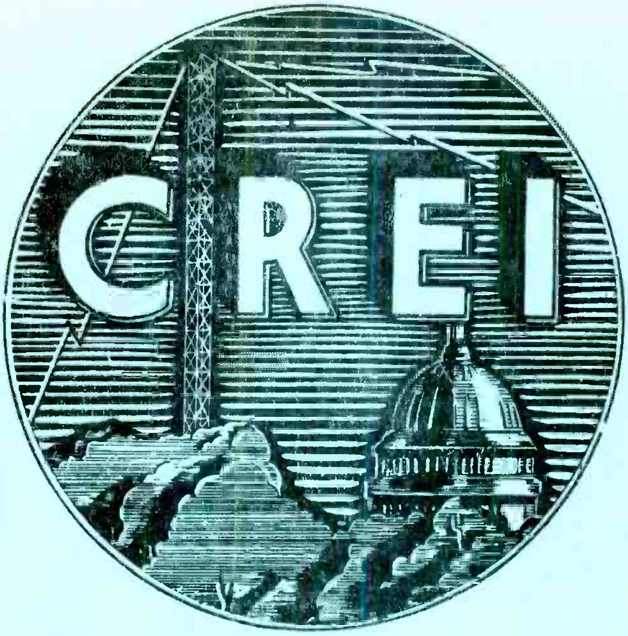

SPECIALIZED
TELEVISION ENGINEERING

TELEVISION TECHNICAL ASSIGNMENT

DESIGN OF OUTPUT CIRCUITS FOR TRANSMITTER POWER AMPLIFIERS

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DESIGN OF OUTPUT CIRCUITS FOR TRANSMITTER POWER AMPLIFIERS

FOREWORD

In the early days of the vacuum tube, engineers were quick to recognize its ability to amplify faithfully voltages of various shapes and frequencies. The telephone companies particularly were alert to its possibilities, because heretofore they had been employing with limited success a carbon-button transmitter and receiver as an audio amplifier, and the vacuum tube was a "natural" for such a task.

The result was the Class A amplifier, in which the tube (or tubes) operated over a limited, linear portion of its characteristic, and thereby provided essentially faithful amplification, but operated at low power output and efficiency. For broad-band amplification, as in audio and video applications, the Class A amplifier is still a very important unit.

However, the vacuum tube was also recognized as preeminent in the field of high-frequency generation of power. Here but a single carrier frequency is involved, or at most, a narrow band of frequencies, as when the carrier is modulated. In such applications, the tube can safely be operated over a much greater and more nonlinear portion of its characteristic, for tuned circuits can be employed to filter out the harmonics generated, and pass only the single carrier frequency desired.

The result is the Class B and Class C amplifier; devices that operate with much greater grid bias and grid swing, and are capable of producing far more power output at much higher efficiency than the Class A amplifier. The mode of operation is more involved in nature, but the calculations and theory are not difficult, and can readily be mastered.

This assignment deals essentially with the analysis and design of Class B and linear amplifiers of the r.f.

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or narrow band type. Linearity refers to the proportionality between grid input and plate tuned-circuit output, even though the actual output of the tube into the tuned circuit is in itself considerably distorted.

You will find this assignment not only interesting and clear, but also exceedingly useful. This is because the units discussed are actual practical equipment to be found in broadcasting stations, as well as in a host of special applications where the Class B and linear amplifiers are particularly suited. A knowledge of the equipment, such as is furnished by this assignment, will therefore be of great value to the practicing radioman.

E. H. Rietzke,
President.

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TECHNICAL ASSIGNMENT

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DESIGN OF OUTPUT CIRCUITS
FOR TRANSMITTER POWER AMPLIFIERS

In order to deliver the maximum power output a vacuum tube must work into a specified load impedance. In the case of the Class A R.F. amplifier of a receiver, or a Class A audio amplifier, the amount of the load impedance is the principal consideration and the impedance may consist of almost any convenient device; it may even be an ordinary resistance, as in a resistance coupled amplifier, or the load may consist of a loud speaker coupled to the tube through an impedance matching transformer.

In the case of the transmitter R.F. power amplifier the load requirements are much more specific. In the first place, due to the very low operating efficiency, Class A amplification is seldom used at radio frequency, the R.F. amplifier usually operating either Class B or Class C. If the input to the amplifier is simple unmodulated radio frequency, the amplifier is ordinarily operated Class C due to the higher efficiency; if the amplifier stage is to be used as a modulated amplifier, modulation being effected in the plate circuit, it is also operated Class C due to the linear relation between E_p and I_p in such an amplifier. However where the input is in the form of *modulated R.F.*, so that the amplifier must operate as a linear amplifier with a minimum of distortion in the input, the Class B or "Linear" method of amplification is employed. That is the type of operation to be assumed in this discussion. (It should be noted at this point that the Doherty high efficiency R.F. amplifier is not considered in this discussion. It is taken up in detail in a later assignment in the special broadcast series.)

The manner in which the plate current (I_p) follows the variations in grid excitation voltage (E_s) is shown in Figure 1. It will be observed that even though the carrier is modulated approximately 75 per cent the audio frequency variations are still within the straight portion of the E_gI_p characteristic curve and there is negligible audio distortion. In this particular case if the percentage of modulation were increased to 100 per cent, both the upper and low-

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er bends of the curve would be entered and a certain amount of distortion would result on the peaks of modulation. From the curves however it appears that the resulting distortion would not be serious. It will be seen that the driving stage which is supplying E_s must have adequate reserve power to carry the added load when the grid of the power amplifier swings actually positive and the input resistance drops with the flow of grid current.

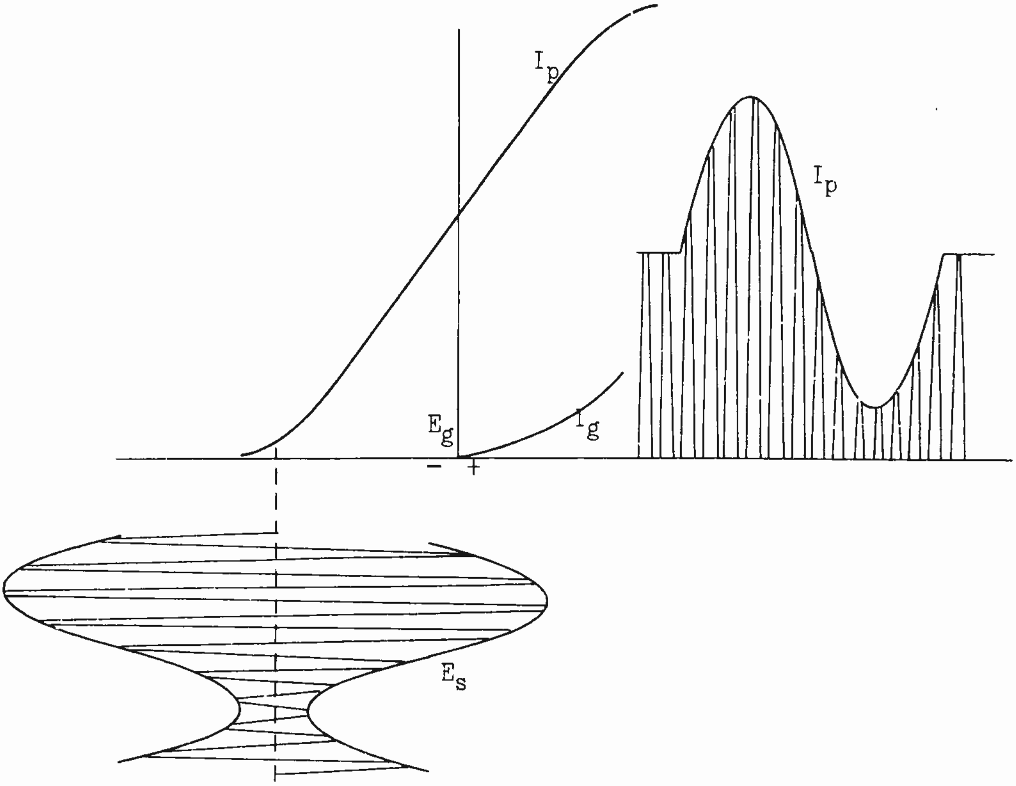

Fig. 1.

Figure 2 shows, on a larger scale, the actual operation of the tube during each radio frequency cycle of E_s. Figure 1 shows clearly how the *audio* frequency distortion of the modulated R.F output is kept to a minimum. Figure 2 shows all the individual tube voltages and currents and clearly demonstrates that considerable radio frequency distortion in the form of harmonic components will exist in the output. The manner in which I_p departs from the sinusoidal form of E_s is due to the non-linear form of the E_gI_p curve as the plate current approaches a low value. E_p is 180° out of phase with E_s, I_p is in phase with E_s, and I_g

flows only during the instants in which E_g is actually positive. Since in Figure 2, E_g is positive for only a very short time and the positive amplitude is low, I_g is small During the peaks of modulation as shown in Figure 1 this would not be the case, and the peak grid current could reach quite large amplitudes.

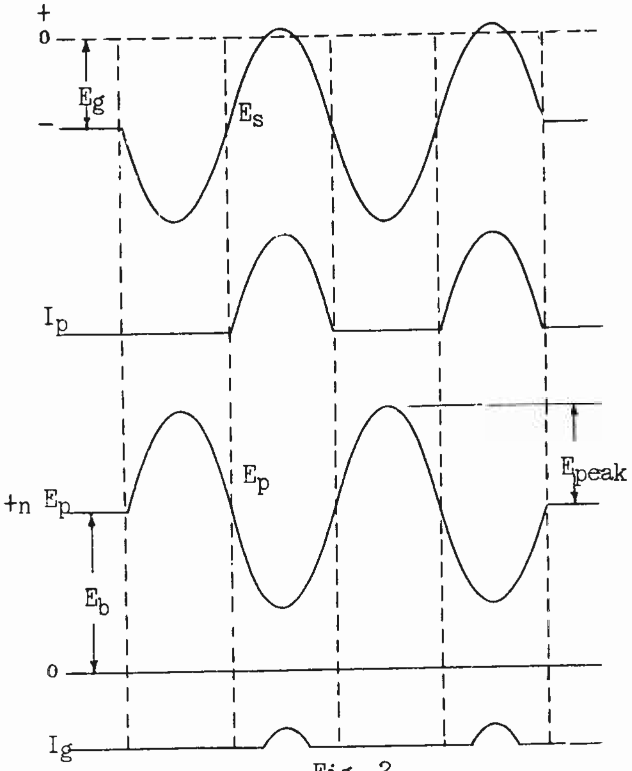

Fig. 2.

