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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

A NEW PUSH-PULL AMPLIFIER CIRCUIT

● **AS ONE RESULT** of a continuing development program on audio-frequency instruments, a new audio power-amplifier circuit[1,2] that promises to be widely useful has been devised. In addition to being suitable for regular audio power amplifiers, this new circuit is particularly well adapted to amplifiers for constant-voltage audio distribution systems, to high-power modulators, to amplifiers for electronic musical instruments, and to audio amplifiers for industrial uses.

This new circuit permits one to obtain the high efficiency of Class AB_1 operation without switching transients, and this feature is obtained without the use of special components. The circuit also has important advantages for direct-coupled power amplifiers and for amplifiers operated Class A when very low distortion is required.

Because of the widespread interest already shown in this development, three practical high-power amplifiers using this new circuit with low-cost tubes will be described and component values will be given to aid the experimenter in making an initial setup. Before discussing these, however, the basic principle of the new circuit will be outlined briefly.

The basic circuit is shown in Figure 1. The output stage consists of two tubes connected in series across the d-c plate supply, and the load connects from the midpoint of this series connection to the plate supply. The output tubes are driven in opposite phase by a phase-inverter stage. The important feature of this phase-inverter

[1] Arnold Peterson and Donald B. Sinclair, "A Single-Ended Push-Pull Audio Amplifier," 1951 I.R.E. National Convention, New York, N. Y., March 22, 1951, published in News Letter of I.R.E. Professional Group on Audio.
[2] Patent applied for.

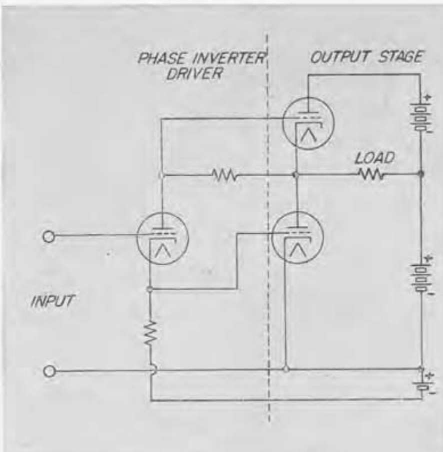


Figure 1. The basic single-ended push-pull amplifier circuit, showing the series connected output tubes supplying a common load and driven by a cathode-follower phase inverter.

stage is that it drives each tube from its own grid to its own cathode, so that the tubes are driven in a balanced fashion. In order to achieve this type of drive, it is necessary to feed the plate impedance of the phase-inverter driver from the midpoint of the series-connected output tubes. If the plate load of this driver were connected directly to the plate supply, the upper tube would be driven with respect to ground as a cathode follower, and the balance of the two tubes would be destroyed. While the voltage driving the upper tube could be correspondingly increased to achieve a net balance of current swing in the two tubes, the operating conditions as far as distortion is concerned would be markedly different, and the push-pull cancellation of distortion would not result. The circuit shown maintains the balance in the two tubes and preserves the distortion-cancelling feature of push-pull operation.

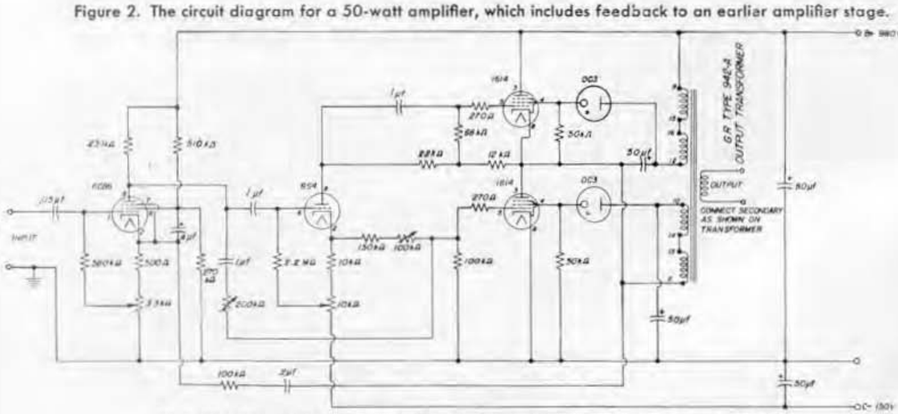
In the usual push-pull circuit the two output tubes are in parallel for the d-c plate supply and operate effectively in series for supplying the a-c load. In a limited sense this new circuit can be considered the dual of the usual circuit since the output tubes are in series for the d-c plate supply, and they supply the a-c load in parallel. Thus the normal optimum load impedance for the new circuit is one-fourth the normal plate-to-plate load impedance for the usual push-pull connection.

