For Golden Ears Only

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Details of an amplifier design which follows standard practices without any corner-cutting in an endeavor to provide the best possible reproduction.

An audio amplifier which will please 99 per cent of the listeners is not difficult to produce; but bridging the gap between this adequacy and the near perfection necessary to please the hypercritical few Golden Ears is another matter entirely.

The assumption that all that is necessary to produce high fidelity is to provide a wide frequency response has been discredited for many years. It can be taken as the fundamental law that the acceptable bandwidth is inversely proportional to the distortion generated by the system. To attain a bandwidth which will embrace the whole audible spectrum, the system distortion must be held down almost to zero.

The inescapable conclusion is that an audio system intended to reproduce sound with the greatest possible realism must be designed first with the end of reducing distortion to a minimum and only secondly for wide response. With tubes and components available today, it is no trick to produce a wide response. But reducing the distortion to a point which will make this bandwidth tolerable, let alone enjoyable, to the critical ear is a difficult and trying problem.

Three years ago the author constructed a laboratory amplifier for the purpose of investigating the problem of attaining the maximum fidelity and minimum distortion. It consisted of a heavy duty power supply capable of delivering any combination of voltages necessary for a home-type amplifier, and of an audio section whose layout permitted relatively easy and rapid changes of circuits and tubes. Meters were built in to provide easy measurement of plate currents and tube balance, as well as of the output voltage across both resistive loads and loudspeaker and line loads. Literally scores of circuits and modifications have been tried and tested; hundreds of frequency runs and distortion measurements have been made; and all have been checked with critical subjective tests. The decreasing residue of distortion was hunted down until no further improvement could be achieved.

These experiences are expressed in the amplifier to be described. It represents the nearest approach to perfection achieved in the three years of experimentation and, we sincerely believe, the best that can be done with presently available tubes and components. It will deliver 10 watts at any point between 20 and 20,000 cps with less than 1 per cent distortion. Below 8 watts the distortion is so low that it cannot be measured accurately with equipment available to us. The intermodulation distortion is approximately 1 per cent at 10 watts and just over 2 per cent at 15 watts, rising more steeply beyond that. All these figures are with a loudspeaker load.

The frequency response is actually much broader than the 20–20,000 cps mentioned above. Without bass attenuation (described and justified later), the frequency response is down only 5 db at 5 cps and 3 db at 30,000 cps. The design is quite foolproof and can be recommended to anybody with any construction experience at all, providing no changes are made in the circuit or components.

A glance at the parts list will show that the total cost of the amplifier—even if receiver type power supply components are used—will run to around $75. Various short cuts and expedients intended to reduce cost were tried. In fact, we don't believe we missed any possible ones, but the total cost is still a considerable saving over commercial amplifiers with a claimed performance approaching this.

The Circuit

With the exception of a few elements which may lift eyebrows slightly, the circuit and parts are standard and conventional. Briefly, the circuit consists of a single-ended input stage, transformer-coupled to a push-pull triode driver stage, transformer-coupled to push-pull triode output stage. All transformers are of broadcast standard quality, and attempts to use cheaper ones with modifications intended to correct deficiencies proved to be unsuccessful. Some feedback is applied to each stage. A two-stage feedback loop embraces the output and driver stages. The driver stage also has a small amount of current feedback through the absence of cathode-bypass capacitors; and the input stage has the same type of simple current feedback. The main loop provides about 14 db and the others about 4 db each. This feedback produces a high order of damping of the loudspeaker, and accounts partially for the excellent transient response.

Output Stage

The output stage employs 6B4's (6A5G's will give a lower hum level if they can be obtained). This stage operates with fixed bias which is obtained from a selenium rectifier fed by a 6-volt filament transformer in reverse. A resistance-capacitance type of filter could replace the one shown with no sacrifice in performance. The bias voltage is regulated by an OA-3 (formerly VR-75). This may be considered an excessive refinement, but we think not. After monitoring the plate currents of the output tubes for three years we are impressed by the wide variations which occur with relatively minor changes in line voltage. We believe the effects of these variations are minimized by the use of voltage regulation. Furthermore, the voltage regulator tube is an effective hum filter, and since the 6B4 family of tubes has a rather high hum level at best because of the filamentary construction, every possible step must be taken to hold the over-all hum down to a minimum.

