What it will and won't do in audio amplifiers

GETTING FEEDBACK STRAIGHT

By NORMAN H. CROWHURST*

IT'S surprising how often feedback is expected to do something it can't possibly do. For example, I recently met an enthusiast with an amplifier that put out about 48 watts comfortably and then ran into severe distortion. He was frantically trying to use feedback to make the amplifier deliver what he wanted—a full 50 watts. He couldn't understand why using enough feedback wouldn't push the output up just this little bit!

Most material on feedback has been based on a theoretical treatment using the algebra of feedback theory. This algebra cannot take into account everything at once—if it did it would become so involved that no ordinary person could possibly understand it. We use one piece of algebra to tell us the effect of feedback on the gain of the amplifier, then we go over the algebra again and find out what its effect will be on the amplifier's impedances, frequency response and distortion. Each investigation uses a separate application of the same math. But this does not prove that the amplifier will do all of these things in equal manner *at the same time.* It depends on just what form distortion (and other things feedback is expected to correct) may take.

Frequency response

Some presentations on feedback have suggested (with deceptive simplicity) that as feedback tends to smooth out fluctuation in gain it must flatten the frequency response—on the basis that deviation from flat in frequency response is merely deviation in the gain of the amplifier at different frequencies. Some readers are doubtlessly aware that this oversimplification of theory can often be the reverse of what really happens. Due to phase shifts in the amplifier, frequency response can often be *accentuated* by feedback, rather than flattened.

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Let's take feedback, step by step, starting from a single stage and using practical examples to see how it can change the response in each case. Fig. 1 shows some examples of single-stage feedback: simple cathode circuit current feedback, voltage feedback from plate to grid on the same stage and the very useful Ultra-Linear circuit where feedback from plate to screen is provided by taps on the output transformer.

With current feedback in a cathode circuit the feedback is effective right down to dc at the low end. At the high end the only modifying factor is the stray capacitance of the tube and its associated circuit. This eventually deteriorates the tube's gain and hence also the feedback. So current feedback in the cathode does not modify the low-frequency response at all, and the high-frequency response is modified according to the distribution of tube capacitances.

In plate-to-grid feedback—shown in Fig. 1-b—a blocking capacitor between the plate and grid keeps dc from feeding back to the grid and there is stray capacitance to ground. The blocking capacitor introduces a rolloff at the low end in the feedback circuit while stray capacitance to ground introduces a rolloff at the high end.

The low-end rolloff causes feedback to fall off and stage gain to rise to its no-feedback value if no other rolloff is introduced into the circuit to compensate for this. The high-end rolloff is the same as that produced without feedback, but feedback extends the frequency range by the same factor as it reduces gain. Thus, if feedback reduces gain by 6 db, frequency range at the high end is extended by a ratio of 2 to 1.

In the Ultra-Linear circuit (Fig. 1-c) the signal fed back from plate to screen is coupled by the output transformer. At the low end of the frequency response the transformer introduces a reactance shunting the plate circuit, due to its primary inductance. When the tube is operating as a straight pentode, without coupling to the screen, its source resistance is much higher than with Ultra-Linear feedback introduced. This means that adding feedback extends the low-frequency response due to the reduced source impedance the primary inductance shunts.

At the high end of the frequency response the transformer introduces a leakage inductance between plate and screen so at some point the amount fed back to the screen begins to fall off. This causes feedback to begin to fall off somewhere in the higher frequencies. However, this does not show up in practice because there is a larger leakage inductance between the whole primary and other windings on the transformer than between the part of the primary feeding the plate and the part coupled to the screen. So the other rolloffs in the amplifier circuit go into effect before the reduction in feedback from plate to screen starts to make itself felt.

Two-stage feedback

Now let's start on feedback over two stages. Take the circuit of Fig. 2, which represents a driver and output stage with feedback from the output stage plates to the driver cathodes. Considering the round-the-loop effect, here we have the coupling capacitors from driver plates to output grids, and blocking capacitors from the output plates to the driver cathodes, which contribute to low-frequency response. At the high-frequency end we have stray capacitances which can be regarded as shunting the driver and output plates, respectively.

