Audio Amplifier Damping

The meaning and measurement of the damping factor in audio amplifiers are shown, using the Williamson circuit as an example. By means of feedback the amplifier output impedance can be controlled so as to damp out oscillations generated in the load

By ROBERT M. MITCHELL

Circuit Applications Engineer
United Transformer Co.
New York, N. Y.

THE growing interest in transient response of electroacoustical systems necessitates increased attention to the means of controlling amplifier output impedance. However, a more convenient concept is the damping factor, D, which is defined as the ratio of the load impedance, R_l, to the effective generator impedance, Z_o. It will be shown how the damping factor can be controlled through the use of feedback.

If an impedance-matching device, such as a transformer, is placed between the two impedances, the ratio is that obtained with both impedances referred to the same side of the transformer as shown in Fig. 1. Except where stated otherwise, the output impedance and load impedance are assumed to be resistive.

The term damping factor has been applied to this ratio because it is indicative of the effectiveness of the generator in damping oscillations generated by the load. Since it is expressed as a ratio, it will be the same for any output tap on a transformer and is therefore a more convenient characteristic to use than the effective output impedance itself.

The output impedance of an amplifier will be considered to be the ratio of voltage E to current i obtained when the input is short circuited and the voltage E is applied to the output terminals as shown in Fig. 2.

The damping factor may be varied by changing either R_l or Z_o. Since it is usually desired to obtain a given power output from a given tube, it is not practical to change the load impedance. A method that will change the effective output impedance of the amplifier, but will leave the load unchanged is to apply feedback so that the output stage is included in the loop.

Damping by Feedback

Figure 3 shows a basic one-stage feedback diagram, with polarities not indicated to make the diagram general. It will be noted that this is the so-called voltage type of feedback. If the polarities are such as to make βE oppose e_{in} (assuming the latter no longer zero) the feedback is negative. For this condition β is considered negative, and the resultant output impedance is less than that without feedback. If the feedback is positive the output impedance is increased. It may be shown that negative-current feedback increases the output impedance, while positive-current feedback reduces it.

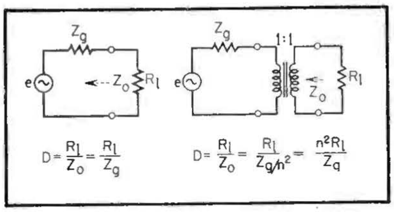


FIG. 1—Damping factor ratio is that with both impedances referred to same side of transformer

