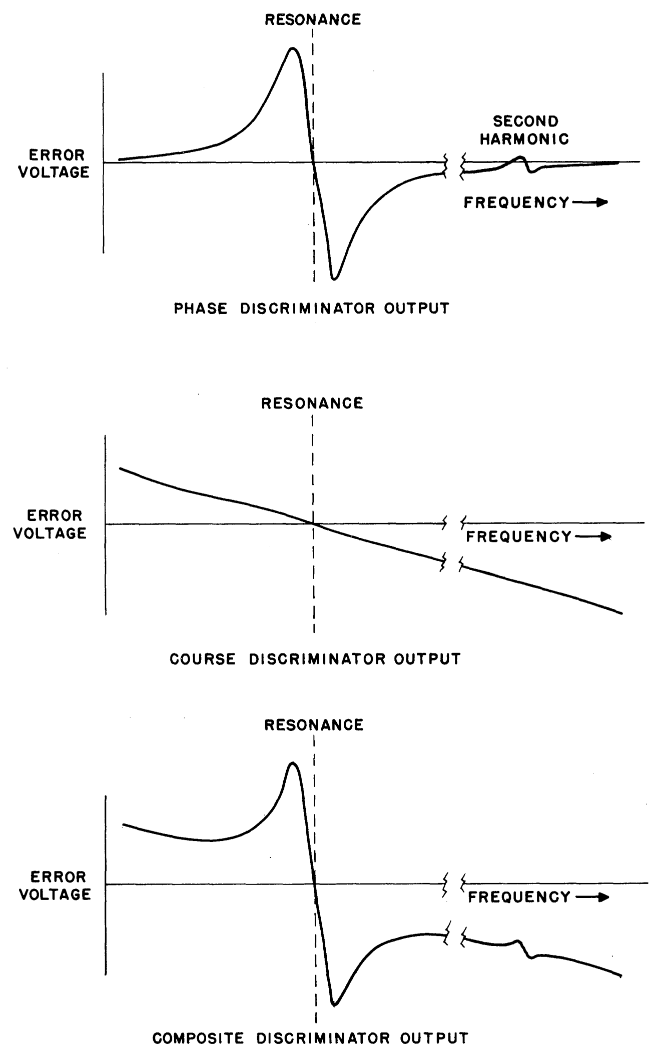

Figure 7-18. Discriminator Output Curves for PA Tuning

c. LOADING COMPARATOR CIRCUIT

Since the voltage gain of a tube is dependent upon the load resistance, a loading comparator circuit, as shown in figure 7-19, can be used to determine proper loading. The loading comparator is designed so that a predetermined ratio between positively rectified grid voltage and negatively rectified plate voltage produces zero error signal output. The power amplifier is then manually or automatically loaded until the error signal output goes to zero. The clamping diode is required so that the circuit will maintain control under light load when the amplifier is driven into plate saturation. In plate saturated operation, the rectified grid voltage will continue to rise with reduced loading while the rectified plate voltage remains relatively constant. This will cause the circuit to lose its sense of direction and result in reducing the load even further. To maintain the sense of direction under this condition, the clamping diode prevents the rectified grid voltage from exceeding a voltage which is proportional to plate current. Therefore, in plate saturated operation, which is similar to class C operation, loading is determined by the ratio of plate current to r-f plate voltage. Proper compromise of the magnitude of the plate, grid, and clamping signal voltages results in a loading comparator that produces proper loading information regardless of the operating conditions, provided the plate circuit is held at resonance.

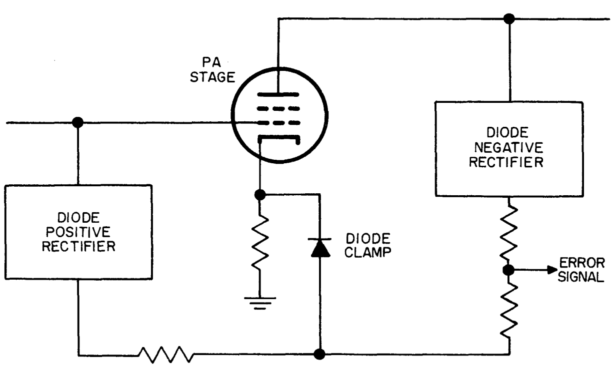

Figure 7-19. Loading Comparator for PA Loading

d. ANTENNA TUNING AND LOADING

The output network of a variable frequency transmitter must be capable of tuning and loading into a transmission line which presents different impedances at different frequencies. This requires output networks which will match a wide range of load impedances with the power amplifier output. In fixed-station equipment, the power amplifier usually works into a transmission line and antenna designed so that the load impedance presented to the amplifier varies over only a limited range. In this case the output network is designed to match the load impedance directly. In mobile and airborne equipment, the power amplifier usually works into a coaxial transmission line terminated with a wide variety of antennas that present unwieldy terminating impedances. In this case an antenna coupler is used which can be located in one of two positions: (1) It can be located near or in the transmitter to provide proper coupling between the transmitter output network and a transmission line which is terminated with a mismatched antenna; (2) It can be located near the antenna to terminate the transmission line properly and provide coupling for maximum power transfer to the antenna. The first method is commonly used in mobile transmitters, and the second method is used in airborne transmitters.

