The importance of BALANCE in push-pull amplifiers

Suggestions for getting maximum output quality from high-fidelity units

By JOSEPH MARSHALL

INVERSE feedback is unquestionably the most valuable high-fidelity tool developed in our generation. The improvements it has made possible are almost magical when viewed in the perspective of the days before feedback. Unfortunately, the tendency has been to consider it a cure-all for any and all high-fidelity problems. If it is not included in a design to begin with, it is thrown in quickly as soon as something goes wrong.

I do not mean to disparage feedback in the slightest, but its versatility and effectiveness have tended to obscure a number of other basic principles in amplifier design. Observing these principles will greatly reduce the probability of a high-fidelity design going wrong in the first place, and makes the application of feedback much simpler and considerably more effective. One of these basic principles is the need for balance in push-pull amplifiers.

The great virtue of the push-pull amplifier in audio design is its ability to cancel even-order harmonic distortion. This feature allows us to drive the tubes harder and get more than twice the output of a single tube if we wish. It also improves the low-frequency response by reducing unbalanced d.c. in the output transformer primary which might saturate the core and reduce the inductance of the windings. In addition, push-pull operation almost entirely eliminates hum and noise from the power supply, but still the principal reason for using it is the distortion-canceling feature. It sounds simple: merely hook up two tubes in push-pull and you cancel second-harmonic and all other even-order distortion, thus disposing of the largest portion of distortion at one crack.

Unfortunately, this does not always follow as inescapably as day follows night. In fact, it is a very rare push-pull amplifier which fully exploits these distortion-canceling characteristics. Very few of them realize even 75% of the possible benefits; and many push-pull amplifiers produce even more distortion than a properly designed single-ended amplifier.

The fact that a push-pull amplifier utilizes only 75% of the distortion-canceling abilities of the circuit may not be serious in speech-range public-address equipment. But in high-fidelity amplifiers enjoyment of the wide frequency response is entirely dependent on reducing distortion to an absolute minimum. The amplitude of most music and voice sounds around and above 10,000 cycles is normally 30 or 40 db below the average sound level. Even 1% distortion of mid-range sounds would be louder than the normal h.f. components, and would not only mask them but also make them annoying to hear. To insure acceptable reproduction of the high frequencies, distortion must be reduced to the smallest possible fraction of 1%. This improvement is easily attainable by making the most efficient use of push-pull design.

The distortion-canceling property of a push-pull amplifier depends entirely on balance. Complete cancellation is achieved only when equal signals are fed to both sides, when both sides amplify equally, and when both produce the same amount of distortion. On the other hand, if the output and distortion of one side are 10% greater than the other, at best only 90% of the distortion is canceled.

The situation actually becomes even worse at some points in the dynamic range, especially at the points of maximum drive. For instance, suppose we deliver equal signals to both sides, but that one side is overbiased, either because the tube draws more current, or because its cathode resistor is higher than that of the other tube. Thus the overbiased tube reaches the bend of its curve before the other, and may generate 5% or more second-harmonic distortion while the correctly biased tube generates only 1%. After cancellation we have one side passing on a signal with 4% distortion, while the other side has none. From a distortion point of view, the amplifier would be much better if the overbiased section were not functioning at all—in other words, if it were an unbalanced single-ended stage.

Theoretically, it's simple to achieve complete cancellation; in practice, however, it may call for rather heroic measures.

Static balance

It is easier to get balance with transformer coupling than with resistance coupling. In high-quality transformers the turns ratios and d.c. resistances of the two sides are balanced to 1% or better; even the cheaper ones are not more than 3 or 4% out of balance. However, an input or output transformer does not automatically insure balance. In the first place, it is difficult to obtain identical tubes, and if one tube draws more current than the other, the two sections will be unbalanced. It is easy to get *static* balance by adjusting the bias voltages of the individual tubes so that both draw equal no-signal currents. This, of course, is fairly standard procedure. Almost all good power amplifiers have some means of adjusting the bias to the output tubes. But for minimum distortion, the driver stage should also be balanced.

Two ways of doing this easily and inexpensively are shown in Fig. 1. At *a* we use a small potentiometer ahead of a common bias resistor. By adjusting in one direction or the other from center, both tubes can be made to draw equal currents under static conditions. In *b* the two tubes have separate bias resistors, but one of these is adjustable.