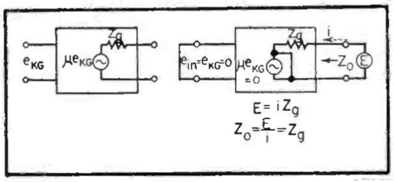
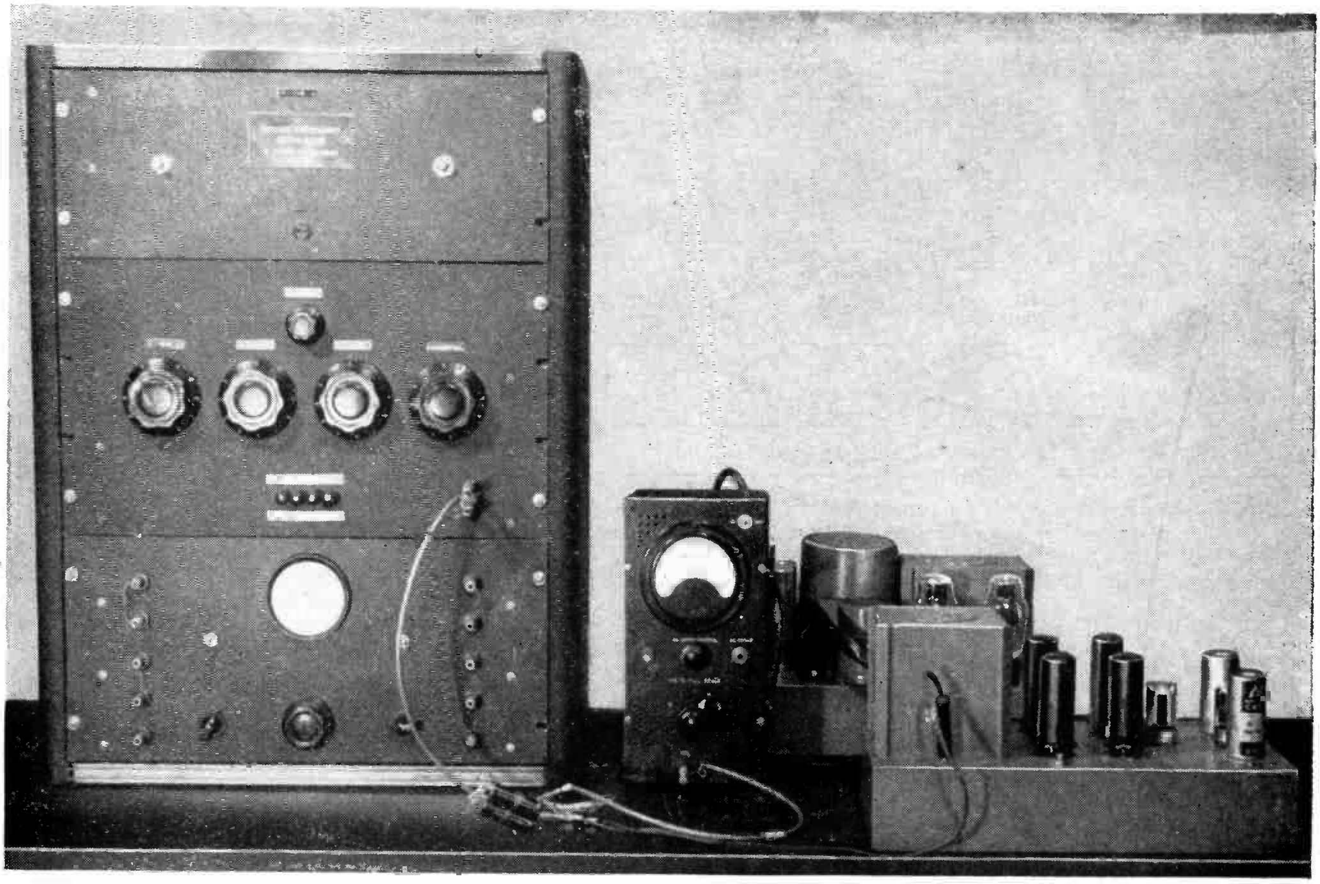


FIG. 2—Conditions under which amplifier output impedance equals E/i

It is important that the definition of the original output impedance be clearly understood. If the output impedance without feedback is the plate resistance alone (as in Fig. 3) then this output impedance is changed by the factor $1/(1 - \beta\mu)$, which is not the same factor by which the gain of the stage is changed. If the output impedance without feedback is the plate resistance of the tube in parallel with the load resistance, then the output impedance is changed by the factor $1/(1 - \beta K)$, where K is the stage gain, when feedback is applied. This is the same factor by which the gain is changed. Such a condition would be encountered seldom, if ever, in a loudspeaker output stage, but might arise in connection with an R-C shunt-fed transformer stage. This difference in definition may lead to misunderstanding when different source texts of feedback amplifier design are consulted, unless the distinctions are clearly understood beforehand. In this article, the discussion is confined to the output stage, with the output impedance without feedback being defined as the plate resistance of



Amplifier for which circuit diagram is shown undergoing measurement using the method indicated in Fig. 7

the output tube in every case.

Most practical amplifier circuits generally comprise more than one stage. In a multistage amplifier it is usually preferable to enclose more than the final stage in the feedback loop, since this, among other things, avoids the requirement of large driving voltages for the final stage. For these conditions the feedback diagram is as shown in Fig. 4.

Multistage Feedback Effects

The results are almost identical to those of Fig. 3, with the exception that the gain K of the intervening stages appears in the factor to increase the effects of the feedback for a given μ and β.

The final equation shown in Fig. 4 is that generally found in textbooks for output impedance of multistage feedback amplifiers. In this form it is not particularly convenient to use for calculation, since it requires a knowledge of the gain of the intervening stages.