This simple relationship means that some standard push-pull transformers can be readily used for the new circuit. If the two halves of the primary are separate, they can be connected in parallel, instead of in the series connection ordinarily used, to obtain this four-to-one ratio.

Because of this parallel or single-ended connection of the primary, both tubes work into the same load, and there is no deleterious effect from leakage reactance between halves of the primary. In contrast, in the conventional push-pull circuit, each tube works individually into half the primary, and leakage reactance between the windings can cause serious switching transients[3] when the tubes are operated Class AB. These switching transients, which cannot be eradicated by negative feedback, are a prime cause of high-frequency distortion, notably intermodulation, in push-

[3]A. Pen-Tung Sah, "Quasi-Transients in Class B Audio-Frequency Push-Pull Amplifiers," *Proc. I.R.E.*, Vol. 24, N. 11, November, 1936, pp. 1522–1541.

Figure 2. The circuit diagram for a 50-watt amplifier, which includes feedback to an earlier amplifier stage.



BIAS VOLTAGES - TYPE 1614, -40 VOLTS; TYPE 884, -42 VOLTS; TYPE 6CB6, -4.6 VOLTS

VOLTAGE INPUT FOR 50 WATTS OUTPUT: 12.8 VOLTS

pull amplifiers. They are often responsible for the objectionable harshness in so-called high-fidelity systems.

When beam-power tubes are used in the output, the two halves of the primary of the usual push-pull transformer can serve a useful purpose in this single-ended circuit by simplifying the problem of supplying the d-c screen-grid voltages to the two output tubes. How these can be used is shown in Figure 2. The output tubes are shown connected in series, as before, for the d-c supply. The screen-grid voltage for the upper tube is supplied through one primary winding from the plate supply. This upper screen-grid is by-passed to its cathode at the midpoint where the plate and output tubes are connected together. The other screen-grid is supplied through the other primary winding from the midpoint, and this lower screen-grid is by-passed to ground. The d-c screen-grid currents flow through the windings in the opposite sense, so that there is no net d-c flux from the screen-grid currents in the windings.

The transformer connections show that the two primary windings are connected in parallel for signal voltages. The screen-grid by-pass capacitors and the plate supply output capacitor make this parallel connection. These capacitors must provide a low-impedance path at the lowest signal frequency.

The circuit of Figure 2 also includes a feedback connection from the output stage to the first stage. Since the output is single-ended, feedback to a single-ended earlier stage is relatively simple. In the circuit shown, a fraction of the output voltage is applied directly to the cathode of the first stage as a voltage feedback.

The circuit of Figure 2 is arranged to operate the final stage Class AB_1. Because this type of operation requires large driving voltages from the phase-inverter stage, the method of connection of this stage is different from that of Figure 1 in certain details. The d-c bias voltage for the upper output tube is obtained from only part of the phase-inverter plate load. The full signal voltage across the plate load, however, is applied to the upper tube through the coupling capacitor between the plate of the phase inverter and the grid of the upper tube.

The a-c plate voltage from plate to cathode of the phase inverter stage of Figure 1 is the sum of the a-c output voltage and the two a-c grid voltages produced across its load resistances. For a 50-watt amplifier using Type 1614 tubes, this a-c voltage is of the order of 500 volts peak. The d-c plate voltage required across this tube, then, must be greater than 500 volts in order to avoid serious non-linearity in the driver stage. If the experimenter has available a tube that can readily handle these voltages, the basic cathode-follower phase inverter of Figure 1 is recommended. In the particular circuit of Figure 2, a standard receiving type has been used within its rating of 500 volts by the circuit dodges shown. The resistance in the cathode is lower than necessary for full drive of the lower stage, so that the required voltage must be obtained from the previous amplifier stage. This lower resistance reduces the a-c voltage appearing from plate to cathode and makes possible the use of a Type 6S4 Triode within its 500-volt rating.

The amplifier circuit of Figure 2 can be used with two Type 1614's in the output stage to yield 50 watts output. At this level the distortion can readily be held to less than 1% (total harmonic) for frequencies in the middle audio

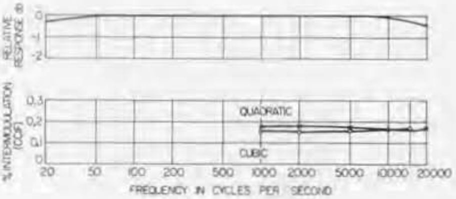


Figure 3. The upper curve shows as a function of frequency the relative output at the secondary of the output transformer, terminated in a resistance load, for constant input voltage to the amplifier of Figure 2. The lower curves show intermodulation distortion as a function of frequency. Two tones of equal amplitude differing in frequency by 400 cycles were used. The peak-to-peak swing, at the load connected to the secondary, was equal to that obtained at a 50-watt single-frequency output level, and the distortion is plotted as a function of the frequency of the lower-frequency tone.

range. By careful adjustment of balance and operating conditions, this distortion can be reduced even further.