Even though audio frequency distortion in the output is kept within negligible values, it is still essential that steps be taken to minimize the radio frequency harmonic component in the output so that harmonics are not radiated to any appreciable extent. It is seen from the curves of Figures 1 and 2 that, regardless of whether the carrier is modulated or not, due to the fact that plate current is cut off for one-half cycle, and due to the lower bend of the E_gI_p curve while plate current does flow, there will be considerable radio frequency distortion which adjustments of tube voltages and load impedance cannot eliminate. In fact, with average operating efficiencies the 2nd harmonic component in the tube output may approach .7 (70 per cent) of the fundamental and the amplitude of the 3rd harmonic component may approach .3 (30 per cent) of that of the fundamental. As a rule harmonics higher than the third are unimportant since any steps taken to reduce the lower order harmonics will also reduce the higher ones.

To prevent excessive radiation of harmonics, these harmonic components must be reduced to a small fraction of 1 per cent before reaching the antenna. This is done in the load circuit. If the output circuit consists of a simple

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resistance, the load impedance requirements for maximum tube output can be satisfied. However the output will contain all the harmonic components as mentioned above, and the output current will be I_p as shown in Figure 2. This is not satisfactory. Thus in practice the output load consists of a resonant tank circuit LC operated at unity power factor. The circuit is shown in Figure 3 and the operating vector in Figure 4.

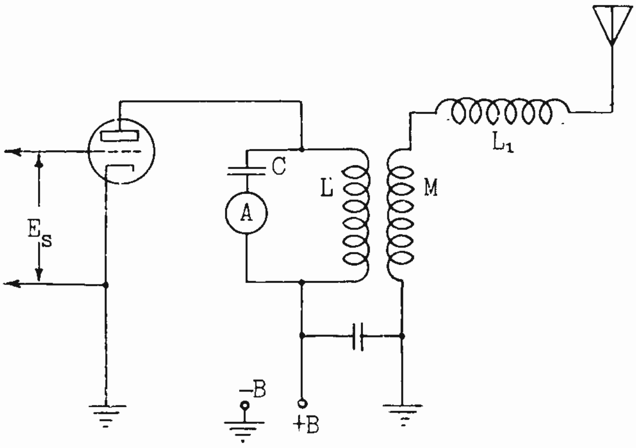

Fig. 3.

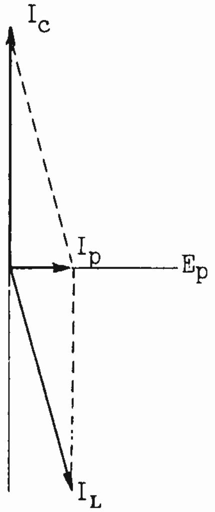

Fig. 4.

Figure 4 assumes that essentially all the effective circuit resistance is in L so that X_L and R are in-series, $I_L = E_p/\sqrt{R^2 + X_L^2}$, and I_L is something less than 90° out of phase, (lag), with E_p. In the capacity branch $I_c = 2\pi FCE_p$, and leads E_p by 90°. (This demonstrates very clearly how R_L—output load impedance—is a function of the effective circuit resistance; and since this effective resistance is partly determined by the reflected resistance of the antenna which in turn is determined by the coupling between L and M, it will be seen that the impedance into which the tube operates can be controlled by the antenna coupling and by the antenna resistance. With a given antenna, the tighter the coupling the lower the effective value of R_L and the higher I_p becomes. It is assumed of course that with variations of coupling the circuit LC is retuned to maintain unity power factor.)

Figure 4 shows clearly that with reasonable values of L, C and R, the tank current, I_L or I_c, will be considerably higher than I_p. It is the ratio of I_t (tank current) to I_p that determines the degree to which the harmonic components

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in the output circuit will be suppressed, the greater this ratio the smaller the harmonic current with relation to the fundamental current in L. This is usually expressed as a ratio between Volt-Amperes/Watts. This will be explained.

Figure 2 shows the manner in which E_p varies with variations of I_p, caused of course by the variations of E_g due to E_s. It has previously been shown that the A.C. component of plate voltage, E_p, is a function of R_L. Thus E_p is also a function of the operating efficiency. This may be expressed as follows:

$$E_{peak} = \frac{4\ E_b \cdot \text{Efficiency}}{\pi} \qquad \text{Eq. 1.}$$

where E_{peak} is the peak voltage variation above or below the normal D.C. value, E_b is the D.C. plate voltage, and $\pi = 3.14$. Thus if a tube is operating Class B with D.C. plate potential of 10,000 volts, power output of 2000 watts, and efficiency of 33 per cent, the peak plate voltage variation will be,

$$E_{peak} = \frac{4 \times 10{,}000 \times .33}{3.14} = 4204 \text{ volts} \qquad \text{Eq. 2.}$$

The RMS value of E_p will be $.707\ E_{peak} = .707 \times 4204 = 2972$ volts Assume that at the operating frequency L and C are so selected as to have a reactance of 285 ohms. Then the radio frequency tank current, as indicated by Ammeter A (Figure 3), will equal $E/X_c = 2972/285 = 10.4$ amperes. With power output of 2000 watts and efficiency of 33 per cent, the D.C. power input to the plate is $2000/.33 = 6060$ watts. Average plate current equals input $\text{Watts}/E_b = 6060/10{,}000 = .606$ ampere. Since I_p is approximately one-half sine curve, the peak plate current $I_{peak} = I_{average}/.318 = .606/.318 = 1.9$ amperes.

(The factor .318 is derived from the relation between average and peak values in a sine curve, .636. Since current flows for only one-half cycle, the peak value must be twice as great to produce a given average current as in a current containing both half-cycles. Since the factor under discussion is to be used as a denominator, to allow a quotient twice as great, the factor itself must be divided by two. Thus the relation between average and peak values for the half-wave direct current becomes $.636/2 = .318$.)

The volt-ampere product (VA) in the tank circuit is equal to $I_t E_p$. The effective or RMS value of E_p as calculated above is 2972 volts, and I_t is 10.4 amperes. $VA = 10.4 \times 2972 = 30{,}900$. The power output is 2000 watts. There-

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fore VA/W = KVA/KW = 30.9/2 = 15.5.

Since in transmitters quite high voltages, currents, and power outputs are encountered, KVA/KW (kilovolt-amperes/kilowatts), is the term usually employed instead of volt-amperes/watts. Of course the ratio will be the same with both expressions. This ratio will be designated as K. That is K = VA/W = KVA/KW for the tank circuit. It will be seen that in this case the ratio K is quite large, (15.5).

A consideration of Figure 3 will show why a large value of K (KVA/KW), in the plate tank circuit tends to reduce the percentage of R.F. harmonic component in the output. In order to obtain a large value of K for a given power output, KVA must be large. KV is fixed by the D.C. plate voltage and the operating efficiency, therefore A, (I_t), must be made quite large compared with I_p. That can be done only by making the values of X_c and X_L small; that is, by using a large capacity and small inductance. With large capacity, the harmonic components (higher frequencies) pass through C very easily but less easily through L, therefore less harmonic energy is transferred through M to the antenna. It has been explained that due to the "flywheel" effect of the resonant circuit LC, the half-cycles of I_p are transferred into full cycles of tank current. These cycles tend to become sinusoidal in character, and the greater the amplitude of the sinusoidal tank current, the smaller the proportion of the distorted I_p to I_t, and the smaller the transfer of harmonic energy to the antenna.

Thus the greater the value of K, the greater the reduction of the harmonic component of I_t. For telegraph transmitters there is theoretically no apparent limit to this principle. However in practice the limiting factor is the greater cost of high voltage large capacity condensers as compared with inductance coils. For a modulated wave, such as the output of a broadcast transmitter, the value of K that can be used is limited by the fact that audio distortion results if it is attempted to apply and remove power from the circuit at a frequency greater than the natural period of build up and decay of power in the circuit. Thus the maximum value of K is limited by this factor as will be explained a little later.

So long as K is greater than 4, the ratio of I'_L, (any one harmonic component of coil tank current), to I_L, (the current at the fundamental frequency

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in L), may be computed as follows: (For this calculation it may be assumed that I'_p/I_p ratio is .7 for the second harmonic and .3 for the third harmonic as previously explained. In design it is assumed that the maximum possible harmonic distortion may appear in the output, hence the factors .7 and .3. In practice the measured distortion is usually somewhat less than that calculated. I_p is the plate current at the fundamental frequency and I'_p the component of plate current at the selected harmonic frequency.)

$$\frac{I'_L}{I_L} = \frac{I'_p}{I_p K(n^2 - 1)} \qquad \text{Eq. 3.}$$

n = the selected harmonic to agree with I'_L and I'_p for which the calculation is to be made.

To find the percentage of second harmonic current component in inductance L with KVA/KW ratio of 23:

$$\frac{I'_L}{I_L} = \frac{.7}{1 \times 23(2^2-1)} = \frac{.7}{23 \times 3} = .01 = 1 \text{ per cent.} \quad \text{Eq. 4.}$$

At the 3rd harmonic:

$$\frac{I'_L}{I_L} = \frac{.3}{1 \times 23(3^2-1)} = \frac{.3}{23 \times 8} = .0016 = .16 \text{ per cent.} \quad \text{Eq. 5.}$$

The modern method of expressing the relation between the harmonic current and the fundamental current in a circuit is in terms of decibels. That is, the harmonic current is said to be a certain number of db's below the fundamental. db = 20 log I_L/I'_L. Thus in Equation 4, the ratio K = 23 reduces the second harmonic component to 40 db below the fundamental. In Equation 5, calculations show that the third harmonic component is 56 db below the fundamental.

For 2nd harmonic:

$$\text{db} = 20 \log I_L/I'_L = 20 \log 100 = 40 \text{ db.}$$

For 3rd harmonic:

$$\text{db} = 20 \log I_L/I'_L = 20 \log \frac{1}{.0016} = 20 \log 625 = 56 \text{ db.}$$

If two tubes are used in push pull so as to balance out the second and all even harmonics, then the greatest harmonic current in L will be at the third harmonic with an amplitude of .16 per cent of the amplitude of the current at the fundamental frequency. *At any harmonic frequency the ratio of the harmonic current to the fundamental current is inversely proportional to K.*

Further proportionate reduction of the harmonic component can be obtained in the antenna, where K_a = KVA/KW for the antenna itself. ($K_a = X_L/R = X_C/R$.

