The New Golden-Ear Amplifier

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In Two Parts—Part 1

Combining virtual direct coupling, neutralization, two feedback loops, and a high degree of balancing, this unit is reasonably free of distortion at normal volume levels. The companion preamplifier offers several unusual features worthy of study.

AUDIO AMPLIFIER DESIGN and components have made tremendous strides in the past few years and there are several commercial amplifiers available today capable of reproduction which, for all practical purposes, is as good as it has to be for even the more critical ears and beyond the various program sources, broadcast or recorded, in over-all fidelity. The Williamson circuit, for instance, though simple, produces results which are very hard to quibble with. And yet the Golden-Ear Complex, frustrated in the absence of sheer perfection, continues to drive many of us into expending much brain energy, money and time, trying to reduce the remaining short distance to be traversed to achieve perfect reproduction. The amplifier described herein represents still another effort at producing an amplifier with the least possible distortion of all forms, and the maximum possible width of frequency response. Its band-width is limited principally by the output transformer and with the best available today runs nearly flat from 2 or 3 cps to over 100,000 cps; amplitude distortion is nearly non-existant except in the top 3 db of the power output where it is just measurable; intermodulation is a fraction of one per cent except again in the very top 3 db of the output; the transient response is almost completely flat throughout the entire audio range of 20 to 20,000 cps; the amplifier is so stable that nearly 100 per cent feedback has to be applied to drive it into oscillation and the period of oscillation when it occurs is between 20 and 40 cycles *per minute*. The power output depends on the output tubes used —a pair of 6AR6's will produce 20 watts of nearly distortion-free output, while 807's, 5881's, KT66's and the like will deliver 15 watts; with an appropriate power supply and output transformer, Ultra-Linear tetrode or Extended Class A operation may be employed to double the output.

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Design Principles

The cardinal principles of hi-fi design can be summarized in the following rules:

1) Operate the various stages under parameters producing as little distortion as possible.
2) Cancel as much as possible of what distortion is produced by balanced configuration or feedback or both.
3) Make the amplifier and indeed the whole reproducing chain as nonresonant as possible by keeping the response curve as flat as possible not only over the audio range but for three or four octaves above and below the audible range.
4) Eliminate, neutralize, or minimize all positive feedback loops which might cause oscillation, regeneration, hang-over, or other transients.

