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A Single-Ended Push-Pull Audio Amplifier*

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Summary—**An amplifier circuit for push-pull operation of two output tubes that provides a direct output to a grounded load is described. This circuit avoids any necessity for close magnetic coupling between halves of a split primary of an output transformer; it does not use any interstage coupling transformer; and its simplifies the application of feedback from the output stage to preceding single-ended stages. Methods for using this circuit with triode and beam-power output tubes are given, and the ultimate possibility of eliminating the output transformer for driving a loudspeaker is discussed.**

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Introduction

AMONG THE VARIOUS GOALS set out for the communications engineer, surely one of the most eagerly sought since the discovery of electronic amplification has been faithful reproduction, after the amplification process, of the input signal. Electronic devices are notoriously nonlinear, and nonlinearity has been the constant enemy of faithful reproduction. The two most potent weapons so far developed to combat nonlinearity in power amplifiers have been push-pull operation and negative feedback.[1] Push-pull operation,

[1] H. S. Black, "Stabilized feedback amplifiers," *Bell Sys. Tech. Jour.*, vol. 13, pp. 1-18; January, 1934.

by making the input-output relation symmetrical about the operating point, eliminates harmonics and combination frequencies produced by even-order distortion. Feedback improves faithfulness of reproduction by feeding a portion of the output wave back to the input in such a manner as to reduce the effects of nonlinearity.

A combination of the two systems has been found, generally, to produce an amplifier of the highest performance. Various difficulties, however, have plagued designers, and over the years continuous development has been carried on to overcome them. One of the most serious problems has been the tendency of even the best amplifiers to develop increasing distortion at the highest frequencies. This increase in distortion has been caused, in many cases, by phase shift which reduces the effectiveness of the negative feedback. General improvements in frequency characteristic and in phase-shift compensation have been found effective in reducing trouble from this source to manageable proportions.

Another serious source of trouble in high-efficiency amplifiers has been emphasized recently. This trouble arises from imperfections of the output transformer necessary to couple the high-impedance balanced output of a push-pull amplifier to a low-impedance single-ended load. The most important imperfection has been found to be insufficient coupling between the two halves of the primary in the plate circuit of the push-pull tubes. At the higher audio frequencies, leakage reactance arising from lack of complete coupling between these windings introduces distortion that may be thought of as switching transients, particularly in class-B operation.[2] In order to eliminate these transients, considerable effort has gone into methods of improving the coupling coefficient between the primary halves.

An ingenious solution has been worked out by McIntosh and Gow.[3] They use a bifilarly wound primary and a circuit that overcomes the problem of capacitance between windings by combined excitation of the primary halves from cathode and plate feed. Through the use of this specialized transformer, one can obtain extremely high coupling coefficients and concomitant low distortion at high frequencies.

Another solution, outlined in this paper, consists of entirely eliminating primary-to-primary leakage reactance by using the same primary for both tubes, thereby obtaining the equivalent of unity coupling. Other advantages accrue from the circuit to be described, not the least of which is the fact that no special components are required, the output transformer becoming basically a device for impedance matching and requiring no special characteristics other than adequate frequency characteristic and power handling capacity.

[2] A. Pen-Tung Sah, "Quasi transients in class-B audio-frequency push-pull amplifiers," Proc. I.R.E., vol. 24, pp. 1522–1541; November, 1936.

[3] F. H. McIntosh and G. J. Gow, "Description and analysis of a new 50-watt amplifier circuit," *Audio Eng.*, vol. 33, pp. 9–11; December, 1949.

The Output System

The basic plan of the output system is shown in Fig. 1, where two triode-amplifier stages are shown. The lower one is a simple amplifier supplying a resistance load in the plate circuit, and the upper one is similar except

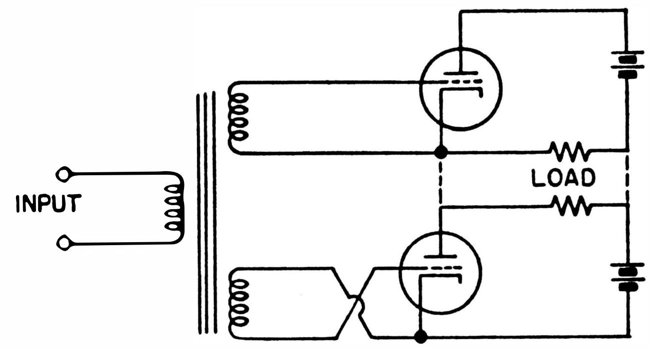

Fig. 1—Circuit to illustrate principle of operation of the push-pull output system. The grids are driven out of phase, and the ac load currents add while the dc load currents subtract.