Note that the circuit at *a* includes a bypass capacitor across the common bias resistor. No doubt you have read that such a bypass capacitor is not really necessary in push-pull stages. As a matter of fact, *if* the stage operates at a low level—one which never approaches the bend of the tube curves and therefore generates little or no distortion—a common *unbypassed* cathode resistor serves as a balancing device. However, if the stage is operated at signal levels high enough to produce distortion, the bypass capacitor is absolutely essential.

Harmonics cancel only where they appear out of phase. This is true in the output circuit. But the cathode resistor

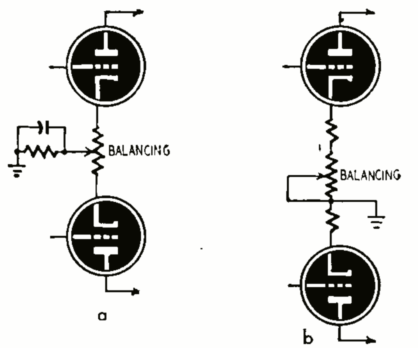


Fig. 1—Static balancing arrangements for push-pull amplifiers. (a) Mutual bias potentiometer with bypass for common cathode resistor. (b) Balance adjustment in one cathode without bypassing. See text for complete analysis.

is common to both the input and output circuits. In the cathode circuit the even-order output harmonics from one side of the stage appear *in phase* with the input signal of the other side. This is a form of positive feedback. The in-phase harmonics add themselves to the input signal and are amplified by the stage, producing a very serious form of distortion. This may not be important in cheap amplifiers, but it is most objectionable in high-fidelity designs.

We have seen a number of 6B4 amplifiers with large amounts of inverse feedback, which sounded terrible for this reason. These tubes need nearly 150 volts drive grid-to-grid. To produce this much, even with an interstage transformer, the drivers themselves have to be driven well into the nonlinear portions of their curves, generating a great deal of distortion. Fed back through the common cathode resistor, this distortion was not affected by the feedback network and was amplified to such an extent that there was much more distortion than the 6B4's would normally produce by themselves. For this reason, it should be routine to include a large bypass capacitor across common bias resistors in all high-level stages of high-fidelity amplifiers.

On the other hand, in amplifiers where the driver has to deliver only moderate voltage to the following stage, the circuit of *b* with separate unbypassed cathode resistors is preferable. Since the positive feedback referred to previously is present only with a common cathode resistor, an unbypassed resistor for a single section will not produce it. In addition, omitting the capacitors gives a small amount of negative feedback which helps preserve the balance and improves the frequency response as well.

Dynamic balance

Unfortunately, *static* balance is not necessarily *dynamic* balance. A stage which is balanced perfectly at zero input or at some fixed value of signal input will probably be out of balance somewhere in its dynamic or frequency range. Even a change in line voltage may throw the sides out of balance; and a stage balanced at zero input will almost invariably be out of balance at maximum input. An amplifier with plate-current meters in all plate circuits and means for controlling bias and plate voltages is very instructive in this respect.

The simplest way to check balance is to connect a high-resistance voltmeter from plate to plate of the stage to be balanced. Balance is indicated by zero voltage: adjust the balancing potentiometer until the meter indicates no voltage difference between the two sections. (This assumes that the d.c. resistances of the two halves of the push-pull plate load are equal.) This is most dramatically visible with power stages but is also true of voltage amplifiers.

Aside from negative feedback, there is another expedient which may be used to get approximate dynamic balance. This is shown in Fig. 2 and is an unbypassed choke of about 25 henries in series with the center-tap of the output transformer or the junction of the plate-load resistors. (A resistor may also be used this way, though it is not as effective as the choke.) Its operation is quite simple. The choke (or resistor) is an impedance common to both

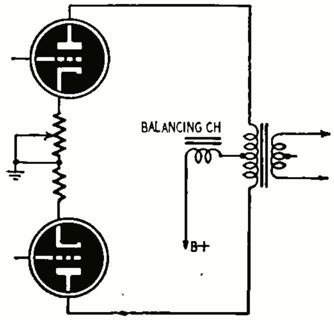


Fig. 2—Inserting a high impedance in the common B plus return improves balance by equalizing plate-current variations in the two sides of the circuit.

sides of the push-pull stage. As long as the currents flowing through both tubes are identical, there will be identical voltage drops for both tubes in the common choke. The moment one tube begins to draw more or less current, the voltage drop across the choke will increase or decrease as the case may me. This in turn will change the current of the other tube in the *opposite* direction, thus bringing the total voltage drop closer to the original. The same thing will apply of course to the a.c. currents generated in the plate circuit, so that both the d.c. parameters and the a.c. signal are kept much more closely in balance than if the common impedance were not there.

