Designing Push-Pull Amplifiers

Calculation methods for better fidelity

By DAVID FIDELMAN

ONE day you will decide to rebuild your audio amplifier system. (If you haven't yet, you will—everybody does, sooner or later.) When you do, the new system should be better than your old one, else there is no point in going to the trouble.

The chances are that most of the circuits obtainable were not designed for your particular requirements. You may already have a good output transformer or some tubes and circuit components which you might like to use to avoid the expense of purchasing new components. The most satisfactory results will almost always be obtained with a good circuit of your own design.

High-quality audio amplifiers should be push-pull rather than single-ended. Push-pull amplifiers have these advantages:

1. There is less distortion, due to the cancellation of all even harmonics.
2. There is no d.c. saturation of a well-balanced output transformer since the plate currents of the two tubes cancel one another in the transformer core, and low-frequency response is better.
3. Effects of power-supply hum are greatly reduced.
4. The push-pull stage does not tend to cause motorboating in the amplifier.

These advantages are so important that a push-pull arrangement using two small tubes is preferable to a single larger tube capable of developing the same total power output.

The design of the amplifier should depend mainly upon where it will be listened to, for example, in an average living room or a large auditorium.

For normal listening levels in the home, a system capable of handling 4 or 5 watts peak power will generally sound good enough. The amplifier of the average table-model a.c. radio is capable of putting out about 4 to 5 watts, but at loud levels a considerable amount of distortion is noticeable. In this case, the distortion is often due to the improper use of a small loudspeaker

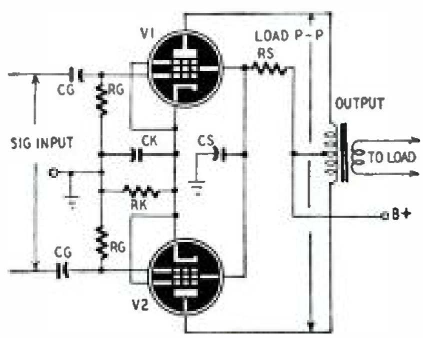
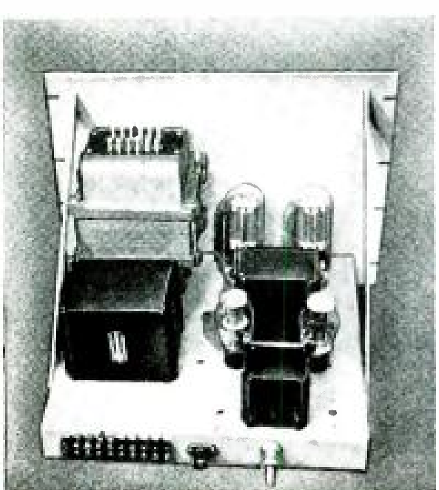
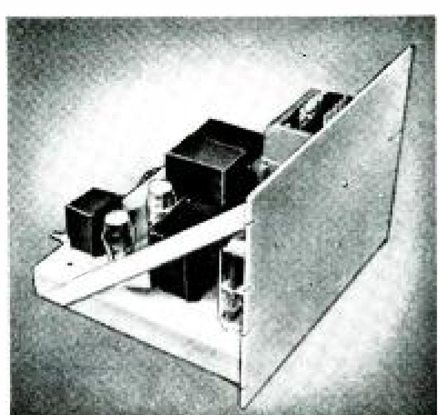


Fig. 1—Circuit of a typical push-pull stage.

which cannot handle the entire output of the amplifier. If the small speaker is disconnected and the amplifier output fed into a good 10- or 12-inch loudspeaker, the quality will be good even at fairly loud living-room levels. Actually, the *average* power into the speaker even during loud levels is considerably less than 1 watt. However, the reserve power is necessary, because transient peaks in speech and music require considerably more power. For reproduction of these peaks without distortion, 10 watts is about the best compromise design value for home listening.