that the load and the dc plate supply have been interchanged. It is important to notice that this amplifier is not a cathode follower, since the ac grid voltage is applied between the grid and cathode. If the two tubes are identical in characteristics and the supply voltages and loads are the same, the dc plate currents in the two loads will be identical. Then, if the connections shown by the dotted lines are made, the two currents will cancel because they are in opposite directions. When equal ac signals are applied to the two circuits, the ac components in the loads are equal. These two components would also cancel, when the connections are made, if the grid driving voltages were in phase. But, with oppositely phased voltages on the grids, the ac plate currents add in the load so that the tubes are in series for the dc plate supply and in parallel for ac signals.[4] However, this first circuit has the serious disadvantage of requiring a driving transformer with its associated expense and difficulties in maintaining proper balance at high frequencies.

Phase-Inverter Driver

In order to avoid a driving transformer, it is necessary to devise a phase-inverter stage that will supply the voltages in the correct phase and at the proper electrodes. One such phase inverter is shown in Fig. 2. This driver stage receives its plate-supply voltage from the midpoint of the two series-connected output stages. It has equal resistors in the plate and the cathode. Then a change in its plate current, produced by a signal on the grid, will result in equal voltages being developed across these resistors. The voltage in the cathode circuit is developed between the cathode and grid of the lower tube, and an equal and oppositely phased voltage is developed between the cathode and grid of the upper

[4] In connection with this circuit, we should like to note that when this paper was in preparation, our attention was called to the work of R. E. Rawlins, presented before the Los Angeles section of the IRE on December 19, 1944.

tube. It is important to notice that this upper grid is not driven with respect to ground. If it were, the upper tube would act as a cathode follower, and the balance of the two tubes would be destroyed.

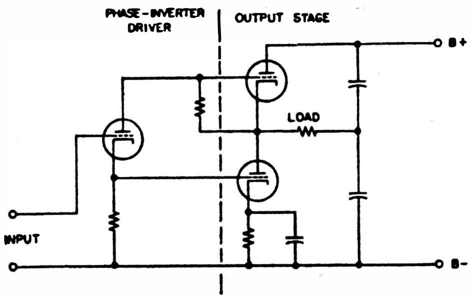

Fig. 2—Method of driving output stage by a phase inverter. Each of the output tubes is driven from grid to cathode.

This driver is shown direct-coupled to the ouput stages. This direct coupling is frequently desirable, even though it is not essential except for a dc amplifier. The dc voltage drop across the resistor in the driver plate develops a negative bias for the upper output tube. The voltage drop in the lower resistor is in the wrong direction for supplying negative bias. In the circuit shown, the proper bias is obtained by the voltage drop in the cathode resistor of the lower output tube, which supplies a voltage equal to twice the bias required for a single tube.

Driving Voice Coil Directly

The amplifier circuit shown here uses no transformers at the output or between stages for class-A or class-AB operation of push-pull triodes. By using some of the newer low-impedance tubes, the optimum output load resistance can be made quite low because the tubes drive the load in parallel. As an extreme example, the use of the two halves of a single type 6AS7-G would lead to an optimum load impedance of about 280 ohms. While this value is still far from the usual 8- or 16-ohm impedance of a loudspeaker voice coil, voice coils can be built with appreciably higher impedances so that they can be driven directly without a matching transformer. To a first approximation, the voice-coil impedance can be increased without affecting the loudspeaker efficiency. As a practical matter, the limit of increase is determined by the smallest aluminum or copper wire that can be handled in a production set up and the maximum allowable mass for the voice coil.

For example, one particular standard 12-inch dynamic loudspeaker uses number 33 wire for its 3.2-ohm voice coil. One of these has been rewound for 100 ohms with number 40 wire, and its efficiency is within 1/2 db of the standard one. Another of these has been rewound for 500 ohms with number 44 wire.[5] While this latter wire is too small in diameter to be readily handled in production, the number 40 wire is entirely reasonable.