Consider the low-frequency response. A first study might suggest that low-end response could be made absolutely flat. By making the time constant of the interstage coupling between driver and output equal to the time constant of the feedback arrangement, the block-

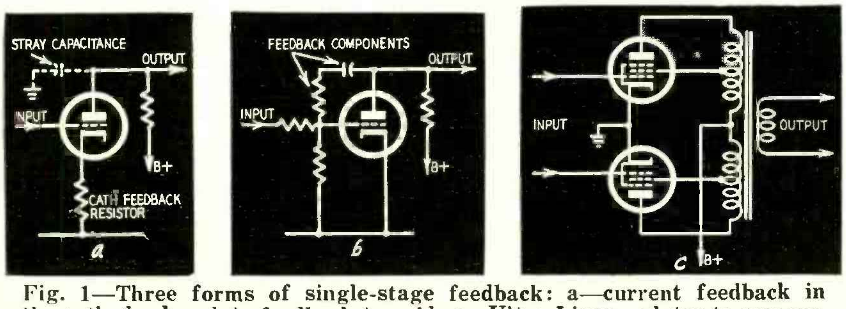

Fig. 1—Three forms of single-stage feedback: a—current feedback in the cathode; b—plate feedback to grid; c—Ultra-Linear, plates to screens.

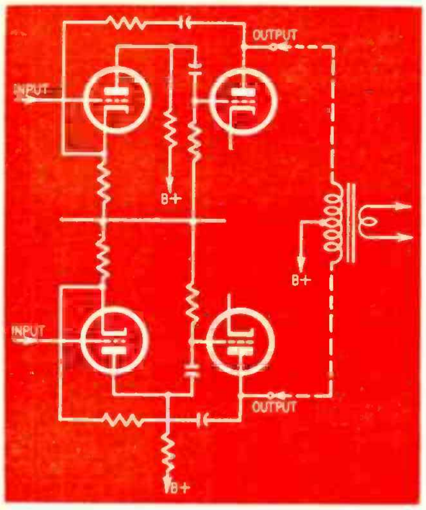

Fig. 2—A form of feedback using two reactances in feedback loop at each end of audio response. (Output transformer not part of feedback circuit.)

ing capacitor in the feedback loop would cause a rise in frequency response as feedback falls off, while the coupling capacitor between stages causes a similar rolloff in the forward response. The two having identical frequency characteristics should result in a flat response. But this assumption ignores one fact.

What happens with phase when there are two or more coupling elements in the feedback loop? If we use two identical time constants, as suggested, then more than 6 db of loop feedback starts to show a peak in the loop response at the low end, due to phase interaction. But 12 db of feedback shows a peak of about 1.25 db; 18-db feedback shows a peak of about 3.6 db; 24-db feedback shows a peak of about 6.3 db, and every successive 6 db of feedback shows approximately 3 db more peak.

This effect is independent of how the coupling arrangements are distributed around the loop. If one coupling element is in the feedback arrangement, the inverse of the response due to feedback coupling must be added to this peaking effect. For example, with 6-db feedback there is a slight peak of a little more than 2 db (curve D, Fig. 3). With 12-db feedback the peak rises to about 7 db (curve F, Fig. 3) and so on, due to the additional boost given by the coupling element in the feedback part of the arrangement.

At the high-frequency end of the response there is no loss in the feedback part of the arrangement. Losses due to both groups of stray capacitance from plate to ground affect the forward response. The only place where loss would affect feedback is at the cathode of the driver stage, where there is no loss worth mentioning. Therefore, assuming the time constant of the stray capacitance from plate to ground is the same for each circuit, the amount of peaking introduced by different amounts of feedback in the loop response would apply without the boost effect due to part of the loss being in the feedback path. See Fig. 4.

In this circuit (Fig. 2) the feedback does not include the output transformer, so any frequency response contributed by the output transformer is added to the response of the feedback measuring overall response.

