THE LOAD OF A POWER TUBE

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I wish to call attention to an error in "radio" practice which has become common in the design of audio amplifiers. It is customary to make the load impedance of the power tube twice the inpedance of the tube, while it is theoretically better, and is practically better except perhaps in the case of over load, to make the load impedance equal to that of the tube.

It seems that this practice is due to a general misunderstanding of the fundamental principles involved. This is a good example of the error that a practical man is liable to make unless he has more than a practical knowledge of his subject.

The circuit in an amplifier may be considered to be a chain of circuits. Such a chain is illustrated in figure 1. In such a chain of circuits there are as a general

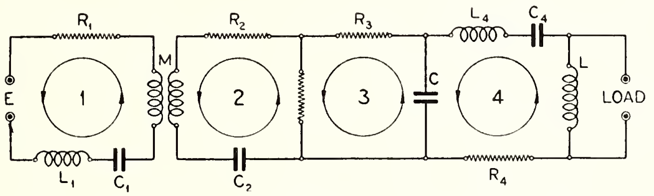

Fig. 1.

Fig. 1. Chain of circuits. Each link contains either resistance, inductance, or capacitance. Usually each link has all three at the same time. The input and output impedance of each link should be the same.

thing reflections from the ends of the sections. These electrical reflections are much the same as the reflections from the ends of a stretched rope as illustrated in figure 2. If the rope is infinite in length there is no reflection from the far end,

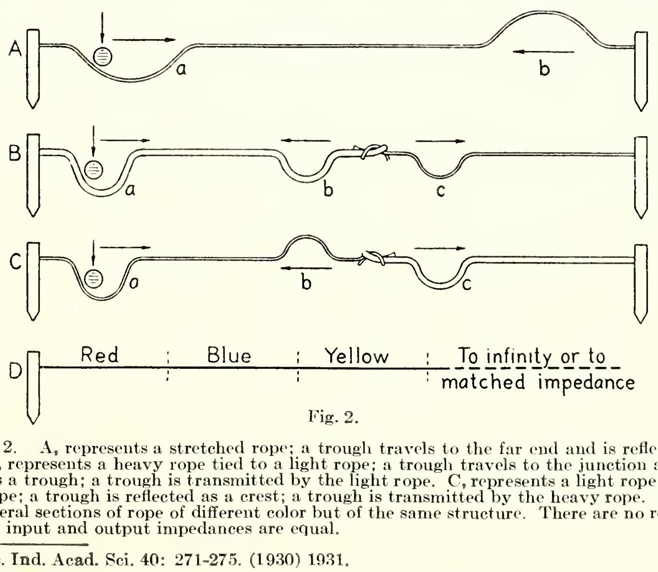

Fig. 2.

Fig. 2. A, represents a stretched rope; a trough travels to the far end and is reflected as a crest. B, represents a heavy rope tied to a light rope; a trough travels to the junction and is reflected as a trough; a trough is transmitted by the light rope. C, represents a light rope tied to a heavy rope; a trough is reflected as a crest; a trough is transmitted by the heavy rope. D, represents several sections of rope of different color but of the same structure. There are no reflections since the input and output impedances are equal.

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since the energy passes to infinity and is absorbed and there is none to be reflected. If the end of the rope could be fastened so it must move in some viscous material like heavy oil, perhaps, so that the end moves exactly like the corresponding point in a rope whose length is infinite, then the oil will absorb all the energy and there will be none to be reflected.

In a chain of circuits it has been found that the condition for no reflections is that the input and output impedances be equal[1]. This also happens to be the condition for maximum output. An example of maximum output is the old problem of connecting a number of cells to a given resistance in order to get the maximum current or output. The solution of this problem is to connect the cells in such a manner as to make the internal resistance of the battery equal to the given external resistance.

Since the condition of no reflections happens to be the same conditions as those for maximum output it seems that the ideas have become confused in the minds of engineers. Engineers seem to think that the goal to be obtained is maximum output while the real goal wished is an output without distortion. One of the sources of distortion is the reflected currents from the ends of the circuits. This will be understood from the analogy of the long rope. If one has a long stretched rope and strikes the rope two times per second there will be waves of frequency two running to the far end. Unless there are special precautions taken there will be waves of frequency two reflected back from the far end and these will be reflected again at the near end and be transmitted a second time in the forward direction. If one happens to transmit waves of frequency three to the far end immediately after a frequency two has been transmitted there will be reflected waves of frequency two moving with those of frequency three. These two frequencies will combine and form a complicated wave. In other words there will be distortion.

