Designing Your Own Amplifier

by Norman H. Crowhurst

Part III: Phase Inverters

MOST modern amplifiers have push-pull output stages, for reasons that will be more apparent when we discuss that part of the design. With push-pull output it is possible to get much more power from tubes and other components of reasonable size, with much less distortion. But before we can operate output tubes (or any other stage) in push-pull, we must convert the single-ended signal handled by most voltage amplifiers to the pair of oppositively phased signals needed for push-pull drive. This can be achieved with a *phase inverter* or *phase splitter*. Two principal kinds of circuits can be used: the transformer phase inverter and the various types of tube inverter. Before going into their design, their relative merits should be stated briefly.

The simplest circuit to design uses transformer coupling. In the early days transformers were not very good — they introduced a significant part of the over-all amplifier distortion. Modern transformer materials and design have remedied this situation, so that now transformer coupling can be the best as well as the simplest, except for one serious obstacle: the problems in applying feedback over an amplifier using interstage transformer coupling are much greater than with RC-coupled types. For this reason, with the current trend toward amplifiers having large amounts of feedback, it is not surprising

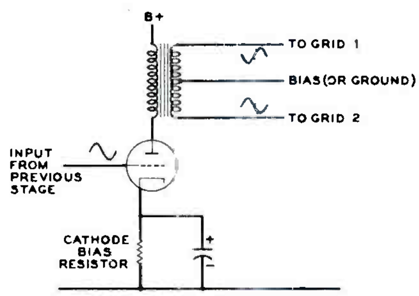


Fig. 1. Circuit of phase inverter using a series or direct-coupled transformer.

to find that interstage transformers are little used. Furthermore, good transformers are costly. But to obtain the same signal-voltage swing from RC-type tube inverters, a greater B+ supply voltage is invariably necessary, as will become evident later in this article.

Series Transformer

The merit of the transformer circuit is the simplicity with which two voltages of opposite phase can be provided on its secondary by the use of a center tap, as shown in Fig. 1. The reason why transformer coupling can handle a larger swing, using the same B+ supply, will become evident from Fig. 2, which shows characteristic curves of a 6SN7 tube (one half) or a 12H4, a miniature single triode having the same characteristics.

The dotted line in Fig. 2 represents the DC voltage drop in the primary winding resistance of the transformer. This way, with a supply voltage of just over 260 volts, we can have 250 volts on the plate at 9 ma plate current, and the voltage swing at the plate can be from 90 volts to 400 volts — *much higher than the supply*. This is because, although the transformer has only a low primary *resistance*, it has a very high *impedance*. To obtain the necessary bias for the operating condition of Fig. 2, —8 volts, the bias resistor should be about 900 ohms. The preferred value of 910 ohms will be near enough.

The excursion shown in Fig. 2 is 160 volts in the negative direction, and 150 volts in the positive. This is an off-center effect of 5 volts in a peak-to-peak swing of 310, representing only about 1.6% harmonic distortion.

Fig. 3 shows one of the problems associated with this circuit. The primary inductance makes the load line open into an ellipse at lower frequencies. This not only reduces the maximum swing, but produces distortion quite rapidly. This ellipse — the widest possible before really serious distortion sets in — shows an AC voltage of 290 peak-to-peak, for a current swing of 14 ma, representing a reactance of 21 K. To respond without distortion down to 20 cps, the inductance would have to be 200 h with 9 ma flowing, which is quite an inductance!

Reducing the current could be done by biasing the tube back a little further, and that would seem to make the inductance easier to get; but we lose more than we gain, because lowering the oper-

Fig. 2. Load line representing one possible operating condition with series transformer coupling. The dotted line represents DC drop from the transformer primary-winding resistance; this operating condition requires a cathode-bias resistor of 910 ohms, with a B+ supply that puts 250 volts on the plate.