Two views of a high-power push-pull amplifier built by the author, using the principles and design information contained in this article.

The output stage

Once the power requirements of the amplifier have been decided, the tubes can be selected. The schematic circuit diagram of the typical push-pull amplifier is shown in Fig. 1. The specific circuit values—plate load impedance, cathode resistance, plate voltage, and so on—are obtained from data and the plate-current-characteristic curves given in the tube manual by a procedure similar to that followed in selecting the values for the ordinary single-ended amplifier stage.

These methods are so well described in the *RCA Receiving Tube Manual* (Technical Series RC15), presumably owned by all radio technicians, that no attempt will be made to duplicate that description here. Reference is made especially to the material appearing on pages 18, 19, and 22 of the tube manual.

However, in using the plate-current characteristics, a *composite set* of curves must be used instead of the ones given in the tube manual. These composite curves are obtained by placing the plate voltage-current curves of the individual tubes back to back with the common operating voltage superimposed, and then averaging the plate current for grid-potential curves corresponding to the same applied signal. (The signal voltages applied to the two grids are opposite; therefore, if the operating grid voltage is —20, for example, then —15 volts for one tube is averaged with —25 for the other, and so on). The load line is then drawn, using the derived composite curves. The actual plate-to-plate load will be four times the resistance represented by the load line.

The procedure may be best understood by considering a specific example. The curves given in Fig. 2 represent the composite plate voltage-current curves for a push-pull 2A3 amplifier. The complete set of curves consists of two sets of plate-current characteristics, one representing tube 1 and the other tube 2. (Each set of curves can be

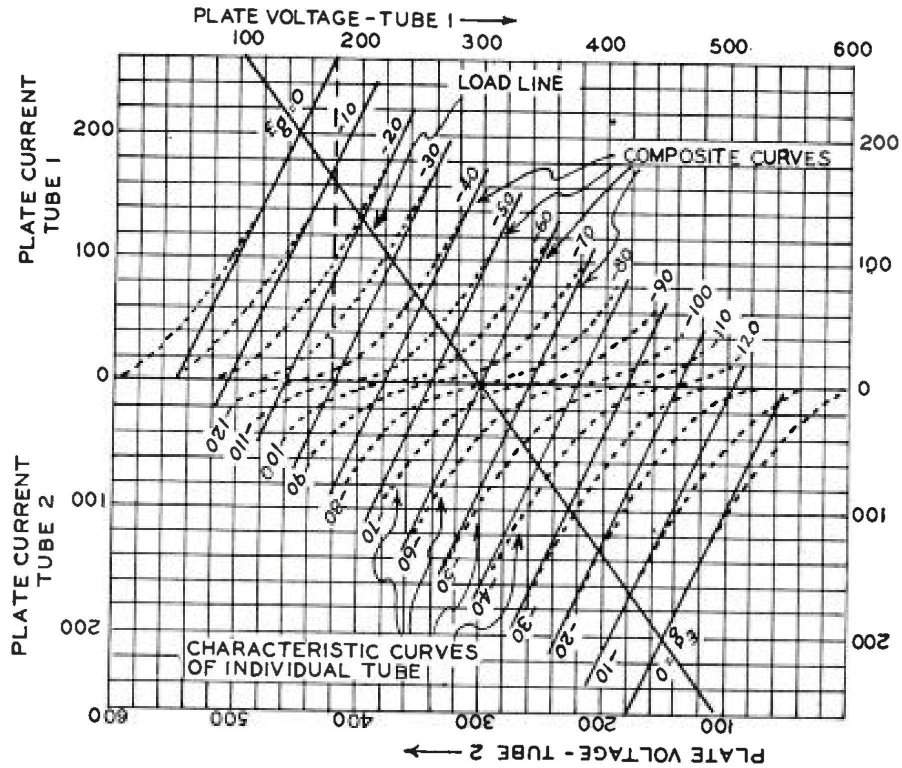


Fig. 2—Composite E_g curves and load line are drawn on superimposed handbook E_p-I_p graphs.

redrawn from the tube manual. For some tubes, these detailed curves will be found only in a professional-grade manual, such as the RCA HB-3 loose-leaf handbooks.) To derive the composite curves, first place the two copied sets back to back, with the 300-volt (recommended plate voltage) points coinciding, as shown.