Two power amplifier control functions are required to match properly the load impedances presented to the power amplifier with the power amplifier network. One is a phasing control, or tuning control, which will balance out undesirable reactance and make the load resistive or as nearly resistive as is possible. The other is a load control which will provide the proper terminating impedance. Figure 7-20 shows

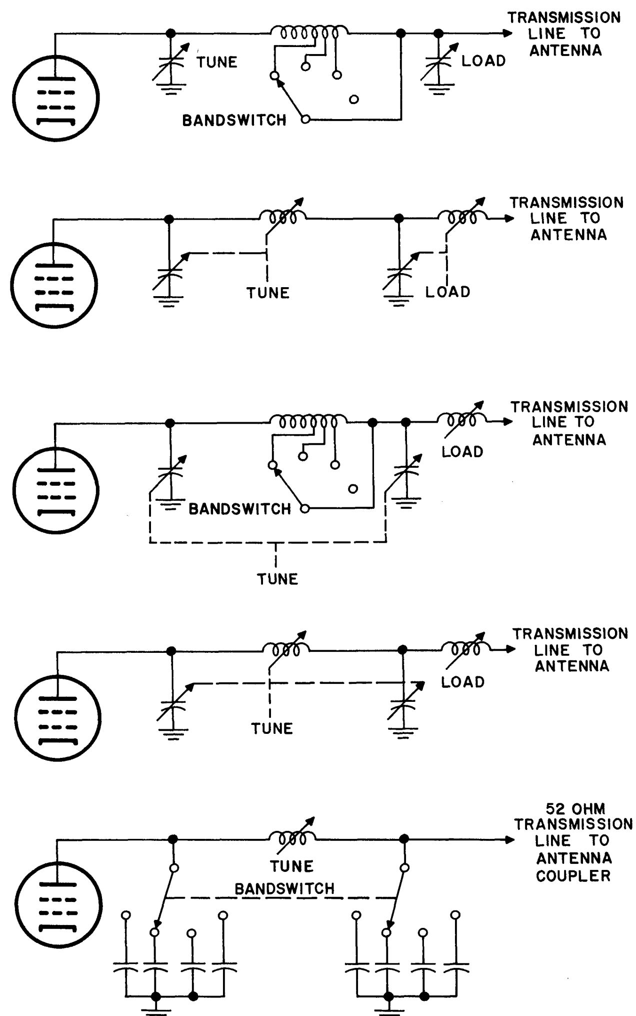

Figure 7-20. Output Network Tuning and Loading Controls

several ways that the output network components can be ganged to provide tuning and loading with two controls. The tuning control is adjusted to produce a plate current dip, which indicates maximum impedance. For more precise tuning and automatic tuning, the phase discriminator circuit is used. The loading control is adjusted to produce a pre-established value of grid voltage and plate current or, in some cases, a pre-established value of screen current and plate current. For more precise loading and automatic loading, the loading comparator circuit is used. The loading and tuning circuits must be so designed that the controls will not lose sense of direction under any circumstances. This is absolutely essential for automatic loading and tuning and is highly desirable for manual loading and tuning.

10. POWER SUPPLIES FOR POWER AMPLIFIERS

Fixed transmitters up to 1 kw usually use a single-phase a-c power source, and larger fixed transmitters usually use a three-phase a-c power source. Mobile equipment may operate from a 6-volt to 28-volt d-c power source using dynamotors or vibrator power supplies to obtain the required high voltages. Airborne equipment usually uses the 400-cycle a-c power source of the aircraft.

In addition to supplying the required d-c voltage and output current, the power supply must have adequate d-c regulation, good dynamic regulation, and low ripple or noise output. Most high-voltage power amplifiers have a varying load characteristic so that good d-c regulation is essential. To reduce ripple and noise, high-voltage filters are used between the rectifier circuit and the power supply load. The filter chokes place a high impedance between the rectifier and the load, making large capacitors necessary in the output side of the filter. These output capacitors supply the rapid variations in load current which are impeded by the filter choke. This is particularly necessary in high-voltage power supplies for linear power amplifier stages.