Output feedback

The next question is: What happens when we apply feedback from the output transformer secondary? So far we have discussed circuits where the factors contributing to rolloff at the low and high ends are easily separable. But when we consider an output transformer they are a little more tied up and perhaps not so easy to recognize.

In the output transformers of conventional push-pull amplifiers, consideration of the low-frequency response, since it is caused by just the primary inductance shunting the plate resistance of the output stage, is simple enough. Hence, for low frequencies, performance is the same whether connected from primary or secondary of the output stage. In fact, by connecting from the secondary, the blocking capacitor can be eliminated and thus the possibility of achieving good low-frequency response is somewhat improved.

At the high-frequency end the output transformer contributes two reactances. There is the plate-to-ground capacitance, to which the output transformer contributes primary-winding capacitance, and the leakage inductance between primary and secondary. Since both of these contribute to high-frequency rolloff, by feeding from the secondary of the output transformer back to the grid of the output stage, we have two reactances contributing to high-frequency rolloff.

This means that peaking starts immediately there is more than a certain amount of feedback, according to the relationship between the circuit constants. The circuit shown in Fig. 5 never becomes unstable, no matter how much feedback we use, but we do run into peaking similar to that produced by the two-stage circuit of Fig. 2.

If we attempt to feed back over more of the circuit than shown in Fig. 5, from the output winding of the

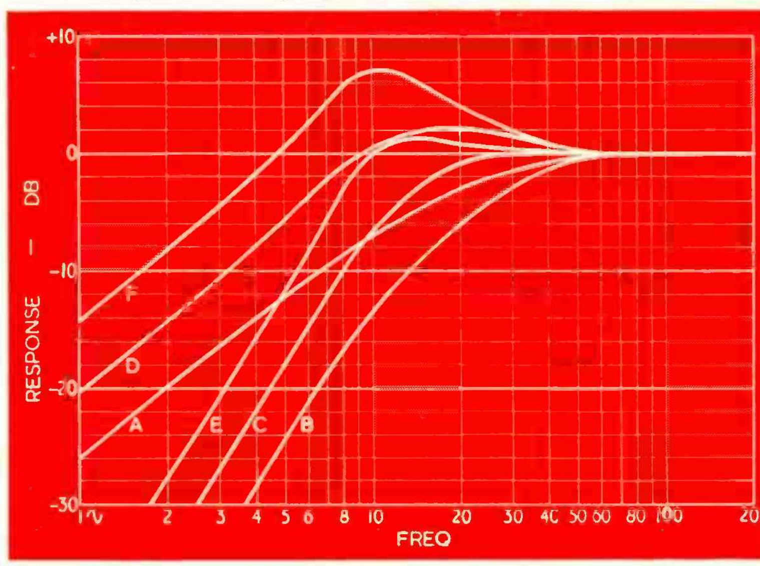

Fig. 3—Sample low-end response curves for Fig. 2. A—Original rolloff of each time constant; response of amplifier without feedback; B—open loop response; C—round-the-loop response with 6-db feedback; D—amplifier response with 6-db feedback (difference between curves A and B); E—round-the-loop response with 12-db feedback; F—amplifier response with 12-db feedback (difference between curves A and E).