Now let us see how these principles

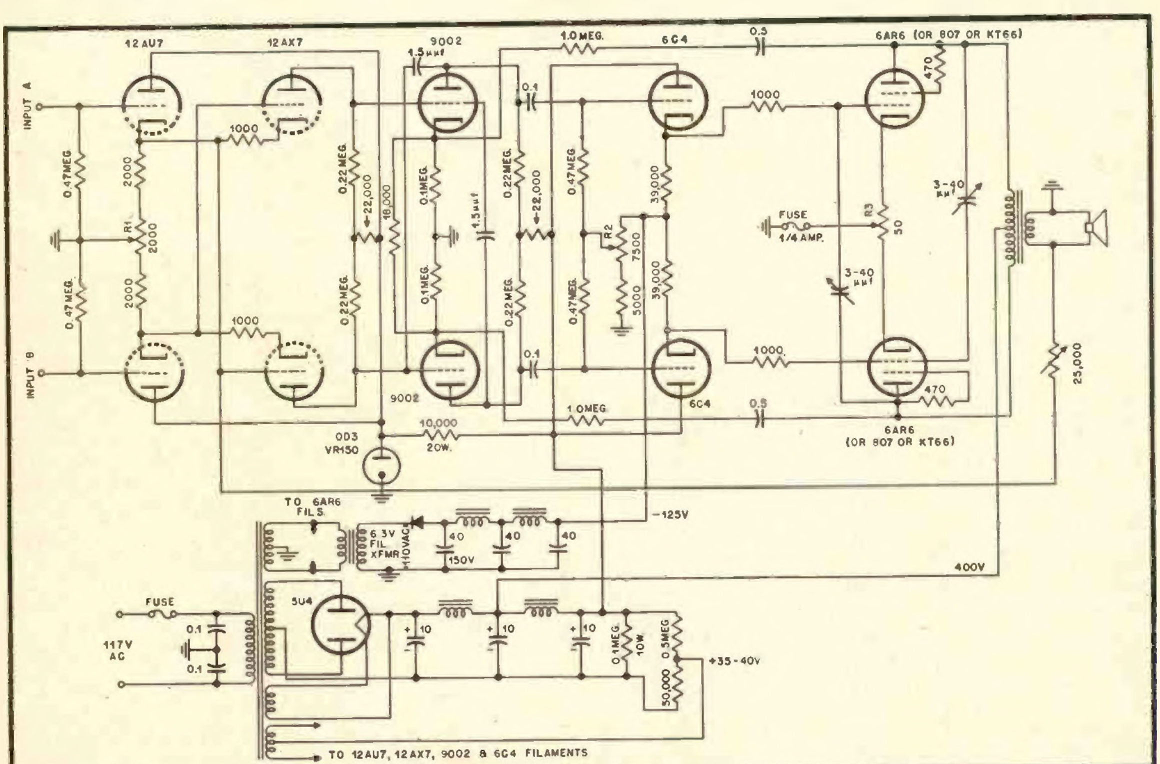

Fig. 1. Schematic of the power amplifier section of the New Golden-Ear amplifier.

are expressed in the practical amplifier diagrammed in *Fig.* 1.

At first glance the circuit resembles that of the Childs amplifier which employs the cross-coupled inverter and which contributed the excellent cathode follower driver used here; but there are several very significant differences. The design is eclectic, using elements derived from others, but in an original combination. The distinctive features are, first the means of broadening both the high- and low-frequency response; second, the high degree of balance and of distortion cancellation; third, the low degree of phase shift which permits huge amounts of inverse feedback; and finally, the minimization of positive feedback and consequent flatness of transient response.

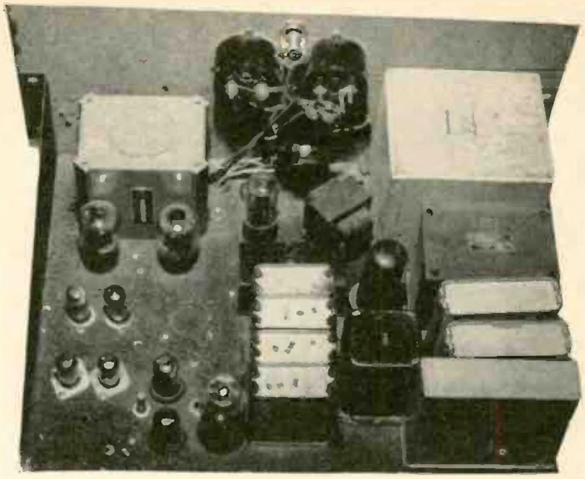

Fig. 2. Top view of the power amplifier chassis.

The Practical Circuit

The author has been much intrigued by the cross-coupled inverter ever since it was described by van Scoyoc five years ago, and called attention to it in an earlier article.[1] We have used it now in several forms not only in audio amplifiers, but in 'scope amplifiers, voltmeters, and distortion meters, and the more extensive the usage the greater the admiration for it. As far as we can see it has no faults as a phase inverter and many virtues not possessed by any other. It can be balanced both in amplitude and frequency response at least as well as the best transformer; if the output voltage is held below 50 volts or less, it is distortion-free; on the low side, its response is down to direct current, and on the high side to more than 50,000 cps; it has inherent voltage and current inverse feedback; and finally, since the input tube is a cathode follower, it presents a very light load to any input and provides a good low-frequency response with a reasonable input capacitor.

With such an excellent phase inverter at hand, and with new output transformers also available flat for an additional octave or more at each end than the best ones, the problem was to keep the response of the amplifier between inverter and output transformer comparably flat.

The direct coupling of the phase inverter immediately suggested that the direct coupling be maintained throughout the entire amplifier, for a really flat low frequency response. Those who tried direct-coupling in its heyday, 15 years ago, will remember the headaches involved. Many of these can today be eased. The cross-coupled inverter, for instance, makes a stable push-pull d.c. amplifier of 3 or 4 stages quite practical. Unfortunately, there were two serious deterrents. One was the fact that for the highest output with lowest distortion we wanted to use big triodes with fixed bias. This is not impossible to achieve with direct coupling but it is difficult. Another was that we would require a power supply (or two in series) delivering 800 volts or more.