The intermodulation results by the CCIF test[4] shown in Figure 3 demonstrate that the amplifier is operating correctly, with low distortion over the audio range. Measurements of intermodulation by the SMPTE method also showed satisfactorily low distortion. Tests at an equivalent 50-watt power level, using a low-frequency tone of 40 cps of four times the intensity of the high-frequency tone of 7000 cps, gave a total intermodulation of 1.6%, which is well below the 5% frequently used for rating high-quality systems.

Beyond the 50-watt limit, the output tubes are driven to the level where they draw grid current, which changes the operating conditions for the tubes. This change will give the results shown in the graphs, which were measured under steady state conditions. For dynamic conditions, such as occur with speech and music signals, the distortion levels above 50 watts will be somewhat higher.

This power level is obtained within the ICAS ratings of the Type 1614 and is the power available at the primary of the transformer. Because of the losses in the transformer, the power available at the secondary is reduced somewhat. When the General Radio Type 942-A Output Transformer[5] is used as specified, the reduction in available power is relatively small. The output transformer also limits the maximum low-frequency power obtainable from the amplifier. The Type 942-A Output Transformer[5] has been designed to handle a particularly high level of power, for its size, at low frequencies. The curve of Figure 4 shows its performance with the amplifier of Figure 2.

The element values given in Figure 2 have been determined to be suitable for an amplifier using four Type 1614's in

[4] A. P. G. Peterson, "An Audio-Frequency Signal Generator for Non-Linear Distortion Tests," *General Radio Experimenter*, August, 1950.

[5] To be described in next month's *Experimenter*.

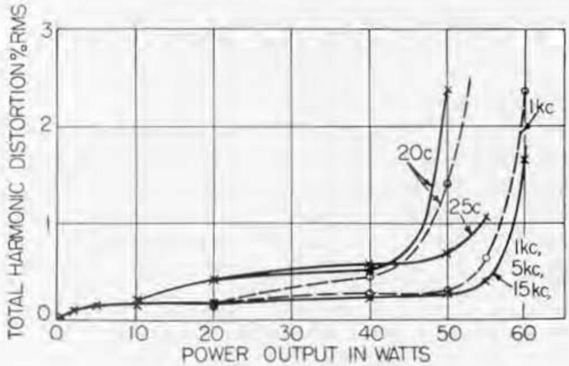


Figure 4. Harmonic distortion as a function of power delivered to the load for the circuit of Figure 2. All the curves except the dashed ones were taken with a 1500-ohm load across the primary. Since there was no essential difference in results at 1, 5, and 15 kc, only one curve is shown for these three frequencies. For frequencies above 50 cps, the results were also practically identical with the 1-kc curve. The dashed curves show the results with the load on the secondary of the transformer.

