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FEEDBACK—HEAD COOK AND BOTTLE WASHER!

BY NORMAN H. CROWHURST

Like a man in a one-man establishment, feedback can do a lot of things: reduce distortion, adjust frequency response, improve stability from variation due to component deviation or fluctuation, adjust or control input and/or output impedance, and variations of same; but also like the one-man establishment, it is seldom able to do all these things at once.

This fact is often overlooked in various ways. We start with some algebra from which we draw a magic factor–(1 + AB)–generally identified as the *feedback factor*. More academic people may prefer $\mu\beta$ instead of *AB*, but it's the same thing with benefit of fraternity letters. Some people prefer to write the factor (1 – AB), or (1 – $\mu\beta$). While the difference in sign may confuse, it's really only a matter of where you start, and both ways of writing it lead to the same conclusions.

If B, or β, is taken to represent a *negatively* phased feedback fraction, we end up with the first expression, (1 + AB), which is greater than unity. From this starting assumption–if the feedback is positive, then B has a negative sign–the expression becomes 1 + A(–B), which results in something less than unity.

Our more academic friends prefer to say that, if B represents negative feedback, it should have a negative sign, and if it represents positive feedback it should have a positive sign. To conform with this rule, the factor should always be written (1 – AB).

But most people visualize something greater than unity any time they see 1 + something, so I find it simpler to use (1 + AB) for negative feedback and (1 – AB) for positive feedback, where B is the feedback fraction in each case, without any implied sign to indicate its phase. We have taken care of that by verbally designating it as negative or positive feedback.

So it's really a matter of algebraic "semantics." I'm not fussy, as long as it's done right. Most important to the whole thing are two facts: first–and perhaps best known, although it's still often overlooked–is that in any practical application, the expression is not a simple scalar quantity. It is complex, or possessed of both magnitude and phase.

Second, and this is almost always overlooked, it is not constant, but subject to variation *with each of the things feedback is supposed to control.*

The usual presentation tells us that gain is reduced by the factor (1 + AB), distortion is reduced in the same proportion, stability of amplification is improved by this same factor, frequency and phase errors are reduced by the same magic number, and impedance is stepped up or down, according to a convenient table, using the same number as operator.

The fact is, it just ain't so. Feedback can do all of these things, but seldom all at once. To illustrate, let's take some typical examples.

Cathode Follower

A common fallacy of this type is the usual understanding of a cathode follower. In this case, B is unity, so the gain degenerates to A/(1 + A), which is usually a fraction slightly less than unity. Any input impedance connected virtually between grid and cathode is multiplied by (1 + A). And the effective output source impedance is the normal source impedance of the plate circuit with the operating condition chosen (plate voltage and current, and load resistor), divided by (1 + A). Finally, the normal distortion for the stage is divided by (1 + A).

Let's put in some figures, to see what all this means. We'll use half of a 12AU7. With a 40kΩ coupling resistor, 250V plate supply, and 5V bias, the plate current is 3.5mA. The bias resistor should be 1.4kΩ (1.5kΩ is near enough for practical purposes; see *Fig. 1*). With these values, a ±5V grid swing will produce a plate swing from 125V to 45V and 182V, according to the curves (*Fig. 2*). This is a gain, or A, of (182 – 45)/10 = 13.7, with a second harmonic of (11.5/137) × 100% = 8.4% distortion. The plate resistance of the tube at the operating point is 12kΩ.

As a cathode follower, working open circuit, the degeneration will be 13.7/14.7 = 0.93. The distortion will be 8.4/14.7 = .57%. This is at 137V output, pk-pk, or 48.5V RMS. At lower voltages, the distortion will be proportionately lower. For example, at the 10V RMS level, it will be 0.57/4.85 = 0.118%.

If the grid-to-bias-point resistor is 1MΩ, the input impedance will be 14.7MΩ. The normal plate circuit resistance is 12kΩ in parallel with 40kΩ, or 9.2kΩ. As a cathode follower, this is divided by 14.7, to give 625Ω.

From that, it sounds like a good circuit to match a 600Ω line. But now, suppose you connect it that way. The load line for the tube is now 600Ω in parallel with 40kΩ, or 590Ω, through the same operating point. For convenience, we'll take it as 600Ω. The ±5V swing now produces a swing from 125V to 118V and 127V.

The gain is now (127 – 118)/10 =

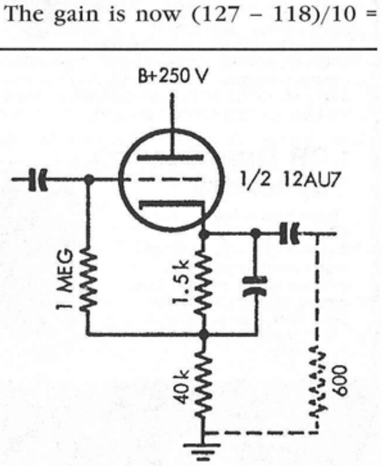

FIGURE 1: Cathode follower circuit.