A simpler, and more convenient equation may be derived as follows. The damping factor without feedback is

$$D_o = \frac{R_l}{Z_o} = \frac{R_l}{r_p}$$

The damping factor with feedback is

$$D_f = \frac{R_l}{Z_o} = \frac{R_l}{r_p/(1 - \beta K \mu_f)} \qquad (2)$$

$$= D_o\,(1 - \beta K \mu_f)$$

The gain of the final stage is

$$K_f = \mu_f \frac{R_l}{R_l + r_p}$$

Solving for μ_f

$$\mu_f = K_f\left(1 + \frac{r_p}{R_l}\right)$$

$$= K_f\left(1 + \frac{1}{D_o}\right)$$

Substituting in Eq. 2

$$D_f = D_o\left[1 - \beta K K_f\left(1 + \frac{1}{D_o}\right)\right] \qquad (3)$$

The amount by which the gain is reduced is

$$1 - \beta K K_f = 1 - \beta K_o$$

where K_o is total gain

That is, if $1 - \beta K_o = 2$, the gain is reduced by 2. Letting this gain reduction factor $= F$, we have

$$D_f = D_o\,[F - (1 - F)\,(1/D_o)]$$

$$D_f = F\,(D_o + 1) - 1 \qquad (4)$$

Note that in this final form it is

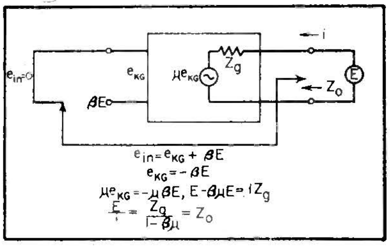


FIG. 3—Output impedance without feedback is represented by plate resistance alone in figure above and in text

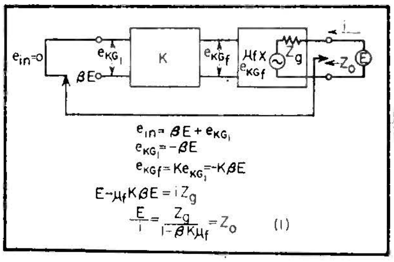


FIG. 4—Conventional concept leading to Eq. 1 above is based on premises illustrated. Equation 4 (see text) is more convenient form

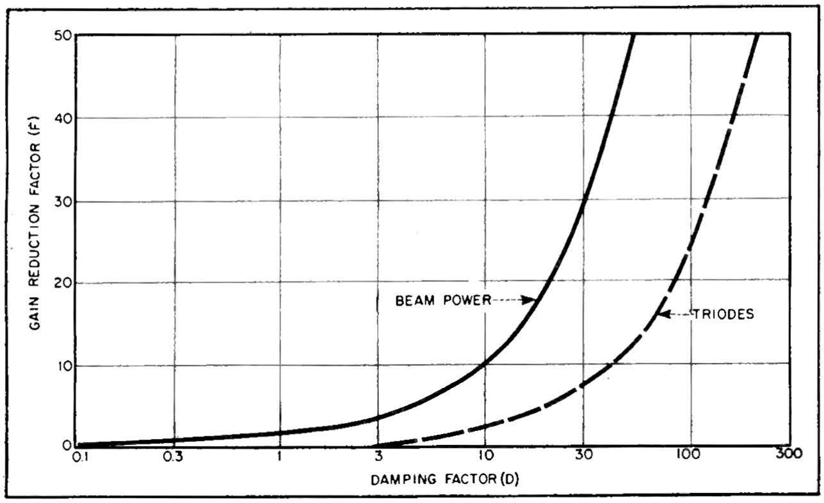


FIG. 5—Curves show changes in damping factor with feedback for typical beam-power and power-triode tubes. Note superiority of triodes

not necessary to know the actual gain of any of the stages, or the feedback ratio, but only the gain reduction and the original damping factor.

For example, it is desired to compute the damping factor obtained in a push-pull 6L6 amplifier when 20 db of negative voltage feedback is employed.

$F = 10$
$R_l = 5{,}000$
r_p (two tubes) $= 45{,}000$
$D_o = 5{,}000/45{,}000$
$D_f = 10\ (0.111 + 1) - 1 = 10.11$

For a push-pull 2A3 amplifier with the same load and the same gain-reduction factor

r_p (2 tubes) $= 1{,}600$
$D_o = 5{,}000/1{,}600 = 3.12$
$D_f = 10\ (3.12 + 1) - 1 = 40.2$

These results show the tremendous changes in output impedance produced by feedback, especially for beam-power tubes. Without feedback the damping factor of the triode amplifier is some 27 times that of the beam-power tubes. With the same amount of feedback applied to each, the damping factor of the triodes is approximately 4 times that of the beam-power tubes. Or looking at it from another point of view, the same amount of feedback produces a 13-fold change for the triodes, but a 90-fold change for the beam power tubes.