To protect against bias failure, a resistor is wired in the filament return circuit and shunted by a 125-ma fuse. The sudden rise of current caused by a failure of the fixed bias will blow the fuse and throw in the cathode resistor, providing cathode-bias operation until the fixed bias is repaired and restored.

The 6B4's are balanced by potentiometers which control the amount of bias applied to each tube. It will be noted that the tubes are neutralized. Our experience, not only with this amplifier, but with others using these tubes, indicates that neutralization is needed in so high a percentage of cases that it might as well be incorporated in the beginning. It is not necessary to neutralize perfectly; if fixed capacitors of approximately 17 $\mu\mu f$ are wired in, there is no need to adjust the neutralization further.

The 6B4 family will produce parasitic oscillations at the slightest provocation, as might be expected, considering the high grid-plate capacitance of 17 $\mu\mu f$. The parasitics may not be audible and indeed may well be way up in the r.f. range. But notice what happens to the plate current when the tubes are neutralized—in more than half the cases the

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current will be reduced, indicating that there was oscillation, or at least regeneration, at some high frequency.

However. even if no parasitics existed, the neutralization would still be sufficiently desirable for other reasons to be worth the slight cost of the fixed capacitors. Neutralization improves the input admittance of triodes and therefore improves the high-frequency response. It also reduces the effective capacitance shunted across the input transformer, and this moves the resonant peak (due to transformer inductance and distributed and stray capacitance) up into the supersonic range, yielding a smoother and wider bandwidth.

The Driver Stage

In an amplifier using triode output tubes. the critical point is the driver stage. We are convinced that most of the troubles experienced with triode amplifiers are traceable to this stage, and also that most of the residual distortion can be traced to this stage rather than the output stage. Yet little attention is usually paid to this stage—either in the original design or in trouble-shooting—when the design fails to meet the expected specifications.

A signal in excess of 100 volts grid-to-grid is required to obtain maximum output from the 6B4 family of tubes. The tube manuals indicate that there are any number of tubes capable of producing an output of 100 volts or more in push-pull. In actual practice, however, it is very difficult to obtain this much drive without distortion, particularly if feedback is used.

In this amplifier, a high-quality transformer couples the drivers to the output tubes. A considerable sum of money could be saved by eliminating this transformer, and we have made repeated attempts to do this; but we can say categorically that if nearly-perfect reproduction is desired, the saving is not worth the troubles produced. As a matter of plain, though possibly incredible fact, we found no combination of tubes and resistance coupling which would provide the necessary drive for maximum output with fixed bias without excessive distortion. (See Appendix.)

The drivers are a pair of 6C4's, by far the best of the tubes tried for this purpose. They will not only supply a higher driving voltage more easily. but their input admittance is low because of low grid-plate capacitance. This is reduced even further by cross neutralization with fixed 1.5 $\mu\mu$f ceramic capacitors. No adjustment of neutralization is necessary. The neutralization is especially desirable if the smaller of the specified input transformers is used; these have a relatively low resonant point, and the neutralization helps move it upward.

A balancing control is incorporated for the drivers. It consists of a small pot in one cathode circuit. Balance is most easily adjusted by connecting a voltmeter from plate to plate and adjusting for zero voltage difference—preferably at near maximum drive.

We found, however, that the static balance obtained this way is not sufficient to insure balance over the full dynamic and frequency range. Actually, the tubes will remain balanced only over a small portion of the range. To provide dynamic balance, a choke is incorporated in the common plate circuit. Since this choke is common to both branches, it tends to equalize both the d.c. plate currents and the resultant a.c. voltages, and to keep this stage operating Class A—with no variation in plate currents.

The Feedback Loop

Originally we tried the type of feedback using a 10 per cent feedback winding on the output transformer. This is common practice with tetrodes. Such transformers are not commercially available for triodes. However, we had one made to order for these experiments. The idea was to eliminate the phase shifts at the extremes of the frequency range due to resistance-capacitance networks. The idea was abandoned after many trials, though with reluctance. The desired part of the result was achieved—unfortunately, not without undesired effects. It is difficult to run this type of loop over two stages with transformer coupling, and the loop had to be confined to the output stage alone. But ten per cent feedback to the grid of the output stage increases the required driving voltage by more than a third—from approximately 100 to over 130 volts grid-to-grid. It is almost incredible that this much drive cannot be supplied without distortion—even with a step-up transformer—but it turns out to be a fact. The 6C4's come closer to it than any other tubes, but even they generate measurable distortion at maximum drive. So the idea was abandoned after many combinations of tubes and circuits were tried.