The load line is then drawn in the same manner as for an ordinary set of tube characteristics, first selecting a convenient value for plate voltage and grid bias, erecting a perpendicular at 0.6 operating voltage, noting the point at which it intersects the zero-bias curve, and then checking for power output. If, as in this case, the plate dissipation is too great, plate voltage may be lowered or load resistance increased and another approximation made. Re-

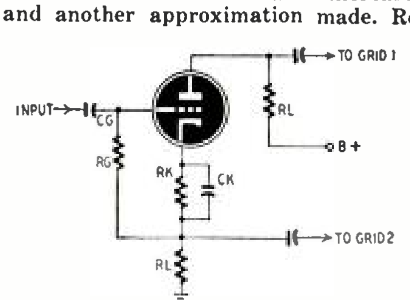


Fig. 3—Cathode and plate outputs are equal.

fer to page 22 of the tube manual for an elaboration of the process, as the constants in the above example have been made to conform with those worked out on that page. The load line which is shown in Fig. 2 crosses the zero-current axis at 300 volts, which is the quiescent (or zero-signal) operating point. If extended in either direction, it would intersect the zero-plate-voltage axis at 400 milliamperes. Therefore its resistance is 750 ohms. This is multiplied by 4 to obtain total plate-to-plate load resistance; thus the load line represents a 3,000-ohm plate-to-plate load.

Therefore, desirable operating conditions for two 2A3 tubes in a push-pull amplifier are:

Plate voltage:	300
Grid bias voltage:	—60
Load resistance (plate-to-plate):	3,000 ohms

(Note that the composite curves which have been derived for this amplifier represent the signal currents through the plate load, and not the actual tube current. Each tube will still draw 40 ma of plate current for zero signal.

The above is a general method for designing any push-pull amplifier. However, in many cases fairly standard values are available.

For convenience in designing the amplifier, the complete operating conditions and circuit values for a number of the tubes most widely used in push-pull audio output stages are given in the table. These values have been determined as just described.

If the specific requirements in a particular case are satisfied by any of the tubes listed in this table, the best results will be obtained with the values given. Values as close as possible to those recommended should be used in the actual amplifier for maximum power output with lowest distortion. For anyone interested in experimenting with tubes other than those given in the table, or with other operating voltages for the tubes given, the method described of using composite curves will give the best design values.

Once the push-pull output stage has been designed, the problem arises of supplying the grids of the two tubes with voltages which are equal in voltage and 180 degrees out of phase. The simplest method of driving the grid in push-pull from a single-ended amplifier is with a center-tapped transformer. This method is not too widely used because a good transformer is expensive and may not give the fidelity which can be obtained with resistance-capacitance coupling. Two different circuits for driving the grids of a push-pull amplifier with the proper out-of-phase voltages are in general use. These are familiar phase inverters, and their schematics are given in Figs. 3 and 4.

The circuit in Fig. 3 is a cathode-follower phase-splitter. Output signal is taken from the cathode circuit as well as from the plate circuit of the tube. The grid-to-grid driving voltage which can be obtained from the phase-splitter is:

$$E \text{ grid-to-grid} = \frac{2\mu R_L}{RL(\mu+2)+R_P} E_{in}$$

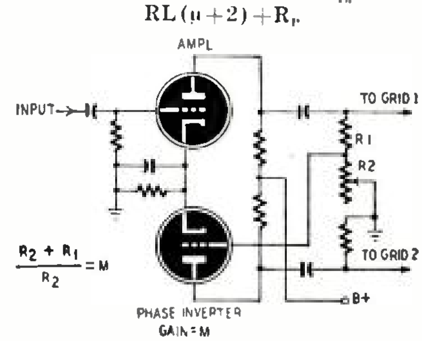


Fig. 4—Common 2-tube phase inverter.

where R_L is the value of the plate and cathode load resistance, μ is the tube amplification factor, and R_P is the plate resistance of the tube. The maximum gain of the phase-splitter stage is 2; therefore, this tube can be used for coupling the single-ended amplifier to the push-pull stage, but cannot be used for voltage amplification.

