Proceedings of the Institute of Radio Engineers
Volume 21, Number 7 *July, 1933*

APPLICATION OF TRANSFORMER COUPLED MODULATORS*

By
J. A. Hutcheson
(Westinghouse Electric and Manufacturing Company, Chicopee Falls, Mass.)

Summary—*A brief résumé of Heising's modulator theory is presented together with a discussion of the class B operation of tubes in a push-pull audio-frequency circuit. Several cases of commercial applications of class B audio amplifiers are mentioned. Several general problems involved in the use of a class B audio amplifier are discussed with the conclusion that such an amplifier will produce more audio power for a given tube complement, at higher efficiency, and with less distortion than amplifiers previously used in commercial applications.*

UNTIL recently, the constant-current system of plate modulation developed by Heising has been the common way by which transmitters were modulated. This system is illustrated by the circuit shown in Fig. 1. The principle of operation in brief is as follows. The total current for both the modulator tube *M* and the load circuit *R*, which may be either a self-excited oscillator or an amplifier, flows

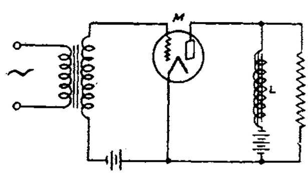

Fig. 1—Class A audio amplifier schematic circuit.

through the modulation choke coil *L*. This choke coil is one possessing a large amount of self-inductance so that it offers a high impedance to a change in current. Now, as the grid voltage on the modulator tube is varied, the current drawn by the modulator tube changes. As the choke coil offers a high impedance to the change in current, a voltage is built up across the choke coil which will oppose the current change. Suppose that the grid potential is made more negative, the modulator plate current decreases, the modulation choke coil builds up a voltage tending to oppose this change in current; i.e., in a positive direction. This increase in voltage appears at the plate of the modulator tube and across the load *R* which causes the load circuit to draw more current. The increase in load current is practically equal to the decrease in modulator tube plate current so that the total current, i.e., the cur-

* Decimal classification: R135×R355.8. Original manuscript received by the Institute, November 30, 1932. Presented before Twentieth Anniversary Convention, April 9, 1932, Pittsburgh, Pa.

rent through the modulation choke coil is a constant, hence, the name, constant-current system. A handy way of plotting the dynamic or modulation characteristic is to assume changes in plate voltage and current in the load circuit. The modulator plate current is assumed to be the difference between the steady current through the modulation choke coil and the load current. The instantaneous value of grid voltage is then found from the tube characteristics and is the value which will cause the instantaneous value of plate current to flow at the instantaneous value of plate voltage. A sufficient number of such points will allow us to plot the dynamic characteristic. Such a characteristic,

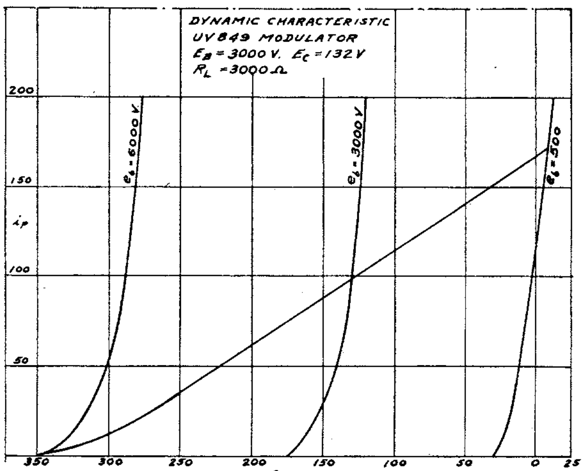

Fig. 2—Class A audio amplifier dynamic characteristic.

shown in Fig. 2, is plotted for a UV-849 as modulator drawing normally 0.1-ampere plate current at 3000 volts, modulating a UV-849 radio tube load circuit which is also drawing 0.1 ampere at 3000 volts. This system of modulation is known as the class A system. Thus, class A operation of a tube can be defined as the operation of a tube so that plate current for the tube never goes to zero at any time during a grid voltage cycle. The limit of operation of such a system occurs at the bend of the dynamic characteristic, as it approaches the condition of zero modulator current, thus entering into the curved portion of the tube static characteristics.