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The current in the antenna, for a given amount of power, is entirely a function of R; $I = \sqrt{P/R}$. KW or power in the antenna is a direct function of R because $W = I^2R$. However for a given antenna current, the KVA factor [K_a] is a direct function of the antenna reactance because $E_c = IX_c$ and $E_L = IX_L$. If A is constant, then VA must vary directly as X because $V = IX$.)

For two antennas of given L and C values, the one having the lower resistance will have the larger current for a given power input and—since the VA value is equal to I^2X_c—the larger value of K_a. This does not mean that the antenna with the larger current and K_a factor will be the better antenna. If the lower antenna resistance is obtained by a reduction in radiation resistance, the antenna having the lower resistance will be the poorer radiator. From the point of view of harmonic reduction, however, the larger the KVA/KW factor, the smaller the harmonic content. If the large K_a factor is obtained by the use of a small capacity antenna loaded with a large amount of inductance, the radiation will be very poor. Thus just as in the tank circuit design, there are limiting factors to the extent to which harmonic reduction may be obtained by increasing the value of K_a.

Considering the total circuit from tube to antenna, with K = KVA/KW for the tank circuit; $K_a = KVA/KW = X_c/R$ for the antenna; I'_p/I_p = the assumed ratio of the harmonic to the fundamental component of plate current, .7 for the second harmonic and .3 for the third harmonic; n = the harmonic for which calculations are to be made; I_a = antenna current at the fundamental frequency; I'_a = component of antenna current at the specified harmonic; then,

$$\frac{I'_a}{I_a} = \frac{I'_p n^2}{I_p K K_a (n^2 - 1)^2} \qquad \text{Eq. 6.}$$

Thus the harmonic reduction of the entire circuit is proportional to the product KK_a.

Extending the problem previously considered where K was assumed to be 23. (See Eq. 4 and 5.) Assume the tank circuit is coupled to an antenna having a resistance of 30 ohms, and at the operating frequency X_c = 240 ohms. Then $K_a = X_c/R = 240/30 = 8$. At the second harmonic,

$$\frac{I'_a}{I_a} = \frac{I'_p n^2}{I_p K K_a (n^2 - 1)^2} = \frac{.7 \times 4}{23 \times 8 \times 9} = .0017 = .17 \text{ per cent.} \qquad \text{Eq. 7.}$$

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At the third harmonic,

$$\frac{I'_a}{I_a} = \frac{I'_p n^2}{I_p K K_a (n^2 - 1)^2} = \frac{.3 \times 9}{23 \times 8 \times 64} = .00023 = .023 \text{ per cent.} \quad \boxed{\text{Eq. 8.}}$$

Expressing the relations as shown in Equations 7 and 8 in terms of decibels, it is found that the second harmonic component in the antenna is down 55 db with respect to the fundamental and the third harmonic component is down 73 db. Comparing these figures with those of the tank circuit alone in Equations 4 and 5, it will be seen that the effect of the antenna design in harmonic reduction is very considerable. In this case the second harmonic is reduced by 55 - 40 = 15 db, and the third harmonic by 73 - 55 = 18 db.

In the case of the second harmonic in the antenna, -55 db, this figure is still high. However in practice this would be reduced before coupling to the antenna by means of a push-pull amplifier, by the use of capacity coupling to the antenna, by the use of a special anti-harmonic coupling circuit between the tank circuit and the antenna, or by a combination of these methods.

PRACTICAL LIMITS OF K AND K_a: It will be seen that so far as the actual reduction in R.F. harmonic component in the antenna is concerned the larger the values of K and K_a the better. Aside from the limiting factors of cost in tank circuit construction, and practical reduction of antenna resistance, (it must be remembered that in practice the radiation efficiency of the antenna is of much greater importance than its harmonic reducing qualities), K and K_a are limited in broadcast transmitters by the allowable audio distortion that excessive KVA/KW ratios will introduce. The audio distortion effect of excessive K_a imposes a limit as follows:

Q

$$\frac{f}{f_m} = QK_a \qquad \text{Eq. 9.}$$

f = radio frequency.
f_m = modulation frequency.
K_a = X_L/R = X_C/R for the antenna.
Q = a factor which is determined by the amount of audio distortion that can be tolerated. For 1, 2, 5 and 10 per cent audio distortion Q = 12.7, 10.2, 7.7, and 5.9 respectively.

Thus at a radio frequency of 900 KC/s with highest modulation frequency of 10,000 cycles, with maximum allowable audio distortion to be introduced by the antenna circuit limited to 1 per cent:

$$K_a = \frac{f}{f_m Q} = \frac{9 \times 10^5}{10^4 \times 12.7} = 7.1 \qquad \text{Eq. 10.}$$

Q for (K)

The same method may be used to determine the maximum value of K for the plate tank circuit LC except that the values for Q should be just one-half as great as shown above. Thus for the same radio and modulation frequencies, and the permissible introduction of audio distortion, 1 per cent, K must not exceed,

$$K = \frac{f}{f_m Q} = \frac{9 \times 10^5}{10^4 \times 6.35} = 14.2 \qquad \text{Eq. 11.}$$

As the radio frequency is increased, to handle the same maximum modulation frequency, 10,000 cycles, with the limit of 1 per cent on the audio distortion that can be introduced, the values of K_a and K can be increased. Thus at the two extremes of the broadcast frequency band, to meet these requirements:

At 550 KC/s

$$K = \frac{55 \times 10^4}{10^4 \times 6.35} = 8.6 \qquad \text{Eq. 12.}$$

$$K_a = \frac{55 \times 10^4}{10^4 \times 12.7} = 4.3 \qquad \text{Eq. 13.}$$

At 1500 KC/s

$$K = \frac{15 \times 10^5}{10^4 \times 6.35} = 23.6 \qquad \text{Eq. 14.}$$

$$K_a = \frac{15 \times 10^5}{10^4 \times 12.7} = 11.8 \qquad \text{Eq. 15.}$$

Since, for a given maximum modulation frequency and permissible audio distortion, the limits of K and K_a are linear functions of f, a graph of these values may easily be plotted to cover the broadcast band and thus be made available for ready reference. Similar curves can be plotted for other distortion percentages. A graph plotted from values determined by Equations 12, 13, 14 and 15 is shown. A calculation was made at **10000 c/s** in both cases to show the linearity of the graphs. Similar graphs may be prepared for other percentages of distortion. However in practice the introduction of 1 per cent of audio distortion by a single amplifier stage should not be exceeded unless some system, such as inverse feedback, is used to counteract the introduced audio distortion. If inverse feedback is used, a considerable amount of audio distortion may be introduced by the final R.F. amplifier and then cancelled out by feedback. This permits more efficient operation of tubes and the use of a higher KVA/KW ratio in the final tank circuit with consequent reduction in R.F. harmonics. The use of inverse feedback will be discussed in a later lesson.

It will be seen that the factor of audio distortion places a somewhat low limit on both K and K_a. In practice it is possible that somewhat less rigid restrictions may be tolerated. However modern broadcast transmitters are designed to handle audio frequency modulation from 30 to 10,000 cycles with prac-

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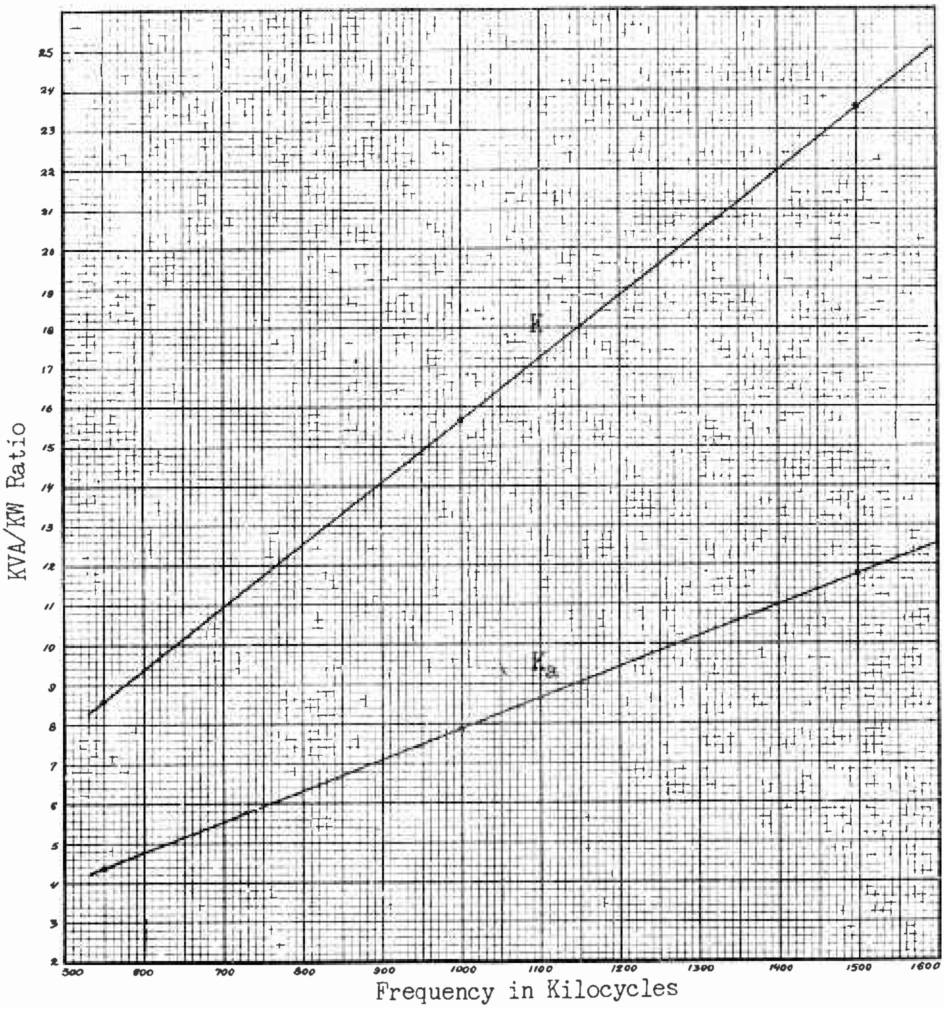
tically no frequency discrimination within the band. It also must be remembered that a certain amount of audio distortion will be introduced in other parts of the circuit so that it is the accumulative effect which must be considered. Thus it is good practice to design each part of the circuit to permit a minimum of audio distortion even though in the final stage this will not permit the desired reduction of radio frequency harmonics. Where the Class B linear amplifier is used, further reduction of radio frequency harmonics can be, and usually is, effected by a combination of push pull amplifier tubes, capacity coupling to the antenna or transmission line, and tuned trap circuits to eliminate particularly troublesome harmonics. To further reduce harmonic coupling between L and M (See Figure 3), due to the capacity between the coils, a grounded electrostatic screen is often inserted between the two coils.