Vacuum rectifiers can be used for small, low-voltage power supplies which have relatively constant load. Gas-type rectifiers are required where better regulation is necessary. The mercury-vapor rectifier is the most common gas-type rectifier used because it has long life when properly operated. Operating a mercury-vapor rectifier above or below its rated temperature, changes the vapor pressure in the tube and reduces its peak-inverse-voltage capability, making the rectifier more susceptible to arc-back. Equipment which is subject to wide ambient-temperature variations, such as military equipment, uses inert gas rectifiers such as the 3B28 and 4B32. These tubes can be operated in ambient temperatures from -75°C to +90°C, which is frequently a necessary feature. The tube life of the inert gas rectifier, however, is only about one-third the tube life of an equivalent mercury-vapor rectifier. Metallic rectifiers, such as selenium and copper oxide, are frequently used in power supplies delivering less than 100 volts for relay operation, etc.

Rectifier tube life is increased by operating the filaments 90° out of phase with the plate voltage. This minimizes the difference in voltage from each end of the filament to the plate and allows a more uniform emission over the entire filament. A 60° phase difference between the filament and the plate voltage is often used when it is more easily obtained because almost the full advantage of quadrature operation is realized. Tube ratings of some of the larger rectifier tubes are increased for quadrature operation.

Transient voltages and currents which far exceed the steady-state values occur in power supplies when the supply is energized. If these transient peaks exceed the peak-inverse-voltage rating of the tube, an arc-back may result. For this reason, rectifier tubes are often operated so that the normal peak-inverse-voltage does not exceed one-half of the rated peak-inverse-voltage. If this is not possible, a step-start circuit is used which starts the transformer with resistors in series with the primary. After a short time delay, these resistors are shorted out. Some high-voltage rectifiers are started with a resistor in series with the filter capacitor, with the resistor being shorted out after a short time delay. This prevents a transient due to the charging current required to bring the voltage up on the filter capacitor. The added resistance in the circuit prevents excessive current in the rectifier.

11. CONTROL CIRCUITS

Power amplifier control circuits must perform three functions; (1) they must supply circuit control, (2) they must provide equipment protection, and (3) they must provide personnel protection. In small transmitters, the control circuits may consist of nothing more than an on-off switch to supply heater power and a push-to-talk button to apply plate voltage and put the transmitter on the air. In larger equipment, push buttons are usually used to initiate a certain sequence of relay operations which complete a function in the proper manner. Many transmitters, particularly those suitable for remote control, are capable of complete energization from a single push-button control.

The filament on-off switch, or push button, initiates a sequence of functions that applies power to the filaments, starts the cooling system, and energizes time delay circuits that make the power amplifier ready for the application of plate power. When operated to the off position, the power amplifier is shut down.

Filaments of high-power amplifier tubes are energized separately, and, in the case of mercury-vapor tubes, a time delay allows warmup time. The blower is started at the beginning of the starting sequence because the life and reliability of many components is greatly dependent upon operating temperature control. Air interlocks prevent the application of power to high-power tubes before cooling air is present and a blower-off delay maintains cooling air after shutdown. In various power amplifier stages, it is essential that bias voltage be applied before plate or screen voltage is applied. This requires sequencing the application of the bias voltage and the plate voltage as well as interlocks between the two so that the loss of bias voltage will result in removing the plate voltage.

Power amplifier control circuits are sequenced and interlocked so that everything else must be on and functioning before the high-voltage plate transformer is energized. Certain power tetrodes require that screen voltage be applied simultaneously with plate voltage to prevent excessive screen dissipation. To prevent high current and high-voltage transients, plate voltage is often applied through step-start circuits which place resistors for a short time in the power supply circuit.

Medium-power and high-power tubes are nearly always protected from excessive plate current by overload relays. These relays remove the high-voltage primary power if the plate current exceeds a preset value. Many overloads that occur during normal operation will clear themselves when the high voltage is removed. For this reason, large power amplifiers are usually provided with an overload recycle circuit. This circuit brings the power amplifier back on after an overload. If the overload reoccurs, the power amplifier will again shut down. The number of recycles before shutdown can generally be preset with a recycle counting switch.

12. TUBE OPERATING CONDITIONS FOR R-F LINEAR POWER AMPLIFIERS

a. GENERAL

SSB amplifiers provide linear amplification and operating conditions similar to those of audio amplifiers. There is one fundamental difference, however, between audio and r-f linear amplifiers. This is that the input and output voltages of a tuned r-f amplifier are always sine waves because the tuned circuits, if they have adequate Q, make them so. Therefore, the distortion in an r-f amplifier results in distortion of the SSB modulation envelope and not in the shape of the r-f sine wave. This can be restated that distortion in an r-f linear amplifier causes a change in gain of the amplifier when the signal level is varied. The greatest difference between an audio amplifier and an r-f linear amplifier is in the grid driving power requirements when driving into grid current. In the audio amplifier, the driver must supply all of the instantaneous power required by the grid at the peak of the grid swing. To deliver this peak power, the audio driver must be capable of delivering average sine wave power equal to one-half of the peak power. In an r-f linear amplifier, the tank circuit averages the power of the r-f cycle due to its "flywheel" effect so that the driver need only be capable of delivering the actual average power required, and not the peak. With these reservations in mind, examination of the audio or modulator data of a tube will give a good idea of its r-f linear power amplifier operating conditions.