This method will not guarantee absolutely perfect balance, but even an arbitrary inductance value of 15 to 25 henries will improve the dynamic balance by a very large factor. This method works well in class A output stages. Whether it should be used in AB operation is another matter. It would improve the dynamic balance over the class A portion of the range; but the reduced regulation in the high-output class AB region might be deleterious. We have found it satisfactory and even valuable in several amplifiers. Many of the tubes used in power stages, especially the transmitting types, may have a variation as great as 5 ma between the two sides. Although they can be brought to static balance by adjusting

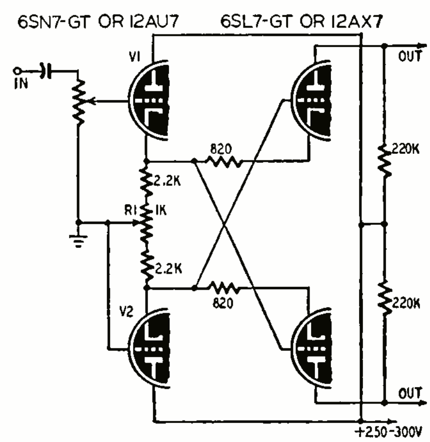


Fig. 3—Cross-coupled phase inverter with cathode balancing potentiometer.

the bias, they are very likely to produce severe unbalance and distortion at maximum output. The common choke reduces this materially without too much sacrifice of output power.

Balancing R-C Stages

The problem of balancing resistance-coupled push-pull stages is a little more troublesome. All the methods described above can and should be applied to R-C amplifiers as well as to transformer-coupled types, provided the much more serious unbalance due to unequal component parameters is also taken care of. One way to solve this is to use precision (1% or better) resistors in the grid and plate circuits, and to balance the cathode circuits by the methods shown in

Fig. 1. It goes without saying that the use of anything but matched pairs is out of the question in a high-fidelity amplifier—but it is not necessary to go to the expense of precision resistors. Ordinary 10% or even 20% resistors can be checked carefully on a bridge or an ohmmeter, to find pairs which match within 1 or 2%. Balance is much more important than actual value. Whether a plate-load resistor is 250,000 ohms or only 200,000 ohms is generally immaterial, as long as the two on opposite sides of the same push-pull stage are as nearly identical as possible. The improvement obtainable in an amplifier by replacing random-value resistors with matched pairs is quite astonishing, especially at maximum output. To a lesser degree, the same thing is true of coupling capacitors, although here the improvement is in frequency balance.

Phase inverters

We come now to a matter of quite serious importance: balance in the phase inverter. It is obvious that no matter how well balanced the succeeding stages are, if the stage which originates the push-pull signal is not balanced, and therefore delivers unequal signals to the two sides, all the balancing work is undone, as far as canceling distortion is concerned. This problem has been discussed many times in this and other periodicals.

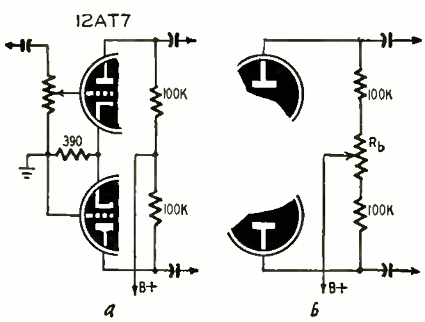


Fig. 4—(a) Basic cathode-coupled phase inverter. (b) Balancing potentiomer inserted in phase-inverter output circuit.

The most foolproof phase inverter is a good center-tapped transformer. True, a transformer with wide-range frequency response is expensive and bulky; but it will supply signals balanced to 1% or better. Only one vacuum-tube phase inverter we know of can approach a transformer in this respect. This is the cross-coupled inverter diagrammed in Fig. 3. By adjusting R1, the output can be balanced to 1% or even better, and the balance holds over its entire dynamic range. A simple way to balance it is to unground the grid of V2 and connect it to the grid of V1. Now feed in any signal and adjust R1 until the signal is inaudible or has minimum value at the output.

The second-best tube-type phase inverter is the cathode-coupled circuit given in Fig. 4-a. Theoretically, the output will be balanced if the plate resistors on both sides are identical. In practice a balance within 5% is achievable. A simple way to balance this inverter is to insert a potentiometer (R_b) between the two load resistors as shown at *b*, and adjust for equal outputs.