Now, suppose that the fixed bias on the modulator tube grid is increased until zero plate current flows at normal plate voltages. If the grid voltage is increased in a positive direction plate current will flow in the tube. Again the modulation reactor opposes the change in current through the load R, an amount corresponding to the increase in modulator plate current. If the cycle is continued the grid will eventually have sufficient negative potential to stop all plate current in the tube, and as the potential will increase negatively for the remaining half cycle, the plate current in the tube will not change during the negative half cycle. No change in plate current will result in no change in voltage across the load circuit for the negative half cycle. Now, if

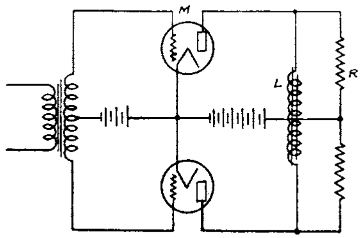

Fig. 3—Class B push-pull audio amplifier schematic circuit.

another tube is connected so that its operation is exactly opposite to the first tube, that is, so that it operates during the half cycle when the first tube is idle, changes in voltage across the load resistance can be made to occur continuously throughout the cycle. Such a circuit is shown in Fig. 3. Here we have both tubes feeding into an inductance which acts like an autotransformer. The voltage developed across the

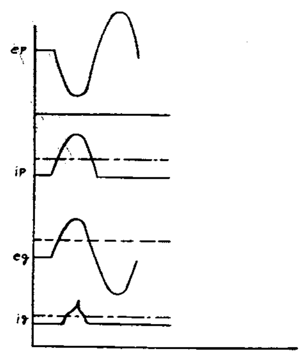

Fig. 4—Relation of plate and grid voltage and current for class B amplifier tube.

impedance of one half the choke coil is auto-induced in the other half, in the same direction. The voltage produced by the operation of one tube is out of phase 180 degrees with the voltage produced by the other so that there is a continuous alternating voltage appearing across the load resistance. This then is the operation of the class B push-pull amplifier. The class B operation of a tube can be defined as the operation so that plate current flows for just one half of a grid-voltage cycle.

As the dynamic characteristic of a tube is practically linear in the region of positive grid potentials, the tube is made to operate with instantaneous positive potentials on the grid, resulting in high values of plate current and, therefore, output load current, and as the tube loss is reduced because of the lower instantaneous values of plate voltage, the efficiency is higher than that of a class A amplifier. Fig. 4 shows the relation of plate voltage, plate current, grid voltage, and grid current for a class B operated amplifier tube. Fig. 5 shows the relation of

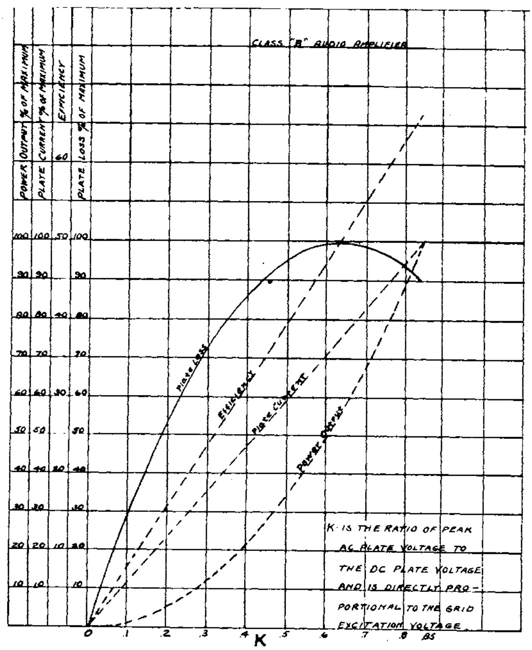

Fig. 5—Relation of output, plate loss, plate current, and efficiency to output voltage.

efficiency, output, plate loss, and plate current for a tube, the ordinates being in per cent and the abscissa being the ratio of the peak alternating component of plate voltage to the steady direct-current plate voltage. Practically, the minimum instantaneous value of plate voltage is limited to 15 per cent of the direct-current plate voltage. Thus, the peak alternating-current component of plate voltage is the remaining 85 per cent. It is interesting to note that the efficiency at this condition is 66.6 per cent. It is also interesting to note that the maximum plate loss does not occur at the maximum output but at a condition of operation which results in 50 per cent efficiency.