b. CLASS A R-F LINEAR AMPLIFIERS

In low-level amplifiers, where the output signal voltage is less than 10 volts, small receiving type tubes, such as the 6AU6, are very satisfactory for class A service. For voltage levels above 10 volts, the 4X150A is the best choice for class A operation because it has short leads, low plate-to-grid capacitance, and high transconductance. Class A amplifier tubes should be operated in as linear a portion of the plate characteristic curves as is practical. This can be done by inspecting the plate characteristic curves of the tube. Usually the static plate current which results in near maximum plate dissipation is the best. The maximum output voltage should be kept to about one-tenth the d-c plate voltage or less to obtain signal-to-distortion ratios of 50 db or better. The d-c plate voltage regulation for class A operation is seldom of importance and cathode bias and screen dropping resistors are commonly used. Even with tubes such as the 6AU6 and the 4X150A which have short leads and low grid-to-plate capacitance, it is desirable to load the input and output circuits to 5000 ohms when operating up to 30 mc.

c. CLASS AB R-F LINEAR AMPLIFIERS

In the power range from 2 watts to 500 watts, class AB_1 is normally used. This class of operation is very desirable because distortion due to grid current loading is avoided and because high power gain can be obtained. At present, tubes are not available which will give low distortion with good plate efficiency operating class AB_1 at power levels above 500 watts. Therefore, for higher power levels class AB_2 operation is used.

For class AB operating conditions with a given screen voltage and given plate load, there is one value of static plate current which will give minimum distortion. The optimum value of static plate current for minimum distortion is determined by the sharpness of cutoff of the plate current characteristic. Grid bias is then set to produce the optimum static plate current.

This optimum point is determined from the load line on a set of constant current plate current curves. Values obtained from this curve are then plotted to obtain the plate current vs grid voltage curve shown in figure 7-21. This curve is the dynamic characteristic of the tube. By projecting the most linear portion of the curve to intersect with the zero plate current line, the grid bias is determined. This point of intersection is often referred to as the projected cutoff. The static plate current which will flow with this grid bias is the proper static plate current for minimum distortion. This procedure is used in audio amplifier design and is nearly correct for r-f linear amplifier design. Perhaps a more accurate procedure for determining the proper bias for r-f amplifiers is to choose the point Q so that the slope of the curve at Q is one-half the slope of the major linear portion. This will allow the amplifier to operate class A with small signals and deliver power over both halves of the cycle. With a large signal, the tube delivers power over essentially one-half the cycle. Then the change in plate current relative to plate voltage swing over half the cycle will be half as much for small signals as it is for large signals and linear operation is obtained at all signal levels.

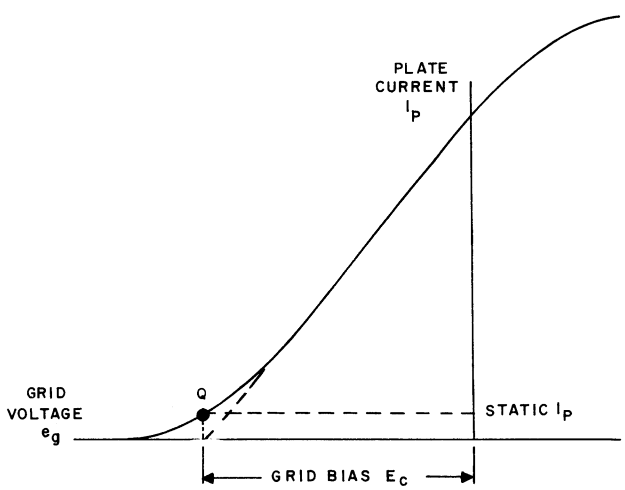

Figure 7-21. Optimum Static Plate Current for Linear Operation

The screen voltage of a tetrode tube has a very pronounced effect on the optimum static plate current, because the plate current of a tube varies approximately as the three-halves power of the screen voltage. For example, raising the screen voltage from 300 to 500 volts will double the plate current. The shape of the dynamic characteristic will stay nearly the same, however, so that the optimum static plate current for minimum distortion is also doubled. A practical limit is reached because high static plate current causes excessive static plate dissipation.