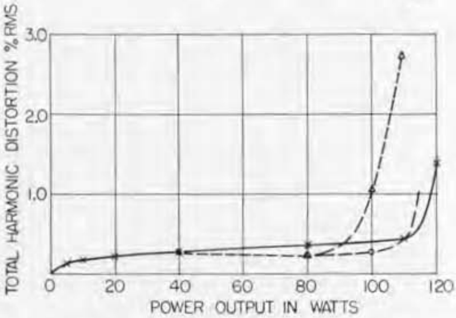


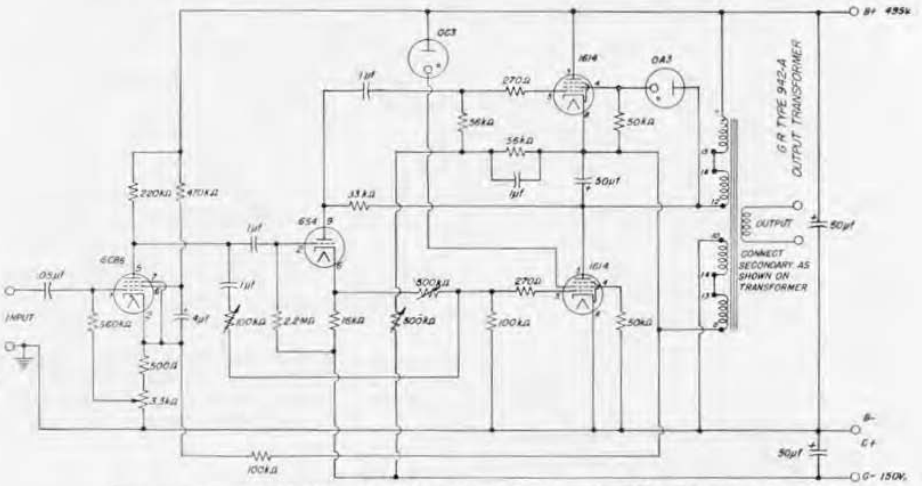
Figure 5. Harmonic distortion at 1 kc as a function of the power delivered to the load for the circuit of Figure 2, but with two Type 1614 Beam Power Tubes in parallel for the upper output tube and two in parallel for the lower tube. The solid curve was obtained with an 800-ohm load on the primary. The values given by the triangles were obtained on the secondary, using a load of about one-half the rated impedance of the transformer, and the values given by the circles, using a load of about twice the rated impedance. In each case the equivalent primary load was about 800 ohms. These latter results show the difference in copper efficiency obtainable with the different connections available on the Type 942-A Transformer.[5]

the output stage. Two tubes are used in parallel where the upper tube is shown, and two are in parallel for the lower tube. This output combination will supply 100 watts of power at the primary of the output transformer (see Figure 5), and the Type 942-A Output Transformer[5] is suitable for use at this power level over the audio range above 40 cps.

The previous circuit has the disadvantage of requiring a plate supply that operates at twice normal voltage. Of course the current taken by the output stage is correspondingly one-half that taken by the usual push-pull stage so that the total input power is normal. The high plate voltage is no longer so serious a disadvantage as it was some years ago, because of the recent development of the high-voltage selenium rectifiers. The circuit, however, is best adapted to moderate total plate voltages if the newer, low-impedance tubes such as the Type 6CD6-G or Type 6BQ6-GT are used in the output stages.

If it is desired to operate with normal plate voltages, the circuit can be modified as shown in Figure 6. Here both plate currents flow through the transformer primary windings so that there is more of a burden on the transformer, because of the d-c copper loss in the windings. More careful balancing of the

Figure 6. The circuit diagram for a 50-watt amplifier, using parallel feed for the plate voltages of the two output tubes.



BIAS VOLTAGES - TYPE 1614, -39 VOLTS; TYPE 654, -42 VOLTS; TYPE 6CB6, -5.2 VOLTS
VOLTAGE INPUT FOR 50 WATTS OUTPUT: 12.5 VOLTS

d-c plate currents is necessary here in order to avoid an unbalanced flux in the transformer.

Because of the way the screen-grid voltages must be supplied, the voltage drop in the two primary halves appears in the supply for the screen-grid of the upper output tube. There is no compensating drop in voltage for the screen-grid of the lower tube. In the circuit of Figure 6, the major part of this difference is taken care of by the use of different voltage-regulator tubes in the two screen-grid supplies. Otherwise, this circuit is essentially the same as that of Figure 2, and the performance is comparable as shown by Figure 7.

The circuit can be appreciably simplified if the full 50-watt power level is not required. A suitable circuit for an output power of 25 watts is shown in Figure 8.

The feedback used in these circuits is about 14 db. This amount is adequate to give a source impedance of about one-fifth the optimum load impedance, which is satisfactory for most applications. This source impedance can be reduced further by increasing the feedback. With the type of feedback used here, however, an increase in feedback usually results in a small decrease in available power, because of the power absorbed in the feedback circuit.

If the distortion from this amplifier is to be kept low, good quality resistors must be used in the feedback circuit. In particular, it is recommended that the resistor from the primary of the transformer to the cathode of the first tube and the resistor to ground from the cathode of the first tube be wire-wound. Some composition resistors have an appreciable voltage coefficient, and, if they are used for the feedback circuit, they can contribute appreciable amounts of distortion.

For best operation at high audio frequencies, it is important to keep stray circuit capacitances as small as possible. Particular attention should be paid to the capacitance to ground of the circuit from the plate of the driver stage to the grid of the upper output tube. This capacitance, which shunts the phase-inverter plate-load impedance, is effectively multiplied by the gain of the output stage. For the present circuit this factor is about ten.

The circuits should be adjusted by observations using a high-resistance d-c voltmeter, a sinusoidal signal source, and a cathode-ray oscillograph. The bias adjustments should be made first to give about the values shown in the figures. Then a 1-kc signal should be applied and the signal balance adjustment should be made. Proper adjustment of this balance can be observed on the c-r-o at levels above 50 watts by noting the condition for equal clipping of the upper and lower peaks.