Since drive is the critical point in a triode amplifier, it is obvious that the best point to apply feedback is to the input of the driver tubes where the difference feedback makes in drive requirements can be compensated for most readily. To avoid frequency discrimination and excessive phase shift in the feedback network, the capacitors are large electrolytics shunted by paper capacitors. for low reactance at both low and high frequencies. This loop provides about 14 db of feedback without increasing the drive problem. With the transformers specified, no trouble should be experienced with this feedback loop.

Phase Inversion

A transformer is used for phase inversion. This, too, reflects a great deal of effort to get along without it. Every type of vacuum-tube phase inverter we could find references to was tried in these experiments. Two gave acceptable performance but were dropped for different reasons. (See Appendix B.)

The transformer provides a 2-to-1 step-up ratio, but since the feedback loop increases the required input level to nearly 50 volts. additional amplification was necessary to bring the amplifier input level to about 1 volt. Another 6C4 is used in the final model. The only notable point about this stage is the use of a OD-3 (VR-150) in the plate circuit.

The voltage regulator tube provides three important good effects: first, it stabilizes the voltage to this stage, and since it is single-ended this is about the only way to insure stable, undistorted operation under varying line voltage. Second, the regulator tube is possibly the best of all hum filters. Third, and most important, it is the best decoupling element at low frequencies—much superior to any combination of choke or resistor and capacitor. In an amplifier whose low-frequency response goes below 20 cps, decoupling is extremely difficult, and even if there is no actual motorboating, there is enough regeneration to produce a considerable hangover and transient distortion, especially when a feedback loop is involved. The regulator tube provides sufficient decoupling so that the lowest audible frequency will not produce any form of feedback and the hangover is minimized though a trace will show on the scope at 20 cps.

Parallel feed is used for the input transformer, and a switch provides for a change in coupling capacitance. With the 0.1 μf capacitor we get a slight rise at 70 cps and a sharp cut-off below 50 cps; with the 0.5 μf capacitor we get a flat response down to about 20 cps, and a gradual falling off below that.

A low-frequency response which is flat to below audibility is necessary for good transient response, but it is not the complete blessing it might seem. As a matter of fact, with the 0.5 μf capacitor, this amplifier has a response which goes down almost to direct current. It will respond readily to signals which are below audibility, such as the low frequency produced by short-wave fading or that produced by a phonograph record whose hole is eccentric.

It is true that these signals are not audible, nor even measurable on ordinary volume indicators. However, they are of high amplitude as compared with the signal and will drive the output tubes into the Class B region of their operating curves, as the plate-current meter will readily demonstrate. Even at low signal levels, where the signal itself is barely sufficient for an output of 100 milliwatts or less and undistorted output, the inaudible transient is producing nearly maximum distortion. This results in serious intermodulation distortion on the desired signal at a listening level at which we should have none at all.

The best cure is a switch which will modify the low-frequency response to conform with the signal situation. We are convinced that a good deal of trouble experienced with high-fidelity designs is accounted for by this response to inaudible signals whose intensity is high enough to drive the output tubes into non-linear operation at levels 20 or 30 db lower than the design calls for.

The secondary of the transformer is shunted by a resistor which should be adjusted in value to produce the flattest possible response and to eliminate or reduce any peak which the input transformer may contribute to the over-all response.

Conclusion

Our three years of experimentation convince us that this amplifier is as good an amplifier for home listening purposes as can be built with presently available tubes and components. It is possible that additional improvements could be obtained by the use of specially designed transformers—those employed here are standard commercial items. Operating at levels below 8 watts, it is essentially distortionless and can therefore be used in the laboratory for measurement purposes. The small residual distortion in the highest 3 db of the range is insignificant from an aural point of view. Given a good loudspeaker system and a signal source of low inherent distortion, it provides a high degree of realism and—perhaps more important—almost no ear fatigue. The best phonograph records, for instance, sound so nearly like the live prototype that only direct comparison could reveal the difference. Because of the lack of resonant peaks, the scratch level with good magnetic pick-ups is quite low, and with the best available records it is possible to dispense with high-frequency roll-offs—providing the speaker system does not have a pronounced peak in the 2 to 6 kc range—and the listener has a tolerance for a small amount of scratch.[1]

But the amplifier alone is no guarantee of perfect reproduction. Experiments reveal that distortion masks distortion and that the elimination of one component of it reveals another underlying layer. This amplifier will therefore reveal distortion which before was relatively unimportant. For instance, the diode detector in AM receivers will be irritating with this amplifier. Moreover, too many stations—FM as well as AM—are still content merely to meet FCC specifications on distortion, instead of improving on them. The great variation in distortion characteristics of phonograph records, not only of competing companies, but even in the output of one company and the run of one recording, has been noted by many listeners.