The recent rapid development of the so-called class B system of amplification of audio frequencies has presented many interesting problems in the design and application of this system to high power radio transmitters. The class B system of audio amplification has made available relatively large amounts of audio power at an efficiency which still allows the practical application of this power. Some of the problems and accomplishments accompanying the application will be given here.

The system of class B amplification is not new, having been used in many radio transmitters, but the use of this system for the ampli-

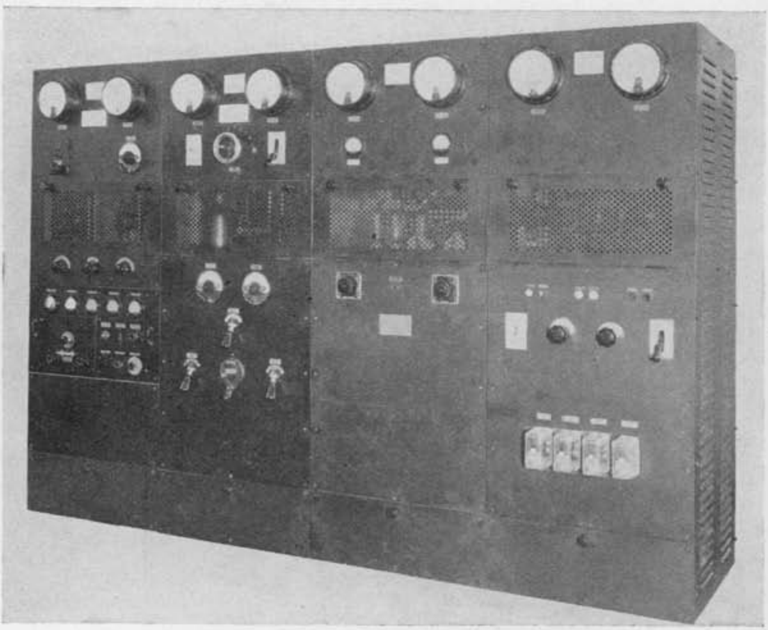

Fig. 6—Department of commerce type TBH radiotelephone and radiotelegraph transmitter.

fication of audio frequencies is a comparatively recent development. A commercial application appears in a transmitter developed for the U. S. Department of Commerce to be used at various airways stations. This transmitter is rated at 1200 watts for telephone transmission in the radio-frequency band of 190 to 550 kilocycles. The over-all efficiency obtained in the radio amplifier of this unit makes necessary for complete modulation approximately one kilowatt of audio power. This power is obtained by the use of a class B audio amplifier using two UV-849 tubes to deliver the necessary power. Had tubes of this type been used in the old class A system of modulation, ten tubes would have been necessary to supply the power. In the class A amplifier, there would have been a steady load of 3 kilowatts drawn from the plate supply for the modulator alone. In the new class B system, the "no-talk" load is approximately 300 watts, the maximum load is approximately 1800 watts and the average load is of the order of