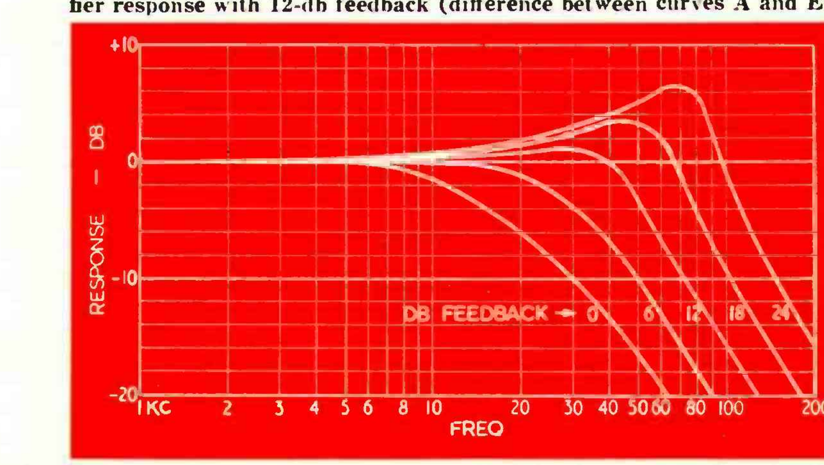

Fig. 4—Sample high-end response curves for Fig. 2, assuming loss due to stray capacitance gives identical rolloff with 3-db point at 20 kc for each stage.

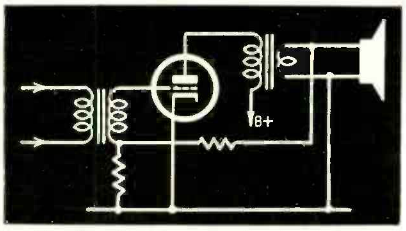

Fig. 5—Feedback over single stage with output transformer.

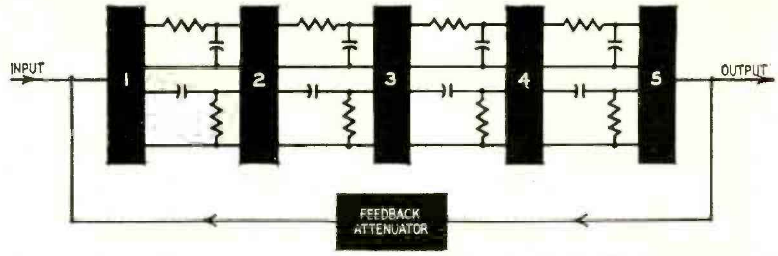

Fig. 6—Basic factors in long-loop-feedback amplifier. Numbered boxes indicate amplifier stages or phase inverters without frequency-discriminating components.

transformer, it becomes possible for feedback to push the peaking up to the point where oscillation begins. This is where *real* care is needed in the design.

The method of tackling this is to arrange the time constants contributing to rolloff response at both ends of the frequency spectrum so they are as widely divergent as possible. The best possibility of increasing the amount of feedback is to make one of the time constants effect a rolloff much closer to the passband of the amplifier than all the other time constants.

For example, if four reactances contribute to an ultimate rolloff, at each end of the response, which is a common arrangement, then by having one time constant at 100 times nearer the amplifier's passband than the remaining three, 24 db of feedback can be used before peaking begins to show up at all. And almost 40 db of feedback can be used before the amplifier becomes unstable. To achieve this range with this particular configuration, illustrated in basic form by Fig. 6, the rolloff point at the low end for one of the networks could be 100 cycles while the remaining three should be moved down to 1 cycle. Similarly, at the high end, one rolloff could be effective at say 10 kc, while the remaining three should be moved up to 1 mc.

To arrive at what the ultimate response will be, suppose we use 24-db feedback. The first acting rolloff is extended by approximately the ratio represented by 24-db feedback. This corresponds with a ratio of 16 to 1. So the 100-cycle rolloff is pushed down to about 6 cycles, and the 10-kc rolloff is pushed up to about 160 kc, both of which are well beyond the limits generally recognized as necessary in an audio amplifier.

Readjusting our figures to finish up with an amplifier that is just about right for audio, we could make the rolloff points for the low end 320 cycles with 3.2 cycles for the remaining three which leaves us with a 20-cycle rolloff for the low end, and 1,250 cycles with the three additional rolloffs at 125 kc gives us an ultimate rolloff at 20 kc.

Such a combination provides a satisfactory feedback amplifier for use on audio, but the trend in most feedback-amplifier designs is to have a much larger margin, and the figures first given are nearer to those used in actual design. Once these figures are chosen, we have to stick with them to get successful performance.