In practice, it is found that the static plate current determined by the above method is so high that plate dissipation is near or beyond the maximum rating of the tube when using desired d-c plate voltage. For example, one of the better medium power triodes for linear amplifier service, the 3X2500A3, requires approximately .5 ampere of plate current for minimum distortion. Using a desirable plate voltage of 5000 volts, static plate dissipation is 2500 watts, which is the maximum rated plate dissipation for the tube. For this reason, it is often necessary to operate the tube below the optimum static plate current, which can be done without causing appreciable distortion. In tetrodes, the optimum static plate current is a function of screen voltage, and the high screen voltages required for class AB_1 operation usually require an excessive amount of plate current for minimum distortion. A choice must then be made between operating the tube at lower than optimum static plate current or using a lower screen voltage and driving the tube into the grid current region, a second principal cause of distortion.

d. ESTIMATING TUBE OPERATING CONDITIONS

The operating conditions of a tube operating class AB in an r-f linear power amplifier can be estimated from the load line on a set of constant plate current curves for the tube, as shown in figure 7-22.

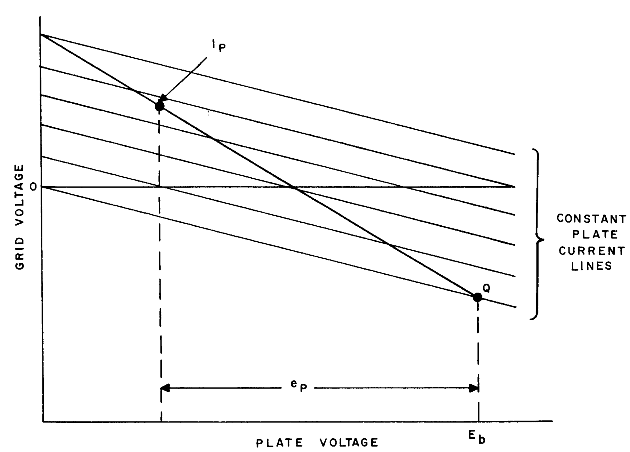

Figure 7-22. Graphical Determination of Tube Operating Conditions

From the end point of the load line, the instantaneous peak plate current, i_p, and the peak plate voltage swing, e_p, can be established. From these two values, the principal plate characteristics can be estimated by using the following relationships for a single-frequency test signal:

d-c plate current, $I_B = \frac{i_p}{\pi}$

plate input watts, $P_{in} = \frac{i_p E_B}{\pi}$

average output watts and PEP, $P_o = \frac{i_p e_p}{4}$

plate efficiency, $Eff = \frac{\pi e_p}{4 E_B}$

For a standard two-frequency test signal the relationships are:

d-c plate current, $I_B = \frac{2 i_p}{\pi^2}$

plate input watts, $P_{in} = \frac{2 i_p E_B}{\pi^2}$

average output watts, $P_o = \frac{i_p e_p}{8}$

PEP watts, $P_o = \frac{i_p e_p}{4}$

plate efficiency, $Eff = \left(\frac{\pi}{4}\right)^2 \frac{e_p}{E_B}$

An actual tube with moderate static plate dissipation will have operating characteristics similar to those shown in figure 7-23 for the single-tone and two-tone signals. Plate dissipation and efficiency at maximum signal level are affected little by even rather high values of static plate dissipation. In practice, the peak plate swing is limited to something less than the d-c plate voltage in order to avoid excessive grid drive, excessive screen current, or operation in the nonlinear plate current region. Most tubes operate with an efficiency in the region of 55 to 70 per cent at peak signal level.

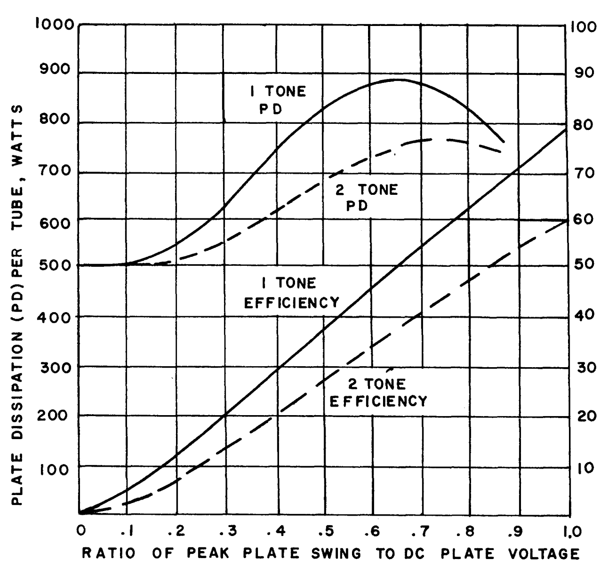

Figure 7-23. Efficiency and Plate Dissipation for Class AB Operation

13. DISTORTION

a. CAUSES OF R-F LINEAR POWER AMPLIFIER DISTORTION

The principal causes of distortion are nonlinearities of the amplifier tube plate current characteristic and grid current loading. In order to confine distortion generation to the last stage or two in a linear power amplifier, all previous stages are operated class A.