ABOUT THE AUTHOR

Norman H. Crowhurst was a pioneer in advanced electronics, having assisted in developments of radar in London during WWII, aiding substantially in the successful defense of Britain against the German Luftwaffe. During the 1950s and '60s, he was regarded as one of the most prolific authors on audio theory and construction. He emigrated to the US in 1953 and was awarded a fellowship by the Audio Engineering Society in 1959. At the time of his death in 1991, he was 77.

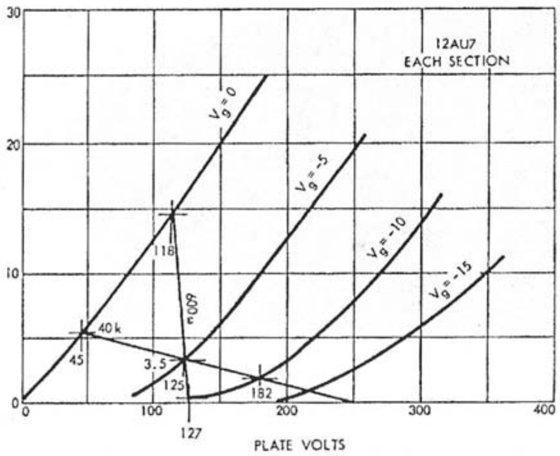

FIGURE 2: Load lines on which calculations for cathode follower are based.

0.9. As a cathode follower, the degeneration will be 0.9/1.9 = 0.475. The distortion is (2.5/9) × 100% = 28% plate-coupled. For cathode coupling, this is no longer divided by 14.7, but by 1.9, to give 14.8%, with a pk-pk output of only 9V, or 3.2V RMS. At this output level, the open-circuit distortion would be only 0.38%. Also, the input impedance is no longer 14.7Ω, but 1.9MΩ.

Quite a difference! We might say the feedback has been "used up" to change the output impedance, so little or none is left for the other functions.

Bootstrap

Now let's take a case of positive feedback: the bootstrap driver, often used for unity-coupled output circuits. We'll assume the output stage develops a 150V swing in both cathode and plate circuit, for a 25V swing at the grid. This means we need 175V total swing at the grid (*Fig. 3*).

To do this, we use a relatively low plate resistor from the screen of the output stage to the driver plate, so the working plate voltage on the drive stage can be kept high at a current approaching maximum dissipation (*Fig. 4*). The positive feedback from the screen connection effectively multiplies this actual value to give a higher dynamic load line. If the actual resistor is 15kΩ, its effective value will be 175/25 = 7 times this, or 105kΩ.

Positive feedback has multiplied the driver load impedance by seven times. Does this mean the overall gain is multiplied seven times? And what happens to the damping factor?

Assume the drive stage has a plate resistance of 12kΩ and an amplification factor of 20. Without the bootstrap, its gain would be 20 × 15/(15 + 12) = 11.1. With the bootstrap, the gain becomes 20 × 105/(105 + 12) = 18. The increased gain factor is only 18/11.1 = 1.62. Use of the bootstrap circuit increases available output *swing* of the drive stage much more than it increases gain, but this only a graphical approach can predict.

Damping factor is a little more involved. Starting with normal pentode operation, if a 25V grid swing produces 300V total swing in a normal load value (the condition on which our earlier figures were based), open-circuit operation would require only about a 5V swing at the grid to produce the same 300V output swing. So in unity-coupled configuration, to get the same output voltage, the grid swing needed drops

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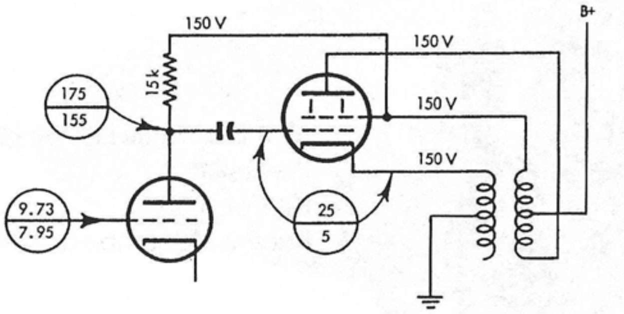

FIGURE 3: Essential features of bootstrap arrangement. One side of a push-pull circuit is shown.