This explains why it is necessary to insure that some stages respond out to 1 mc to get satisfactory performance out of the amplifier. A while ago someone asked why Joseph Marshall added neutralizing to some of the stages in his Golden Ear amplifier (RADIO-ELECTRONICS, April, 1954). From this discussion we see that there can be a good reason for doing this, although it might appear to be going to extreme limits, until we realize the fundamentals necessary to achieve stability in a feedback amplifier.

So much for frequency response and stability problems. The statements made can be substantiated by the necessary mathematics and, if any readers are doubtful about them or want further detailed information for design purposes, they are referred to my article, "A New Approach to Negative Feedback Design" *(Audio Engineering*, May, 1953). But here we want to get on to the question of sorting out some of the things that the mathematics seem to have left open.

Distortion

Let's revert to the question introduced at the beginning of the article. Can feedback actually extend the output of an amplifier? We could go into a lot of theory on this but probably the best way to illustrate the matter is to take some typical waveforms from amplifiers we want to improve.

Fig. 7 shows the output waveform at two different levels for an amplifier where the overloading effect is not too sudden—it runs into a gradual curvature. This could be, for example, an amplifier employing power drive, so the output tubes are driven into positive grid current, and there is power in the driver stage to supply the necessary grid current. This type amplifier shows a rounding of the top of the waveform before it begins to flatten. And this rounding can introduce considerable distortion before actual clipping begins.

In this kind of amplifier, feedback can help. The feedback signal can make the driver give a slightly more peaky waveform to offset the roundings, and the resultant wave comes closer to the sinusoidal. This is shown in Fig. 8.

Now look at Fig. 9, which shows sample waveforms from an amplifier at two different levels, where clipping occurs quite suddenly. This might be a push-pull amplifier fed by a nonpower-driver stage, so commencement of grid current at the output tubes causes very abrupt clipping. Since the driver cannot supply any power to the grids of the output tubes, nothing feedback can do will ever overcome the clipping. If the driver delivers a small amount of power that starts to give a little positive grid current in the output tube, rounding the corners of the clipped waves slightly, feedback will be able to accelerate the rate at which this power is provided. So applying feedback makes the output waveform even more squarely clipped than it is without feedback.

In other words, feedback stands a chance of improving the waveform of an amplifier below maximum output but, once clipping starts, feedback tends to make the clipping sharper rather than to eliminate it.

Another effect of feedback on the overall distortion of an amplifier seems to get overlooked. At lower levels feedback does reduce the *total* harmonic content of an amplifier. But it also *changes* the harmonic present, and this change is not always an improvement. This is best illustrated with some simple figures.

Suppose we have an amplifier that introduces a distortion of 5% third harmonic. This could be due to too high a value for the plate load resistor for a pentode in an early stage and the percentage might be almost independent of operating level—5% third harmonic would appear on signals of all levels. Now suppose this amplifier has its gain increased, to make it possible to apply a total overall feedback of 40 db. This sounds quite good. We should be able to knock the 5% third harmonic down to .05% third harmonic and probably we can.

But we have overlooked something which is illustrated in Fig. 10. To reduce the third harmonic from 5% to .05% the input to the amplifier consists of a 100% original input signal, offset against a 99% fed-back signal. To offset the 5% third harmonic that the amplifier is going to introduce, the final input signal, made up by the 100% minus the 99%, must contain a third-harmonic component almost 5% in value but in opposite phase to the 5% the amplifier introduces. This 5% of third harmonic goes through the amplifier as does the original 100% fundamental. Besides offsetting the distortion produced by the fundamental, it produces some distortion of its own, to the extent of 5% of 5%, at a harmonic which is the third of the third. This produces 0.25% of ninth harmonic. So what our feedback

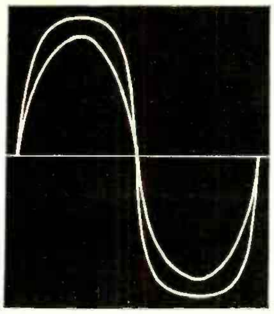

Fig. 7—Amplifier output waveform at two levels, where distortion sets in gradually.

