OPERATION OF THE MODULATOR TUBE IN RADIO TELEPHONE SETS

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ABSTRACT

The modulator tubes of radio telephone transmitters used in commercial and military sets operate essentially as aperiodic power amplifiers of speech currents. The load on these tubes is determined approximately by the volt-ampere characteristics of the radio generating circuit, as measured at its plate power input terminals. At speech frequencies other effects occur as follows:

1. Current to the modulators and the generating circuit in parallel is supplied through an audio choke coil. The finiteness of the inductance of this coil results in an inductive component to the load.
2. The radio generating circuit contains suitable impedances to prevent consumption of radio power by the modulator tubes. These and other parts of the generating circuit may produce reactive components.
3. In consequence of the variation of the input power to the generating circuit, the desired speech variations of radio output power occur. Power must be generated to vary the electromagnetic energy associated with the output circuit, as well as to supply the resistance losses. A reaction occurs tending to produce a capacitive component to the load on the modulators.

The value of a radio telephone transmitter in conveying speech signals is measured not by the power output, but rather by the variation of power output during speech. Usually optimum results are obtained when the power rating of all the modulator tubes equals the power rating of all the radio generator tubes. Under these conditions the load upon the modulators is one into which they may operate with best efficiency.

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I. INTRODUCTION

The function of a modulating device in radio communication is to vary the output current of a radio generator at a frequency or at frequencies lower than the radio frequency involved. In a certain sense practically all radio communication using single wave-length signals is by a modulation method. In continuous wave transmission, the keying by which the signals are conveyed constitutes a dot-and-dash modulation of the antenna current. In the operation of spark and other tone transmitters, the radio frequency wave trains are sent out at more or less regular intervals at an audio frequency, so that an audible note is heard upon rectification with a detecting device. In addition to this audio modulation, a second order of dot-and-dash modulation is required for conveying the telegraph signal. In radio telephony the message which is conveyed depends upon the first order modulation itself. The antenna current is made to vary, not at a single tone frequency, but with frequencies and in degrees corresponding to the pitches and intensities of the sound waves produced by the voice of the speaker. In consequence, upon rectification of the received radio signals, there are produced in the receiving telephones electrical currents which are of precisely the same nature as would be produced by communication by wire telephony.

The present paper deals with the essential electrical phenomena associated with the modulating device used in most of the present types of radio telephone transmitters employing electron tubes. The various methods of modulating the output of a generating circuit are discussed and the inherent superiority of plate modulation is pointed out. A complete radio telephone network using such plate modulation is analyzed into simpler units, and the essential and elementary operation of the modulator unit described in detail. The electrical limitations upon the proper functioning of the modulator tube are pointed out and the relative importance of these limitations discussed. The strength of speech signal conveyed by a radio telephone set is discussed, and suggestions are made as to the proper method of rating radio telephone sets as to power output.

II. METHODS OF MODULATING THE RADIO OUTPUT CURRENT OF AN ELECTRON-TUBE GENERATING CIRCUIT

With the generating device of an electron-tube circuit, speech modulation is accomplished usually by one of three general methods. The simplest is by variable absorption of the radio fre-

quency output of the circuit, as, for example, by the insertion of a speech operated microphone in the antenna lead from a continuous wave generator. A different method of variable power absorption is by shunting the generator tube, or parts of the output circuit, with another electron tube. The grid voltage of this power absorbing tube is varied at speech frequencies by the use of a microphone and speech transformer. The combination of microphone and power tube is capable of absorbing more radio power than the microphone itself would be able to handle, otherwise the operation is quite similar to modulation with a microphone directly in the antenna lead. These methods of radio power absorption are very little used in practice, largely because the generating device is required to produce much more radio power than that utilized by the actual antenna or other radiating device.

A second method of modulation is by varying the operating grid voltage of a generating tube at speech frequencies. In such apparatus the secondary of a speech transformer is inserted in the grid lead, this secondary being shunted with a radio condenser so that the operation of the generator circuit will not be influenced by the high reactance of the transformer windings. A microphone and battery in the primary of the transformer cause variations in the average grid voltage taken over successive radio cycles, and therefore change the operation of the radio generator. This method of modulation is not extensively used, chiefly because the radio frequency output of a generator circuit is usually not readily altered by varying the operating grid voltage. The grid voltage operating point is important in determining efficiency, but not the output current, provided the conditions are such that good articulation results. By reducing the operating grid voltage on a generating tube sufficiently, usually a point is reached at which the oscillation suddenly breaks and the radio output current immediately drops to zero. Grid modulation which thus cuts off the antenna current suddenly and completely results in very poor articulation. While with careful adjustments the breaking of the oscillation may be sufficiently gradual to permit good speech, this method is not considered to be one in which the modulation process is inherently reliable in telephone sets.

A third method of modulation is by varying the input plate power of a generating circuit; that is, the average plate voltage and plate current of the generating tube or tubes of a radio circuit are caused to vary at the lower or modulating frequencies. This

method is employed in practically all present commercial and military types of electron-tube radio telephone sets. It possesses the advantage over the first method that practically all the radio power output may be used in transmission of signals. On account of the nearly linear relations between cause and effect with this method, it is inherently superior to both the other methods as to articulation. In the transmission of speech signals the plate power of the generating tube is altered by the use of a power tube, which from its functioning is termed a modulator tube. It is the operation of this tube which is the center of discussion in the present paper. In connection with the discussion, however, are developed other topics, some of which are of interest in connection with any method of modulation.

III. GENERAL RELATIONS IN RADIO TELEPHONE TRANSMITTER SETS USING PLATE MODULATION

A radio telephone set using plate modulation is a more or less complicated network in which three classes of currents coexist—radio frequency, audio frequency, and direct. In Fig. 1 is shown schematically a typical radio telephone transmitter set, analyzed for purposes of discussion into four distinct units. At the extreme right is the radiator unit, which joins up the transmitter with the distant receiving station. The signal which is conveyed depends upon the nature of the wave form of current in this radiator unit, and is independent of the process by which that current is produced. The useful currents in this circuit are of radio frequency. The modulating mechanism may cause slight audio currents to flow in the radiator unit, but these produce practically no effect except at near-by stations. In the figure shown such audio currents result from the audio current flowing in the lead to the tube *O*, which is inductively coupled to the antenna or radiator circuit. During speech the radio frequency current is of variable amplitude and is known as modulated radio frequency. For the purpose of explaining the general operation of the transmitter it is unnecessary to analyze completely the wave form of this current. Curves showing the nature of the wave form with sine wave modulation are shown later in Figs. 8 and 11, and the analytical expression for such a wave form is given by equation 14, page 397.