However, this amplifier will take the listener the longest part of the road to perfection, and the total effect, even granting the inadequacies mentioned above, is worth several times the cost to anybody whose ears are golden enough to be irritated by the inadequacy of ordinary reproducing systems. Distortion doesn't always add; on the other hand, sometimes it multiplies. The elimination, or virtual elimination, of the substantial amount contributed by the amplifier provides the greatest—almost the only—improvement within our means. When enough Golden Ears possess equipment which will reveal the inadequacies of program material and produce a sufficient demand for improvement, manufacturers and radio stations will be forced to provide it. The sermon is included merely to warn that the amplifier is only *one* element—if perhaps the most important—and that it is not sufficient in itself to guarantee perfect reproduction.

[*Continued on page 32*]

[1] *(The de-emphasis network is still considered necessary.—Ed.)*

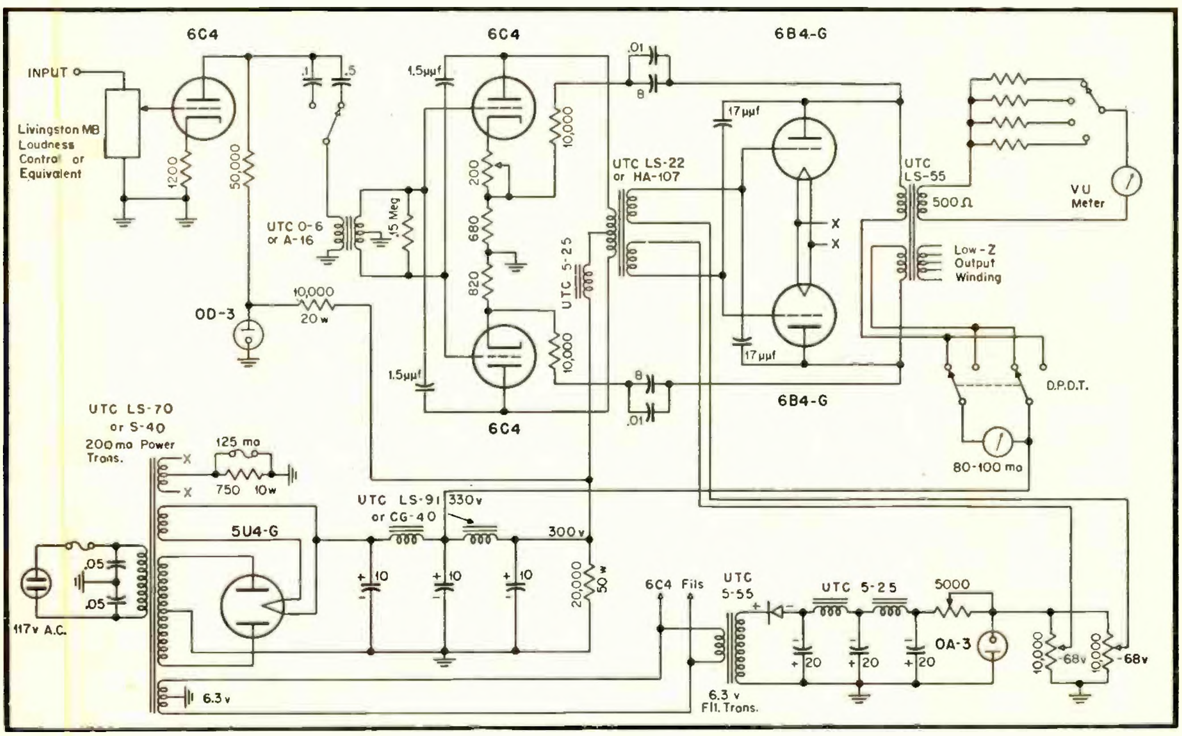


Fig. 1. Schematic of the "Golden Ear" amplifier.