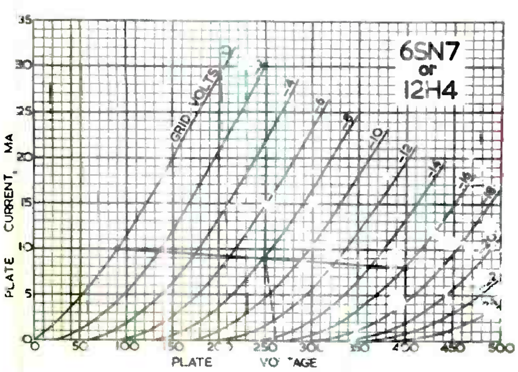
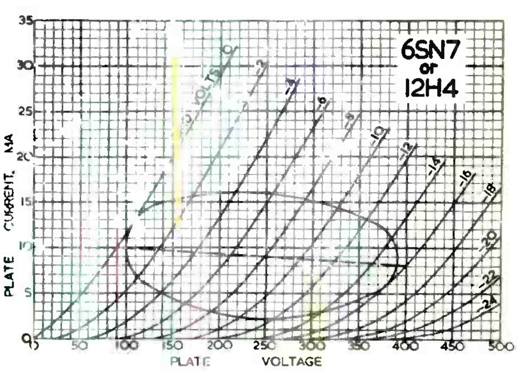


Fig. 3. The ellipse approximating the load condition for minimum permissible shunt reactance has been sketched over the load line in Fig. 2 (shown dotted).



ating point on Fig. 3 means that the width of ellipse permitted is narrowed and we need much more inductance. The gain in inductance does not keep pace with need for more.

Parallel-Fed Transformer

One way around this is to apply the parallel-fed method of connection shown in Fig. 4. That keeps the plate current out of the primary, so a transformer utilizing a better core material can be used. This will be a much more compact unit, with a considerably improved frequency response. Also, the possible improvement in design makes practical a transformer with a bigger voltage step-up from primary to secondary, so that the loss in signal-handling capacity resulting from the parallel-fed connection (because of reduced plate voltage) can be made up in the transformer.

But we can take the design of this stage as a starting point for considering the various RC-type tube inverters, which will make it easy to compare relative performance. Fig. 5 shows the load line for a plate resistor of 25 K from a supply voltage of 275. Bias for maximum signal swing should be —7 volts, permitting a swing from 0 to —14 volts. Plate voltage at this operating point is 182, for a current of 3.8 ma. This means the bias resistor should be 1,800 ohms.

The peak-to-peak plate swing, from 75 to 265 volts, is 190 volts. This should be compared with 310 volts for the series transformer with a lower supply voltage. If the change permits us to double the transformer step-up ratio we shall be better off. The distortion is not so good, however. Midpoint between 75 and 265 is 170 volts, so the swing is 12 volts off-center in 190, a distortion of about 6.3%.

The dotted ellipse represents a shunt reactance that permits a peak-to-peak current of 4.8 ma at a peak-to-peak voltage of 180, about 37.5 K. The inductance to maintain this to 20 cycles is 300 h, which is reasonable with no DC in the primary.

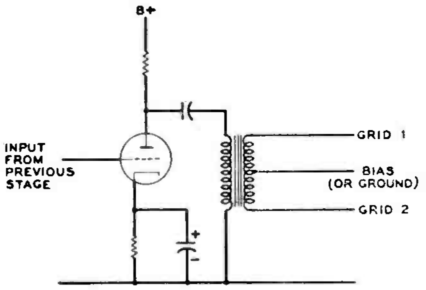


Fig. 4. Parallel-fed transformer phase inverter. DC is kept out of the primary.

Split-Load Inverters

The 6SN7 is representative of tubes used for RC-type inverters, so we will continue making comparisons of circuits using this tube. All tube-type inverters effectively use one tube section to provide inversion without any gain. The difference lies in the method of sacrificing the tube gain to provide the reversal of phase, and the merits of each circuit are connected with this feature. A transformer does have the advantage that, if the turns on each half of the secondary are equal in the first place, nothing is likely to throw them out of balance subsequently. But using a tube as an inverter means that balance tends to be more or less dependent on the gain of the tubes. Some circuits avoid this deficiency, at the expense of something else.

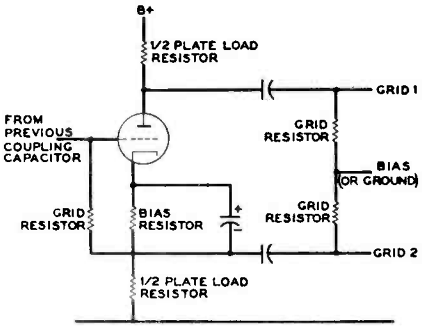


Fig. 6. A split-load inverter. Significant components are marked on diagram.