To the left of the radiator unit is the radio generator unit. This contains electron tubes which, from the functions performed by them, are known as oscillator tubes, and also contains the other electrical equipment essential to the production of radio frequency

power from whatever power is supplied at the input $b+$ and $b-$ terminals of this unit. An essential part of any generating unit in radio telephony is a device such that the radio frequency voltage across the input terminals is small compared with other voltages of lower orders of frequency. In the present case this device is a condenser C_b , the reactance of which for radio frequencies is low compared with the ratio of average plate voltage of the oscillator tubes to the average plate current. In any continuous wave transmitter a device of this nature is required in case the radio impedance of the system supplying the plate power is so high that otherwise considerable radio voltage variations would occur across the input terminals, limiting the useful power output. In the present case the condenser C_b may be thought of as an electrical

FIG. 1.—Analysis of radio telephone transmitter set

valve which prevents radio frequency power working back into the part of the network to the left, but which does not interfere with the lower frequency power entering the generating system. The particular type of generating circuit is known as the Meissner circuit, which is classified electrically as one with plate and grid both inductively coupled to the radio frequency circuit, using series power supply with the same radio frequency circuit flowing through the plate coupling coil as through the tube. In place of such a circuit any of a large number of other types might be used, as, for example, the type shown later in Fig. 6. In the generator unit all three types of electrical currents exist. The power entering the unit during operation is direct power and audio power. The output through the antenna and ground terminals, A and G ,

is modulated radio frequency. While a tube in continuous wave telegraphy may be thought of as a converter of power from direct to radio frequency, in a radio telephone set the generator tube converts power from direct and audio to modulated radio frequency.

To the left of the generator unit is the modulator unit, the function of which is to supply audio and direct power to the generator unit, the audio power being controlled by the operator speaking into the microphone. In the case shown an electron tube is shunted across the input terminals of the generator unit, the two in parallel being supplied with direct power from a direct-current source through the iron cored choke coil L_B . The tube in this case is a speech-controlled resistance in which the instantaneous resistance, or ratio of plate voltage to plate current, is determined largely by the instantaneous grid voltage. On account of the functions it performs it is known as a modulator tube. Mechanically it is usually the same as the oscillator tube. When tubes are paralleled, approximately as many modulator tubes are used as oscillator tubes. The modulator tube is a converter of power from direct to audio frequency and the audio current and voltage output of the modulator tube is a more or less faithful reproduction of the audio voltage impressed upon the grid of the modulator tube by the use of a microphone and transformer. The modulator tube therefore functions as an aperiodic power amplifier. The audio power output may be tested, for example, by connecting a suitable resistance and stopping condenser in series across from m to n of Fig. 1, instead of the generating circuit. The power which is manifested by the heating effect upon the resistance, during speech, is entirely audio power, converted from direct power from source E_B through the agency of the modulator unit. Tubes for modulating are usually designed to operate with a negative average voltage on the grid, which in the case shown is obtained by the use of a battery in the grid lead. The choke coil L_B of the modulator circuit partially performs the same function for the modulator unit as does the condenser C_b for the generator unit. It prevents audio currents produced by the unit from working back through the input terminals $B+$ and $B-$, and in this it is aided by the condenser C_B . It performs, however, another important function.

If a fixed impedance and a variable impedance be connected in parallel and placed across a direct power source of zero internal impedance, then variations of one impedance will not disturb the

current to the other unless the two in parallel are supplied with power through a common line impedance. The generator unit may be thought of as the fixed impedance and the modulator tube as the variable impedance in parallel, both being supplied with power through the common impedance L_B . Without this impedance practically no variations in the audio frequency voltage across the $b+$ and $b-$ terminals could occur. The impedance of L_B is usually high for the average speech frequency of 800 cycles per second, in comparison with the impedance given by the ratio of the direct voltage across the $B+$ and $B-$ terminals to the direct-current constituent flowing through the choke coil. Choke coils for this purpose are usually built with an air gap in the magnetic circuit and with a large number of direct-current ampere turns per unit length of the magnetic circuit.

To the left of the modulator unit is the direct-power supply unit. In this case it consists of a direct-current generator provided with filter circuits to prevent voltage due to commutation from existing across the terminals $B+$ and $B-$. The condenser C_B functions doubly as a part of the filter network and as a device which by-passes any audio frequency current which may flow through the choke coil.

To summarize, tracing from left to right, the primary power supply to the set is direct power delivered at the $B+$ and $B-$ terminals of the modulator unit. By an audio frequency variation of the modulator tube impedance, audio power is produced and, together with direct power, is supplied to the $b+$ and $b-$ input terminals of the generator unit. As a result, the amplitude of the radio frequency output current of the generator unit is varied at speech frequencies and a wave form emitted, which upon reception gives rise again to speech currents.

IV. THE ELEMENTARY FUNCTIONING OF THE MODULATOR UNIT

The elementary and fundamental functions of the modulator tube may be readily shown by a symbolization of the adjacent units. The power supply unit is readily symbolized by a battery of voltage E_B , which represents the direct voltage across condenser C_B of Fig. 1. Across this battery is shunted in the symbolized diagram a condenser C_B to represent the capacity reactance of the filter network to an audio current flowing through the $B+$ and $B-$ terminals. The symbolization of the generator unit and

radiator unit may be by the use of experimentally determined external characteristics. Thus if the instantaneous voltage e_b across the $b+$ and $b-$ terminals be varied at a low frequency there will be corresponding changes in the current i_b through these terminals, and in the r. m. s. antenna current i_a produced by the generator system. In making such characteristics it will be understood that all controls of the generator unit, such as filament current, operating grid voltage, and couplings are left fixed. Such characteristics for a typical generator circuit are shown in Fig. 2, in which low frequency plate current and value of antenna current are plotted against the low frequency plate voltage. Over the

FIG. 2.—External characteristics of tube generating circuit

range shown, an approximately linear relation exists between these three quantities. The proportionality relation between plate voltage and plate current indicates that, as far as the modulator unit is concerned, the generating and radiator unit behave roughly as a resistance in this case of approximately 3000 ohms. This ratio of e_b to i_b may be termed the input impedance of the generator unit. The modulation characteristics for plate modulation inherently give better linear relations between cause and effect than similar characteristics for the other types of modulation.