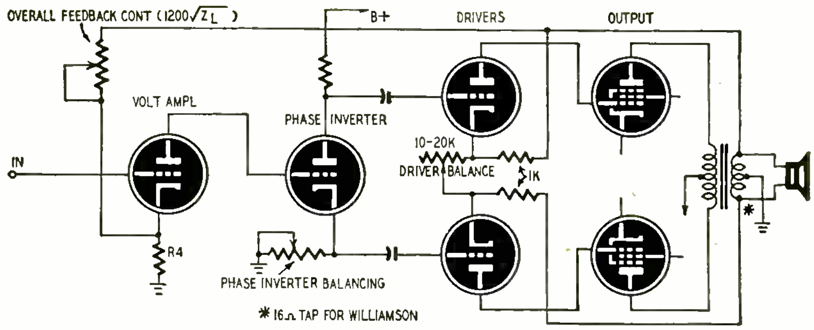


Fig. 5—A combination of balancing arrangements for a Williamson-type amplifier. The adjustable cathode resistor in the phase inverter equalizes the outputs to the driver grids. Feedback from the output-transformer secondary to the driver cathodes helps equalize the push-pull stages. See discussion in the text. Only components essential to the discussion are shown in this schematic.

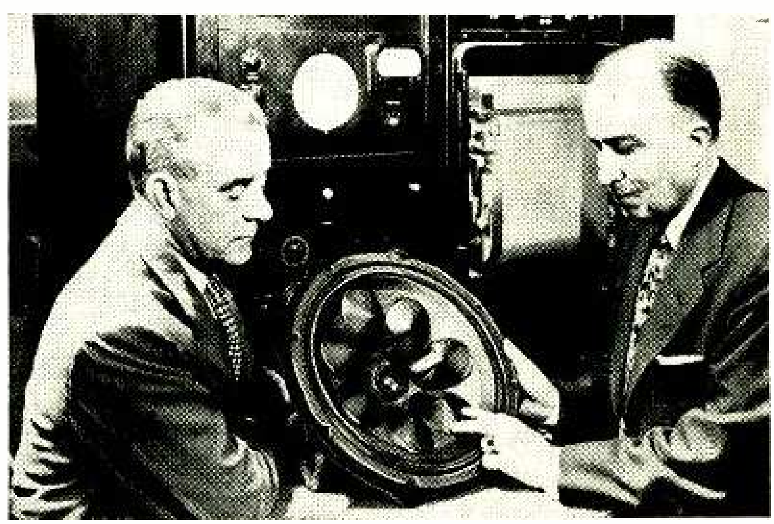
The split-load inverter used in the Williamson and other amplifiers can be balanced by making the cathode resistor variable and adjusting it for equal outputs from cathode and plate. This inverter is not balanced perfectly at high frequencies but this is said not to be serious. In any case, whichever circuit is used, the resistors in the two sides should match as closely as possible.

Feedback balancing

There is one more tool for balancing which remains for discussion and that is inverse feedback. It is the most important single corrective and, moreover, it produces dynamic rather than static balance. (More important, perhaps, it produces frequency balance as well.) To be effective in balancing, inverse feedback itself must be balanced. The single-ended type of feedback used in the Williamson circuit is not effective for balancing, although it is effective in reducing distortion by other means.

The ideal amplifier should have two feedback networks: one for balancing push-pull stages, and another to the input of the amplifier, for over-all frequency correction and distortion cancellation. For example, in the Williamson circuit balanced feedback could be applied to the driver cathodes by using an output transformer with a center-tapped secondary or split output windings. See Fig. 5. This is in addition to the feedback to the cathode of the input stage. About 10 db of feedback could be applied to the drivers and another 10 db to the input stage. In this way, and in conjunction with the other balancing measures described, we could combine the distortion-canceling properties of push-pull operation with those of inverse feedback, and presumably produce an amplifier with the absolute minimum of distortion.

In any case, the first and most important goal in high-fidelity design is to reduce distortion to the point where it cannot mar the enjoyment of a wide frequency range, which in itself is relatively simple to achieve. In approaching this goal, the use to the fullest extent of the distortion-canceling feature of push-pull amplifiers is an important and relatively inexpensive step that should be taken by all designers who want highest possible fidelity. END



New RCA LC-1A high-fidelity speaker shown here by Dr. H. F. Olson (right) and John Preston, co-developer, has irregularly spaced deflector domes mounted on its 15-inch main diaphragm to break up symmetrical standing-wave interference patterns and flatten the frequency response.