Another type is shown in Fig. 4. In this circuit, the single-ended amplifier drives one of the push-pull grids directly. An additional tube is used to amplify a small part of this voltage, with a 180-degree phase reversal, and thus to drive the second push-pull grid in the proper phase. The voltage for the phase-inverter grid is obtained by tapping down on the grid resistor of the first push-pull grid, as indicated. For satisfactory balance of the push-pull amplifier, the resistances should be chosen so that

$$\frac{R2 + R1}{R2} = M$$

where M is the gain of the phase inverter stage. In using this type of phase inverter in a circuit, it is best to make resistor R2 adjustable so that balance may be obtained between the two sides. Once the circuit is constructed and placed in operation, a rectifier- or vacuum-tube-type a.c. voltmeter should be connected from each push-pull plate to ground, and R2 adjusted until both audio-frequency voltages are the same.

In addition to the preliminary adjustment, it is an excellent idea to check the balance periodically. Aging of tubes and components will almost always make readjustment necessary after a time. If the adjustment is not made, distortion may develop.

A number of variations on these phase inverters have been made at one time or another. Several are shown in John W. Straede's article on page 34 of the July, 1948, issue of this magazine. One of the most popular is the floating paraphase, in which the grid of the second inverter tube is connected to the junction of the two final grid resistors. This point is grounded through a resistor. Any inequality of voltage across the two final grid resistors causes a voltage to appear across the grounded resistor and therefore on the inverter-tube grid.

The phase-inverter stage should be chosen according to the driving voltage required at the grids of the push-pull stage. Normally a general-purpose triode, used either as a cathode-follower or as a phase inverter, will furnish sufficient output voltage to drive any of the various receiving tubes listed in the table above in a push-pull power output stage.

Earlier stages

The stages preceding the phase inverter are conventional single-ended voltage amplifiers, readily designed according to the values given in the resistance-coupled amplifier chart in the receiving-tube manual. The number of stages, the over-all gain, the input impedance, and any equalizing or tone control circuits which may be used will depend upon the individual requirements, and should be selected in the usual manner to satisfy the conditions under which it is desired to operate the amplifier.

The circuit of a simple push-pull amplifier which has been constructed according to the information given in this article is shown in the schematic in Fig. 5. It consists of a single voltage amplifier stage, a phase inverter, and the push-pull output stage which drives the loudspeaker. The frequency response and sound quality of this amplifier are excellent, and it has sufficient gain to operate a loudspeaker from an r.f. tuner or a crystal phonograph pickup. (No tone controls are included since they are not the subject of this article, but they may be included in the conventional manner if desired.) The circuit is included to illustrate the ease with which the design principles discussed may be applied to the practical construction of a high-fidelity audio amplifier. By proper application of these methods, good, high-fidelity, push-pull amplifiers may be designed with ease to satisfy almost any audio requirements.