In audio circuits we have all frequencies in the audible range from 30 cycles perhaps to 10,000 cycles. The frequencies are continually changing from one value to a second frequency. Due to reflections a pure tone of middle C, say will be distorted by the reflections of the note or notes which preceeded. Thus one of the conditions for no distortion is that there be no reflections, and this condition requires that the input and output impedances be equal.—The impedance of the loudspeaker must be equal to the impedance of the tube.

In vacuum tube curcuits distortion can be introduced by other means, also. By the curvature of the characteristic curve of the tube and by the tube drawing grid current. In 1924 W. J. Brown[2] showed that the maximum output of a tube with no distortion due to curvature and grid current was obtained with the load impedance equal to twice the impedance of the tube. The same thing is shown later by Warner and Laughren[3]. The method of both papers are much the same. Brown used the mutual characteristic of the tube while Warner and Laughren used the plate characteristics. Figure 3_a is copied from Brown's paper while figure 3_b is copied from Warner and Laughren.

In these discussions the characteristic curves are supposed to be parallel straight lines except near the foot of the curves. In most tubes the grid draws no current except when the grid is positive. On this account the grid operates with a negative bias so adjusted that the grid potential swing is between the two limiting conditions. The grid bias is adjusted for position B, figure 3_a, and the grid

[1] Pierce's Electrical Oscillations, p. 291.
[2] Physical Society of London, Proc. **36**:218. 1924.
[3] Proc. Inst. Rad. Engr. **14**:735. 1926.

swing is limited by C and N in the same figure. In figure 3_b the grid is adjusted to position O and the grid swing is limited by Q and b.

In figure 3_b when the grid swing is the maximum the plate current varies between A and Q, or between I_{max} and I_{min}, while the plate potential varies from E_{max} and E_{min}, or between b and Q. The power is proportional to the product of the voltage change and the current change. This is proportional to the area of a rectangle whose area is twice that of the rectangle AQDN.

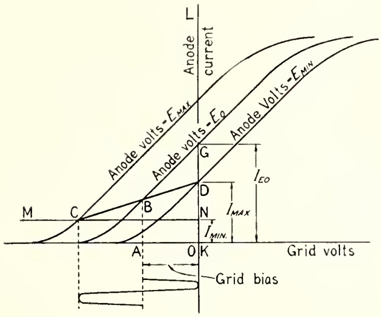

Fig. 3a

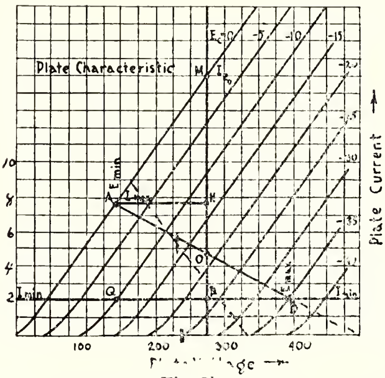

Fig. 3b

Fig. 3a. Mutual characteristic reproduced from W. J. Brown's paper. The portion of curves used is assumed to be a straight line. If the lower curved portion is used or if the tube draws grid current there will be distortion.

Fig. 3b. Plate characteristic, reproduced from Warner and Laughren's paper.

Since we are dealing with alternating potentials and alternating currents, the line ON represents the amplitude of the current and the line DQ, represents the amplitude of the plate potential, and it can be shown that the power is represented by one-eighth of the area of the rectangle whose sides are Qb and QA.

The current and potential fluctuates about the normal or average position, O, on the line AOb. The tube is supposed to be connected to a resistance, R, in series with the plate circuit. The line AOb is the characteristic of the resistance, R. The equation of the line, AOB is $E=Pd-IR$. Where E, is the potential of the B, battery and I is the plate current. In Figure 3_b Pd at the position O, is 275 volts, the B, battery has a potential of 500 volts, and the plate current, I, is about 4.8 milliampers. The resistance, R, is therefore a little smaller than 45,000 ohms.

The reciprocal of the slope of the line AOb is the resistance, R. The reciprocal of the slope of the characteristic, AM, is the resistance of the tube. MN/AN is the slope of the characteristic, AM and AQ/Qb is the slope of the line AOb.