The loudspeaker cited does not have an unusually heavy voice coil, and therefore it seems reasonable that the voice coils of moderate-size to large loudspeakers can be wound to the level required in order to dispense with a matching transformer. Furthermore, it is entirely possible that a suitable ring-armature drive[6] for small speakers can be developed. Then there should be no difficulty in winding this type for an impedance of almost any desired level.

In order to determine to what extent one should go to eliminate coupling transformers, it is useful to review some of their characteristics. Audio power transformers are generally expensive, heavy, and bulky. They usually limit the low-frequency capabilities of an amplifier by increasing the distortion and reducing the output at low frequencies. Furthermore, because the output transformers are only moderately efficient, they absorb an appreciable fraction of the available power. These disadvantages are sufficiently important that considerable effort toward eliminating coupling transformers is justified.

Circuit Limitations and Requirements

Two characteristics of the circuit of Fig. 2 limit its range of operation. One is the inherent negative feedback, and the other is the effect of capacitance from the plate of the driver stage to ground. Since the plate voltage of the driver tube is taken from the output, the output voltage is fed back to this stage. This feedback is negative, and it can be considered useful for reducing distortion. However, when it is desired to avoid the associated loss in gain, the feedback can be minimized by using a pentode driver.

The impedance level at the plate of the driver stage is, in effect, multiplied by the gain of the output stage. That is, the frequency characteristic of the drive for the upper tube is determined by the RC combination of the total capacitance from the plate to ground and the plate resistor multiplied in value by one more than the gain of the output stage. For the audio-frequency range, the resulting drop in output can be kept very small. But, if an attempt is made to use an amplifier of this type over the video range, this effect will be serious.

The load is shown in Fig. 2 connected in a balanced fashion to the output stages to make it easier to see the principle of operation. Actually, it is usually more useful to have one end of the load grounded to the negative side of the plate supply and to feed the other end from the midpoint through a series blocking capacitor.

When the output tubes are to be operated over the wide ranges required for full output in class-AB_1 operation, these circuits must be designed, just as any other, to meet the requirements of that operation. For example, the circuit should be arranged to provide constant bias for the output tubes even with large plate-current swings. Another requirement is that adequate driving voltage must be available from the phase inverter. In

[5] We are indebted to Dr. Harry F. Olson of the RCA Laboratories, Princeton, New Jersey, for the information on this standard, 12-inch loudspeaker and the higher impedance versions.

[6] E. E. Mott and R. C. Miner, "The ring armature telephone receiver," *Bell Sys. Tech. Jour.*, vol. 30, pp. 110–140; January, 1951.

the simple connection of Fig. 2, the plate voltage for the driver is only one-half the total plate voltage, and the resulting output from the phase inverter is usually inadequate for class-AB_1 operation. By using a resistance-capacitance coupling for the driver and by taking advantage of the bias supply as added plate voltage for the driver, this output can be increased. A pentode driver stage is also a suitable alternative in some cases. When an output matching transformer is used, the available plate swing from the driver can also be increased by a connection of a form shown later in Fig. 3.

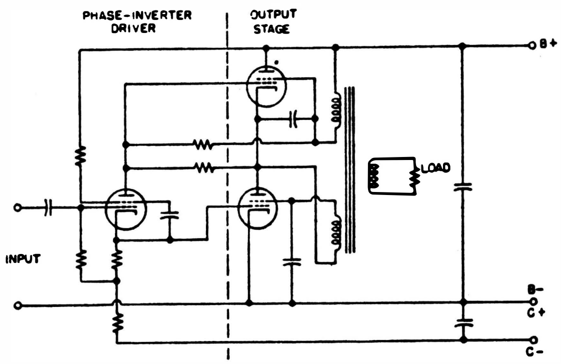

Fig. 3—Method of supplying proper screen voltages for beam-power tubes. The dc screen currents flow through the two windings in the opposite sense so that there is no net dc flux from the screen currents.

There additional current is supplied to the phase-inverter stage by the resistor connected from the one transformer primary to the plate of the phase inverter.