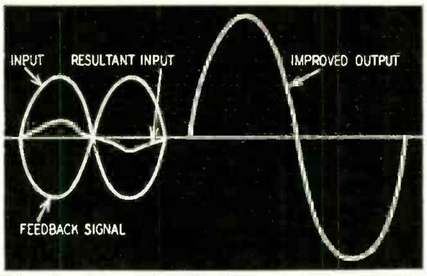

Fig. 8—How feedback can improve the output in Fig. 7.

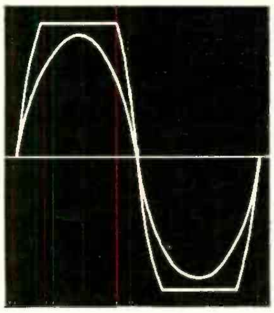

Fig. 9—Amplifier waveform where distortion appears suddenly as clipping. Feedback cannot help appreciably.

has done is to reduce the original 5% third harmonic to .05% and at the same time gives us a 0.25% ninth harmonic we never had before.

Measuring this on a distortion analyzer, it will look as if the feedback has produced an improvement, not quite as much as we calculated, but quite a good reduction and so we are happy. But if we *listen* to the amplifier, it may not sound as much better as we expected, because 0.25% *ninth* harmonic can be quite noticeable.

More than this, we have only considered the effects of feedback on a single sine wave. When we come to consider intermodulation products, we find them multiplying up out of all proportion, and a great variety of intermodulation products is introduced by an amplifier designed in this manner. The resulting reproduction sounds extremely muddy, although the figures might appear quite presentable—an overall distortion figure of 0.25% is not generally considered to be too bad.

You can't eat your cake . . .

Before leaving the question of distortion let's look at one more aspect. When we apply feedback, sometimes we achieve more than one purpose. We can make feedback do two or three things at the same time, but sometimes we use up the feedback on one purpose so that it is not available for others. This can happen, for example, where feedback is used to change an impedance.

Suppose we use a regular type of feedback amplifier to provide a lower source impedance than its nonfeedback cousin. Next we apply an output load equal to the source impedance.

We calculate the amplifier performance on the basis of either no load impedance or the optimum load impedance for the output tubes used. So it is not really legitimate to change just the load impedance and expect the same performance from the feedback amplifier. To find out what really happens we should recalculate the performance of the amplifier on the basis of the revised load impedance. What we will probably find is that the new load impedance allows much smaller output before distortion starts to be really serious and that feedback has become almost nonexistent, due to the change in loading impedance reducing the gain of the output stage.

Just take some figures to illustrate. Suppose that the optimum load of a certain output stage is 8,000 ohms and its source resistance is 3,000 ohms. By applying 26 db of feedback, the source resistance can be reduced from 3,000 ohms to 150 ohms. Now suppose we load the amplifier with a 150-ohm load (by the same matching transformer used for the 8,000-ohm load).

Let's take the feedback off for a moment and see what happens by changing the load in this condition. When we take the 8,000-ohm load off, the gain rises, due to an open-circuit condition, in the ratio of 11/8. Then, when the 150-ohm load is connected in place of it, gain is reduced in the ratio of 150/8,150. The net result, is reduced gain due to the change of load, by a factor of 1/40.

With the 8,000-ohm load the feedback was designed to be 26 db, which is a ratio of 20/1. As the gain has already been knocked down by a ratio of 40/1, the feedback factor will not be only 0.5, instead of 20. The amount of feedback resulting from 0.5 fed-back signal injected in series with the input is only 3.5 db.

This can do little toward reducing distortion. To be precise, it will reduce distortion by a factor of ⅔. If connecting a 150-ohm load to the output of this stage produces a distortion of 20%, which is quite a normal figure for such low loading, feedback reduces this only to 13.33%, which is still a very high distortion figure.

However, the amplifier *will* have an apparent source impedance of 150 ohms, which is what we have used the feedback up for. All of which reminds us of the old proverb about eating one's cake and having it too.

