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Control of Amplifier Source Resistance[*]

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Many varieties of variable damping-factor control have appeared in commercial high-fidelity amplifiers during the recent past. This paper discusses and categorizes the different forms, introducing an analysis of a general nature that is applicable to all present configurations. General equations are developed for the design of any type of circuit utilizing current-voltage feedback control of amplifier source impedance, whether it be fixed, semi-variable, or continuously variable. A new improved type of variable damping control characterized by a broad range of adjustment and simplicity of circuitry is described.

SINCE THE introduction of the variable damping control in March 1954, a great amount of interest has been shown both in the effects of damping on loudspeakers and in methods of controlling power-amplifier source resistance to obtain variable damping. The effects of damping on the loudspeaker have been treated elsewhere.[‡] The contention that some form of variable control is desirable is indicated by the fact that the majority of the quality power amplifiers now on the market incorporate this feature. The various control circuits take the form of several configurations. Described in terms of function, they are:

A. Switch activated with selectable but fixed positions such as +2, +20, −2.

B. Continuously variable, covering a range from the normal damping factor of the amplifier down to some lower positive value such as +20 to +0.1.

C. Continuously variable, covering a range from the normal amplifier damping factor up to a higher positive or even a negative value (beyond infinity the values become negative) such as +20 to infinity or to −2.

D. Continuously variable, covering a range from below to above the normal amplifier damping factor, such as +0.1 to −1.5.

The expression "normal damping factor" is used here to denote the inherent damping factor of the amplifier prior to addition of current feedback. All variable damping controls in use at present operate on the principle of introducing a feedback voltage that is proportional to the current passing through the amplifier load; this voltage is mixed in controlled proportions with the overall negative voltage-proportional feedback voltage.

The relationship between source impedance and damping factor may be stated as follows:

$$Z_s = \frac{Z_l}{DF} \tag{1}$$

where Z_s is the amplifier source impedance, Z_l is the load impedance, and DF is the amplifier damping factor. As is evident from eq. 1, an amplifier DF range of from +0.1 to −1.5 (related to a 16-ohm load) is equivalent to a source resistance range of from +160 ohms to −10.7 ohms.

The example given above pertains to the D-type of control circuit which provides for introduction of controlled amounts of either negative current feedback or positive current feedback. Type A does this also but is not continuously variable. Type B utilizes only negative current feedback while type C makes use only of positive current feedback. This paper treats only the two variations of the type D configuration, inasmuch as such an analysis is applicable to each of the other three types merely by restriction.

TWO POSSIBLE SYSTEMS

Let us examine the mechanism upon which the two systems of each of the aforementioned configurations are based. This can be clearly envisioned if we look at the method used to measure source resistance (or regulation). The source resistance of any circuit may be defined in terms of the variation in output voltage between loaded and no-load conditions.

$$Z_s = \frac{Z_l\,(E_o - E_c)}{E_c} \tag{2}$$

where E_o is the output voltage with no load and E_c is the output voltage under load.

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It may be seen by inspecting eq. 2 that we may choose whether we wish to keep *either* E_o constant *or* E_c constant as source impedance, Z_s, is varied. In a system designed to keep E_o constant, the damping control will have no effect on the output voltage under a condition of no load but will produce a variation in output voltage when the load is connected. In a system designed to maintain E_c constant, the damping control will produce a variation in output voltage with no load but will have no effect on the output voltage with load connected.

E_O-CONSTANT SYSTEM

The E_o-constant system can be used to advantage if a filter is employed in the current feedback circuit to restrict the gain variation and damping control to frequencies below roughly 300 cps. It is in this region that damping is most needed and most effective with the average loudspeaker. The gain variation can be utilized advantageously to equalize for low-frequency attenuation resulting from speaker overdamping or for low-frequency accentuation produced in an underdamped speaker. This system is shown in Fig. 1.

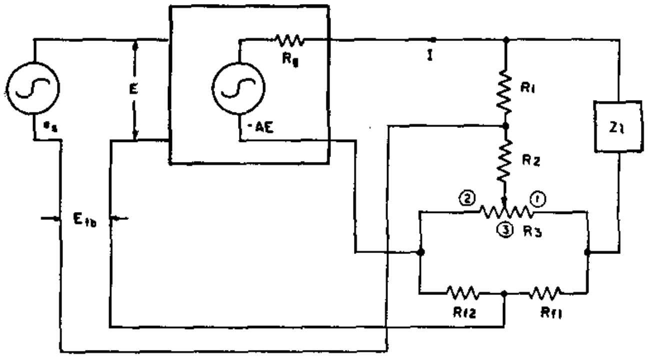

FIG. 1. Equivalent circuit of E_o-constant system for gain analysis.

CIRCUIT ANALYSIS

Figure 1 shows the equivalent circuit of an amplifier driving load Z_l. In the load return, a bridge circuit composed of R_{f1}, R_{f2}, and R_3 has been inserted to sample a voltage that is proportional to the current through the load. When the slider of potentiometer R_3 is in position 1, the current feedback is negative and adds to the negative voltage feedback. In position 2 the current feedback is positive and subtracts from the negative voltage feedback. Position 3 balances the bridge and there is zero current feedback.