One objection that might be raised to the basic series circuit is that the required plate voltage for the output

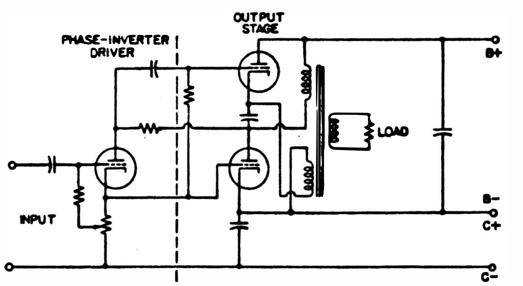

Fig. 4—Method of using the load matching transformer to put the output tubes in parallel for the dc supply.

stage is twice normal. The development of the high-voltage selenium rectifier, with voltage-doubler circuits, has made this point less objectionable at the present time. Another factor is the development of the low-impedance or high-perveance tubes for television use. Their use in this circuit permits the production of relatively high powers with moderate total plate voltage.

If a transformer is to be used in the output as a matching device, it is possible to set up the single-ended output circuit with normal plate voltage in several ways. One method is shown in Fig. 4. Here the plate currents of the two tubes flow through the two halves of the primary winding, and the two halves are connected in parallel for signal currents by the by-pass capacitors. It is important to notice here that the driving voltages for the two output tubes are again developed between cathode and grid in each case. The capacitor in the cathode-to-plate connection must be large enough to avoid a degenerative effect in the cathode circuit.

Amplifiers Using Beam-Power Tubes

These amplifiers show triodes in the output stages. But many designers of audio amplifiers are interested in using beam-power tubes with their possibilities of high gain and high efficiency. It is obvious that the proper connections for the screen voltages can readily be made in the circuit of Fig. 4, but the connections for the basic series circuit are not so simple.

The main problem in using these beam tubes is in the method of supplying the proper voltage for the screen of the upper tube. The dc voltage of the screen is normally near that of the plate, and the screen should be at cathode potential for the signal voltage. If the screen of the upper tube is supplied through a dropping resistor from the plate supply, then the by-pass to the cathode puts the dropping resistor in parallel with the load, and some signal power is lost. In some cases this loss in power can be made small. In other applications, the voltage for the upper screen can be fed through the load so that no signal power is lost.

Since loudspeakers with high-impedance voice coils are not available at present, an output transformer is still needed for driving a speaker. How this transformer can be used for supplying the screen voltages is shown in Fig. 3. The primary is in two sections. One section is connected from the plate supply to the upper screen, which is by-passed to its cathode at the midpoint where the plate and cathode of the two output tubes are connected together. The other section is connected from the screen of the lower tube, which is by-passed to ground, to the midpoint. The dc screen currents flow through the windings in the opposite sense, so that there is no net dc flux from the screen currents in the windings.

By following the transformer connections, it can be seen that the two sections of the primary are connected in parallel, for signal voltages, by the by-pass capacitors. Because of this parallel connection, the two halves of a standard push-pull transformer can be used to obtain the required impedance level for this single-ended circuit. Furthermore, because these windings are connected in parallel by capacitors, the circuit does not depend on close magnetic coupling between the two sections of the primary. This point is important, since in class-AB operation the usual push-pull connection does have serious switching transients unless the coupling between the two halves of the primary is very good. In order to verify this point experimentally, the circuit shown was set up, using a type 6AK6 pentode to drive a pair of type 6L6 beam-power tubes. The operation was with fixed bias as shown, class AB_1, and with no feedback. An output of 50 watts was obtained with a plate efficiency of 59 per cent. The output waveform was independent of the magnetic coupling between the halves of the primary. To illustrate this independence,

Fig. 5 shows a photograph of some pertinent waveforms. For this case, two separate chokes were used in place of the transformer so that the magnetic coupling was essentially zero. The operating frequency shown here is 20 kc, and the power level is 50 watts. The upper trace is the output voltage and the lower trace is the cathode current in the lower tube. It is clear that current is flowing in each tube for only slightly longer than one-half cycle, and there is no sign of a switching transient. Thus the general behavior of the circuit is verified.