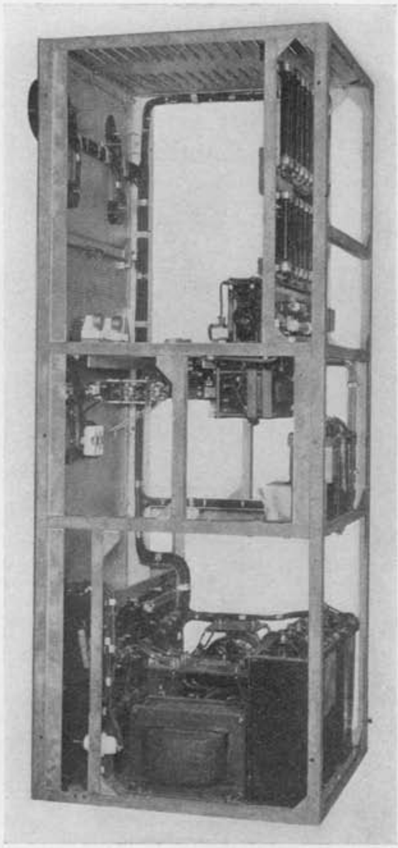

Fig. 7—Modulator unit for type TBH transmitter

one kilowatt or less with ordinary voice modulation. It is quite obvious therefore that the class B system offers an advantage from the standpoint of power required and also from the standpoint of tube complement. The audio quality of the amplifier under discussion is fully as good as the best broadcast transmitter in existence today. The oscillogram of rectified antenna current showing essentially complete modulation at an audio frequency of 400 cycles will give an idea of the quality of such a modulator. The total distortion is a result of not only the class B modulator but also five preceding audio-frequency amplifier stages, three of them operating class A and two operating class B. This oscillogram has been analyzed and shows a total audio harmonic distortion of slightly over six per cent. The audio system described is capable of amplifying a signal level of one one-hundredth of a microwatt up to one kilowatt with a total of only slightly more than six per cent distortion. The total power amplification is 10^{11} times, or one-hundred billion times.

Another example of such a system is now in use at KDKA where an amplifier is in operation which will deliver more than fifty kilowatts of power. This tremendous amount of audio-frequency power is used to plate modulate a radio-frequency amplifier which will deliver fifty

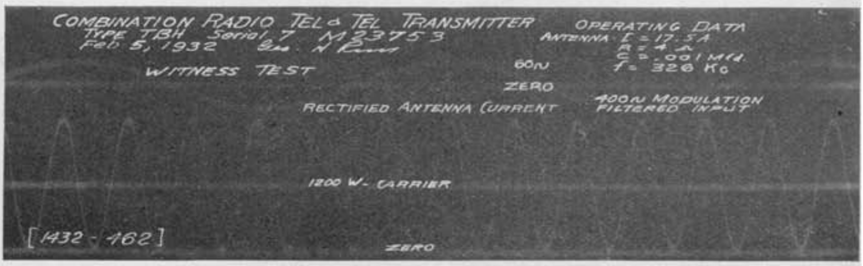

Fig. 8—Oscillogram of rectified antenna current.

kilowatts of carrier power to an antenna. This amplifier is essentially the same as the one previously described with the addition of another stage to bring the power level up to fifty kilowatts. The tube complement of the output audio amplifier is six UV-863 tubes. An equivalent amplifier using UV-848 tubes, similar to the UV-863 except of lower mu and developed for class A operation, would require in a class A circuit at least twenty such tubes to deliver the same amount of power. Such an amplifier would require a steady power of at least 150 kilowatts for the plate supply, whereas the maximum power under steady full load output for the class B system is 75 kilowatts and the average power required during regular program broadcast is of the order of forty to fifty kilowatts. The advantages of the class B system are at once apparent.

The problems associated with the development of the aforementioned equipment have been very complex, involving new lines of thought. A class B amplifier must be thoroughly coupled into the load to which it will deliver its power. This involves the coupling transformer and the coupling network. As the amplifier is intended to be used as a modulator, the load is defined as the plate voltage of the modulated stage, divided by the plate current. For complete modulation the peak value of the modulating voltage must equal the direct-current plate voltage of the modulated stage. Therefore, as the load circuit is considered to be a pure resistance the peak value of modulating current must equal the direct plate current of the modulated stage.

Fig. 9—Class B modulator unit at KDKA.

Thus, the root-mean-square voltage is equal to 0.707 E_B and the root-mean-square current equals 0.707 I_B. The power delivered by the modulator then is $0.707\ E_B \times 0.707\ I_B = \frac{1}{2} E_B I_B$. For complete modulation then the modulator must deliver an amount of power equal to one half the power which it is desired to modulate. For high power work it is deemed best to separate the direct-current and alternating-current components in the load, allowing the direct-current component to flow through a modulation reactor and the alternating-current component only to flow in the secondary of the modulation transformer.