Probably the simplest type of RC phase inverter is made by simply putting half of the plate load in the cathode circuit, as shown in Fig 6. It does not matter where the resistance in series with a tube is, so long as it has the same effect in restricting the plate-to-cathode voltage according to the current the tube draws. A load line for this method of operation can be drawn in exactly the same manner as for a normal voltage-amplifier stage, using a resistance value made up of the two resistances in series.

With the same operating conditions for the 12H4 (or half of a 6SN7) that we just considered for a parallel-fed transformer load, but putting 12.5 K in the plate and 12.5 K in the cathode, and with the same bias, we would have a total maximum swing of 190 volts peak-to-peak or 95 volts peak-to-peak for each output. In the more conventional RMS units, that is about 33.5 volts.

This is further restricted because we have to use grid resistors for the following tubes. Output tubes should have grid resistors of not more than about 250 K. Using this value to construct a load line, the total shunt effect across 25 K will be 500 K, giving an AC load line of 23.7 K. This is shown in Fig. 7. The maximum swing is between 79 and 260 volts, or 181 volts peak-to-peak, with a distortion of 6.9%. Although this is second harmonic distortion it is in the same phase on each output tube grid and cannot be cancelled. Some reduction will occur because of feedback in the cathode of this tube, leaving about 1.5% which is comparable with the transformer type although the swing is much smaller.

There is the limitation with this kind of circuit: the output swing is not very great. For some output tubes requiring a bias less than 45 volts, this drive voltage would be adequate; but, for other types, a phase inverter that gives a larger swing will be necessary.

This kind of circuit does, of course, avoid all the problems encountered in the transformer-coupled circuit. There are no shunt reactances of a value anything like as low as those we have been discussing. But another disadvantage of this circuit is that it has very little gain; in fact, as considered from the grid of the phase inverter to the grid of each output tube, it actually has a loss. Assume that the circuit is being driven at full amplitude so we have 90 volts peak-to-peak being supplied to each output tube grid. This 90 volts appears between cathode and ground of the inverter tube. To get this output in

Fig. 5. A typical load line for parallel-fed transformer inverter, with a plate-load resistor of 25 K and a bias resistor of 1,800 ohms. B+ is 275 volts. Compared with series coupling, maximum output swing is considerably restricted, but improved transformer design may compensate for this by providing increased step-up. The ellipse represents minimum permissible shunt reactance.

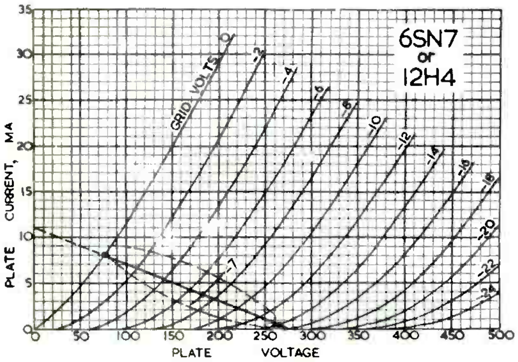
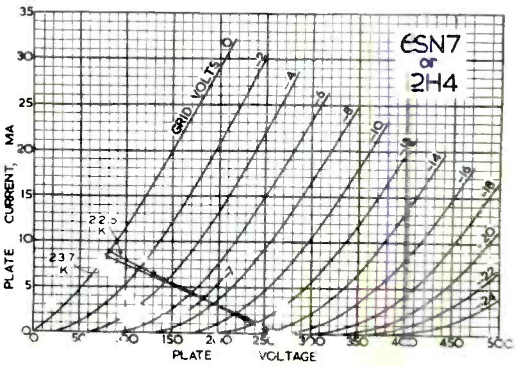


Fig. 7. Load lines for the various RC phase inverters discussed in the text. The same operating point as given in Fig. 5 is assumed, with 275 volts B+.



its plate circuit the tube requires a *grid-to-cathode* voltage swing of 7 volts peak, or 14 volts peak-to-peak. This is over and above the voltage appearing at the output from *cathode to ground,* so the total voltage necessary from *grid to ground* will have to be 104 volts peak-to-peak.