Hum and noise reduction

Another thing feedback is used for is to reduce amplifier hum and noise. In other words, to clean up any unwanted sounds not present in the input.

Many users have applied feedback with this object in view, only to be disappointed in finding either that it has had no effect whatever or that it has had the reverse effect. Let's just see how this can be.

First, let's take hum. One point not to be overlooked is: when adding feedback to an amplifier that must give full output for a specified input, more gain is necessary, so adding feedback leaves us with the same gain we had originally. Generally speaking, hum gets induced in the earlier stages of an amplifier so, if we're going to apply 20-db feedback, we need 20 db more gain in the first place, and the hum will get 20 db more amplification before feedback is applied. Application of feedback then knocks the hum back to where it started from.

This is assuming that the hum is injected somewhere within the feedback loop. If however, as sometimes happens, the hum creeps in outside of the feedback loop, it is possible for the addition of feedback actually to *increase* hum instead of reducing it.

Noise in feedback amplifiers actually tends to be higher, other things being equal, than in nonfeedback amplifiers. The reason for this is fairly easy to see.

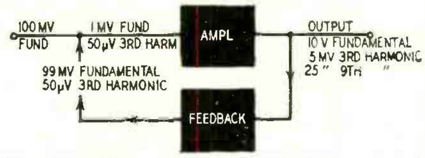

Fig. 10—How feedback affects harmonic distortion.

Suppose noise at the input to a nonfeedback amplifier is equivalent to 10 μv at the grid of the first stage, which is intended to accept an input level of 10 mv. If 20 db of feedback is added to the amplifier, it will need 20 db more gain, and hence should be able to load with only 1 mv on the first stage grid. But this grid will still have a noise level of 10 μv. If the feedback is successful in reducing the noise level by the complete amount of feedback added, then this reduces the effective noise back to its original 60-db discrimination. But this depends on every element in the noise signal being fed back completely out of phase with the original noise signal.

The lower component frequencies in noise may be successfully reduced by the 20 db in this way but, at the upper end of the response, where the random happenings that constitute noise are of shorter duration, feedback cannot keep pace with the changes and hence fails to make a reduction of the full 20 db.

Therefore, the noise level is higher in the feedback amplifier and it tends to concentrate in the upper frequencies.

Also—if due care has not been paid to eliminating the peaking effect mentioned earlier—the noise will definitely be colored by peaks at both ends of the frequency response, resulting in the familiar hissy, boomy background common with amplifiers using a large amount of feedback. This is quite independent of the fact that frequency response throughout the audio range may be quite flat.

Does multi-loop help?

A final question concerns the relation between single-loop and multi-loop feedback, in all these points of discussion. In an earlier article, I called attention to some of the deficiencies of feeding back over the whole amplifier ("Why Feed Back So Far?," RADIO-ELECTRONICS, September, 1953).

The use of multi-loop feedback does overcome some of these deficiencies. The short-loop feedback, toward the output end of an amplifier, stabilizes that part of the amplifier and usually extends frequency response beyond the audio range to give a satisfactory margin for application of longer-loop feedback. Also the short-loop feedback, over a section of the amplifier operating at higher level, will not aggravate hum or noise troubles in the same way as the equivalent amount of feedback applied in an overall loop would.

It is advantageous to apply as much feedback as possible over a shorter loop and minimize the long-loop feedback, if possible, avoiding any feedback right back to the input stage at all. It is better to take the feedback to a stage immediately following the input stage, so the first stage operates at maximum gain and gets the signal level above the inherent noise of tubes and other things, before we introduce any feedback.

This last remark applies especially to high-gain amplifiers or preamps which operate from low level inputs. Amplifiers designed to operate from high-level inputs are quite satisfactory with overall feedback, provided precautions are taken to minimize the possibility of conditional stability. END

Adding a simple guide to your turntable assures safe handling of delicate pickups

The Seeing-Eye Pickup

By ALBERT H. TAYLOR

MANY of us prefer manual changing for best reproduction with modern pickups but worry every time we try to plant that delicate, invisible point exactly on the edge of the record. With shaky hands or imperfect vision, the task becomes impossible. My father, at nearly 80, almost gave up his records after breaking a diamond. Our cure, which costs very little and can be adapted to any pickup and turntable, is to press the pickup against a guide while lowering it.