In Fig. 3 is shown the simplified modulator diagram which may be used in discussing the elementary functioning of the modulator

tube. In this diagram the power supply unit has its representative in the battery E_b , and the generator and radiator units are symbolized by a resistance R_b . The value of this resistance is an important factor in determining how many tubes must be used in order that the modulator part of the set may operate with good electrical efficiency. Another important factor is discussed in Section IX.

V. LOAD IMPEDANCE AS SPECIFIED BY WAVE FORM OF PLATE VOLTAGE AND CURRENT

With the modulator unit as symbolized in Fig. 3, operating under the ideal conditions, with choke coil L_B of infinite impedance, the pulsations of the load current i_b and of the modulator tube current i_m will be exactly 180° out of phase with each other, since the sum of these currents will be the direct and unvarying current through the choke coil L_B . The voltages across the load e_b and across the tube e_m are obviously the same and therefore in phase. Since the load current and voltage are in phase, on account of the load being a resistance, it therefore follows that the tube alternating voltage and the alternating current are exactly 180° out of phase, with the total plate current a maximum when the plate voltage is a minimum. Moreover the load resistance is simply related to the plate voltage and current wave forms. In this simple case the maximum departure of voltage from mean divided by the maximum departure of current from mean gives the value of the load resistance R_b .

FIG. 3.—Simplified modulator diagram

The conception of the impedance being specified by the plate voltage and current wave forms, however, is of more general application than in this special case. Thus, in any circuit in which the tube is functioning with direct currents and voltages present as well as alternating fundamentals and harmonics, the wave forms of plate voltage and plate current with a single fundamental present must necessarily be of the form

$$e = \bar{e} + \Sigma e_n \sin (n\omega t + \theta_n) \quad (1)$$

$$i = \bar{i} + \Sigma i_n \sin (n\omega t + \phi_n) \quad (2)$$

in which $\bar{e}$ and $\bar{i}$ are time averages, or direct values of voltage and current, e_n and i_n are the amplitudes of the n^{th} harmonic voltage and current, and θ_n and ϕ_n are phase angles. In terms of the wave form, $\bar{e}$ and $\bar{i}$ are the direct values of the voltage and current supplied by the power sources jointly to the tube and its load. In the present case, the current through the choke L_B may be thought of as being in two portions, that which supplies the direct or average current to the tube and that which supplies the average current to the resistance R_b . The product $\bar{e} \bar{i}$ represents the total power delivered by the battery which is consumed in the tube structure and converted into alternating power by the tube action. By taking the product of the instantaneous tube voltage and current, and averaging over a complete cycle the power consumed by the tube is

$$\overline{e i} = \bar{e} \bar{i} + \sum \frac{e_n i_n}{2} \cos (\phi_n - \theta_n) \quad (3)$$

The quantity $\bar{e} \bar{i}$ may be termed the direct power consumed by the tube, and the remaining terms the alternating power. For $n = 1$, the power $\frac{e_1 i_1}{2} \cos (\phi_1 - \theta_1)$ is the fundamental alternating power and for the higher values of n the powers are the harmonic power. Neglecting the slight plate power which may be derived from the filament heating source through the action of initial velocity of emission, and that which might in some cases be derived from the grid circuit through the agency of secondary emission, the plate battery is the only source of power which heats the plate of the tube and supplies the output power of the tube. Since the power delivered to the tube and to the alternating current load upon the tube is $\bar{e} \bar{i}$, and since analytically the direct power consumed by the tube is also this quantity, it follows that the alternating power consumed by the tube is equal in magnitude and opposite in sign to the alternating power consumed by the load on the tube. The total alternating power consumed by the tube must therefore be a negative quantity, and the actual power consumed by the tube is less than the product of the average plate voltage and the average plate current. For the fundamental output power the value $\cos (\phi_1 - \theta_1)$ must be a negative quantity; that is, the alternating constituents of plate voltage and plate current must differ in phase by more than 90° . Let

$$\psi_n = 180 - (\phi_n - \theta_n) \quad (4)$$

define the angle by which current and voltage depart from being exactly 180° out of phase. The power output of the tube of any harmonic is

$$P_n = \frac{e_n i_n \cos \psi_n}{2} \quad (5)$$

this being determined entirely from the wave forms of tube voltage and current.

The quantities $e_n i_n$ and ψ_n further define an output impedance of the load on the tube, the resistance and reactive components of which are given by

$$R_n = \frac{e_n}{i_n} \cos \psi_n \quad (6)$$

$$X_n = \frac{e_n}{i_n} \sin \psi_n \quad (7)$$

This resistance and reactance may in some cases correspond to what may be computed from constants of apparatus in the tube circuit. For example, if in Fig. 3 L_B is a perfect choke coil, analysis of the plate wave form will necessarily give $\psi_n = 0$ and $R_n = R_b$ for the fundamental and every harmonic frequency. In other cases when apparatus with nonlinear volt-ampere relations is used as a load, the wave forms will not correspond to any that may be computed from values of simple impedances. Thus in Fig. 3, if R_b is replaced by a resistance with nonlinear volt-ampere relations as, for example, a two-electrode electron tube, then the analysis of wave forms of plate voltage and current will give values of R_n which are not the same for all harmonics. Moreover, the values of R_n for a given harmonic will vary with the amplitude of the voltage impressed on the modulating tube. The values of R_n and X_n will nevertheless be effective values which may be used in computations of the power output and may properly represent the impedance load upon the tube.

The load impedance and power defined in this manner correspond to the entire alternating output of the system, irrespective of the localizations of the dissipation of that power. In the case of a tube in an oscillating circuit, it includes the alternating power fed back to the grid branch of the tube, determined in a similar manner from harmonic analysis of the grid voltage and current wave forms. In the case of the modulator tube, the grid alternating power is supplied from the output of the microphone and transformer, and the load impedance upon the modulator tube is

dependent upon the relation of the tube and the apparatus associated with the plate circuit only.