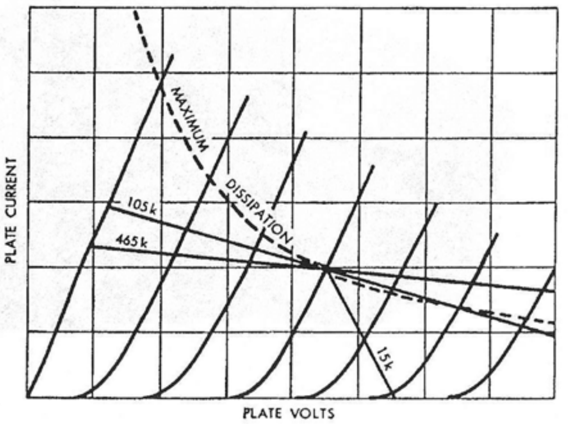

FIGURE 4: Principle of the bootstrap illustrated by load lines.

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from 175 (i.e., 150 + 25) to 155 (i.e., 150 + 5), representing a damping factor of about 7.8.

But that's assuming a constant-voltage drive stage, unaffected by feedback. Now to see what the bootstrap does.

When the load is removed, the positive feedback to the drive-stage plate resistor jumps from 7 times to 155/5 = 31 times. So the effective (dynamic) plate resistor is now 465kΩ. The gain will be 20 × 465/(465 + 12) = 19.5. (This is neglecting the effect of any output-stage grid resistors, which admittedly would modify the result, and must be reckoned into complete design calculations.) With normal load, the input to the drive stage—to get full output voltage (150V swing at cathode and plate) —is 175/18 = 9.73V swing. With the output-stage open circuit, the input to the drive stage needs to be 155/19.5 = 7.95V swing. So the overall damping factor is now about 4.5.

This illustrates the principle that feedback can do different things in different places, and that different factors are involved according to what you are calculating, and how the overall effects combine. But so far we've assumed the simple case where, although (1 + AB) may have different values according to the purpose involved, AB is always either positive or negative: no phase angles.

Reactance Loading

Now let's take the case of a typical feedback amplifier. We'll assume it has a midband feedback of 14dB, with normal resistance load, and uses pentode output stage with plate resistance (without feedback) seven times load value.

The output shunt resistance, without feedback, is $^{7}/_{8}$ times the load value (*Fig. 5*). Feedback will reduce this by 5:1 (equivalent of 14dB) to $^{7}/_{40}$ times load value. Since part of this is still the actual load, the effective source resistance is $^{7}/_{33}$ times load value, or the damping factor is 33/7 = 4.71. The feedback component, AB, is $^{4}/_{5}$ of the external input. Assume distortion is 5% without feedback. So with feedback, it will come down to 1%.

For now we'll assume that stability criteria have been taken care of and the amplifier performs satisfactorily (at least remaining stable) when a loudspeaker is connected. We'll stay strictly in the range where amplifier phase shifts and gain changes are negligible. The phase shifts we'll talk about are not those that occur at frequency extremities. These have been discussed before. But at about 2000 cps (for one place) the loudspeaker's reactance will about equal its resistance.

With the resistance load, AB was 4. With the resistance load removed, *AB* would be (1 + 7) × 4, or 32. With a loudspeaker load whose impedance is (1 + j1) times nominal value (or 1.414 at 45°), *AB* will be

$$\frac{32(1+j1)}{8+j1} = \frac{32}{65}(9+j7) = 4.43 + j3.45$$

The factor (1 + AB) thus becomes 5.43 + j3.45.

Without feedback, the transfer phase shift into this reactive load will be

$$\tan^{-1}\frac{7}{9} = 38^\circ$$

With feedback, this reduces to

$$\tan^{-1}\frac{7}{73} = 5.5^\circ$$

which is a considerable improvement.

Without feedback, the output voltage would rise, from the value into a resistance load, in the ratio

$$\frac{4.43+j3.45}{4}$$

or by a factor of 1.4. With feedback, this rise is held down to

$$\frac{4.43+j3.45}{5.43+j3.45} \times \frac{5}{4}$$

which evaluates to 1.09, also a considerable improvement. In short, this means the improved damping factor effect is realized. But what about distortion?

When the feedback was combined precisely antiphase, the distortion was reduced by the gain reduction factor, 5. But now the feedback meets the input at a phase angle of 38° to antiphase. Actually, the feedback is now more than 14dB; it's just over 16dB. Exactly what happens to the distortion depends on the exact distortion components and on the feedback loop gain and phase shift at those component frequencies. Remember, the loudspeaker impedance contributes to the phase shift.

First, assume it's practically all second harmonic, which is one extreme possibility. The loop gain-phase angle is likely to have risen from 38° to $\tan^{-1}7/6$ or 49° by then. This means the in-phase cancellation will be cos 49°, or 0.65 times what it was with resistance load. But there will be a sin 49° component in quadrature, about 0.75 times the no-feedback value. So the 1% will jump to almost 4%.