The generation of distortion products due to the nonlinear characteristics of the amplifier tube can be derived from the transfer characteristic of the tube, also called the dynamic characteristic, as shown in figure 7-24. The shape of this curve and the choice

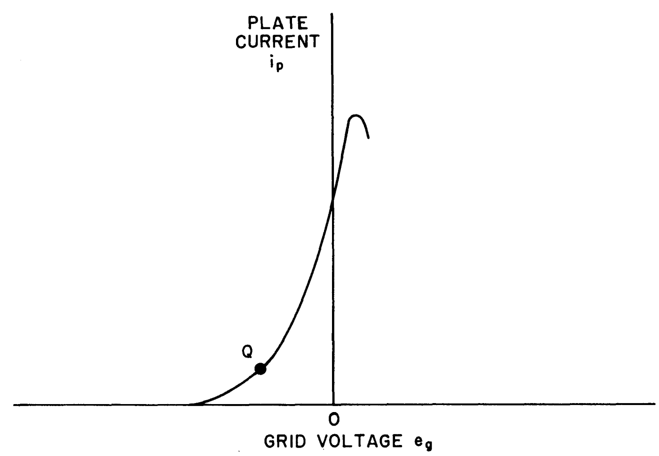

Figure 7-24. Typical PA Tube Transfer Characteristic Curve

of the zero signal operating point, Q, determine the distortion which will be produced by the tube. A power series expressing this curve, written around the zero signal operating point, contains the coefficients of each order of curvature, as shown in the following expression:

$$i_p = k_o + k_1 e_g + k_2 e_g^2 + k_3 e_g^3 + k_4 e_g^4 + k_5 e_g^5 + \ldots k_n e_g^n$$

In this expression, i_p represents instantaneous plate current, k_1, k_2, etc, the coefficients of their respective terms, and e_g the input grid voltage signal. The values for the coefficients are different for every power series written around different zero signal operating points. By making the input signal, e_g, consist of two equal amplitude frequencies with a small frequency separation, the distortion products of concern in linear amplifiers can be obtained. Figure 7-25 shows the spectrum distribution of the stronger plate current components. It is seen that tuned circuits can filter out all products except those which are near the fundamental input frequencies. This removes all of the even-order intermodulation products and the harmonic products. The odd-order intermodulation products fall close to the original frequencies and

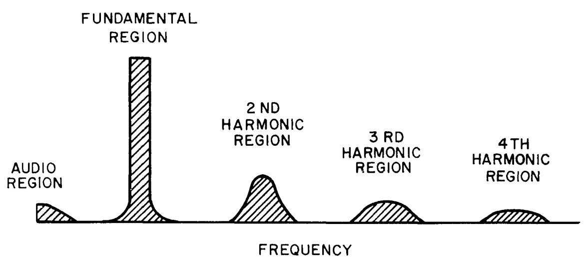

Figure 7-25. Spectrum Distribution of Products Generated in PA Stage

cannot be removed by selective circuits. Figure 7-26 shows these odd-order products which fall within the passband of selective circuits. The inside pair of intermodulation distortion products are third-order, the next fifth-order, seventh-order, etc. The first and most important means of reducing distortion, then, is to choose a tube with a good plate characteristic and choose the operating condition for low odd-order curvature (see paragraph 12c, chapter 7).

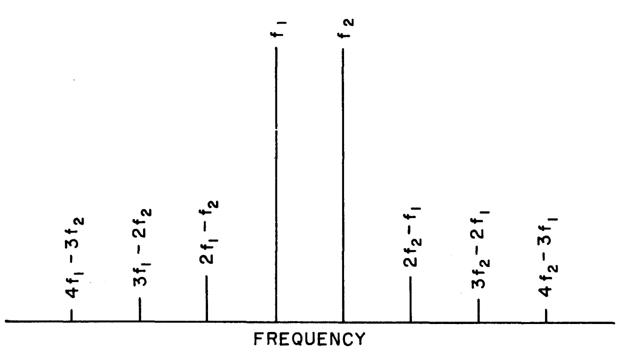

Figure 7-26. Odd-Order Intermodulation Products Causing SSB Distortion

The nonlinearity caused by grid current loading is a function of the regulation of the grid driving source. In general, this regulation with varying load is poor in linear amplifiers. It is common practice to use swamping resistors in parallel with a varying grid load so that the resistance absorbs about ten times the power that the grid of the tube requires. This provides a low, constant driving source impedance and improves linearity at the expense of increased driving power.