With the conception of the load due to the generating system given by Fig. 3, if it is assumed that the choking action of the coil L_B is perfect, then the load impedance is a pure resistance. Even if the resistance R_b is not a pure resistance but one which varies with the current (as Fig. 2), with the conception here presented the load on the modulator tube is a resistance load, although the value of this resistance is dependent on amplitude and is different for harmonic frequencies than for fundamental. If on a plane with voltage as abscissa and current as ordinate, successive simultaneous values of plate voltage and current for the modulator tube be plotted, corresponding to a complete cycle of operation, and if this trace is a line, inclosing no area, then the load is a resistance. For a specified voltage the current is the same for an increasing voltage and decreasing voltage. If this line of operation or any portion of it incloses area, then there is a reactive component to the load, so that in general a different tube current exists for an increasing voltage of a given value than for a decreasing voltage of the same value.

Neglecting harmonic currents and voltages, for a reactive load the trace on the modulator plate current plate voltage plane will be an ellipse, with a clockwise sequence of successive points for an inductive load, and a counterclockwise sequence for a condensive load. Considering total instantaneous values, however, the trace will not be elliptical. Any phenomena in the telephone set which tends to make an elliptical trace for the fundamental line of operation of the modulator tube may be said to tend to produce a reactive load.

In a telephone set of the type analyzed in Fig. 1, there are three distinct types of phenomena which prevent the load on the modulator being a resistance load. The first arises from the imperfections of the choke coil L_B , which in practice is not entirely free from audio currents. The second is due to the reactive impedance of parts of the generating system. A third effect, of a more subtle nature, and not expressible in terms of reactances of inductors or condensers, arises from the resonance phenomena in the radiator unit. These three effects will be considered in turn.

VI. EFFECT OF IMPERFECTIONS IN THE AUDIO CHOKE COIL UPON THE PERFORMANCE OF THE SET

In the modulator unit the choke coil L_B is imperfect due to the reactance not being infinite and due to the direct resistance of the windings and effects which give rise to purely alternating current power losses. On account of the reactance being finite an alternating current will pass through the choke coil when the tube is operating. Due to the resistance of the windings, a direct voltage drop occurs across the coil, so that the net direct voltage supplied to the tube, given by the average voltage $\bar{e}$ is less than the direct voltage E_B supplied by the generator or battery. These effects may be represented by the use of the diagram Fig. 4, which represents a tube circuit with the same performance as that of Fig. 3, as

FIG. 4.—Load due to audio choke coil

far as tube voltage and current and the current to resistance R_b are concerned. In this latter figure, the choke coil in the battery lead is to be considered a perfect choke coil, with infinite impedance but no resistance. The battery E_B' represents a voltage opposing the main battery E_B of magnitude derived from the circuit of Fig. 3, being the product of resistance of the windings and the average current delivered by the battery. It is the difference of these two voltages which gives the net direct voltage impressed on the tube. The chain of impedances $L_B' R_B' C_B'$ represents the effects of the finite impedance of the choke coil of Fig. 3. L_B' represents the inductance of that choke coil with the direct current flowing through the windings, and R_B represents approximately the alternating-current resistance of the choke coil, being larger than the direct-current resistance. C_B' represents the effective capacity of the power supply unit, as measured from the $B+$ and $B-$ terminals.

With the circuit of Fig. 4, the plate wave forms of voltage and current correspond to the impedance of $L_B' R_B' C_B'$ in series, paralleled by the resistance R_b . The total load current i_l which is 180° out of phase with the modulator current i_m is composed of two portions, that passing through the choke coil i_c and the useful output current i_b through the resistance R_b . Usually the reactance of the choke coil is the greatest of the three impedances in the choke-coil chain, so that the impedance of that branch is inductive and, as a result, there is an inductive component to the load upon the tube. It results in the current pulsations in the tube current i_m being required to be greater than the pulsation in current in the useful load branch R_b . If, for example, the resistance R_b is 5000 ohms, the value of L_B' is 1.33 henry with the impedances of C_B' and R_B' negligible, then the impedance of the choke-coil branch at the speech frequency of 800 cycles is 6700 ohms. Accordingly the alternating current through the choke coil will be 75 per cent of that through the resistance R_b . The variation in the modulator tube current will in consequence be required to be 125 per cent of the variation in current to the resistance R_b . To produce, for example, an 8-milliamperere variation in the useful output current of the tube, the variation of current through the tube must be 10 milliamperes. It is because a reactive component to the load limits the possible output that care must be taken to design the circuit in such a way that the tube voltage and tube current shall be approximately out of phase. To avoid excessive reactive component to the load due to the choke coil, a safe rule is to make the reactance at 800 cycles at least two or three times the value of the resistance R_b .

VII. EFFECT OF AUDIO FREQUENCY IMPEDANCE OF PARTS OF THE GENERATING SYSTEM UPON THE PERFORMANCE OF THE SET

Referring back to the diagram of Fig. 1, a source of reactive component to the load on the modulator tube has been derived due to the reactance of apparatus in the modulator unit. Similarly a second source of reactance load exists in the generating unit. Thus in the diagram, Fig. 5, condenser C_b is required to be of low reactance for the radio frequency current, but of high reactance for audio currents. If the ratio of the radio frequency to the audio frequency is low, it may not be possible to satisfy both these requirements. The characteristics of the generating system shown in Fig. 2 were for very low audio frequencies, such that

reactive effects due to the condenser are negligible. Even with the condenser present, and with actual operating audio frequencies, the current i_b may be interpreted as the average space current to the oscillator tubes during a radio cycle, corresponding to the average plate voltage e_b . However, to produce the plate voltage e_b the

FIG. 5.—Series type generating circuit

modulator tubes must supply not only the conductive current i_b , but also the charging current to the condenser. As a result, the generating unit as a whole is behaving as an impedance with a capacity component.

Another type of generating circuit is shown in Fig. 6, which may be used in radio telephone sets. It may be described as a circuit

FIG. 6.—Parallel type generating circuit

with plate direct coupled and grid inductively coupled to the antenna circuit and with a parallel power supply. Choke coil L_b performs the same function for radio frequencies as does the choke coil L_B for audio frequencies in the modulator unit. However, there is an upper limit to the possible value of the choke coil

L_b , since it must permit the audio current to pass into the generating unit. At low ratios of radio to audio frequencies, both conditions can not be met, so that, in general, an inductive component is imposed upon the modulator tube, which may be represented as an inductance in series with the resistance R_b .