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POWER CONSIDERATIONS: It has been shown that the Class B amplifier will deliver large instantaneous peak power. However there are very definite limits which must not be exceeded if audio distortion is to be kept to a minimum. When the input consists of modulated radio frequency, (as shown in Figure 1), and where modulation peaks of 100 per cent must be handled (the requirement of modern broadcast transmitters) the power output on the modulation peaks is 4 times that of the unmodulated carrier, and the tank current during the modulation peaks is equal to twice the unmodulated value. Since the voltage across the load tank circuit is equal to IX_L or IX_C, if the current is doubled the voltage is also doubled on the modulation peaks. Thus with current and voltage both doubled in the load circuit, the power output is increased by four times. Obviously the tube must be capable of delivering this peak power without distortion.

In order that the wave form of E_p is not distorted, the minimum value of E_p must not be less than 20 per cent of E_b. (It previously has been shown that in practice the plate voltage cannot be driven between zero and $2E_b$.) This means that E_p can be allowed to vary, in *peak* amplitudes, between $.2E_b$ and $1.8 E_b$.

The operating efficiency of a properly adjusted Class B amplifier is given by the equation:

$$\text{Efficiency} = 78.5\left(1 - \frac{E_{min}}{E_b}\right) \qquad \text{Eq. 16.}$$

100% For 100 per cent modulation in which E_{min} becomes $.2E_b$, this becomes,

$$\text{Efficiency} = 78.5\,(1 - .2) = 62.8 \text{ per cent.} \quad \boxed{\text{Eq. 17.}}$$

Since with 100 per cent modulation the plate voltage can be allowed to vary 80 per cent of E_b, and since at 100 per cent modulation the peak A.C. component of plate voltage is double the unmodulated A.C. peak voltage, then when there is no modulation the peak R.F. voltage variations cannot exceed $.4\,E_b$. Thus the peak R.F. voltage variations across the tank circuit without modulation are $.4E_b$ and the minimum plate voltage reached during the R.F. cycle, E_{min}, becomes $.6E_b$. The optimim operating efficiency without modulation becomes,

0%

$$\text{Efficiency} = 78.5\left(1 - \frac{E_{min}}{E_b}\right) = 78.5\,(1 - .6) = 31.4 \text{ per cent} \quad \boxed{\text{Eq. 18.}}$$

(The Federal Communications Commission allows an assumption of 33.3 per cent.

When calculations are made on that basis E_p will become somewhat less than $.2E_b$ during peaks of 100 per cent modulation.)

It particularly should be observed that during modulation the D.C. power input to the Class B amplifier does not vary but the operating efficiency, with optimum adjustments, varies between 31.4 per cent and 62.8 per cent. Since the *average* efficiency is increased during modulation, for given fixed power input the output power will increase with consequent increase in tank and antenna current, this increase representing the sideband power. Under such conditions, the tube anodes should operate cooler during modulation.

DESIGN OF R.F. CLASS B POWER AMPLIFIER: In the design of an amplifier for a given power output, with audio distortion limited to a specified percentage and R.F. harmonics reduced to a minimum, all of the above factors must be taken into consideration.

Consider the design of a linear amplifier to deliver 1 KW of unmodulated output to an antenna. Assume a power loss of 150 watts in the tank inductance, so that it will be necessary for the tube to deliver unmodulated power of 1150 watts to the tank circuit. The amplifier must handle peaks of 100 per cent modulation with highest modulation frequency of 10,000 cycles; the operating frequency is to be 1200 KC/s; audio distortion introduced by the amplifier is not to exceed 1 per cent. It is desired to use a type 1652 water-cooled tube in a circuit similar to that of Figure 3 with D.C. plate potential of 6000 volts.

It is first necessary to find the KVA/KW ratio (K) which is limited by the permissible audio distortion, (1 per cent), and by the ratio of radio frequency (1200 KC/s) to highest modulation frequency (10,000 cycles). It is desired to use the highest value of K consistent with the above requirements in order to minimize the R.F. harmonic components. This can be found from the graph previously drawn, or from Equation 11,

$$K = \frac{f}{f_m Q} = \frac{12 \times 10^5}{10^4 \times 6.35} = 18.9 \qquad \text{Eq. 19.}$$

In order that the peak voltage across the load when unmodulated may not exceed $.4E_b$, the maximum operating efficiency when unmodulated should be approximately 31.4 per cent. Thus the peak output voltage across the tank cir-

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cuit is , from Equation 1,

$$E_{peak} = \frac{4 \cdot E_b \cdot \text{Efficiency}}{\pi} = \frac{4 \times 6000 \times .314}{3.14} = 2400 \text{ volts.} \qquad \text{Eq. 20}$$

$$E_{RMS} = .707\ E_{peak} = .707 \times 2400 = 1697 \text{ volts} \qquad \text{Eq. 21}$$

Since $K = VA/W$, then $VA = K \cdot W$, and tank current,

$$I_t = \frac{VA}{E_{RMS}} = \frac{K\ \ W}{E_{RMS}} = \frac{18.9 \times 1150}{1697} = 12.8 \text{ amperes} \qquad \text{Eq. 22}$$

The D.C. power input to a tube is equal to power—output/efficiency. Thus D.C. watts input,

$$W_i = \frac{1150}{.314} = 3662 \text{ watts} \qquad \text{Eq. 23}$$

The D.C. plate current is equal to,

$$I_p = \frac{W_i}{E_b} = \frac{3662}{6000} = .61 \text{ amperes.} \qquad \text{Eq. 24}$$

This is the average value, and since plate current in the tube flows for only one—half the cycle,

$$I_{peak} = \frac{I_p}{.318} = \frac{.61}{.318} = 1.91 \text{ amperes.} \qquad \text{Eq. 25}$$

Since the output voltage is built up across the inductance and capacity of the tank circuit, and since both the current in the circuit and the voltage across the circuit have been calculated, the necessary reactances, X_L and X_c, to produce the conditions can be determined.

$$X_L \text{ (and } X_c) = \frac{E_p(RMS)}{I_t} = \frac{1697}{12.8} = 132.6 \text{ ohms} \qquad \text{Eq. 26.}$$

$$L = \frac{X_L}{2\pi F} = \frac{132.6}{6.28 \times 12 \times 10^5} = 17.6\ \mu H \qquad \text{Eq. 27}$$

$$C = \frac{1}{2\pi F X_c} = \frac{1}{6.28 \times 12 \times 10^5 \times 132.6} = .001\ \mu F \qquad \text{Eq. 28}$$

The effective tank circuit resistance is,

$$R_t = W/I^2 = 1000/12.8^2 = 6.13 \text{ ohms.} \qquad \text{Eq. 29}$$

Since $R_L = L/CR$, when properly adjusted with values as shown, the tube will be operating into a load impedance,

$$Z = 17.6/(.001 \times 6.13) = 2800 \text{ ohms} \qquad \text{Eq. 30}$$

Assume the antenna into which this transmitter is to operate has a resistance of 30 ohms and capacity of .0007 µF. The mutual inductive reactance necessary to couple the tank circuit to the antenna is equal to

$$X_m = \omega M = \sqrt{R_t R_a} = \sqrt{6.13 \times 30} = 13.5 \text{ ohms.} \qquad \text{Eq. 31}$$

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$$L_m = \frac{X_m}{2\pi F} = \frac{13.5}{6.28 \times 12 \times 10^5} = 1.8\ \mu H. \qquad \text{Eq. 32}$$

K_a, the KVA/KW antenna ratio, is equal to X_c / R_a

$$X_c = \frac{1}{2\pi FC} = \frac{1}{6.28 \times 12 \times 10^5 \times 7 \times 10^{-10}} = 189 \text{ ohms} \qquad \text{Eq. 33}$$

$$X_c/R_a = 189/30 = 6.3 \qquad \text{Eq. 34.}$$

The highest permissible K_a for not more than 1 per cent audio distortion is, from Equation 9,

$$K_a = \frac{f}{f_m Q} = \frac{12 \times 10^5}{10^4 \times 12.7} = 9.4 \qquad \text{Eq. 35}$$

This antenna is well within the required limits of K_a. The component of second harmonic current in the antenna as compared with the fundamental is, from Equation 7,

$$\frac{I'_a}{I_a} = \frac{I'_p n^2}{I_p K K_a (n^2 - 1)^2} = \frac{.7 \times 4}{18.9 \times 6.3 \times 9} = .0026 = .26 \text{ per cent} \qquad \text{Eq. 36}$$

The second harmonic current in the antenna is 52 db below the fundamental.

The percentage of third harmonic component is, from Equation 8,

$$\frac{I'_a}{I_a} = \frac{I'_p n^2}{I_p K K_a (n^2 - 1)^2} = \frac{.3 \times 9}{18.9 \times 6.3 \times 64} = .00035 = .035 \text{ per cent} \qquad \text{Eq. 37}$$

The third harmonic current in the antenna is 69 db below the fundamental.

When the transmitter is delivering 1 KW to the antenna, the antenna current should be,

$$I_a = \sqrt{W/R_a} = \sqrt{1000/30} = 5.8 \text{ amperes} \qquad \text{Eq. 38}$$

The grid bias is calculated approximately as E_b/μ, in this case 6000/14 = −428 volts. The required excitation is determined as follows. Take a family of E_g–E_p–I_p curves for the tube in question. (See curves for Type 1652 tube.) Plot in the unmodulated peak E_p–I_p point; in this case E_p = 6000 − 2400 = 3600 volts and I_p = 1.91 amperes. Plot a second point at the E_g = −428, E_b = 6000 volt point. Draw the load line between these points. In this case, when unmodulated, the grid must be driven from −428 volts to +110 volts so that peak excitation unmodulated equals 538 volts. The RMS excitation voltage is then 538 x .707 = 380 volts.