Fig. 12 shows such a circuit. A little thought will show the reason for this. The requirements of broadcast equipment today as regards harmonic audio distortion are very strict, limiting the arithmetic sum of all harmonics to ten per cent. It is seen then that every precaution must be taken to assure the linearity of the modulator. If the load direct

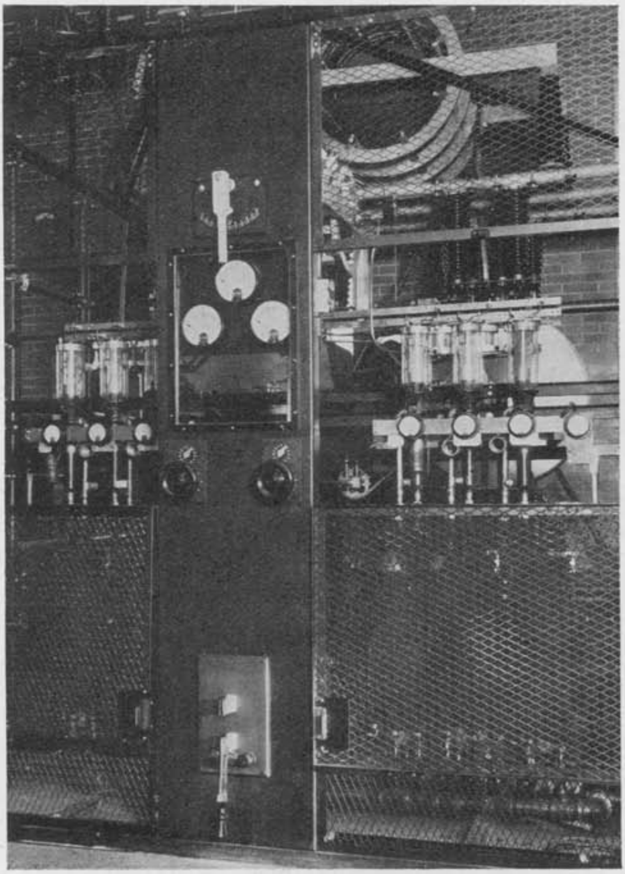

Fig. 10—Modulated amplifier at KDKA.

current were allowed to flow through the secondary of the modulation transformer, it would produce a steady flux in one direction. Now during one half of an audio cycle, the flux caused by the audio voltage would be in the same direction as that caused by the direct current, and for the other half cycle the flux would oppose that caused by the direct current. Thus, the inductance of the primary of the modulation transformer would be reduced for one tube and increased for the other.

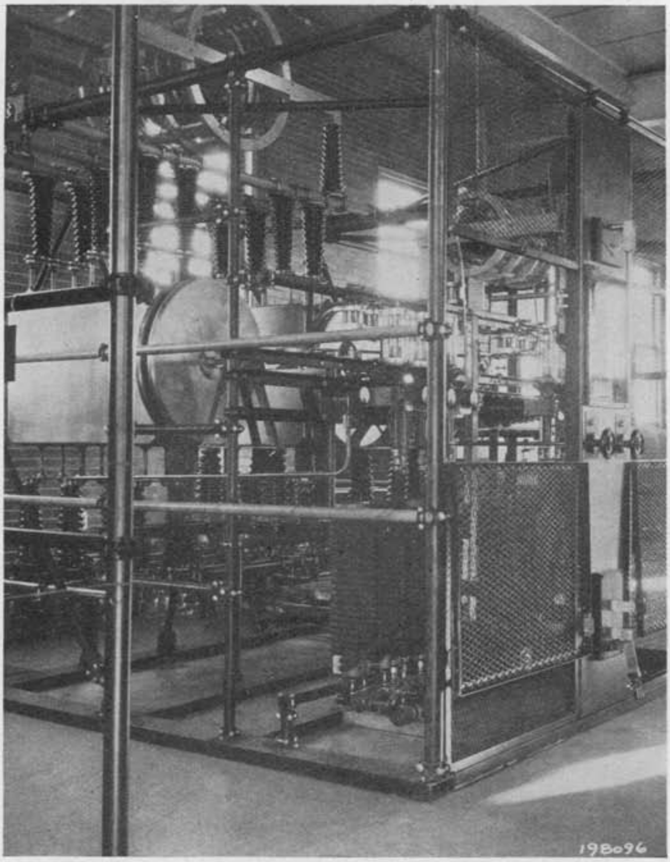

Fig. 11—Modulated amplifier at KDKA.