This output of 50 watts was obtained within the plate dissipation ratings of the Type 6L6 of 38 watts for two tubes. But the screen ratings were exceeded to obtain this output with class-AB_1 operation. However, this output can be obtained within the ICAS ratings of the type 1614, the transmitting version of the type 6L6. Using two type 1614's with two cascaded stages of type 6AK6's in this circuit and with negative feedback, we have obtained at 1 kc less than 0.1 per cent harmonic distortion for all output levels up to 50 watts. To obtain this low level of distortion, careful adjustment of operating conditions and feedback of 25 to 30 db are necessary, and the method of obtaining stable operation with this feedback will now be discussed.

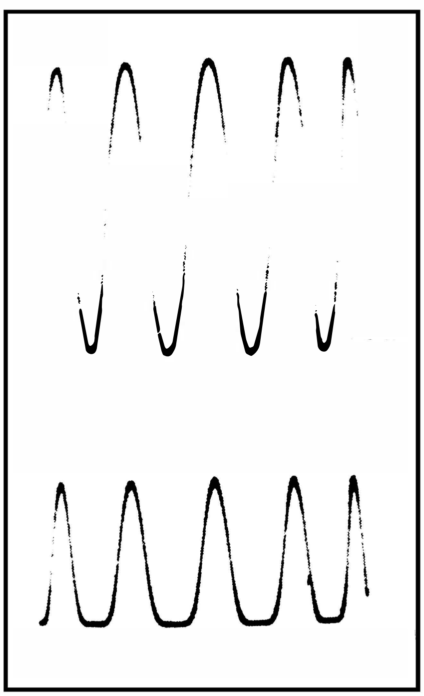

Fig. 5—Upper trace is the wave form of the output voltage for the circuit of Fig. 4, and the lower trace is the cathode current in the lower tube. Both traces were obtained at a 50-watt power level and at 20 kc.

Use of Negative Feedback

One method for applying negative feedback to an amplifier of this type is shown in Fig. 6. Since the output is single ended, the feedback can be made directly from the midpoint of the output stage to a preceding single-ended stage. In the three-stage amplifier shown, the feedback is applied to the cathode of the first stage. Because of the direct coupling of the phase-inverter driver, there is little danger of low-frequency motorboating with feedback. Furthermore, since the feedback does not have to be taken from the secondary of the output transformer, there is less danger than usual of

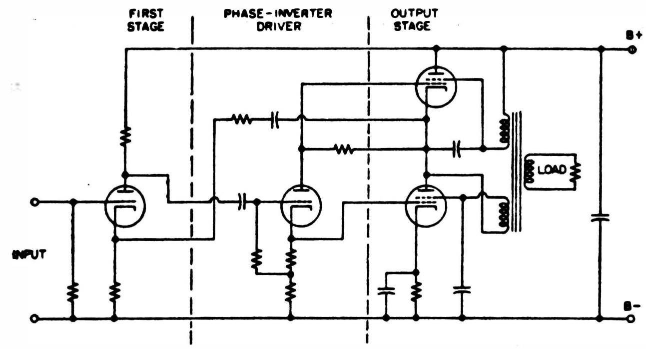

Fig. 6—Circuit to illustrate one method of applying feedback. The feedback is taken from the junction of the two output tubes to the cathode of the first stage.

high-frequency oscillations. Or, expressed differently, greater amounts of negative feedback can be used, when applied as shown, with stable operation, than can be used with feedback from the secondary of the usual output transformer.

The usual feedback from the secondary tends to correct for the drop in response at the high-frequency end by the feedback system. This feedback forces the output system to operate at higher levels than normal at high frequencies to produce the uniform output desired. Unless the transformer is very good, with feedback from the secondary, the result may be high distortion at high frequencies. This distortion is usually exhibited as intermodulation of high-frequency signals, and serious distortion of this type is more easily avoided with feedback from the primary as shown here.

The feedback shown in this circuit puts the secondary of the transformer outside the feedback loop. Then corrective networks can be used, if necessary, at the secondary without introducing serious phase shift in the feedback loop.

Conclusion

The circuits shown here should be useful in many applications. The series circuit using the phase-inverter driver has the advantage of requiring no coupling transformers for obtaining push-pull operation. The circuits have other advantages, principally for amplifiers that must have very low distortion. In addition, the developments described should serve to show possible new lines of approach for improving audio reproduction. These further developments might include high-impedance loudspeakers, loudspeakers of different fundamental design, low-impedance twin output tubes with 117-volt heaters, and the elimination or simplification of output transformers.

Acknowledgment

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