TUBES IN PUSH PULL: In most transmitters where a linear amplifier is used to amplify a modulated radio frequency input, it is found desirable to employ

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a push pull circuit as shown in Figure 5. The principal advantage of the push pull circuit is the great reduction of second harmonic output. The calculations for the design of the plate output circuit are very similar to the calculations for the single tube circuit with several important exceptions.

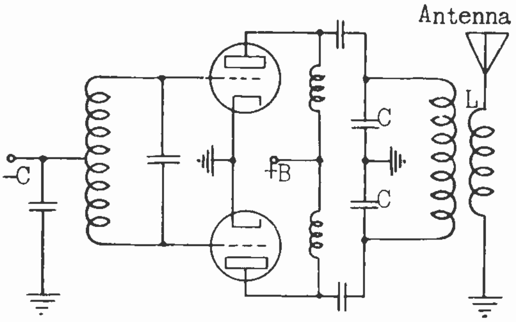
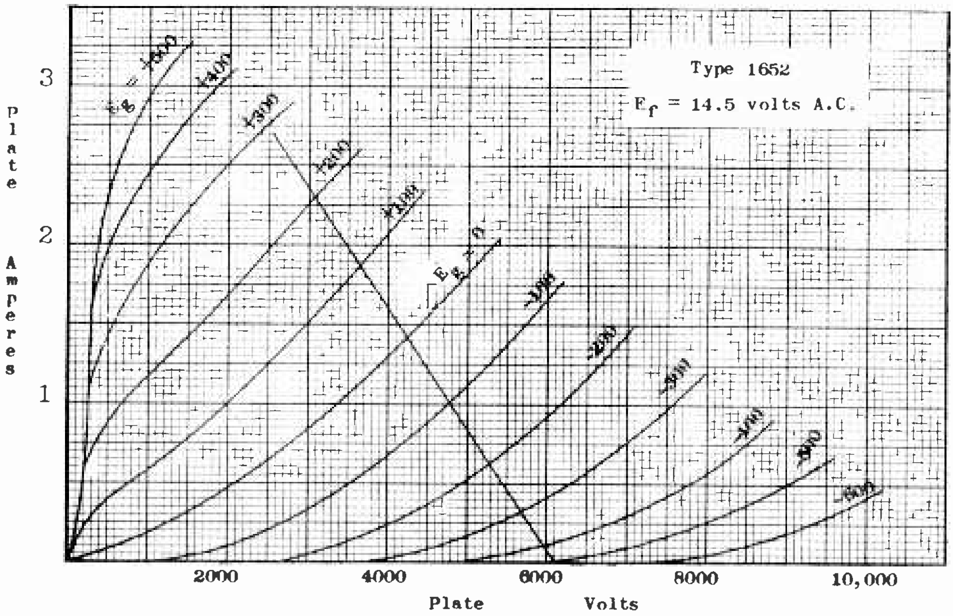


Fig. 5.

In the first place, for a given power output, each tube supplies only one-half the total power. Thus in calculating the plate current for each tube, the equation becomes,

$$\text{Average } I_p \text{ (one tube)} = \frac{\frac{1}{2} W \text{ (output)}}{E_b \cdot \text{Efficiency}} \qquad \text{Eq. 39}$$

where W(output) equals the total power output of the amplifier, both tubes.



Second, the load circuit for each tube consists of one capacity C and one-half the total inductance, to ground. Thus the KVA/KW ratio, the RMS tank current, the value of C and L, the grid excitation voltage, etc., are calculated just as for a single tube, using as a basis one-half the total power output.

However in the actual construction of the circuit L is made twice the calculated value for one tube, and two capacities C, each equal to the calculated value, are connected in series so that the total capacity equals C/2. Thus with total L doubled and total capacity reduced to one-half, the entire circuit still has the same resonant frequency as calculated on the basis of a single tube.

If, with the previously designed transmitter, it is desired to double the power output, two 1652 tubes may be used in push pull as in Figure 5. The tank circuit will consist of 17.6 x 2 or 35.2 µH of inductance and two capacities in series, each equal to .001 µF. Parallel plate feed would probably be used, (it probably would be used also with the single tube), and E_g, E_b, E_p and I_p for each tube would be the same as the values already calculated.

With the power output doubled, but with the tank current I_t unchanged, the effective resistance of the circuit, which is equal to $R = W/I_t^2$, will be doubled. The mutual reactance X_m, necessary to couple the circuit to the antenna will be changed. $X_m = \sqrt{R_t R_a}$. R_a is unchanged but R_t has been doubled, therefore X_m should be increased by $\sqrt{2}$ or 1.41. Since L_m varies directly as X_m, L_m should now be 1.41 x 1.92 µH = 2.71 µH. The antenna current will be, $I_a = \sqrt{W/R} = \sqrt{2000/30} = 8.16$ amperes.

There is a common misunderstanding regarding the proportioning of L and C in the push pull R.F. tank circuit as compared with the single-ended circuit. The confusion arises from the fact that in the case of the push pull audio amplifier the total inductance of the primary of the output transformer is made four times that of the inductance of the primary for single-tube operation. This is necessary in order to have the proper number of turns between each plate and ground, because the circuit of each tube from plate to ground consists of only one-half the total winding and the required output voltage must be developed by the current variation through those turns.

In the push pull R.F. circuit as shown in Figure 5 there is a continuously circulating R.F. current ***through the entire tank circuit LCC***, and with the same power output from each tube as in a single-tube circuit, the tank current in the push pull circuit for twice as much power output is the same as for the single tube. Thus if ***each*** value of C in the push pull circuit is made equal to C in the single-ended circuit and L is doubled to maintain the correct resonant frequency, the R.F. voltage between each plate and ground remains the same as that calculated for a single tube. The tank current is unchanged as is the KVA/KW ratio for each tube, and the entire operation of each tube is the same as calculated for a single tube. Each tube delivers the same amount of power as previously calculated, the total power output of course being doubled.

The fact that the output circuit between each plate and ground is the same as that for a single tube is easily shown by a simple calculation. In the case of the single tube tank circuit at resonance $X_C = X_L$. In the case of the push pull circuit, the reactance between one plate and ground in one branch is X_C and in the other branch $2X_L - X_C$. Since $X_L = X_C$, the second branch reduces to simple X_L. The R.F. voltage across each condenser is the same as for a single tube and the total voltage across the inductance is twice as great as for one tube.

The preceding stage of amplification must supply twice the excitation voltage required for one tube because the excitation voltages for the two push pull tubes are in series and each is equal to the voltage as calculated for the single tube 1 KW circuit.

CAPACITY COUPLING TO ANTENNA: In order to further reduce the coupling to the antenna at the harmonic frequencies, at the same time maintaining optimum coupling at the fundamental frequency, capacity coupling is very often used. A typical circuit is shown in Figure 6. Power is transferred to the antenna by means of the voltage drop across C_2. This voltage is equal to IX_{C2}. At any harmonic frequency the harmonic voltage $E' = I'X_{C2}$. X_C is equal to $\frac{1}{2\pi FC}$, so that, varying inversely as the frequency, the harmonic voltage across C_2 is less, even if the harmonic current remains high. Thus the coupling, for given tank current, is reduced at the harmonic frequencies with capacity coupling

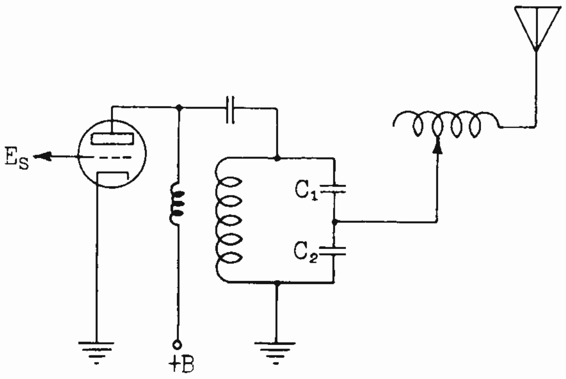


Fig. 6.

instead of being increased as with inductive coupling.

The total capacity of the circuit is equal to,

$$C = \frac{C_1 \cdot C_2}{C_1 + C_2} \qquad \text{Eq. 40}$$

The capacity of C_2, for given R_L (resonant tank impedance), and antenna resistance, R_a, is determined as follows,

$$\frac{C_2}{C} = \sqrt{\frac{R_L}{R_a}} \qquad \text{Eq. 41}$$

In the problem above (single tube) for which calculations were made, $C = .001\ \mu F$, $R_L = 2500$ ohms, $R_a = 30$ ohms.

$$\frac{C_2}{C} = \sqrt{\frac{2500}{30}} \qquad \text{Eq. 42}$$

$$C_2 = .001\sqrt{\frac{2500}{30}} = .00913\ \mu F. \qquad \text{Eq. 43}$$

$$C_1 = \frac{C \cdot C_2}{C_2 - C} = \frac{.001 \times .00913}{.00913 - .001} = .001123\ \mu F. \qquad \text{Eq. 44}$$

With the above values and the circuit of Figure 6, the same power will be transferred to the antenna at the fundamental frequency as with the circuit of Figure 3 with proper inductive coupling. However there will be a considerable reduction in the harmonic power transferred to the antenna. Thus if the KVA/KW ratio in the tank circuit is made comparatively low in order to reduce the audio distortion to a minimum, with the consequence that the R.F. harmonics are not sufficiently attenuated, considerable reduction of the harmonic radiation can be obtained by the use of capacity coupling to the antenna.

If, as is usually the case with broadcast transmitters, a transmission line is to be used to transfer power from the tank circuit to the antenna, the surge impedance of the transmission line Z_t is used in place of R_a in the above equation for C_2. Thus, where a 70 ohm transmission line is used, with the same tank circuit requirements,

$$\frac{C_2}{C} = \sqrt{\frac{R_L}{Z_t}} \qquad \text{Eq. 45}$$

and $$C_2 = C\sqrt{\frac{R_L}{Z_t}} = .001\sqrt{\frac{2500}{70}} = .006\ \mu F. \qquad \text{Eq. 46}$$

and $$C_1 = \frac{C \cdot C_2}{C_2 - C} = \frac{.001 \times .006}{.006 - .001} = .0012\ \mu F. \qquad \text{Eq. 47}$$

At the antenna end, the transmission line must be terminated with a circuit

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by which the transmission line impedance can be matched to the resistance of the antenna. With one side of the line grounded and with such a low impedance line specified, a coaxial type line would be employed.