Equation 4 has been used to obtain the graph of Fig. 5. In this graph the two curves show changes in damping factor with feedback for typical beam-power tubes and typical power triodes. From this it may be seen that approximately 12 db of feedback is required to make the damping factor of a beam-power tube equal to that of a triode without feedback. It is also evident that the same amount of feedback will always give a greater damping factor in a triode amplifier than in a beam-power amplifier, since the original damping factor of the triode amplifier is greater.

These curves may be used in several ways, although Eq. 4 is so simple that it may be used almost as readily, especially if the following simplifications are made.

The initial damping factor for most beam-power tubes is approximately 0.1, while it is approximately 3 for most triodes. Using these values the following approximate equations, quite suitable for design purposes, are obtained:

For beam power tubes

$$D_f = F - 1 \tag{4B}$$

For triodes

$$D_f = 4F - 1 \tag{4C}$$

Both these equations are reasonably accurate when F is equal to or greater than 2 (6-db feedback). For less feedback, Eq. 4 should be used for beam power tubes, while Eq. 4C is still applicable for triodes.

Similar relations may be derived for current feedback, but since this

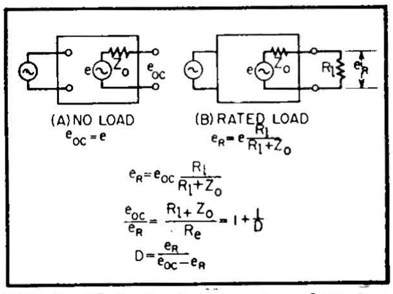


FIG. 6—Method of measuring damping factor by means of no-load and rated-load output voltage shown in bottom equation

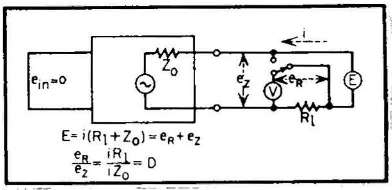


FIG. 7—Simplified method of obtaining damping factor by measurement across series resistor equal to secondary winding

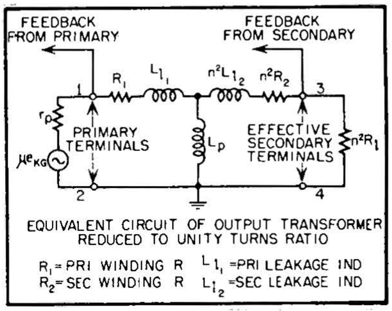


FIG. 8—Limits of the damping factor with feedback obtained from one of two points. See text for discussion

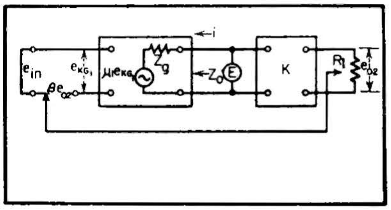


FIG. 9—Effective internal impedance of intermediate stage is reduced by feedback taken from succeeding stage

type is relatively little used over the output stage, they will not be derived here.

Measurement

The measurement of the damping factor is generally done indirectly, that is, it is usually the practice to measure output voltages under differing load conditions, and to calculate the damping factor from the results. However, it is equally easy, and often more accurate, to measure it by other methods, which are also described below.

The first method often consists of measuring the output voltage with no load and with rated load, and then calculating D as shown in Fig. 6. This method is satisfactory for amplifiers with low values of D, such as pentode or beam-power amplifiers with little or no feedback. When the internal impedance is low, as in highly degenerative amplifiers, however, there is very little difference between e_R and e_{oc}. Since the difference of these two terms appears in the denominator, it is possible, when they are almost equal, for an error of a few percent in either of these terms to produce an error of several hundred percent in the answer.

A more accurate procedure is to use a low-impedance-type a-c bridge. For such measurements the signal-input terminals of the amplifier are short-circuited, the output terminals are connected to the unknown impedance terminals of the bridge, and the bridge balanced as in normal measurements.

An even simpler method, and one quite accurate for damping factors as high as 50 or more is shown in Fig. 7. The input terminals of the amplifier are short-circuited and the output terminals are connected to a generator E in series with a resistance R_l, which is the rated value of the secondary winding of the output transformer. The damping factor is then equal to the ratio of the voltage drops across R_l and across the secondary winding respectively. The generator E may conveniently be the 6.3-volt filament winding of a power transformer. In a highly degenerative amplifier almost all the voltage drop will be across R_l; consequently, it must be fairly high power rating.