Actually, the very difficulty self suggested the solution. Unless a driving transformer is used, the only practical high-fidelity method of coupling fixed-bias power triodes to an R-C coupled amplifier is through a cathode follower which may be direct coupled to the power tubes. But a cathode follower has a very high input resistance. Therefore, a moderate sized coupling capacitor would produce a time constant which would extend the frequency response down to 1 or 2 cps, or even lower. If then, the amplifier were designed in the form of *two* direct-coupled sections, one containing the phase inverter and voltage amplifiers, and the other the cathode follower directly coupled to the output tubes, and if we then joined these two sections with a capacitor at the cathode follower input, we would have an amplifier which, for all practical *audio* purposes, is as good in low-frequency response as a direct-coupled amplifier but, being isolated so far as direct current is concerned into two sections, would require only a single 400-volt power supply and would permit the use of fixed bias on the output tubes; it would, moreover, be much more stable than a d.c. amplifier.

The practical amplifier fully realized the expectations and produced no construction or adjustment headaches whatever; indeed, it was, if anything, easier to adjust and keep in adjustment than any other amplifier we had ever used. It is, to be sure, somewhat extravagant in the use of tubes, but the direct coupling holds down the number of component parts to a number no greater than that in much simpler amplifiers, and the performance is quite superior.

[1] Joseph Marshall, "For golden ears only," Audio Engineering, April 1950.

Fig. 3. Underside of the power amplifier chassis.

The Amplifier Circuit

The 12AU7 and 12AX7 comprise the cross-coupled inverter. This is direct coupled to a pair of 9002's, as driver amplifiers. Miniature tubes were used up to the power stage to hold down tube capacitance. Either a 12AU7 or a 12AX7 could be used instead of the 9002's. The former would yield a somewhat higher output and be more suitable for use with 6B4's in the output stage; the latter would yield more gain and permit more feedback or obviate the need for additional voltage amplification. The 9002's, however, are excellent tubes for the purpose and provide a gain of about 17—as against 12 for the 12AU7—and a practically undistorted output of 60 volts per side.

The 9002's are coupled to the 6C4 cathode followers (one 12AU7 would serve identically) through a 0.1 µf capacitor. Since the effective input resistance of the cathode follower is ten times the grid resistor, or in this case, 5 megohms, the time constant is 0.5

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which brings the response down to about 2 cps before phase shift sets in. The capacitor would be made larger but this value fits in well with the values of the feedback loop, as we shall see.

To maintain the best possible balance, all the resistors in the two opposite sides are matched to about 1 per cent. It is not necessary to use precision resistors. Ordinary resistors can be matched on a bridge or even an ohmmeter. Out of any five of a given value, two can usually be found which match to 2 per cent or better. To insure against changes in value, be careful not to overheat the resistors when wiring them in place. If a large pair of pliers grips the lead between the soldering point and the resistor body, most of the excess heat will be dissipated in the pliers. Even inexpensive carbon resistors, if not overheated, will maintain their value to 1 per cent for years. The remaining unbalance of the whole amplifier can later be balanced to one per cent or better by adjusting R_1.

The Driver and Output Stages

The cathode follower, direct-coupled to the power tubes, is the circuit developed by Ulric Childs and works very well indeed. In fact, it is the only method the author has used which is entirely foolproof and adaptable to different types of output tubes. The cathode and grid resistors of the follower are matched. Bias to the power tubes is adjusted with the pot R_2, and the output tubes are balanced by the pot in the cathode legs, R_3. Any of the big triodes (or tetrodes as triodes) except possibly 300A's and the 6AS7 can be used in this circuit providing only that the output transformer and power supply are suitable. The 6AR6's are the optimum tubes delivering 20 watts with only nominal distortion. The drivers are driven a trifle hard to supply the 60-plus volts needed by 6B4's but they can manage it. 807's, KT66's and 5881's will provide 15 watts with very low distortion and their lower driving requirements improve the over-all gain by a factor of between 50 and 100 per cent. Using a set of adapter sockets, the author has tried all these tubes (except the 6AS7 and 300A) in the circuit and all work comparably well, although to repeat, the 6AR6 appears to be the optimum tube.