Impedances in the generating circuit other than that of a radio by-pass condenser or a choke coil may be of importance. Thus in Fig. 6, if the stopping condenser be of sufficiently high capacity, and L_b and L in series are of sufficiently high inductance, the system L_b , C_s , and L in series may constitute a series resonance circuit, which will be modified by the resistance R_b being shunted across C_s and L when the tube is operating. Such effects may give rise to distortion provided the resonance occurs within the audio-frequency range.

The choice of suitable choke coils, stopping condensers, by-pass condensers in the generator unit, depends jointly upon the radio frequency and upon the audio frequency. With too large values of the radio choke coil or by-pass condenser, a reactive load is imposed upon the modulator tube. With too low values, radio power will flow back into the modulator unit, interfering with its proper functioning as well as cutting down the radio power available for the radiator unit. In short wave-length radio telephone sets there is usually little difficulty in making a suitable choice of values, but in long wave-length sets particular care must be taken.

VIII. EFFECTS OF RESONANCE POWER IN THE RADIO OSCILLATORY CIRCUIT UPON THE PERFORMANCE OF THE SET

A third effect causing alteration of the load upon the tube from a simple resistance arises because of the energy in the electromagnetic field of the radiator unit. This effect is of a more complex nature than the other effects previously mentioned, which were expressible in terms of reactances of condensers and inductances. It is, moreover, an effect of importance not only in plate modulation methods of radio telephony, but in any method of radio communication involving modulation methods. Two methods of analysis of the phenomena will be presented. The first is based on considerations of the variations in power required to cause a specified variation in current in a radio resonance circuit. In this treatment, attention will be directed to the physical phenomena involved. The second method is based upon the analysis of the wave form of the modulated radio currents into

the carrier and side frequencies, and upon the behavior of the resonance circuit for currents of each of these frequencies.

For purposes of discussion it will be of advantage to refer to a simple type of resonance system and a simple method of modulating the current in that system. A possible method of modulating is shown in Fig. 7, involving the use of two alternating-current generators, G_r and G_a , the former turning at a speed corresponding to a radio or modulated frequency and the latter at a speed corresponding to an audio or modulating frequency. With the key K open, the field of the radio generator is excited by direct current, so that continuous radio currents flow from the armature of that generator. By closing the key, the field strength of the radio generator is varied at an audio rate, and therefore the output voltage is varied and modulated radio frequency current flows

FIG. 7.—Modulation of resonance circuit

from the armature. The resonance load upon the radio generator is the parallel system L, C, R tuned to the frequency corresponding to the speed of rotation of the generator G_r .

1. POWER RELATIONS IN RESONANCE SYSTEMS DURING MODULATION

With the key of Fig. 7 depressed, the actual wave form of current through condenser C of the resonance system may be approximately as shown in Fig. 8, which may be described as a radio frequency current with amplitude pulsating at an audio frequency rate. For the purpose of discussing the phenomena from power considerations, imagine the instruments e, i, i_a of Fig. 7 to record root mean square values sufficiently rapidly to follow accurately an audio current, but not a radio current. Thus the instrument i_a will follow the audio variations in the antenna current, as shown by the trace i_a of Fig. 8. Similarly instruments i and e will follow

the variations in the input radio current and voltage to the resonance system. With sine wave modulation, it is apparent that all of the instruments will record sine wave forms. The relations between the three wave forms depend only upon the constants of the circuit L , C , R , and the radio and audio frequencies. For a given wave form of current i_a , the audio variations in the power which must be supplied to the oscillating circuit may be computed. This must be equal to the power registered by instruments e and i , since the resonance load behaves as a resistance for the radio frequency and the radio current through i must be in phase with the radio voltage across the circuit as determined by the current through e . Consequently the product of e and i at any time in the audio cycle gives the radio power which is being taken by the

FIG. 8.—Antenna current

resonance circuit. It is by equating the values for power as specified by these two methods that the modulation phenomena in the resonance circuit will be examined.

For the determination of audio variation of power in terms of the current i_a and the constants L , C , R , two parts must be taken into account. At any instant in the audio cycle power must be supplied to balance the losses given by Ri_a^2 , in which R is the lumped resistance and i_a is the instantaneous reading of the instrument. Power must also be supplied to change the electromagnetic energy which at any instant of the audio cycle is present in the circuit. This energy is given by Li_a^2 in which L is the lumped inductance of the circuit. During the radio cycle this energy flows back and forth from the condenser to the inductance,

the amount of energy, however, remaining constant for a fixed amplitude. With the amplitude changing, power must be supplied to alter the energy content of the circuit, given by the time rate of change of energy, the derivative being taken in the audio time scale. Consequently, the total power given is by

$$P = Ri_a^2 + \frac{d}{dt}(L i_a^2) \quad (8)$$

and is readily computed from the audio wave form of i_a and the lumped resistance and lumped inductance of the circuit.

As a numerical example assign the following constants to the resonance circuit:

$$L = 160 \text{ microhenries.}$$

$$C = 0.004 \text{ microfarad.}$$

$$R = 4 \text{ ohms.}$$

These correspond to a resonance circuit of resonant wave length very close to 1500 meters, a log decrement per cycle of 0.063, and a resonance impedance of 10 000 ohms. Let the ratio of the audio frequency to the radio frequency be 100 to 1, so that the modulating frequency is very closely 2000 cycles per second. Let the degree of pulsation of current i_a be 50 per cent about the value 4 amperes, so that the wave form of current is

$$i_a = 4 (1 + 0.5 \sin 12\,500\,t) \quad (9)$$

Under these conditions the audio variations in power delivered to the resonance circuit computes to be as shown in the upper curve of Fig. 9. The curve P_r gives the variations in power consumed by the resistance R , and the curve P_e gives the variation of the power required to change the energy content. The average value of the latter is zero when taken over a complete audio cycle. The sum of the curves P_r and P_e gives the variation of total power P_t which must be supplied to the resonance circuit to cause the wave form i_a to exist. It is this total power which must be given by the product of the pulsating sine wave forms of voltage e and input current i to the resonance system during the modulation. The problem is to find what the wave forms of e and i must be to have a product given by the curve P_t . This problem is to some extent indeterminate.