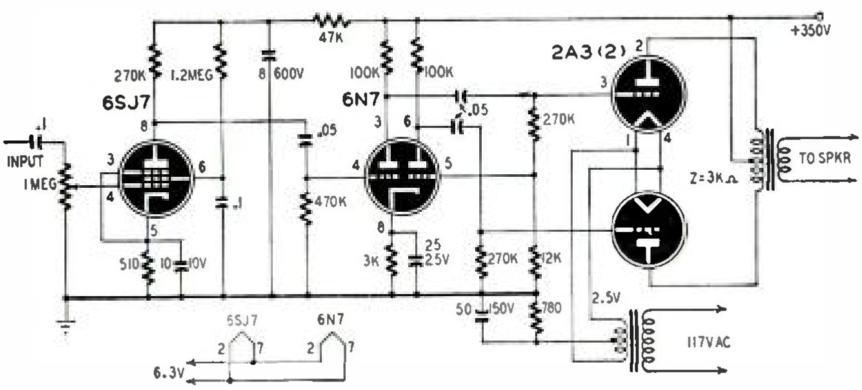


Fig. 5—This simple push-pull amplifier circuit shows how the design information is used.

AMPLIFIER DESIGN TABLE

Tube Type	Power Output (Watts)	High Voltages: Plate	High Voltages: Screen	Grid Bias: Fixed Bias	Grid Bias: Self-Bias (Cathode Resistor)	Peak Grid-to-Grid Driving Voltage	Load Plate-to-Plate (Ohms)	Typical Commercial Output Transformers
2A3 Also: 6A3 6B4-G 6A5-G	10	300	—	—	780Ω	156	5000	UTC: LS-57, LS-55, PA-16 Kenyon: T-301 Thord: T-67S51 (5000Ω) T-58S72 (3000Ω)
	15	300	—	-62v	—	124	3000	
6F6	11	315	285	—	320Ω	58	10,000	UTC: LS-63, PA-19 Kenyon: T-303 Thord: T-75S75
6V6	14	285	285	-19v		38	8000	UTC: LS-52, LS-54 Thord: T-15S90; T-17S11
6L6 807	18	360	270	-22.5v	—	45	3800	UTC: LS-6L4, PA-4L6 (3800Ω) LS-6L3; PA-2L6 (6600Ω) Kenyon: T-317; T-319 Thordarson: T-17S13(6600Ω)
	26.5	360	270	-22.5v	—	45	6600	
845	100	1200	—	-185v	—	Drive from transf.-coupled push-pull 2A3's	8800	UTC: LS-845

A MODULATION MONITOR

A simple, low-cost, visual modulation monitor that can be added to many existing phone transmitters was described in *RCA Ham Tips*. It consists of a 2BP1 C-R tube, eight resistors, three capacitors, and a little hardware.

All components can be mounted in a 3 x 4 x 5-inch metal utility cabinet. The socket is mounted inside the cabinet at one end so the tube can project through a hole drilled in the opposite end. A shield originally made for an 807 tube protects the sides of the C-R tube and prevents some of the stray light from striking its face. Operating potentials are taken from a transmitter with voltages up to approximately 1,000 volts. Heater voltages are tapped off a 6.3-volt supply in the speech amplifier, exciter, or elsewhere in the rig. If the filament supply is ungrounded, peak heater-cathode voltage should not exceed 125.

Voltage for the second anode is tapped from a 1,000-volt point on the high-voltage power supply for the final amplifier. A modulation voltage tapped off the hot side of the secondary of the modulation transformer is applied to the horizontal deflection plates. Modulated r.f. voltage, picked up with a special loop, constructed as shown in the drawing, is applied to the vertical plates. Trapezoidal patterns will appear on the screen when the transmitter is modulated. The modulation envelope can be viewed if the lead is removed from the plate end of the modulation transformer secondary and clipped to the plate of one of the transmitter's rectifier tubes.

When the monitor is used on transmitters with voltages higher than 1,000 on the modulated amplifier, bleeder resistors consisting of several 1-megohm, 1-watt resistors in series should be used so the voltage applied to the monitor does not exceed 1,000.

No centering controls are provided. The small metal cabinet may become magnetized while it is being drilled. This residual magnetism will probably deflect the spot from the center of the screen. To compensate for this, take a small horseshoe magnet or an old PM speaker and move it around the outside of the cabinet until the spot is deflected further in the same direction as the original error. When the magnet is removed, the spot will return closer to center. Continue till spot is centered.