We need to put in 104 volts, then, to get out 90 volts for each output grid. It is quite easy to get a swing of 104 volts from a similar amplifying tube, operated single-ended; a suitable circuit is shown at Fig. 8. The first stage has a 25-K plate resistor. A 470-K grid return to the off-ground bias point is adequate for the second stage, or phase splitter. But because this resistor is connected between points with a swing of 104 and 90 volts respectively, it will

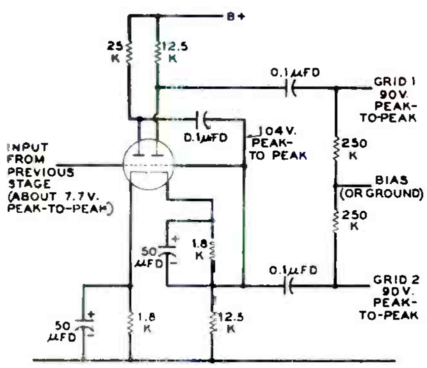


Fig. 8. Complete double stage of the split-load inverter. The values shown are based on design figures in the text.

draw much less current from the 104-volt circuit than if it were connected to ground. The voltage difference across it is only 14 volts, instead of 104 volts, so the current will be divided by 104/14. The *effective* AC resistance in parallel with the first stage's 25-K plate resistor will be 470 K multiplied by 104/14, which is about 3.5 M. The shunting effect of this can be ignored.

Going back to Fig. 5 to calculate the gain of this stage, 14 volts swing gives an output of 190 volts swing — a gain of 13.5. So an output of 104 volts swing will require an input of 7.7 volts swing, or about 2.7 volts RMS.

The response of the phase splitter section will be 3 db down at the frequency for which the coupling capacitor reactance is equal to the grid resistors, 250 K. With 0.1-μfd capacitors this is 7.5 cps; good balance and response will certainly be maintained down to 20 cycles. For the previous stage: the *effective* grid resistor that determines response is 3.5 M, which extends the response down to below 0.5 cps with 0.1 μfd.

This kind of inverter gives good balance, because the balance is determined by the equality of the plate and cathode resistors. They can be selected precisely and can be expected to remain fairly well matched. Frequency response can be made as good as we want, but harmonic distortion is not as low as has been claimed, and the output voltage is limited.

If the kind of output stage we're thinking of needs more than 90 volts to swing each output tube, we have to consider another kind of phase

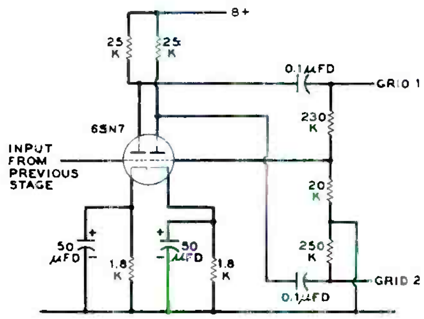


Fig. 9. Paraphase circuit has higher maximum output swing than the split-load circuit, because each output comes from an individual complete plate load.

splitter. Unless we are prepared to furnish an appreciably larger B+ voltage, the only way out is to use some kind of phase splitter in which each output comes for an entire plate load. This means we must use a separate plate circuit to drive each grid. If we can do this, using a 6SN7 tube and the same operating values we have already discussed, we shall get the full 190 volts (or nearly that) from *each* plate circuit.

Paraphase Inverter

A simple system of using both plates for drive, known as a paraphase circuit, is shown in Fig. 9. We will continue using the same basic circuit values to get the advantage of relative performance comparison. But here the 250-K output grid resistors are coupled one to each plate, which brings the AC loads down to about 22.5 K. This is shown on Fig. 7 also. A maximum swing between 82 volts and 254 volts is obtained, using the same bias point and 14 volts grid swing. This is a gain of 12.3, and the distortion is about 8.1% which is much higher than the split-load type ended up with.

In this case, however, each tube will produce second harmonics of opposite phase, which will cancel at least partially in the output. At full load the distortion in the output originating from the phase inverter would probably be about 3%. But the distortion will not be so high *at the same level* as in the previous circuit. The figures just discussed are for a swing of 172 volts. To get approximately the same output swing as the first circuit, we can use a grid swing from −3 to −11 volts (or, better still, from zero to −8 volts, using a new operating point). This gives 100 volts peak-to-peak output swing, and reduces the distortion on each side to 2%. The resultant in the output will be well under 1%.