In general let the wave forms be given by

$$i_a = I_a [1 + k_a \sin pt] \quad (10)$$

$$e = E [1 + k_e \sin (pt + \phi_e)] \quad (11)$$

$$i = I [1 + k_i \sin (pt + \phi_i)] \quad (12)$$

in which the capital letters give average values of quantities over an audio cycle and the k 's denote degrees of pulsation, and ϕ_e and ϕ_i represent phase angles with respect to the wave form of current

FIG. 9.—Modulating power

i_a . From the condition that for all instants of time in the audio cycle the identity must be satisfied

$$ei = Ri_a^2 + \frac{d}{dt}(Li_a^2) \quad (13)$$

the following relations will be found;

1. Either ϕ_e must be zero or ϕ_i must be zero.
2. If $\phi_e = 0$, then $k_e = k_a$, $\phi_i = \tan^{-1} \frac{2L\phi}{R}$, $k_i = k_a \sec \phi_i$
3. If $\phi_i = 0$, then $k_i = k_a$, $\phi_e = \tan^{-1} \frac{2L\phi}{R}$, $k_e = k_a \sec \phi_e$

The reasons for the two possible solutions coming out of this expression is that nothing is specified as to the nature of the resonance circuit. The quantities e and i are similarly involved in the equation, and consequently two solutions arise, in one case e being in phase with i_a , and of the same degree of pulsation, and in the other i is in phase with i_a , and of the same degree of pulsation. The latter case corresponds evidently to a series resonance circuit, in which i and i_a must be of necessity the same wave form, as they are the same identical currents. The former case corresponds to resonance circuits of the parallel type in which the input voltage wave form is similar in shape to the oscillating current wave form. In this particular circuit, the ratio of e to i_a is the impedance of one branch of the resonant circuit. The solution is further incomplete because the ratio of E to I is not determined by the analysis. More detailed knowledge of the circuit must be had to determine uniquely what of the possible wave forms are correct.

For the case of the oscillating circuit as specified above, audio wave forms of radio current and voltage which are consistent with the configuration of the resonance circuit, and which when multiplied together give the total power P_t , are shown in the lower part of Fig. 9. In this case the phase angle ϕ_1 is 45° , and the degree of pulsation of input current is the square root of two times the degree of pulsation of the current i_a . The input current form is seen to lead the voltage form in the audio time scale.

2. RADIO FREQUENCY PHENOMENA IN A RESONANCE CIRCUIT CARRYING MODULATED CURRENT

To determine the relations between the radio wave forms of input current, input voltage, and condenser current, analysis must first be made of the condenser current into its radio frequency constituents. Then the performance of the resonance circuit must be determined for each of the frequencies present in the condenser current. This, then, will determine what the radio wave forms of voltage e and current i will be, corresponding to any condenser current i_a . In the present discussion these three symbols will refer to instantaneous radio frequency values of these quantities and not, as previously, to the instantaneous audio value of the effective radio values.

The wave form of a sine wave modulated radio frequency current may be expressed as

$$i_a = I\sqrt{2} (1 + k_a \sin pt) \sin (\omega t + \phi) \quad (14)$$

which states that it is a radio frequency current, with an amplitude changing sinusoidally at a lower frequency. The expression may be readily expanded into

$$i_a = I\sqrt{2}\left\{\sin(\omega t + \phi) + \frac{k_a}{2}[\cos(\omega t + \phi - pt) - \cos(\omega t + \phi + pt)]\right\}$$

This latter expression states that the wave form is the sum of three currents of different frequencies, corresponding to angular velocities ω , $\omega + p$, $\omega - p$. The amplitudes of the currents of the

last two frequencies are the

same, and $\frac{k_a}{2}$ times the am-

plitude of the current of the first frequency. These three frequencies are known as the carrier and the two side frequencies.

Important relations may be brought out by representing these currents vectorially as in the top diagram, Fig. 10, which represents the current flowing in condenser C of Fig. 7. Vector C represents the current of the carrier frequency, and is to be considered as rotating in a

FIG. 10.—Modulation of resonance system

counterclockwise sense, with an angular velocity ω . The vectors $s+$ and $s-$ represent currents corresponding to the side frequencies. The vector $s+$ is rotating with an angular velocity $(\omega + p)$ and therefore at a velocity $+p$ with respect to the carrier frequency. The vector $s-$ is similarly rotating with an angular velocity $(\omega - p)$ and therefore at a velocity $-p$ with respect to the carrier frequency. The two side vectors, upon addition, lie along the vector for the carrier frequency, and this relation is maintained throughout the rotation. The degree of modulation is the ratio of the sum of the lengths of the side vectors to the carrier vector, in this case it is 50 per cent. The position of the vector C indicates the point in the radio cycle which is represented by this configuration of the vectors. In the figure, a time corresponding to 120° in the radio cycle has elapsed since the vector C was in a horizontal position. The position in the audio cycle is

given by the angle between the carrier vector C and the side vector s +. Thirty degrees in the audio time scale have elapsed since the three currents were additive to give maximum instantaneous current.

Thus the diagram shown represents a particular instant of time and a particular point on the wave form of a modulated current, just as a single vector represents a point in a sine wave form. Successions of points on the modulated wave form are determined through the rotations of these vectors, the side vectors rotating slowly with respect to the carrier vector, and all three rapidly about the point O .

In order to determine the wave form of currents and voltages existing in other parts of the resonance circuit, it is necessary to know the performance of that circuit for currents of each of the three frequencies. This knowledge will enable computations and vector diagrams to be made, showing, in particular, the wave form of modulating current i and of modulating voltage e , in comparison with the wave form of output current i_a .