Having achieved a more than satisfactory low-frequency response, the next problem was to improve the high-frequency response. The cross-coupled inverter and the cathode follower driver, offered no problems. The first section of the inverter is a cathode follower and the second section is fed by the very low impedance of the cathode follower; moreover, the second section has considerable inverse feedback of both the current and voltage type. The combination therefore has an extremely good high-frequency response. The 9002's and the output tubes, however, were a different matter. Ordinarily, the high-frequency output of triodes begins to fall off at 15,000 cps or even less because of the Miller effect. The first measure was to neutralize these two stages. This was done with fixed 1.5 μμf capacitors with the 9002's, and with 3–40 μμf ceramic trimmers in the case of the output tubes. Neutralization corrects for the Miller effect, all but eliminating it, and extends the high-frequency response considerably beyond 20,000 cps. However, it doubles the output capacitance. This was the reason for using miniatures. The output capacitance of 9002's is about 1 μμf, as against 3 μμf for each section of a 6SN7. Thus even after neutralization, the output capacitance of the miniatures, and therefore the high-frequency response, is better than with the larger tubes unneutralized.

No adjustment of the neutralization for the 9002's is necessary. The power tubes, fed from a separate filament winding, are neutralized by opening the filament circuit and adjusting the neutralizing capacitor for minimum output with a steady tone applied to the amplifier input.

Neutralization brought the high-frequency response to about 50,000 cps but this was still not as good as desired. Therefore, an inner feedback network was introduced from the plates of the output tubes to the cathodes of the 9002's. Since the cathode resistor is 0.1 megohm, it was easy to keep phase shift down. For 10 per cent feedback, 1.0-meg series feedback resistors could be used. With a 0.5 μf bathtub capacitor, the time constant was 0.5, or the same as that of the coupling to the cathode follower. Thus, in effect, the two capacitors neutralize each other and extend the flat response below 2 cps. This loop provides about 16 db of feedback which is sufficient to extend the high-frequency response to nearly 100,000 cps. The amplifier response from input to plates of the output tubes is now flat from 2 cps to nearly 100,000 cps.

This feedback network includes the two stages responsible for most of the distortion—the drivers and the output tubes; and therefore reduces the distortion by a factor of six. Since the feedback is balanced (the feedback resistors are matched) it also produces dynamic and frequency balance.

With so little phase shift in the amplifier proper, it is obvious that the feedback which can be applied from the transformer secondary to the input is limited only by the phase shift of the output transformer and the sacrifice in gain which can be tolerated. Although balanced feedback could be used, the unbalanced, single-ended type, suffices to perform the two jobs which need to be done—first, to compensate for any irregularities and slopes in output transformer response, and second, to provide additional cancellation of distortion. We have applied as much as 40 db of feedback, in addition to the 16 db of the inner loop, before instability resulted. In practice, however, about 18 to 20 db is more than sufficient to do the job and still leave sufficient gain to produce full output with an input signal of 10 volts, easily provided by the triode amplifier of a tuner. With a total feedback factor, so far as the drivers and output tubes are concerned, of between 30 and 50, depending on the feedback of the main loop, it is no wonder that distortion is reduced to an insignificant minimum even at full output.

One other factor remained for solution before such stability could be achieved. The flat frequency response was one item on the way to a good transient response. There remained the minimization of feedback loops. These loops, of course, exist in every amplifier using a common power supply and triode tubes. Neutralization eliminates the feedback loops through tube capacitance. The rest was a matter of adequate decoupling. Although the amplifier has five stages, two of these are cathode followers and produce no phase shift. Therefore, the amplifier can be considered a three-stage device. Nevertheless, decoupling down to 2 cps or less presented a problem. In this amplifier, as in the original Golden Ear amplifier, it was solved by the use of a VR tube in the input stage. The VR tube is the best of all decoupling devices. After all an element which will smooth the long period variations of a d.c. supply, has a very low impedance to a.c. even of periods as low as 1 or 2 cps. The VR tube simultaneously performs two other functions: as an excellent hum filter, it delivers very pure d.c. to the amplifier input stages; it also stabilizes this stage by maintaining a constant voltage. Since the whole balance of the amplifier is dependent on the stability of this first stage, an extremely stable d.c. amplifier is achieved.