Power of 1 KW is to be transferred over a 70 ohm line. $P = I^2R$ and $I = \sqrt{\frac{P}{R}} = \sqrt{\frac{1000}{70}} = 3.78$ amperes. The voltage across the line, $E = IZ = 3.78 \times 70 = 265$ volts. Since the line is assumed to be properly terminated, it may be considered, for ease of calculation, as a simple resistance. This is discussed in detail in another lesson.

Assume that in the case of the push pull 2 KW amplifier of Figure 5, it is desired to capacity couple the tank circuit to the 30 ohm antenna by means of a 100 ohm transmission line. The circuit will be modified as shown in Figure 7.

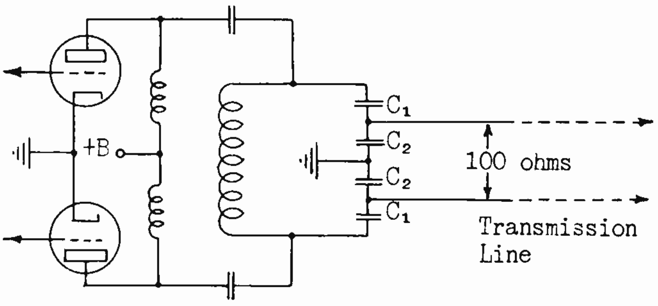

Fig. 7.

In the previous push pull calculations each value of C was found to be .001 µF or a total series capacity of .0005 µF. The total series capacity of the tank circuit of Figure 7 must also be .0005 µF. For ease of calculation the total series capacity of the two units of C_1 will be considered as one capacity, similar procedure being adopted in the preliminary calculation for C_2.

The effective load impedance R_L for the single tube was 2500 so for the two tubes R_L is 5000 ohms. The transmission line impedance Z_t is to be 100 ohms. Then from Equation 46,

$$C_2 = C\sqrt{\frac{R_L}{Z_t}} = .0005\sqrt{\frac{5000}{100}} = .00354\ \mu F \qquad \text{Eq. 48}$$

From Equation 47,

$$C_1 = \frac{C \cdot C_2}{C_2 - C} = \frac{.0005 \times .00354}{.00354 - .0005} = .000582\ \mu F \qquad \text{Eq. 49}$$

Since C_1 is made up of two equal capacities in series, each unit of C_1 must be twice as great as the total, so that each unit of C_1 is equal to $.000582 \times 2 = .00116$ µF.

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Likewise each unit of C_2 should be equal to .00354 x 2 = .007 μF.

This arrangement will permit the same energy transfer to the antenna at the fundamental frequency as will the circuit of Figure 5 but at a considerable reduction of all harmonic frequencies.

It should be noted that capacity C_2 in both Figure 6 and Figure 7 is simply an impedance matching device, the amount of capacity being a function of the total circuit capacity required and the ratio of the impedances being matched.

ADJUSTMENT FOR LINEAR OUTPUT: In modern broadcast transmitters the output must be capable of 100 per cent modulation with a minimum of audio component distortion. The calculations above indicate the amplitudes of voltages and currents desired and the required circuit constants. These figures are adequate for design purposes. However when the transmitter is built and installed it will be found that the exact calculated values are usually difficult to obtain. This is due to lack of exact uniformity in tubes, stray inductive and capacitive coupling, etc., so that even though the transmitter is excellently designed and is capable of adjustment within the required tolerances, the calibration job is found to be more than simply connecting in the calculated value of capacity and the calculated number of turns of inductance.

For example, where two tubes are operated in push pull it may be found, with the preliminary adjustment, that the plate currents of the two tubes are approximately equal but that the plate of one tube becomes much hotter than the other. Thus one tube is operating less efficiently than the other. If the characteristics of the two tubes have been checked and the tubes found to match quite closely, and the excitation to both tubes is the same, the trouble will probably be found in the adjustment of the plate load impedance of one tube. The adjustment should be made so that both tubes are operating with equal efficiency and power output. To facilitate such adjustment, in the design of the transmitter the coil construction and mounting should be such that the capacity to ground is the same from both ends of the coil. In any push pull circuit it is *very* desirable that the circuit construction be such that symmetrical mechanical adjustments provide symmetrical electrical relations. That is, with matched tubes, the same number of turns between plate taps and ground on both sides should permit the tubes to work into identical impedances.

Figure 1 illustrates the conditions necessary for undistorted modulated output. It is not particularly difficult to determine if the adjustments are correct. One method of making a preliminary adjustment and check on the output characteristics is as follows: With the proper plate voltage and negative grid bias, apply unmodulated excitation voltage and increase the excitation to the linear amplifier until the antenna current is double the calculated value for the required power output. Carefully note the plate current and the antenna current. Then decrease the excitation until plate current and antenna current are reduced to one-half the former values. This should be the operating excitation voltage. (The reason for first using double the carrier excitation is to be sure that plate and tank currents will rise linearly to the required values.)

With this adjustment, at 100 per cent modulation of the excitation voltage the antenna current should vary between zero and double on the excitation peaks, the plate current variation during modulation peaks as indicated by the plate current ammeter should be negligible, and the power output on the modulation peaks should be four times that of the unmodulated carrier. If sinusoidal modulation is applied, at 100 per cent modulation the antenna current should increase 22.5 per cent over the unmodulated carrier. (This latter point will be discussed in detail in a later lesson.)

To check the linearity of the Class B output, a curve should be run by varying the plate voltage of the Class C modulated amplifier between zero and double the normal value, plotting antenna current against Modulated Amplifier plate voltage. The curve should be essentially linear from $E_p = 0$ to $E_p = 2E_b$. This curve will provide a check on the linearity of both the modulated Class C amplifier and the linear Class B amplifier. The further check of course is to apply modulation in the regular manner and check the characteristics of the output by means of a cathode ray oscilloscope and a distortion meter. It is very essential that the plate voltage, grid bias, grid excitation, plate impedance, and circuit coupling be such that full modulation, with the percentage of distortion within the required tolerance, is possible at the specified power output.

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Proper adjustment of a modern broadcast transmitter requires a thorough understanding of all the circuit and power relations concerned. Equipment which will provide means for quickly checking the quality of the modulated output is available at reasonable prices, and should be a part of the equipment of each station.

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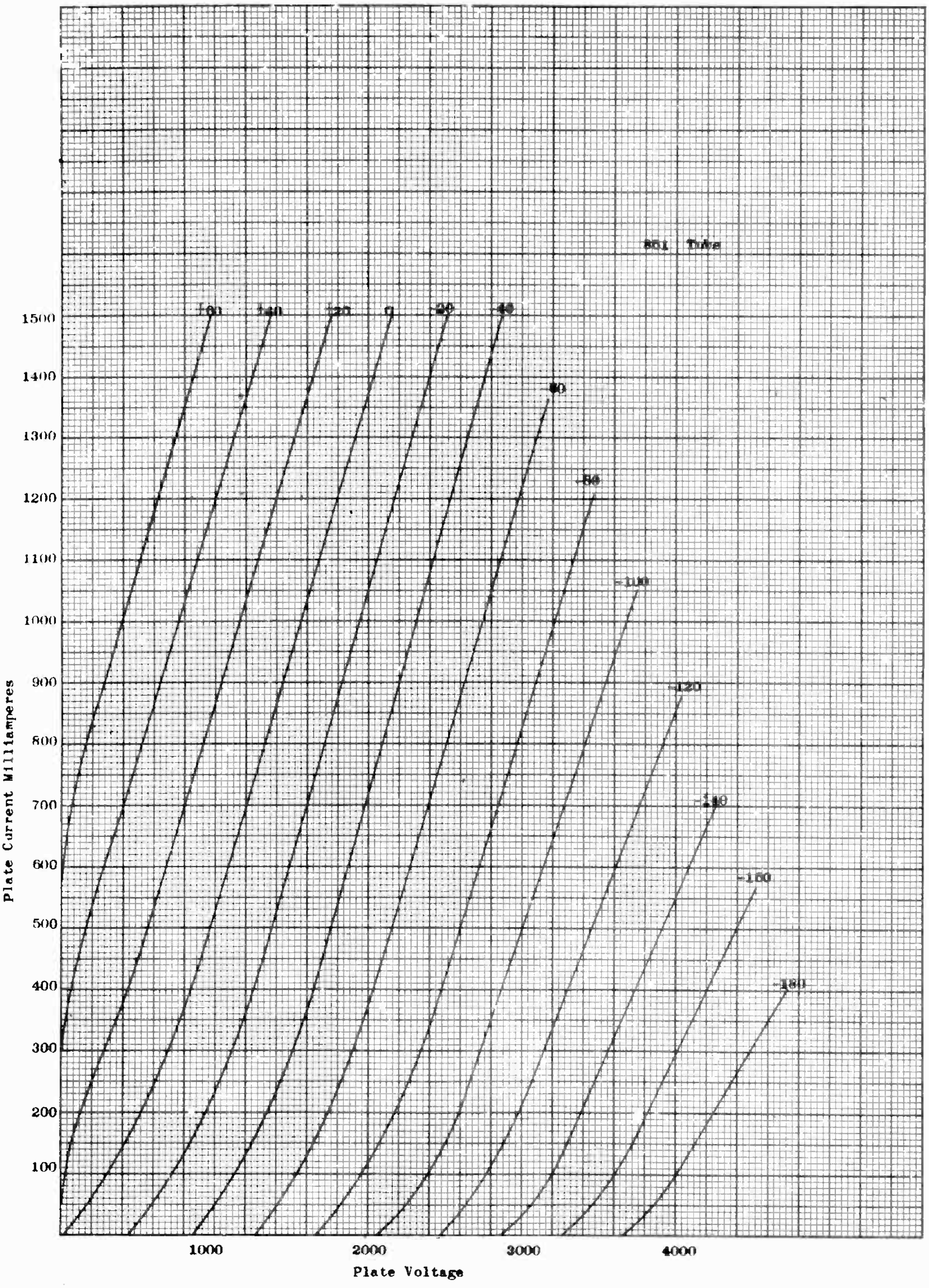
851 Tube
+60
+40
+20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
Plate Current Milliamperes
1000
2000
3000
4000
Plate Voltage

DESIGN OF OUTPUT CIRCUITS FOR TRANSMITTER POWER AMPLIFIERS

SUPPLEMENTARY NOTE

In this lesson, a method of adjusting a linear (Class B) R.F. amplifier has been described, in which excitation is first raised to twice normal carrier value by increasing the plate voltage of the previous Class C modulated stage in the absence of modulator output voltage. In certain cases, it may be difficult to make the adjustment in this manner owing to lack of provision for a sufficient range of variation of the modulated amplifier d.c. voltage by manual control. It is to be noted that in these cases it may still be possible to adjust and to check the linearity of the final amplifier by variation of excitation through a change of the positions of the excitation taps on the input tuned coil.