To complete the design, though, we need a drive for the second tube section equal to that for the first section. Since the gain is 12.3, we need to tap off 1/12.3 of the output from the first half, which will be in opposite phase to its input. The values shown give this, and provide the same total resistance in each grid circuit. Frequency response will be similar to that of the split load circuit, if similar values are used, so there is no need to discuss this again.

This kind of circuit will usually work quite well with a low-gain tube such as the one we have chosen. It is not too successful, however, when used with a high-gain tube in which the amplification factor is subject to considerably greater variation with operating conditions. This is particularly likely to happen if the heater voltage fluctuates, which alters the operating temperature of the tube and hence its space charge. Low-gain tubes are not so susceptible to this kind of variation.

The fact that the balance of the drive to the two halves of the output is dependent at all upon the exact gain of the tube is considered a disadvantage by some, for which reason methods have been devised to equalize the output so it is less dependent upon the gain of the individual tubes. We will not at this point go through the full design procedure, but merely indicate the method.

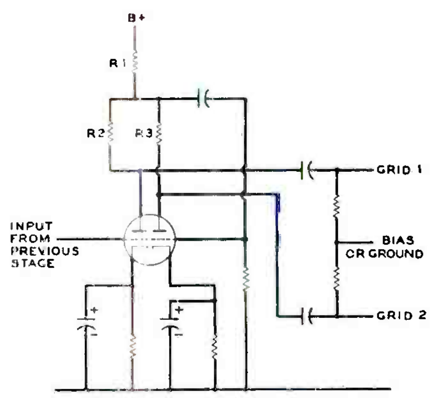


Fig. 10. Modification of the paraphase circuit, intended to minimize any out-of-balance condition caused by variations in individual tube characteristics. This is called the floating paraphase circuit.

The Floating Paraphase

Instead of using a predetermined tap in the grid circuit to obtain drive for the second stage, a common section of plate resistor is employed in the floating paraphase circuit, in Fig. 10.

Plate currents of both tubes pass through R_1. The second tube needs a grid swing that is only a fraction of

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TAPE RECORDER

Continued from preceding page

If a machine has a single record-playback head, azimuth error in record is compensated by the same error in playback. However, when it comes to playing tapes made on other machines, a misaligned single head obviously provides very poor high-frequency response.

To permit easy azimuth alignment, test tapes generally provide a steady high-frequency tone, such as 5,000 cps at 7.5 ips or 10,000 cps at 15 ips. As the tape is played the playback head is alternately tilted slightly to the left and right, so as to change the angle of the gap with respect to the tape. The position of the head which yields maximum output is the correct one. Maximum output can be measured by the level indicator or it can even be gauged by ear, because the correct azimuth setting is quite critical and the ear is sufficiently sensitive.

If the tape machine has a separate record head, the next step is to align this head. The procedure, using a fresh roll of tape, is to record a high-frequency tone and adjust the record head to give maximum output when played back through the already aligned playback head. This tone can be furnished by the phonograph test record.

BALSA TONE ARM

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lacquer. To assemble, force-fit the pivot shaft to the yoke, and the ball bearings in the bearing case. Then complete the base assembly as shown in Fig. 9.

Final Assembly

The arm is now ready for final adjustment and assembly. Install the cartridge, using self-tapping screws, and run the shielded cable in the cable slot, gluing or stapling it to the arm (Fig. 10). Mount the arm to the base by inserting the ⅜-inch drilled rod in the arm between the needle bearings. The lead counterweights are lightly screwed into place, using enough weight to give approximately the correct stylus pressure; final adjustments will be made when the arm is mounted. An armrest can be made from balsa or a 3-inch piece of ¼-inch Lucite rod.

Properly mounting this arm, as with any other, is most important. The amount of time spent in doing this correctly will be more than compensated for in better over-all performance and reduction of tracking error. There are three basic considerations in mounting the arm. First, the cartridge stylus must overhang the turntable spindle by a critical distance. Second, the arm must be horizontally parallel with the turntable when playing a record. Third, the stylus pressure must be correct.