In the photograph guides have been fitted to a Western Electric 300-A reproducer panel. The original WE 5-A arm with 9-A head plays all old-style records with 2.5-mil tip radius. Its stand (just over the word OLD) has been relocated to guide the pickup onto the edge of 16-inch transcriptions. For 12-inch 2.5-mil records, the wooden gauge at the lower left marked OLD is slid to the right while bearing against the front cabinet wall, until it strikes the adjustable stop. Then it is locked in place with the wing nut. With the user's forearm resting on the edge of the cabinet and the pickup pressed against the guide arm, even shaky hands can set the point down gently in just the right place. (The panel is not in the cabinet in this picture.)

For 10-inch 2.5-mil records, wire extension A is swung into position against the brad stop B and the pickup pressed against its end in lowering.

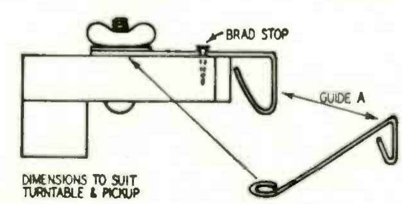

Fig. 1—Details of the guide for the Pickering arm.

The point of descent on 10-inch records is adjusted by bending A after the stop has been set for 12-inch records.

Of course I would need only another 9-A plug-in head with 1-mil diamond to play LP records with the same pickup and guide. I use a Pickering D-140-S cartridge in a Gray 108-C arm instead to avoid any chance of dropping heads and for the added safety of the viscous-damped arm.

The LP guide slides along the edge of a raised plate, hits adjustable stops at either end for 10- or 12-inch records, and is clamped by a wing nut (under the arm) which is not visible in the photo. I have no 7-inch (45-rpm) records, but for these I could easily add a mark or detent to fix an intermediate position. A further refinement might be a continuous cuing scale for setting the pickup on the record at any predetermined point—on the narrow silent bands separating different selections on some LP records. A mirror helps to observe the point in cleaning it or setting the stops. Of course either pickup is lifted over its guide to set it onto its stand, and only one would be used at a time, not both as shown.

Note that once the stops are set and guide A bent correctly, a blind person can shift the guides and play standard record sizes without difficulty. The viscous-damped arm is ideal for guided pickups. I simply adjust it to fall 1 inch per second, swing it against the guide and let go. Children could use it safely. If I could find a turnover cartridge for it, I would use it exclusively and discard the WE. I recommend one viscous-damped arm with turnover cartridge (if available) or two with fixed cartridges, with guides, for carefree record playing.

For children and unmechanical adults who would not remember to press a sliding guide against the cabinet wall or some other raised object while shifting it, the guide could slide *between two strips of molding*, but this would require a very good fit with no play. The present design is cheap and easily built, requiring only scraps of wood, small nails, screws, bolts, washers, wing nuts, a wire coathanger for the guides and the stops (Figs. 1 and 2), and tapped holes in the panel if it is not wood. Adjustments make all dimensions noncritical except the eye in guide A, which must fit the bolt accurately. Many other forms of guide are possible and you can probably improve upon this design for your own player. END

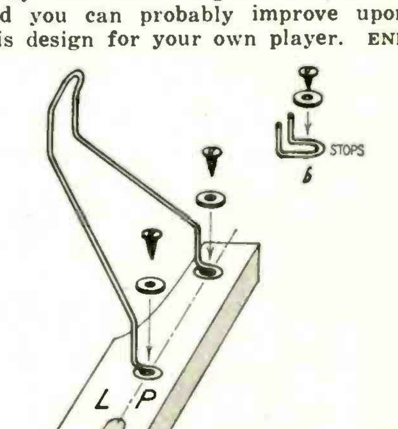

Fig. 2-a—The arm guide for the Gray arm: b—stop construction.