Actually, the amplifier alone can be driven into oscillation only by applying something between 90 and 100 per cent feedback—in other words, oscillation sets it just before the input signal is completely cancelled out. Indeed, even when the preamplifier, with four additional stages, was fed from the same power supply, the stability was still remarkable, although the transient response deteriorated considerably.

It will be noted that the over-all feedback network, being direct coupled, will unbalance the input stage since the feedback resistor and voice coil appear in parallel with the cathode resistor. Therefore, after feedback is adjusted, the balance control should be readjusted. D.c. balance may be measured by connecting a VTVM from plate to plate of the 9002's and adjusting for zero voltage. Better over-all balance, however, is obtained by using the following method: after balancing the output tubes with their cathode balancing potentiometer, connect the "off" grid of the inverter to the signal grid, feed in a constant tone signal and adjust the balance control for a null in the output. The cross-coupled inverter is a differential amplifier and if the same signal is fed to both grids and the amplifier is fully balanced, complete cancellation occurs. (This fact makes the circuit highly useful for distortion measurement and phase angle measurement and indeed with slight modifications this amplifier could serve as a distortion measuring amplifier.) At any rate in this way the whole amplifier can be balanced almost perfectly from input to output.

A few details remain. Since failure of the output tube bias supply would apply a high positive voltage to the grids of the output tubes with almost inevitable damage to them, a ¼-amp fuse is placed in series with the output cathodes and ground. A rise of plate current such as would occur with a bias failure, will blow the fuse, opening the plate-supply circuit and protecting the tubes until repairs are made.

The cathodes of the 9002's and the 6C4's are 50 volts or more above ground. The center-tap of the filament winding feeding these and the cross-coupled inverter, is therefore returned to a positive voltage of around 40 volts, provided by a high-resistance divider across the power supply. Actually this makes little if any discernible difference in the hum level which is completely inaudible, even with ear at the woofers and even when 6B4's are used. However, it is good insurance against heater-cathode leakage and breakdown.

The bias supply should deliver −125 volts if 6AR6's or 6B4's are used. The same value will do for other tubes, but as little as 105 will suffice for 807's, KT66's and the like. The author used a 150-volt power transformer, of the type used in TV boosters, but a filament transformer used backward, as diagrammed, will serve.

It will be seen that all five rules of design are faithfully followed: (1) distortion is held down by operating high-power tubes at a fraction of their maximum output, and the voltage amplifiers well below their maximum output; (2) nearly perfect balance and a huge amount of feedback in two loops results in a high degree of cancellation of what distortion is produced; (3) by virtual direct coupling, neutralization, and feedback the amplifier is made non-resonant from nearly d.c. to more than 200,000 cps, and finally, by neutralization and effective de-coupling, the amplifier is made extremely "stiff" and resistant to oscillation, regeneration, or the formation of various transients.

Performance

It is easy to be extravagant about one's own brain child and hand work, particularly when instrumentation bears out subjective impressions. As Æ has pointed out editorially, audio design is approaching the stage where instruments of distinctive character, rather than mere reproducers, are being produced. The new Golden Ear amplifier has a distinctive character. It is very clean, particularly in the bass—much cleaner than any previous amplifier used by the author. This is partially because of the extended bass response but perhaps more because of the really extraordinary transient response which reduces the production of ringing and other forms of transients to a point of mere academic rather than practical import, and therefore greatly improves the definition of the reproduced sound. The measurable aberrations over the normal operating range of 6 milliwatts to 10 or 12 watts are very small—too small for accurate measurement on the author's rather crude home-made instruments—and too small for discernment by ear. No doubt time will provide circuit and components improvements which offer hope of further perfection, but for the moment, the Golden-Ear Complex is satisfied more completely than ever before, and there is hope that this satisfaction will last long enough to channel brains and energy into other, less well-realized channels—including those of making an adequate living.