Height adjustment is done simply by changing the height of the arm, moving the bearing case up or down in the base. Tighten the set screw in the base to hold the correct position. Proper overhang, the distance that the stylus extends beyond the turntable spindle, is determined by drilling a 1-inch hole for seating the bearing case in the mounting board; this is drilled at any desired point on the circumference of a circle of 9 in. radius having its center at the turntable spindle. The overhang should be exactly .048 in. With the bearing case in the 1-inch hole, move the arm so that the stylus is this distance past the center of the turntable spindle. The 1-inch mounting hole will permit movement of the arm for this minor adjustment. When overhang is correct, fasten the arm base to the mounting board with flat-head screws.

Stylus pressure is set according to the cartridge manufacturer's specifications, using a stylus-pressure gauge. Changes in stylus pressure are made by changing the size and number of the lead counterweights.

If reasonable care has been taken in the construction, painting, and mounting of the arm, you now have a pickup that looks and performs with the best. Mine has been in use for over a year. It has been extremely satisfactory and sufficiently durable.

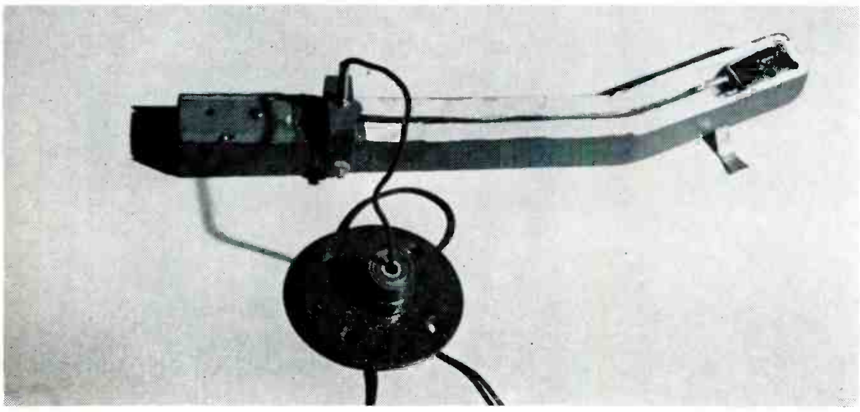

Fig. 10. Cable is run from cartridge through channel in arm and base assembly.

AMPLIFIER DESIGN

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each plate output swing to drive it, so as to give an output equal to that of the first tube. If both plates had exactly equal swing in plate *current*, there would be no swing across R_1; the swing at this junction point automatically adjusts itself so that the plate currents are out of balance by a fraction sufficient to provide the grid swing for the second tube. By adjusting the values of plate resistors R_2 and R_3, which are responsible for developing the actual output voltages, one stage can be arranged to have a gain larger than the other by this fraction.

Assuming that the gain of each stage can be 12, the voltage appearing at the junction must be 1/12 the voltage appearing at each plate. If R_1 is equal to R_2 and R_3 (approx.) then the plate-current swings will have to be in the ratio of 12:11. This means that, to give equal plate-voltage *swings*, R_2 and R_3 must be in the ratio 11:12. Thus we can obtain equal outputs by altering the plate-load resistances only a fraction. Error due to variation in individual tube gain is reduced to a smaller fraction. This is a form of feedback, and we can expect the improvement to be about equivalent to the working gain of each tube.

Here is the rub: the series resistance R_1 drops some of the available B+ voltage, so that the load line starts from a lower point. Otherwise viewed, it could be said that only part of the active plate load is used. This has the effect of restricting the maximum available output in comparison with the straightforward paraphase circuit. Of course, the circuit must be tailored to the desired swing; if a swing of 25 to 30 volts RMS is adequate for each output tube the arrangement can serve as is. Otherwise, higher B+ is needed.

This circuit provides distortion cancellation in the same way as the straight paraphase, and frequency response is calculated in the same way. A special case of floating paraphase inverter with feedback will be considered in detail in a later article.

Cathode-Coupled Inverter

Another circuit that works almost the same way is called the long-tailed or cathode-coupled phase inverter. Instead of putting the common resistance in the plate lead, we put it in the common cathode return, as shown in Fig. 11. The signal voltage for driving the second half is developed across this common resistance; the direction of the voltage drive is reversed by having the second-stage grid effectively connected to ground through a large capacitor. Bias for both tubes is taken from a suitable point on the cathode resistor.