The instantaneous plate current of all tubes drops off and causes distortion when the instantaneous plate voltage is low. The main reason for this drop is that current taken by the grid and screen is robbed from the plate. In all but a few transmitting tetrodes, the plate can swing well below the screen voltage before plate saturation occurs. However, when the plate swings into this region, the instantaneous plate current drops considerably. If distortion requirements are not too high, the increased plate efficiency realized by using large plate swings can be realized. However, to minimize distortion, the allowable plate swing may have to be reduced.

b. DISTORTION REDUCTION

There is a need for reduced levels of intermodulation distortion from r-f linear power amplifiers used in SSB systems. This need exists not because the distortion noticeably reduces the intelligibility of the SSB signal, but because distortion products outside of the channel width necessary for transmission of intelligence interferes with adjacent channel transmission. The distortion of some of the early SSB power amplifiers was so great that voice channels were placed a full channel width apart to avoid adjacent channel interference. Recent power amplifier developments permit adjacent channel operation, using power amplifiers with signal-to-distortion ratios of from 35 db to 40 db. However, power amplifiers with signal-to-distortion ratios of from 45 db to 50 db would further increase the utility of single sideband.

There are two basic means of reducing distortion to levels better than is obtainable from available tubes. These are r-f feedback and envelope distortion canceling.[1] An r-f feedback is very effective and quite easy to obtain (see paragraph 7, chapter 7). Ten decibels of r-f feedback will produce nearly 10 db of distortion reduction which is realized at all signal levels. Envelope distortion canceling has an inherent weakness because it depends upon envelope detection for its feedback signal. This means that distortion canceling must be instantaneous to be perfect. Since some delay is inherent in the envelope detector and feedback loop, the effectiveness of this circuit depends upon how short the time delay can be made. Development work indicates that a combination of r-f feedback

[1] W. B. Bruene, "Distortion Reduction Means for Single-Sideband Transmitters," IRE Proceedings, Dec. 1956

and envelope distortion canceling will provide more distortion canceling than either method separately. Using 10 db of r-f feedback around all three stages of a 20-kw PEP power amplifier, and a signal synthesized from the input envelope to grid modulate the first stage, a better than 50 db signal-to-distortion ratio has been obtained for all distortion products at any signal level up to the 20-kw PEP.

c. LINEARITY TRACER

The linearity tracer consists of two SSB envelope detectors, the outputs of which connect to the horizontal and vertical inputs of an oscilloscope, as shown in figure 7-27. A two-tone test signal is normally used to supply an SSB modulation envelope, but

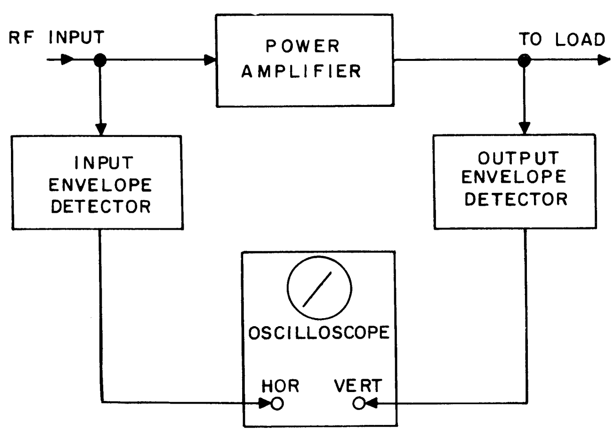

Figure 7-27. Linearity Tracer, Block Diagram

any modulating signal that provides from zero to full amplitude can be used. Even speech modulation gives a satisfactory trace. This instrument is particularly useful for monitoring the signal level and clearly shows when the amplifier is overloaded. It can also serve as a voltage indicator which can be useful for making tuning adjustments. The linearity trace will be a straight line regardless of the envelope shape if the amplifier has no distortion. Overloading, inadequate static plate current, and poor grid circuit regulation are easily detected with the linearity tracer. The instrument can be connected around any number of power amplifier stages, or it can be connected from the output of the SSB generator to the power amplifier output to indicate the over-all distortion of the entire r-f circuit.