When the amplifier is to be adjusted in this manner, the following procedure may be followed: Set the coupling adjustment to what is considered to be about right for a load impedance of the usual value for the type of tube involved. Adjust bias to approximately cut off. With tank at resonance apply plate voltage. Apply excitation without modulation. Raise excitation by moving excitation taps away from R.F. ground on coil until point is reached where further increase fails to increase antenna current. Note the antenna current. It should be approximately twice that to be expected from the tubes at carrier level, and the plate efficiency should be over 60%.

If the output is low with an input of greater than twice the normal carrier level plate current, the plate load impedance should be increased by decreasing coupling. If, on the other hand, output and plate current are both low, then the plate load impedance should be decreased by tightening coupling. In this manner it should be possible to make preliminary adjustments of load impedance to obtain an efficiency approaching 66%.

The excitation should then be reduced until the antenna current is just one half of the previous value. (Plate or tank current may also be used as a reference in this adjustment.) Modulate the excitation and look for an upward swing of antenna current.

Linear amplifiers are somewhat difficult to adjust, mainly because of the two variables, grid excitation and plate load impedance that are involved. The wave form of the modulation envelope of the output should be checked with an oscilloscope. In general, the adjustment is considered

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complete when reasonable efficiency together with a specified minimum of distortion is obtained. The aforementioned procedure may have to be repeated with small variations of the load impedance (by slight changes in coupling) until a satisfactory adjustment is found. 33% efficiency at carrier level is considered satisfactory in standard technique. Distortion can be caused by over-modulation of the excitation (not a fault of the linear amplifier) or by operation of the linear amplifier up into the region where plate saturation becomes the limitation on the height of the current pulses.

An alternate method to adjust, termed the "Half-voltage Method" has the advantage that plate loading is made independent of excitation adjustments. The procedure is to reduce plate voltage to one half, and the bias is adjusted to cut-off for this reduced value of the plate voltage; apply unmodulated excitation and resonate the tank. This should saturate the grids (if not, excitation may be increased until such saturation begins to take place). Now adjust the load coupling to give normal rated carrier power to the antenna, with the best efficiency attainable for the particular current. The plate voltage is now increased back to its normal value, the bias adjusted to cut-off for this normal value of plate voltage, and the excitation modulated while observing the wave form with an oscilloscope. Adjustment of the excitation may improve the wave form *but the load impedance should be left unchanged.*

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DESIGN OF OUTPUT CIRCUITS FOR TRANSMITTER POWER AMPLIFIERS

EXAMINATION

Design a push pull 500 watt linear (Class B) amplifier employing two radiation cooled Type 851 tubes. The amplification factor for this tube is 20. Use D.C. plate potential of 2000 volts and circuit as shown in Figure 5 with inductive coupling to the antenna. The transmitter is to operate on a frequency of 1400 KC/s and must be capable of 100 per cent modulation at frequencies between 30 and 10,000 cycles. The maximum audio distortion introduced by the final amplifier must not exceed 2 per cent. The unmodulated operating efficiency is to be 33 per cent. The antenna has capacity of .00065 µF and resistance of 40 ohms. The R.F. losses in the tank circuit inductance may be assumed to be 75 watts. Use the largest possible KVA/KW ratio in the tank circuit consistent with the limiting value of allowable distortion. Show all your work.

1. (a) What is the inductance of the tank circuit? 10.16 uH.
   (b) What is the capacity of each tank circuit condenser? .000255 uf

2. What is the R.F. tank current in amperes? 13.3 amps

3. What will a plate current ammeter in the D.C. circuit of each tube read? .435 amp.

4. What is the antenna current? 3.53 amps.

5. How much mutual inductance between the tank and antenna circuit is required for optimum coupling? 1.3 uH.

6. (a) What is the percentage of second harmonic current in the antenna circuit as compared with the fundamental? .26%
   (b) What is the percentage of third harmonic current in the antenna circuit as compared with the fundamental? .035 %

7. What is the required R.M.S. excitation voltage for each tube? 100 V.

8. At the peaks of 100 per cent modulation how much power must each tube deliver? At steady 100 per cent modulation with sinusoidal audio wave form, what should the antenna current be?
   (a) 1150 W. (b) 4.33 amp.

9. Explain in detail how you can determine whether or not the modulated wave form of the output will closely approximate that of the input. In making such measurements for the above amplifier what should the various determining readings be?

10. Determine the required coupling capacity for coupling the above amplifier to a 200 ohm transmission line.
    $C_2 = .0087$ uf $C_1 = .00596$ uf.

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Total power out $= 500 + 75 = 575$ W.

Power out for 1 tube $= \frac{575}{2} = 287.5$ W.

Q for audio distortion of 2% = 5.1

$$K = \frac{f}{f_m Q} = \frac{14\times10^5}{10^4\times5.1} = \frac{140}{5.1} = 27.4$$

$$K = VA/W \qquad I_t = A = \frac{KW}{V}$$

$$E_{peak} = \frac{4\cdot E_b\cdot Eff.}{\pi} = \frac{4\times2000\times.33}{3.41} = 840 \text{ Votls}$$

$$E_{rms} = 840\times.707 = 594 \text{ volts.}$$

$$I_t = \frac{27.4\times287.5}{594} = \underline{\underline{13.3}} \text{ amps } ②$$

$$I_p = \frac{W_{in}}{E_b} = \frac{W_{out}}{E_{ff}\times E_b} = \frac{287.5}{.33\times2000} = \underline{\underline{.435}} \text{ amp. } ③$$

$$I_{peak} = \frac{.435}{.318} = 1.37 \text{ amp}$$

$$X_L \text{ (and } X_c) = \frac{E_{rms}}{I_t} = \frac{594}{13.3} = 44.6\ \Omega$$

~~X~~L (for each tube) $= \frac{X_L}{2\pi F} = \frac{44.6}{6.28\times14\times10^5} = 5.08$ uH.

Total $L = 5.08\times2 = \underline{\underline{10.16}}$ uH. ①

$$C = \frac{1}{2\pi F X_c} = \frac{1}{6.28\times14\times10^5\times44.6} = \underline{\underline{.000255}} \text{ uf } ①$$

$$I_a = \sqrt{W/R_a} = \sqrt{\frac{500}{40}} = \sqrt{12.5} = \underline{\underline{3.53}} \text{ amp. } ④$$

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$R_T = \frac{W}{I_t^2} = \frac{500}{13.3^2} = \cancel{3.26}\ \Omega$ → 2.83 Ω

check math

Total $R_L = Z = L/CR = 10.16 / \left(\frac{.00255}{2}\right) \times \boxed{3.26}_{2.83} = \cancel{12{,}200}\ \Omega$ → 2820 Ω

12~~20~~

$X_m = \sqrt{R_t R_a} = \sqrt{\boxed{3.26} \times 40}$ 11.4 Ω

$L_m = \frac{X_m}{2\pi F} = \frac{\boxed{11.4}}{6.28 \times 14 \times 10^5} = \underline{1.3\ \mu H}$ ⑤

see solution for correct values

You used total L, and total R, so you have to use total C, also.

$K_a = X_c / R_a$.

$X_c = \frac{1}{2\pi F C} = \frac{1}{6.28 \times 14 \times 10^5 \times 6.5 \times 10^{-10}} = 175\ \Omega$

$K_a = \frac{175}{40} = 4.37$

Permissable K_a for 2% aud. dist. $= \frac{f}{f_m Q} = \frac{14 \times 10^5}{10^4 \times 10.2} = 13.7$

so $k_a = 4.37$ is OK.

% 2nd Harmonic

$\frac{I_a'}{I_a} = \frac{I_p' n^2}{I_p K K_a (n^2-1)^2} = \frac{.7 \times 4}{27.4 \times 4.37 \times 9} = .0026 = \cancel{.26}\ \%$ ⑥

OK for tube!

% 3rd Harmonic

$\frac{I_a'}{I_a} = \frac{I_p' n^2}{I_p K K_a (n^2-1)^2} = \frac{.3 \times 9}{27.4 \times 4.37 \times 64} = .000352 = .035\ \%$ ⑥

Grid Bias $= \frac{E_b}{\mu} = \frac{2000}{20} = -100$ V.

Unmodulated peak. $E_p = 2000 - 840 = 1160$ V

$I_{peak} = 1.37$ $E_g = +42$ V.

Peak excitation $= 100 + 42 = 142$ V.

Rms excitation $= 142 \times .707 = \underline{100\ \text{Volts}}$ ⑦

10. $\frac{C_2}{C} = \sqrt{\frac{R_L}{R_T}}$: $C_2 = .00177\sqrt{\frac{1220}{200}} = .00435$ uf

Each unit of $C_2 = .00435 \times 2 = .0087$ uf

See solution

(10)

$C_1 = \frac{C \times C_2}{C_2 - C} = \frac{.00177 \times .00435}{.00435 - .00177} = .00298$ uf

Each unit of $C_1 = .00298 \times 2 = .00596$ uf (10)

8. Unmodulated $I_a = \sqrt{\frac{P}{R}} = \sqrt{\frac{500}{40}} = \sqrt{12.5} = 3.54$ amps

Modulated (with 100% sin.) $= 3.54 \times 1.225 = 4.33$ amp (8)

9. With proper plate voltage & grid bias apply unmodulated excitation voltage and increase it until double the calculated antenna and plate current is obtained. (7.06 amp). .87 for plate. Decrease excitation so as to cut the antenna current in half. This will show that the plate & tank currents will rise linearly with the excitation.

To further check the linearity run a curve between excitation and antenna current. Vary the plate voltage of the preceding stage from $E_p = 0$ to $E_p = 2E_b$. The current curve should be linear over this range.