That's the most optimistic case. If some of the distortion is due to clipping that occurs during a relatively short part of the fundamental, the phase shift will mean the feedback "correction signal" will completely miss the original distortion kink, and will set up another one in opposition. This will go round the loop again, repeating the miss, until the irregularity dies out—or develops into a parasitic, depending on the stability margin of the

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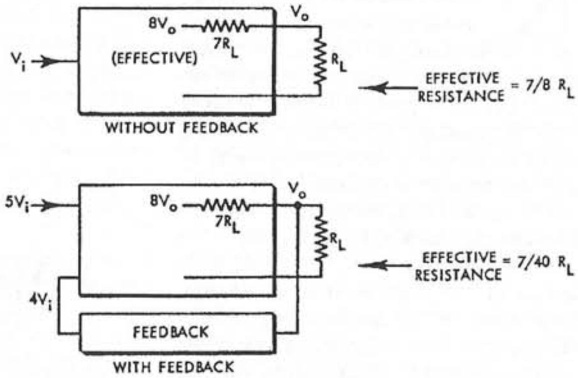

FIGURE 5: Some of the quantities discussed in the complete feedback amplifier.

reader found the information useful then the effort was worthwhile. It appears that this has been accomplished. I hope you make good use of your treasure.

I had another opportunity to use my VT stock when I was asked to resurrect a vintage RCA radio. I did it with a VT-114 (5T4), much to the delight of the senior citizen owner who was astounded that the tube was a WWII surplus and almost as old as she.

CHANGE OF VENUE

As an update to your 1998 World Tube Directory, I have information regarding the whereabouts of Varian/Eimac. After much time-consuming research, I managed to find Varian had moved its headquarters to Palo Alto, CA. However, it seems Varian has sold off about 60 divisions, including what was called the Eimac/Power-Grid Tube Products division. The Eimac division was sold to CPI (Communication and Power Industries), located at 301 Industrial Way, San Carlos, CA 94070, 650-592-1221. CPI has told me it will continue to use the Eimac trade name along with the original tooling and production personnel on such classic products as the 3-500Z and the 3-1000Z transmitting triodes.

Bob Schoonmaker
Flushing, NY

ONLINE SOURCE

While reading "Different Parents" (*GA* 3/97, p. 61), it occurred to me that a collection of this material was available on the Internet. http://Cam041214.student.utwente.nl/mattijs/stereo/tubes/numbers.htm. It is headlined "Tube type explanations" and is quite a valuable resource for a nontechnically oriented amateur such as myself.

By the way, I really dig your operation. The big three magazines and the Old Colony Sound Lab have made significant improvements in my ongoing music crusade. I couldn't be happier in this realm. Thanks for offering these resources. ❖

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amplifier at the frequency represented by this repeated transition time.

If you don't believe this happens, set up an amplifier with a load impedance consisting of a variable phase load. As you vary the phase of the output load, the amplifier will probably go through a distortion minimum at the point where output and input voltage are precisely in phase. For other phase loadings on the output, the feedback holds the overall transfer characteristic to reduced phase deviation limits. But the loop gain phasing is upset, so it cannot *at the same time* hold down distortion according to formula.

We have simplified the discussion considerably. We assumed the distortion would not change according to output loading, which is seldom true, of course. Reactive loading itself often causes more severe distortion. This will further aggravate the overall effect.

We have shown in this case that there's no guarantee that the same distortion-reducing factor works for all purposes.

What's the remedy? That's another story. In short it is to calculate quite specifically the feedback effects for each purpose in hand. In each calculation, there will be a factor 1 + AB. But it is unlikely to involve the same circuit elements or parameters for each purpose considered. So the relevant factors are *not* the same for each purpose, except in the very basic algebra. ❖

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Professor of Electrical Engineering at Stanford. In many ways, his book is a simplified summary of colleague Spangenberg's, although it provides insights not found elsewhere.

One of its most significant features is its preface. The author's pedagogical insight is every bit as great as his physical insight. He explains the basics of electron ballistics within electric, magnetic, and electromagnetic fields for both static and time-varying fields.

1957

John D. Ryder, *Engineering Electronics* (McGraw-Hill Book Co., Inc., NY). (Reviewed in Part 1.) Ryder's insights into tube physics are well worth pondering. His analysis of the trajectory of a single electron within a vacuum tube is fascinating (pp. 5–7); as is the whole of Chapter 2, "Physical Phenomena in Electron Tubes."

1967

Jacob Millman and Christos C. Halkias, *Electronic Devices and Circuits* (McGraw-Hill Book Co., Inc., NY). (Reviewed in Part 1.) This book presents the essentials of Millman's earlier book, *Electronics* (reviewed above), in a more concise and easily digested form. ❖

OF NOTE IN *Speaker Builder*

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