APPENDIX A

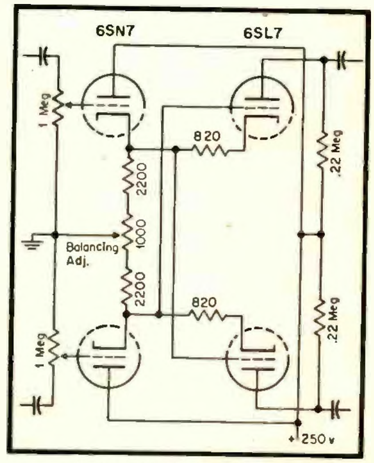
The tube manuals which indicate that several triodes can supply 100 volts or more push-pull into a resistive load are not in error; they merely start with theoretical assumptions which are difficult to satisfy in practice. For instance, they assume that the tubes and circuit will be well balanced. The only way to achieve sufficiently good balance is to match the resistors and capacitors, and though this is fairly simple when the required instruments are on hand, it is a complication which must be kept in mind.

More important, however, is the fact that with fixed bias 6B4's require an input resistance not greater than 50,000 ohms. It is possible that one or two types of tubes could produce 100 volts grid-to-grid into 50,000 ohms; but it would not be easy, and there would be no safety factor, because the stage would have to operate at its extreme limits. The cathode loaded type of driver is promising but is rather ticklish to adjust for best performance. Moreover, with the use of the cathode-loaded driver, the driving problem is merely pushed front-ward; appreciably more than 100 volts will have to be supplied to the drivers—not taking a feedback loop into account—and it is no simpler to supply such a signal at this point than anywhere else. Also, it requires another pair of voltage drivers, and the additional cost of these brings the saving in money to very little.

The easiest and cheapest way to achieve high-fidelity performance is to build in a good safety factor. The critical driver stage is the place where a good safety factor is most desirable. A good transformer provides balance of one per cent or better, provides additional gain, and simplifies biasing. In short, it results in better performance and saves most of the headaches.

APPENDIX B

The trouble with phase inverters of the tube type is that they cannot be balanced dynamically. With two exceptions which we shall note in a moment, all phase inverters of the tube type are unbalanced in their frequency response. Those in which the second section obtains its voltage from the output of the first section are unbalanced at low frequencies because the second section obtains its input through two frequency discriminating networks, while the first section obtains its input through only one. Those in which the load is divided between plate and cathode are unbalanced at high frequencies because of differences in plate-to-ground and cathode-to-ground capacitances. The latter type, whose unbalance is preferable, suffers additionally from high heater to cathode leakage. Finally, being *RC* coupled devices, they are difficult to balance without the use of matched or precision resistors and capacitors. Those who may be skeptical of the importance of balance in *RC* coupled circuits are invited to make distortion measurements first on an amplifier in which one *RC* coupled push pull stage is unbalanced by ten per cent, and then when the stage is balanced by matching resistors. These disadvantages may not be important enough in ordinary usage to outweigh the advantage of low cost, but in an amplifier for the Golden Ears—where even the best attainable performance falls short of perfection—the additional increments of distortion are too serious to tolerate.



Cross-coupled phase inverter.

The cathode-coupled inverter does not suffer any frequency unbalance if properly used. However, being an *RC* coupled device, it does require balancing or matching of components. Moreover, the heater-cathode voltage is high—about 70 volts. This can be corrected by applying negative bias available from the bias supply, but even so the residual unbalance is inferior to that of a good transformer.

The best of the phase inverters is the new cross-coupled circuit recently developed. It has no frequency unbalance except that due to differences in capacitance between individual tubes of the same type. It is very easily balanced and, being directly-coupled, has an excellent low-frequency response. It requires few resistors and no capacitors, and the resistors are easily matched. However, it requires two twin-triodes which consume more space than a transformer, and the cost is probably as great. Its one deficiency in our application was that the gain of 30 was not enough—without an additional amplifier—to provide the high input voltage made necessary by the feedback loop. So, in the end, we returned to the transformer and a voltage amplifier as the simplest and most satisfactory over-all solution to the phase inverter problem. Nevertheless, it is the best phase inverter we have tried. In many ways superior to a transformer. The circuit is given for those who would like to try it.

(See J. N. Van Scoyoc, "A Cross Coupled Input and Phase Inverter," Engineering edition of *Radio and Television News*, Nov. 1948.)

Note: The two inputs can be used to mix two input signals. If a dual potentiometer is used, a two-wire input (as a line or a high impedance pair from remote phono) can be connected grid-to-grid, and the circuit will provide complete cancellation of any hum pickup on the line.