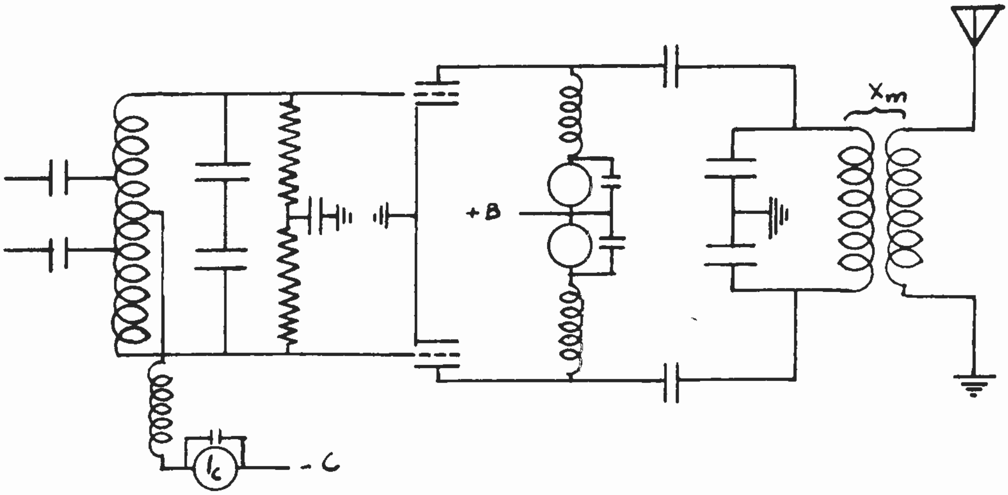
Best check is to apply regular modulation and measure output with a CRO & a distortion meter.

SOLUTION OF EXAMINATION CLASS B LINEAR AMPLIFIER

This solution follows the discussion of Examination 36 in regard to the theory involved and formulas used.

Problem: To design a push pull Class B linear R.F. amplifier to the following specifications:

Operating frequency: 1400 KC/s
Tubes employed: Two 851's ($\mu = 20$)
Plate supply voltage: 2000 volts
Power output to antenna: 500 watts
Tank loss: 75 watts
Modulation capability: 100 per cent
Modulation frequency range: 30 to 10000 C/s
Carrier level efficiency: 33 per cent
Maximum audio distortion introduced by tank: 2 per cent
KVA/KW ratio: Largest within 2 per cent audio distortion limit.
Antenna capacity: 650 $\mu\mu$F
Antenna resistance: 40 ohms
Coupling to antenna: Inductive



1(a) What is the inductance of the tank circuit?

Q factor of tank = 10.2/2 = 5.1

Maximum permissible KVA/KW $= F/F_M Q$

$= 1.4 \times 10^6/(10^4 \times 5.1) = 27.45$

E_{PEAK} across push pull tank $= 2(4E_B \cdot EFF/\pi)$

$= 8 \times 2000 \times .33/3.14 = 1680$ volts

$E_{RMS} = .707\, E_{PEAK} = .707 \times 1680 = 1190$ volts

Total RF power output of two tubes = 500 + 75 = 575 watts

Total RF volt amperes of tank = 27.45 x 575 = 15800 VA

Tank current $I_T = VA/V = 15800/1190 = 13.3$ amps

Tank coil reactance $= E_{RMS}/I_T = 1190/13.3 = 89.4$ ohms

INDUCTANCE OF TANK COIL $L_T = X_l/(2\pi F) = 89.4/(6.28 \times 1.4 \times 10^6) = 10.2\ \mu H$

1(B) WHAT IS THE CAPACITY OF EACH TANK CIRCUIT CONDENSER IN μμF?

TANK CAPACITIVE REACTANCE $X_C = X_L = 89.4$ OHMS.

TANK TOTAL CAPACITY, $C_T = 10^{12}/(2\pi F X_C) = 10^{12}/(6.28 \times 1.4 \times 10^6 \times 89.4) =$ [illegible] μμF

THIS IS THE TOTAL CAPACITY ACROSS THE TANK. THE CAPACITY OF EACH SECTION WILL BE DOUBLE, OR 2540 μμF.

2. WHAT IS THE R.F. TANK CURRENT IN AMPERES? SEE ANSWER TO 1(A).

3. WHAT WILL A PLATE CURRENT AMMETER IN THE DC CIRCUIT OF EACH TUBE READ?

I_P PER TUBE $= .5W/(E_B \cdot \text{EFF}) = 575/(2 \times 2000 \times .33) = .436$ AMP (AVERAGE)

PEAK I_B PER TUBE $= .436/.318 = 1.37$ AMPS

4. WHAT IS THE ANTENNA CURRENT I_A?

I_A AT CARRIER LEVEL $= \sqrt{P/R_A} = \sqrt{500/40} = \sqrt{12.5} = 3.54$ AMPS.

5. HOW MUCH MUTUAL INDUCTANCE (LM) BETWEEN THE TANK AND ANTENNA CIRCUIT IS REQUIRED FOR OPTIMUM COUPLING?

MUTUAL REACTANCE FOR REQUIRED TRANSFER OF 500 WATTS TO THE ANTENNA $= X_M$.

$$X_M = \sqrt{R'_T R_A}$$

R'_T = EQUIVALENT RESISTANCE REFLECTED INTO THE TANK CIRCUIT FROM THE ANTENNA. THIS MUST BE BASED UPON THE POWER DELIVERED TO THE ANTENNA, 500 WATTS.

$R'_T = 500/13.3^2 = 500/176.5 = 2.83$ OHMS

$X_M = \sqrt{R'_T R_A} = \sqrt{2.83 \times 40} = 10.63$ OHMS REACTANCE

$\mu H\ L_M = 10^6 X_M/2\pi F = 10.63 \times 10^6/(6.28 \times 1.4 \times 10^6) = 1.21\ \mu H$

6(A) WHAT IS THE PERCENT OF 2ND HARMONIC CURRENT IN THE ANTENNA CIRCUIT AS COMPARED WITH THE FUNDAMENTAL?

THE 2ND HARMONIC IS REDUCED BY PUSH PULL AMPLIFICATION. THERE IS SOME REMAINING DUE TO TUBE UNBALANCE AND ELECTROSTATIC COUPLING BUT THE ACTUAL AMOUNT CANNOT BE CALCULATED.

(B) WHAT IS THE PERCENT OF THE 3RD HARMONIC CURRENT IN THE ANTENNA CIRCUIT AS COMPARED WITH THE FUNDAMENTAL?

$K_A = X_C/R_A = 1/(2\pi \times 1.4 \times 10^6 \times .00065 \times 10^{-6} \times 40) = 4.38$

$I_A/I_A = I'_P N^2 \big/ \left[I_P K K_A (N^2 - 1)^2\right]$

$= .3 \times 9/(27.45 \times 4.38 \times 64) = .000351 = .035$ PERCENT

7. WHAT IS THE REQUIRED RMS EXCITATION VOLTAGE FOR EACH TUBE?

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Choose Grid Bias = E_B/μ = 2000/20 = 100 volts

I_{PEAK} at 0 Mod. = .436/.318 = 1.37

E_B min = $E_B - E_P$ = 2000 - 839 = 1161 volts.

Constructing a load line on 851 tube curves at points I_B = 1.37, E_B = 1161, and I_B = 0, E_B = 2000, it is seen that e_C max is +42 volts. (Note that at 100 per cent modulation I_{PEAK} must be 2 x 1.37 = 2.74 and $E_{MIN} = E_B$ - 2 x 839 = 322 V).

E_G max = e_C max + E_C = 42 + 100 = $\underline{142}$

E_G rms = .707 x 142 = 100 volts per tube

8. At the peaks of 100 per cent modulation how much power must each tube deliver? At steady 100 per cent modulation with sinusoidal audio wave form, what should the antenna current be?

At 100 per cent peak modulation the peak instantaneous power drawn from each tube = 4 x 287.5 = 1150 watts.

Note that 287.5 is used instead of 250 because the tank loss will increase in the same proportion as the output.

At 100 per cent sine wave modulation the antenna current will increase to a peak of 2 x 3.54/.707 = 10 amps or an RMS value of 1.22 x 3.54 = 4.34 amps.

9. To make a test for Class B amplifier linearity, apply double normal unmodulated excitation voltage. The tank current, antenna current, and plate current should rise to double normal value. The plate voltage on the Class B amplifier of course will remain at normal value during this test. Under this condition these values would be

RMS tank current = 2 x 13.3 = 26.6 amps.
Peak tank current = 26.6/.707 = 37.6 amps.

RMS ant current = 2 x 3.54 = 7.08 amps
Peak ant current = 7.08/.707 = 10 amps

Avg plate current = 2 x .436 = .872 amps per tube
Peak plate current = .872/.318 = 2.74 amps per tube

Max peak voltage between plate and cathode = E_B + .84 E_B = 1.84 E_B. (At 33 per cent efficiency it was seen that the plate voltage swing was .84 E_B at 100 per cent modulation).

10. Determine the required coupling capacity for coupling the above amplifier to a 200 ohm transmission line.

Method 1. $R_L = L/CR'_T = 10.2 \times 10^6/1270 \times 2.83 = 2850$ ohms
$C_2 = C\sqrt{R_L/Z_T} = 1270\sqrt{2850/200} = 4790\ \mu\mu F$
Z_T = surge impedance of line
R_L = impedance of tank based on R'_T (Eq. 4)
C = total tank C
C_2 = capacity mutual to both load and tank
C_1 = capacity in tank circuit only

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C_2 is divided into two sections of 9580 $\mu\mu F$ each so that the ground may be connected at the center to provide a path to ground for even harmonic power. See figure 7 page 20.

$C_1 = C_2C/(C_2 - C) = 4790 \times 1267/(4790 - 1267) = 1720\ \mu\mu F$

C_1 also must be divided into two sections of 3440 $\mu\mu F$ each

Method 2. $I_L = \sqrt{P_O/R_L} = \sqrt{500/200} = 1.58$ amps

$I_2 = \sqrt{I_T^2 - I_L^2} = \sqrt{13.3^2 - 1.58^2} = 13.2$ amps

E across line $= \sqrt{P_O R} = \sqrt{500 \times 200} = 316$ volts

$X_{C_2} = 316/13.2 = 23.95$ ohms.

$C_2 = 1/\omega X_C = 10^{12}/(2\pi \times 1.4 \times 10^6 \times 23.95) = 4750\ \mu\mu F$

This answer checks very closely with the No. 1 method preceding.

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