For best operation at low frequencies, the d-c currents in the two halves of the primary of the output transformer should be carefully balanced. This balance can usually be obtained by adjusting the grid biases. Occasionally some tube selection is desirable.

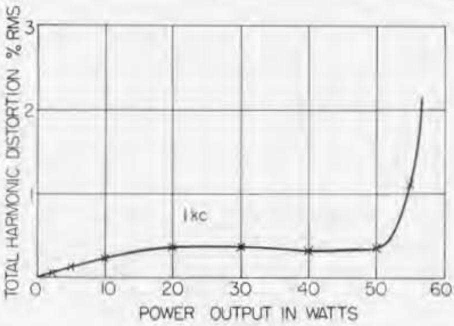


Figure 7. Harmonic distortion at 1 kc as a function of the power delivered to a 1500-ohm load across the primary for the d-c parallel connection of output tubes as shown in Figure 6.

If the amplifier is to be used for speech and music signals, it is recommended that the adjustments be trimmed to favor very low distortion at low levels. This trimming can best be done by using a very low distortion source and a wave analyzer or distortion meter.

The output tubes of these circuits operate in the Class AB region, and the plate current for the last stage varies with operating level. The main power supply should, therefore, have good regulation to maintain proper operating conditions with varying levels. The bias supply, on the other hand, can be very simple, since only a few milliamperes are needed and the load is constant.

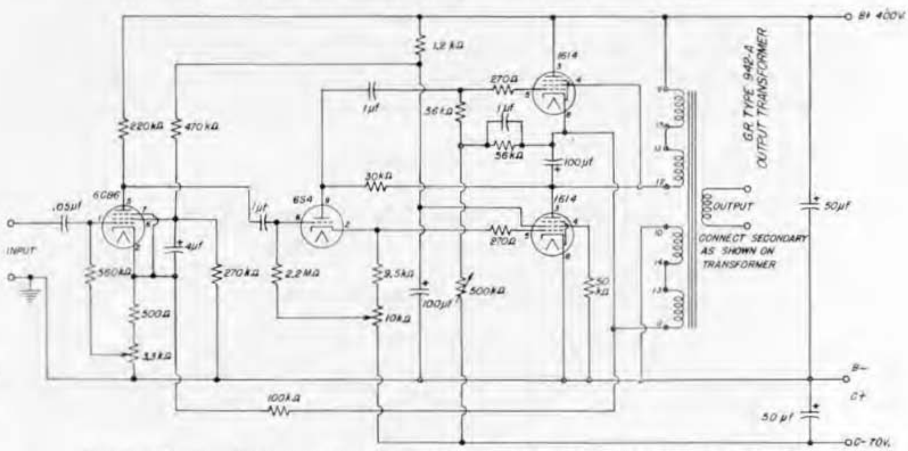
The basic circuit can, of course, be used with other output tubes. If lower plate voltages are also used, the driver voltage problems are simplified, and the straightforward cathode-follower phase inverter can be used. In some cases the load can be matched directly to the output tubes so that the impedance-matching effect of the transformer is not needed, and the efficiency is correspondingly increased.

The circuits shown here are intended only as a guide for the experienced experimenter. Numerous measurements and adjustments are usually necessary in an initial setup to make certain that the circuit is operating properly. In making those tests, the experimenter should remember that the voltages used here are dangerous, and, because of the unusual output circuit, particular care is necessary to avoid being misled by experience with standard output systems.

The power levels quoted in this article are not conservative but actual values measured on an experimental setup, so that the experimenter should not expect to find any reserve margin of power beyond the levels quoted. It is important also to notice that the vacuum tubes are not being used according to conservative instrument practice, but rather in the fashion of commercial equipment where high stability and long tube life are not important. Conservative instrument practice would dictate lower voltages than used here, and the available power would be correspondingly reduced.

— A. P. G. Peterson

Figure 8. The circuit diagram for a 25-watt power amplifier, which uses lower supply voltages than the higher power versions and which does not operate so far into the Class AB_1 region.



BIAS VOLTAGES - TYPE 1614, 31 VOLTS; TYPE 6S4, 31 VOLTS; TYPE 6CB6, 3.3 VOLTS

VOLTAGE INPUT FOR 25 WATTS OUTPUT: 7.8 VOLTS

MISCELLANY

CREDITS—The single-ended push-pull amplifier described in this issue was originally developed by Dr. Donald B. Sinclair and Dr. Arnold P. G. Peterson. Credit is also due to Carlton A. Woodward, Jr., and William F. Byers for their helpful suggestions and to Mr. Woodward for his assistance in the experimental work.

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