For convenience, the ratio of the input voltage e to input current will be termed the impedance Z of the resonance circuit. Similarly the ratio of the condenser current to the input current may be termed the transformer ratio T , since it gives the ratio by which current is increased by the resonance action. Define the resonance frequency n_o as that frequency for which the reactance of the condenser is equal and opposite to the reactance of the inductance. Let any other frequency n be specified relative to the resonance frequency by the equation

$$n = n_o (1 + \beta) \quad (15)$$

so that, for example, if $\beta = -0.01$, the frequency n is 1 per cent less than the resonance frequency. Let δ = the log decrement per cycle of the resonance circuit, which is π times the ratio of the series resistance of the circuit to the lumped inductive reactance.

$$\delta = \frac{\pi R}{L\omega}$$

Then, for any frequency in the resonance region it may be readily shown that the two ratios as given above are approximately

$$\frac{e}{i} = Z = \frac{Z_o}{1 + j \frac{.2\pi\beta}{\delta}} \quad (16)$$

$$\frac{i_a}{i} = T = \frac{jT_o}{1 + j \frac{.2\pi\beta}{\delta}} \quad (17)$$

in which Z_0 and T_0 are numerical values for resonance frequency at which $\beta=0$. For this type of resonance circuit, $Z_0 = \frac{L}{CR}$, $T_0 = \frac{L\omega_0}{R}$. For other types of parallel resonance circuits, including the case of a resonance transformer with inductive coupling but with negligible primary impedance, the values of Z_0 and T_0 will be different, but the ratios $\frac{Z}{Z_0}$ and $\frac{T}{T_0}$ will vary with frequency in quite the same manner as in the case cited.

By using the values of these ratios for the three cases $\beta=0$, $\beta = +\frac{p}{\omega}$, and $\beta = -\frac{p}{\omega}$ the carrier and side vectors may be evaluated for the input modulating current and modulating voltage. The results thus obtained for a case in which $\frac{2\pi\beta}{\delta} = 1$ is shown in the last two diagrams of Fig. 10. These three diagrams show the conditions in various branches at the same instant of time.

From these diagrams the modulating current is seen to be different in wave form from either the modulating voltage or the condenser current, having a degree of modulation greater in the ratio of $\sqrt{2}$ to 1. Moreover, the audio phase of modulating current is greater by 45° than the audio phase of voltage or condenser current. The general formula for phase shift of modulation and change in degree as determined by this method is the same as that obtained by the less complete but more general treatment given on pages 393 to 397.

As an illustration of the actual wave forms of a resonance circuit, the oscillogram, Fig. 11, shows the input current, input voltage, and the condenser current obtained by low-frequency modulation of current in a low-frequency resonance circuit, by the method shown in Fig. 7. The input current is clearly shown to be of a greater degree of modulation than the input voltage and moreover to precede it on the audio time scale. That more power is being supplied when the condenser radio current is of a given value but increasing than when of the same value but decreasing is evident, since the input current is greater in the former case than in the latter.

The effect described here is of importance in any electrical circuits in which current in a resonance system is modulated at a lower frequency. While in radio telephony the effect is not of importance at short wave lengths, it does commence to be of considerable importance at long wave lengths.

FIG. 11.—Change of modulation. Wave form at the radiator unit

In any modulation system whatsoever, the variation of resonance energy will of necessity influence the operation of the modulating device, since it requires greater amount of radio power to be generated when the antenna current is a given amount and increasing than when it is the same amount and decreasing. In the circuits using plate modulation, it is apparent that the radio generating circuit will react on the modulator tube by drawing more audio output current when the audio output voltage is a given value and increasing than when it is the same value but decreasing. Assuming that the effects of imperfections of the choke coil and of audio impedance of parts of the generating circuit are negligible, the line of operation on the plate voltage plate current diagram for the modulator tube will in consequence be distorted into a loop with rotation in a sense corresponding to a condensive load.

By way of summary of the effects tending to produce reactive components in the load on the modulator tube, in Fig. 12 are shown

four impedances Z_1 , Z_2 , Z_3 , and Z_4 in parallel which symbolize the load for a telephone set analyzed as in Fig. 1. The first impedance Z_1 , consisting of the chain L_B' , R_B' , and C_B' , represents the effects of imperfections of the

FIG. 12.—Modulator and load

choke coil L_B . The second impedance Z_2 represents the effect due to audio impedance of parts of the generating system, and is of very simple nature for this type of circuit. For other types as, for example, that shown in Fig. 6, the representation is more complex, and the succeeding impedances Z_3 and Z_4 would not be in parallel with Z_1 and Z_2 , but be incorporated as a portion of Z_2 . The third impedance Z_3 represents the equivalent condensive load due to the resonance energy in the radiator circuit. The fourth impedance Z_4 is a resistance R_b' in which most of the audio output power of the modulator tube is usually consumed. Due to the phenomena of resonance energy, the numerical value which may best represent R_b' is not necessarily the same as the value R_b of Fig. 3. Of these four impedances, the last two are possibly of the most symbolic nature, since their values depend not upon the simple electrical elements of inductance, capacity, and ohmic resistance, but rather upon the characteristics of the

generating tubes, values of plate and grid couplings and grid biasing voltage, and resonance impedance and decrement of the radiator circuit.

With a plate modulation set used for telegraphing, with grid voltage for the modulator tube supplied at a definite frequency either by buzzer or by use of an audio resonance circuit, it may be possible to balance out one of these impedances against another in such a manner as to produce a resistance load upon the modulator for the fundamental frequency. But for telephoning, the audio fundamentals are constantly changing in frequency and in amplitude, so that any audio frequency resonance due to balancing reactances to produce resistance load is undesirable because of the distortions which would occur. For good operation and articulation it is essential that the load impedance Z_4 be the most important throughout the speech range of frequencies.

IX. THE STRENGTH OF SIGNAL TRANSMITTED BY A RADIO TELEPHONE SET

In a continuous wave transmitter the reading of an instrument reading effective current in the antenna circuit is qualitatively an indication of the strength of signal which is being transmitted. In transmission of signals by modulation methods maximum reading of antenna current does not indicate maximum received signal. If, for example, the wave form of antenna current is one with perfect sine wave modulation, as given by equation 14, and the detection at the receiving station is according to the square law of reception, then neglecting variations of audio impedance of parts of the receiving circuit with frequency the received fundamental audio current is proportional to the product $k_a I^2$. The reading of the antenna ammeter, on the other hand, for this wave form is $I\sqrt{1 + \frac{k_a^2}{2}}$. These functions are obviously not proportional.