When E is 6.3 v a rating of 10 watts will be adequate for almost all situations.

Two points of interest concerning damping factor may be pointed out in passing. First, it can be seen from Fig. 8 that when the feedback is taken from the primary of the output transformer (terminals 1 and 2), the damping factor approaches R_l/R_w as a limit, where R_w is the total winding resistance of the transformer referred to the same side to which R_l is referred. When the feedback is taken from the secondary terminals (3 and 4), however, this limit does not exist, and D can theoretically approach infinity.

Internal Impedance

Second, it is demonstrated below by reference to Fig. 9 that the effective internal impedance of a stage inside the feedback loop is also reduced by negative feedback taken from a succeeding stage.

$$e_{in} = \beta e_{02} + e_{KG1}$$
$$e_{KG1} = -\beta e_{02}$$
$$e_{02} = K_2 E$$

$$E + \mu_1 e_{KG1} = i Z_0$$
$$E + \mu_1 (-\beta e_{02}) = i Z_0$$
$$E + \mu_1 (-\beta K_2 E) = i Z_0$$
$$\frac{E}{i} = \frac{Z_0}{1 - \beta \mu_1 K_2} = Z_o$$

This shows, for example, that overall feedback from the final stage of a class-B modulator will reduce the output impedance of the driver stage as well, thereby contributing to reduced distortion by virtue of this action as well as by its normal distortion-reducing action.

Practical Applications

Although feedback can increase the initial damping factor to a high degree, the values realized in practice are somewhat less than theory indicates. The large damping factors that can be achieved in practical design, however, are well exemplified in the 20-watt wide-range, feedback amplifier shown in Fig. 10. This is the commercial type W-20 Williamson amplifier, in which 20 db of negative feedback is taken over four stages and the output transformer. The damping factor of this amplifier without feedback, measured by the method of Fig. 7, is 2 at 50 cycles (a common value of resonant frequency for high-quality low-frequency type loudspeakers). When 20 db of negative feedback is applied the damping factor is increased to 27, which is only slightly less than the theoretical value of 29 based upon the initial measured value of D_o.

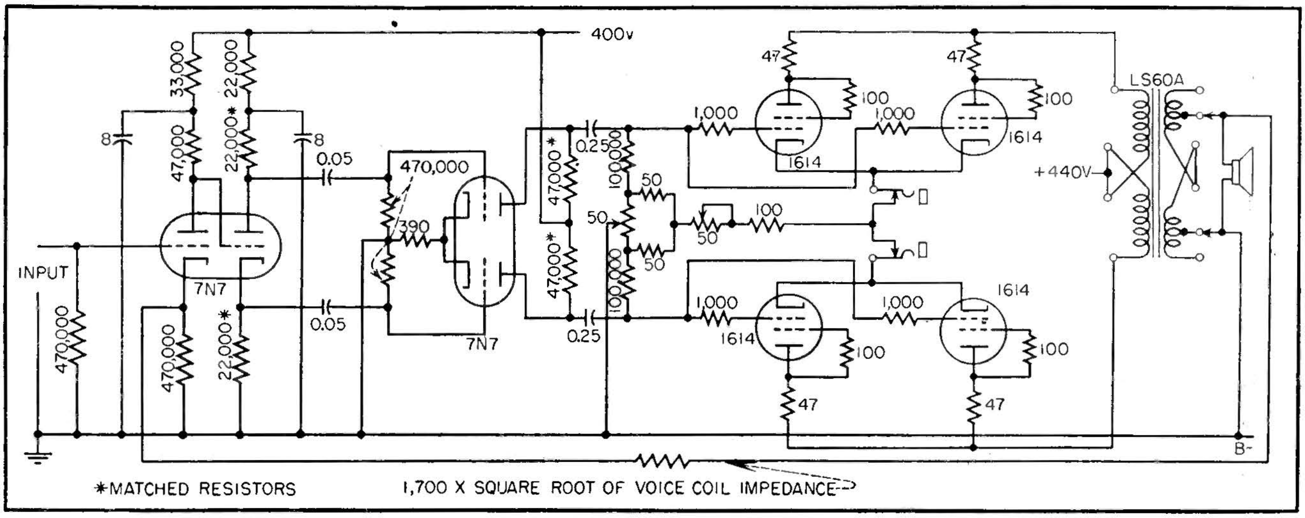


FIG. 10—Circuit diagram of the UTC W-20 Williamson feedback amplifier with damping factor of 27