Apart from this, the circuit's operation and the available swing that it can give are quite similar to the floating paraphase. There is, however, the following difference: the voltage for the second grid is developed across R_1, which is a cathode load for the first half also. This being so, the input to the second grid is linearized by feedback, which does not occur with the floating paraphase. Accordingly the second-harmonic cancellation stands a chance of being a little better when this circuit is used as an inverter, although the gain is reduced.

Output Impedances

It is essential that the impedance presented to the output-tube grids by the drive stage not be very high. Voltage-amplifier tubes can have grid-circuit

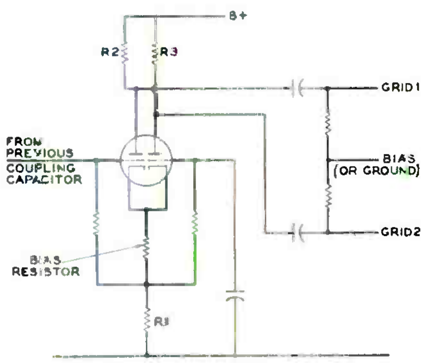

Fig. 11. Similar to the floating paraphase is the cathode-coupled or long-tailed inverter. This is one variation.

resistances on the order of a megohm, with an impedance or AC resistance of 100 K or 200 K. But output tubes must have much lower grid resistance than this, because of the bigger physical size of the tube and the fact that the grid current, although minute, is larger than in the voltage-amplifier tube.

So long as the grids of the output tubes are always operated in the negative region, and large grid currents do not begin to flow, a grid resistance in the range of 100 K to 250 K, but never greater than 500 K, is acceptable for stabilizing the bias. The driving impedance should be in the region of perhaps 20 K, as typified by the inverter circuits we have discussed.

We shall find that in push-pull power-output stages, high power can be obtained much more easily if we "drive" the grids [illegible]king them go positive during [illegible] the wave form. This means [illegible] we [illegible] to supply a current to the grid, as [illegible] maintain the potential swing [illegible]quired to give the right output wave form.

Otherwise stated, the stage driving the output must be capable of supplying power for grid current to avoid the kind of distortion that occurs when such power is not available. As soon as the drive reaches zero grid voltage, conduction of the grid in conjunction with the high source resistance prevents the voltage from swinging any further positive, and the wave form becomes "clipped".

Source resistances and impedances for drive stages have to be very much lower than when the same output tubes are operated without going into the positive-grid region. But the design of a drive stage to supply power for the output grids is somewhat more complicated than the design of a simple power-output stage. We will reserve discussion of this until after we have covered the design of the push-pull power stage itself. Sometimes, also, to get sufficient swing for a large power-output stage, even without positive grid drive, a push-pull stage is used between the phase inverter and the output. This is also called a drive stage, although not called on to handle power.

HI-FI MILESTONE

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This was proved when, just before the finish of the program, the indicator lights were extinguished and Mr. Hilliar left the console unobserved by the audience. It was startling to see him standing by the exit door as the closing chords sounded, since the last indication of the lights had been "live". The experiment was an unqualified success.

Joint promoters of the demonstration were The Audio League, The Harmonic Hill Radio League, and Saint Mark's Church; Richard W. Burden was director. The program consisted of *O Gott, Du frommer Gott* and *Toccata,* Flor Peeters; *Gigue* from *Concerto No. V*, Handel; and *Concerto in C*, J. S. Bach.

BASS WITH BUSTER

Continued from page 31

ing them at the apex of the triangular speaker arrangement also increases greatly the depth of perspective.

The middle-range speaker, a Super 12 Wharfedale, lies in a horizontal position pointing upward toward a foot-high curved reflector. This reflector is formed over wooden knees by several sheets of cardboard cemented together and covered with vibration-proof rubber floor matting. This is not, strictly speaking, a simple direct radiator; the curved reflector, combined with the corner walls, provide a considerable front-loading factor. The rear of the cone is totally enclosed in about 10 cu. ft. of air. The corner structure is heavily constructed and insulated, and is larger than it appears in Fig. 5, because it connects with a former wood-box re-

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