In radio telephone transmission, however, the electrical conditions are such that sine wave modulation rarely occurs. An important factor contributing to this is the curvature of the characteristics of the generating unit as, for example, in Fig. 2. While there is no theoretical limitation upon the voltage which may be impressed upon a generating circuit, the current which can be taken by the circuit will in no case exceed the total filament emission of the generating tubes. Under conditions of efficient operation, the direct current to a tube is usually of the order of not greater than a third or half of the total emission. As a result,

if the operating plate voltage is increased, the current to the circuit can not increase indefinitely but will approach a constant value. At the same time, since the input power is no longer proportional to the square of the input voltage, the output current increases less rapidly than the input voltage, and linear relations no longer exist. The result is that during speech if a sine wave is impressed upon the generating circuit by the modulator tube, the maximum increase of antenna current is less than the maximum decrease. In other words, the upward variation is less than the downward variation of antenna current.

This type of distortion at the transmitter is not necessarily detrimental to good speech transmission. In fact, with a sine wave modulation, the received audio current is not a sine wave, but contains a double frequency term, which is $\frac{k_a}{4}$ times the fundamental. It may be readily shown that the proper wave form to impress upon a detector with square law of reception in order to obtain a pure audio signal is

$$e = E\sqrt{1 + k \sin pt} \sin \omega t$$

in which k is a constant, less than unity.

Assuming there is no difference in the wave form of voltage impressed upon the detector and the wave form of current in the transmitting antenna, then to transmit a pure sine wave audio signal the transmitter antenna current should be of the form

$$i_a = I_a \sqrt{2\sqrt{1 + k \sin pt} \sin \omega t}, \quad k < 1 \quad (18)$$

The wave form of equation 18 is one which approximates that produced by transmitters in case the output current is limited by the amount of input current which is possible. If, for example, in this expression k is unity, the peak r. m. s. value of antenna current is $\sqrt{2}$ or 1.4 times the unmodulated r. m. s. value, while the minimum value is zero. In other words, this wave form is one corresponding to less upward modulation than downward modulation. Since this wave form is the proper one for transmitting a pure note and, moreover, is one which is often approached in practice, it possesses advantages over a sine wave modulated form as a basis of rating of telephone sets.

For the wave form of equation 18 the r. m. s. antenna current averaged over an audio cycle is independent of the modulation parameter k , and if this wave form is being produced, the reading of the antenna ammeter will neither rise nor fall during speech.

This is in contrast with the case of sine wave modulation (equation 14) in which the reading increases in the ratio $\sqrt{1 + \frac{k_a^2}{2}}$ during speech. The upward variation of antenna power is equal to the downward variation of power, being kRI_a^2 . Moreover, the received signal is also proportional to the variation of power from mean. In consequence the received signal is proportional to the difference between the peak antenna power and the minimum antenna power. The rating of a telephone set might well be specified simply by this variation of antenna power with specified speech conditions at the transmitter microphone.

These considerations of signal strength have an important bearing upon the choice of the ratio of the number of modulating tubes to the number of oscillator tubes in a transmitter set. The average antenna power which can be obtained is determined almost entirely by the number of oscillator tubes used and is quite independent of the number of modulators. On the other hand, the variation of antenna power is not determined to the same degree by the number of modulator tubes, because the number of oscillator tubes determines the nature of the load upon the modulator tubes. For example, compare the relative merits of a telephone set with three oscillators and two modulators with one using four oscillators and one modulator, using identical tubes and assuming that the sufficient grid power for the modulator tubes will be supplied in either case. The latter combination is possibly capable of producing 15 per cent greater antenna current than the former. The former, however, may be expected to produce more than twice as much audio current in the receiving telephones as the latter, first, because there are twice as many units for varying the antenna power, and second, because two modulating tubes may be expected to operate much more efficiently into the generating circuit of three tubes than one modulating tube can work into a generating circuit of four tubes.

The signal, however, can not be indefinitely improved by increase of ratio of modulator tubes to oscillator tubes, not only on account of the poor audio efficiency of the modulator under such conditions, but also because of the speech distortions which will occur due to any overmodulation. For these reasons, in constructing transmitters with tubes operating in parallel the number of modulator tubes usually about equals the number of oscillator tubes for best operation.

X. SUMMARY

1. Three methods of modulating the output current of an electron-tube generating circuit are commonly used—modulation by radio absorption, by variation of the operating grid voltage, and by variation of the operating plate voltage. Of these, the method of plate voltage modulation is the most satisfactory.

2. A telephone transmitter network may be conveniently analyzed into four units—the plate power supply, the modulator unit, the generating unit, and the radiator unit.

3. The essential operation of the modulator tube in the modulator unit is as an aperiodic power amplifier, the essential load into which the tube operates is a resistance as given by the external characteristics of the generating unit.

4. The actual load impedance of a tube acting as an amplifier, modulator, or generator is defined in terms of harmonic analysis of the wave forms of plate voltage and plate current. For modulator tubes the actual load impedance is not given exactly by the characteristics of the generating unit, on account of imperfections of the audio-choke coil, audio impedance of parts of the generating circuit, and the presence of electromagnetic energy in the radiator unit.

5. Imperfections of the audio-choke coil due to its reactance being finite tends to produce an inductive component to the load on a modulator tube. This effect can be made small as desired, and is not an essential limitation in radio telephony.

6. Audio impedance of component parts of the generating circuit may tend to produce an inductive load, resistance load, or capacity load, depending upon the nature of the generating circuit. The choice of suitable constants of condensers and inductances to function properly for radio purposes and not seriously affect the operation of the modulator tube becomes difficult only with a high ratio of modulating frequency to modulated frequency.

7. The presence of electromagnetic energy in the radiator unit requires that more power be delivered to the radiator when the antenna current is a given value and increasing than when it is the same value and decreasing. The tendency is to impose a capacitive component to the load upon the modulator tube. This effect is of more importance the greater the ratio of modulating to modulated frequency, and the less the decrement of the radiator circuit.

8. The strength of speech signal produced by a telephone transmitter set is not indicated by the reading of an ammeter in the radiator unit. The signal strength under conditions of no distortion with a receiving set with square law of reception is proportional to the difference between the peak radio power and the minimum radio power in the transmitter radiator unit. This power difference under specified speech conditions at the mouth-piece of the transmitter microphone is suggested as a suitable basis of rating radio telephone sets as to power output.

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