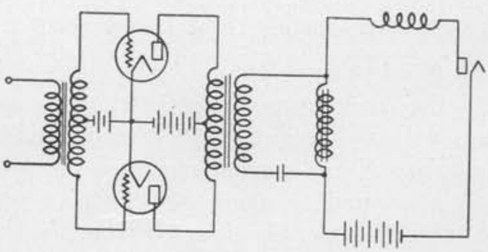

Fig. 12—Schematic modulation circuit using class B push-pull audio amplifier.

While this change in inductance could be made small by having sufficient iron in the core of the transformer, the slight variations might still be sufficient to produce large enough even harmonic components in the output wave to make the use of the equipment impracticable. Therefore, the output circuit was designed to make the transformer carry only the alternating-current component of the load current. From calculations involving tube characteristics it can be shown that

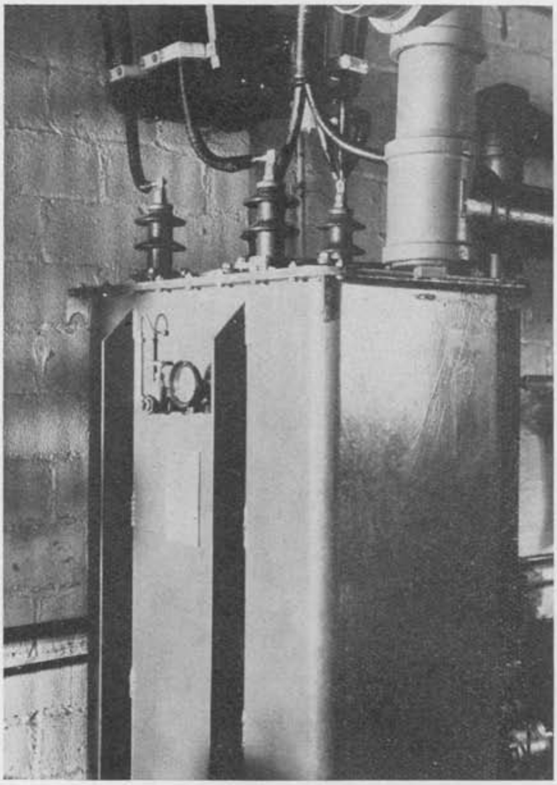

Fig. 13—Modulation transformer at KDKA.

the maximum practical primary voltage is 1.2 times the direct-current plate voltage of the modulators. That is, the root-mean-square alternating-current voltage across the full primary winding is equal to 1.2 times the modulator direct-current plate voltage. Knowing the load voltage which it is desired to modulate, the root-mean-square secondary voltage is 0.707 times the direct-current load voltage for 100 per cent modulation. Thus, we know both the primary and secondary voltages at full load and also the load current.

Thus, we have the general size requirements of the transformer determined.

The transformer used to supply the audio power to the plate circuit of the radio-frequency amplifier at KDKA is certainly unique, and as the problems and their methods of solution applicable to this transformer are typical of the modulation transformer for a transmitter of smaller power, a description of it is given here.