A circuit diagram of an envelope detector is shown in figure 7-28. Any type of germanium diode may be used for the detector, but the diodes in each of the two required envelope detectors must be fairly well matched. Using matched diodes cancels the effect

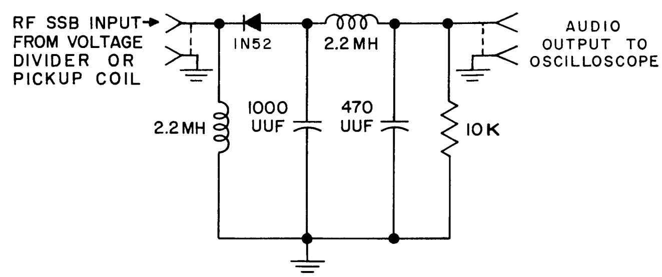

Figure 7-28. Envelope Detector, Schematic Diagram

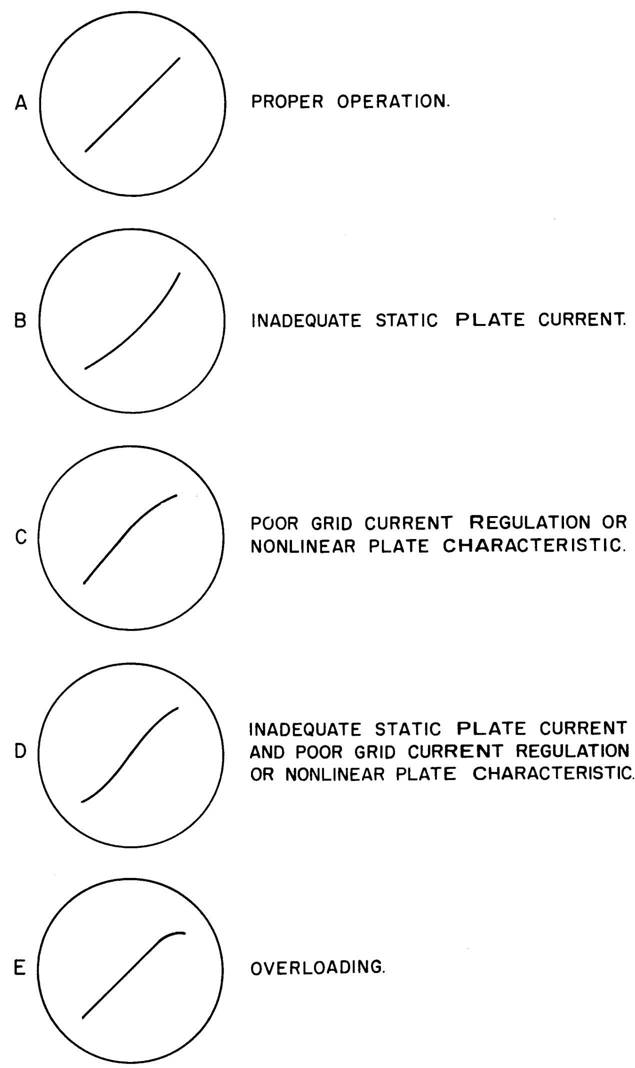

Figure 7-29. Typical Linearity Traces

on the oscilloscope of their nonlinearity at low signal levels. A diode load of from 5K to 10K minimizes the effect of diode differences. Operation of both detectors at approximately the same signal level is important so that diode differences will cancel more exactly. It is desirable to operate the envelope detectors with a minimum of 1 volt input to further minimize diode differences. It is a convenience to build the detector in a small shielded enclosure with coaxial input and output connectors. Voltage dividers can be similarly constructed so that it is easy to patch in the desired voltage stepdown from the voltage sources. A pickup coil on the end of a short coaxial cable can be used instead of voltage dividers to obtain the r-f input signal.

The frequency response and phase-shift characteristics of the oscilloscope vertical and horizontal amplifiers should be the same and should be flat to at least twenty times the frequency difference of the two test tones. Excellent high-frequency characteristics are necessary because the rectified SSB envelope contains harmonics to the limit of the envelope detector's ability to detect them. Inadequate frequency response of the vertical amplifier may cause a little foot to appear at the lower end of the trace. If the foot is small, it may be safely neglected. Another effect which may be encountered is a double trace, but this can usually be corrected with an RC network between one detector and the oscilloscope.

The best way to test the linearity tracer is to connect the inputs of the envelope detectors in parallel. A perfectly straight diagonal trace on the oscilloscope will result if everything is working properly. One of the detectors is then connected to the other source through a voltage divider which will not result in appreciable change in the setting of the oscilloscope gain controls.

Figure 7-29 shows some typical linearity traces which might be observed in linear power amplifier operation. Figure 7-29a indicates proper linear operation. Inadequate static plate current in class A amplifiers, class AB amplifiers, or mixers will result in the trace shown in figure 7-29b. This condition can be remedied by reducing the grid bias, raising the screen voltage, or lowering the signal level through mixers and class A amplifiers. The trace shown in figure 7-29c is caused by poor grid circuit regulation when grid current is drawn, or by nonlinear plate characteristics of the tube at large plate swings. This can be remedied by using more grid swamping or lowering the grid drive. The trace shown in figure 7-29d is a combination of the traces shown in b and c. The trace shown in figure 7-29e is caused by overloading the amplifier. It can be remedied by lowering the signal level.