The output of the tube will be the greatest when the rectangle, AQDN, is the greatest. The rectangle, AQDN, is inscribed in the right angle triangle, I_{min}DM. It can be shown from geometry that the area of the rectangle is the greatest when the corners A. Q. and N bisect the sides of the triangle. If the rectangle has maximum area the line MN is equal to the line DN. Then the load resistance is twice the resistance of the tube.

This is the condition for maximum output under the special conditions for no distortion due to grid current or due to the curvature of the characteristic. This however does not take reflections into account. Since the general conditions for no distortion due to reflections happens to be the general conditions for maximum load engineers have taken this special case of maximum output as the best condition for power tube load.

When the grid potential of the tube becomes so great that the tube draws grid current or uses the curved portion of the characteristic, the tube is said to be over loaded. In figure 3_a the tube is over loaded when the grid swing becomes so great as to swing past the points C and N. Since the output per grid volt squared

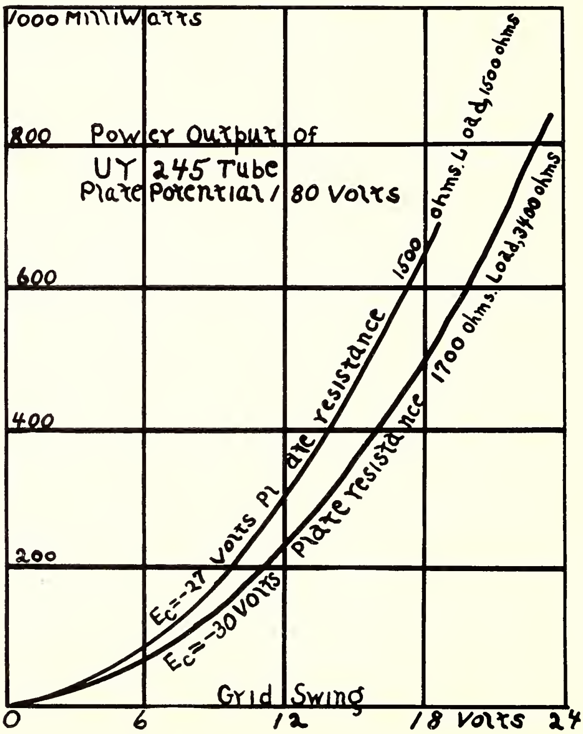

FIGURE 4

Fig. 4. Output curves for a 245 tube. The output per volt is greater when the load is equal to the resistance of the tube. With a load of 2Rp the output per volt is less but the maximum output is about 30 percent greater.

With a load of Rp there is no distortion due to reflections, grid current, or from curvature of characteristic.

is $\mu^2R/(R+R_p)^2\delta$ it can be shown that the output per grid volt squared is the greatest when the load, R, is equal to the Tube resistance R_p. However, the tube can handle about 25 percent more grid swing with the load equal to $2R_p$ without becoming "over loaded." It is due to this fact that the greatest output is obtained when the load is $2R_p$.

Figure 4 shows the output of a UY 245 tube with average plate potential held at 180 volts. The upper curve is drawn to show the output when the load is equal to R_p and the lower curve shows the output with a load of $2R_p$. With the load equal to R_p the tube becomes overloaded at 18.5 volts. With a load of $2R_p$ the tube is overloaded at 23.5 volts.

Both of these curves are calculated assuming that there is no distortion due to grid current or due to curvature. Since the load in the upper curve is R_p there is no distortion due to reflections. Since the lower curve is for a load of $2R_p$ there is distortion due to reflections. It will be noted that as long as the grid potential is less than 18.5 volts the upper curve give the greater values. To get the same output with $R = 2R_p$ it is necessary to increase the potential to about 21 volts. When the larger load is used the tube becomes over loaded at 23.5 volts and gives 25 percent more output than the smaller load at 18.5 volts.

All arguments, either output or distortion, are in favor of the smaller load except in the region where the tube becomes overloaded. In that region we get perhaps 25 percent more output with the larger load. This 25 percent is undistorted by grid current or by curvature, but it is distorted by reflections at all potentials. The smaller load gives undistorted output up to 18.5 volts. If we should allow the grid swing to increase beyond this we get distortion and at 23.5 volts the output is perhaps 25 percent or 30 percent greater than that of $R = 2R_p$.