The audio transformer operates over a wide range of frequencies. In order that its response will be uniform over a wide range of frequencies it is necessary that it have low reactance between the input and output windings and that its internal capacitance be low. Also, since the input may contain a direct component of current provisions must be made to prevent the core of the unit from becoming saturated and causing serious magnetizing current distortions. To obtain low reactance the transformer was made very large in iron section and low in number of turns, the number of turns being fixed by the maximum permissible reactance at the highest frequencies and the cross section of the core being fixed by the minimum operating frequencies. Low internal capacitance was obtained by making the windings of a large number of pancake coils connected in series, thus approximating a banked winding. The various sections of the windings were then so connected as to give balanced capacitance of the two ends to ground. In order to prevent direct-current saturation of the core an air gap was placed in the core of such length that the maximum direct-current flux density would approximately equal the maximum alternating-current flux density. This gives a good compromise between total magnetizing current and distortion in magnetization.

The external circuits of a class B amplifier present several interesting problems. For instance, the power supply source must have good regulation. The plate current of a class B amplifier is not steady but varies directly as the input voltage. Suppose at a certain audio input voltage the plate supply voltage is a definite value. Now for proper reproduction of broadcast programs it is necessary that the percentage of modulation follow directly the changes in audio voltage input. If the plate supply voltage drops, the output voltage will not double but will be some value less than twice the original value. If the regulation is bad then it is apparent that the variations in output voltage or per cent modulation will not follow directly the input voltage, and the resulting output will not be a true reproduction of the input. This problem is not as serious as might at first be thought, however, because these changes do not take place during an audio cycle providing there is sufficient capacity in the plate circuit to carry over peaks of plate current at an audio-frequency rate. The changes in level occur with phrase modulation, that is, changes of program level from a low percentage of modulation to a high percentage of modulation. As a ten per cent reduction in voltage represents a change of less than one decibel, it is seen that a reasonable amount of regulation in the power circuits can be allowed. One point which makes possible the use of ordinary plate supply equipment is the fact that usually the supply carries not only the modulator but also several other parts of the circuit, which makes the modulator load only a portion of the total load. Thus, the variations of load on the supply source are not relatively large.

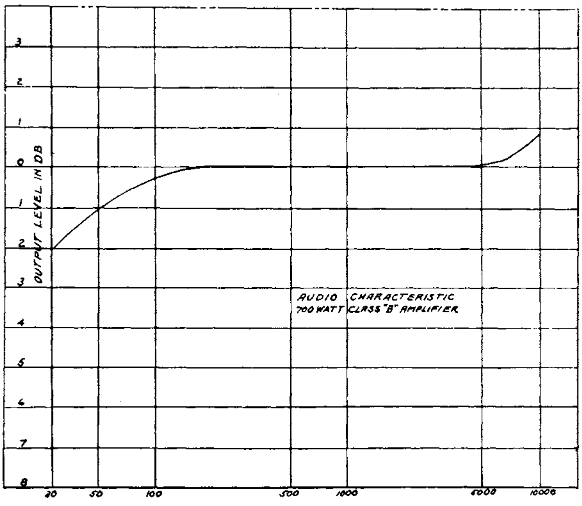

Fig. 14—Typical audio characteristic class B push-pull audio amplifier.

Another point in the external circuit which must be carefully considered is the supply of audio voltage to excite the grids of the modulators. The grid circuit absorbs quite an appreciable amount of power during peaks of modulation, while at somewhat reduced levels the grids may take zero power. The driving stage must not be seriously affected by the change of load due to the effective resistance of the modulator grids varying from infinity to a low value, depending upon the type of tube and the conditions of operation. In addition the bias voltage circuit must be designed so that the variations in bias voltage due to the flow of grid current will not be appreciable. Both of the above-mentioned items, that is, the ability of the audio supply source to supply peak grid power, and the variation in bias voltage, affect the output of the modulator during an audio-frequency cycle, and therefore result in distortion.

The audio characteristic of a class B audio modulating system can be made as good as that of an old type constant-current system. Fig. 14 shown here is an audio characteristic taken on a class B system showing the variation in output level plotted in decibels as ordinates as a function of the frequency plotted as abscissas. This curve was taken with the audio input voltage maintained at a constant level.

The quantitative values which can be assigned to the various items which govern the quality of a modulation system are a function of the quality required. It is safe to say that a properly designed class B audio amplifier will supply more audio power with less distortion (for the same tube complement) than any type of audio amplifier previously in commercial use.