GAIN ANALYSIS

The gain, A', of a feedback amplifier is defined by

$$A' = \frac{A}{1 - A\lambda} \qquad ($$

where A is the gain with no feedback and λ is the feedba factor. Let the following assumption be made:

$$R_1 + R_2 >> R_g$$
$$R_1 + R_2 >> R_f$$
$$R_f = R_{f1} + R_{f2}$$
$$\beta = \frac{R_2}{R_1 + R_2}$$

The voltage distribution about the loop can be expressed

$$AE = I(R_g + Z_l + R_f) \qquad ($$

The voltage, E, applied to the input of the amplifier is th sum of the signal e_s and feedback E_{fb} voltages.

$$E = e_s + E_{fb} \qquad (5$$

When the slider of R_3 is in position 3, no current feedbac is introduced. The total feedback voltage E_{fb} is

$$E_{fb} = IZ_l\beta \qquad (6$$

and

$$E_{fb} = -AE\lambda_3 \qquad (7$$

where λ_3 is the feedback factor in position 3. Combining eqs 4, 6, and 7,

$$\lambda_3 = \frac{Z_l\beta}{R_g + Z_l + R_f} \qquad (8$$

When the slider of R_3 is in position 1, negative current feedback is introduced. The total feedback voltage is

$$E_{fb} = I[Z_l\beta + R_{f1}(1 - \beta)] \qquad (9)$$

and

$$E_{fb} = -AE\lambda_1 \qquad (10)$$

where λ_1 is the feedback factor in position 1. Combining eqs. 4, 9, and 10,

$$\lambda_1 = -\frac{Z_l\beta + R_{f1}(1 - \beta)}{R_g + Z_l + R_f} \qquad (11)$$

When the slider of R_3 is in position 2, positive current feedback is introduced. The total feedback voltage is

$$E_{fb} = I[(Z_l + R_f)\beta - R_{f2}(1 - \beta)] \qquad (12)$$

and

$$E_{fb} = -AE\lambda_2 \qquad (13)$$

where λ_2 is the feedback factor in position 2. Combining eqs. 4, 12, and 13

$$\lambda_2 = -\frac{(Z_l + R_f)\beta - R_{f2}(1 - \beta)}{R_g + Z_l + R_f} \qquad (14)$$

By substituting λ_1, λ_2, and λ_3 in general gain eq. 3, the gain A' of the amplifier may be determined for each case. It can be seen from inspecting eqs. 1 and 2 that for a *DF* range of from +2 to −2, the *loaded* output voltage variation will be 3:1, or 9.5 db as the slider of R_3 is moved from position 1 to position 2.

SOURCE IMPEDANCE ANALYSIS

Figure 2 shows the same equivalent circuit as in Fig. 1, with the exception that the signal input terminals have been shorted and a current generator has been substituted for the load. The assumptions are the same as for the gain analysis. The voltage developed across the current generator will be

$$E_1 = IR_g - AE + IR_f \tag{15}$$

With the slider of R_3 in position 3, no current feedback is introduced. The voltage E applied to the amplifier input terminals is

$$E = E_1\beta \tag{16}$$

Combining eqs. 15 and 16 and solving for E_1/I,

$$Z_{s3} = \frac{R_g + R_f}{1 + A\beta} \tag{17}$$

With the slider of R_3 in position 1, negative current feedback is introduced. The voltage applied to the amplifier input is

$$E = E_1\beta - IR_{f1} \tag{18}$$

Combining eqs. 15 and 18 and solving for E_1/I,

$$Z_{s1} = \frac{R_g + R_f + AR_{f1}}{1 + A\beta} \tag{19}$$

With the slider of R_3 in position 2, positive current feedback is introduced. The voltage applied to the input terminals is

$$E = (IR_g - AE)\beta + IR_{f2} \tag{20}$$

Combining eqs. 15 and 20 and solving for E_1/I

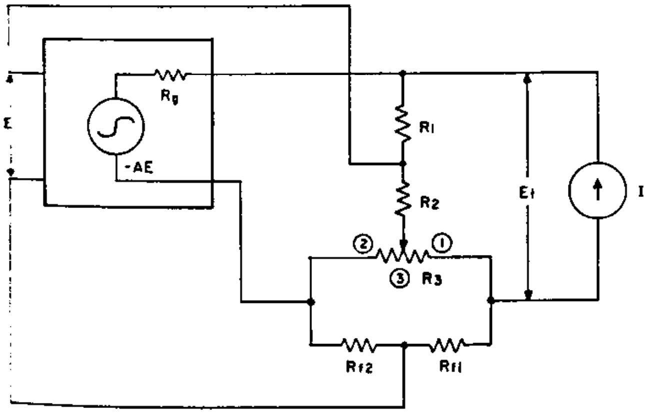

FIG. 2. Equivalent circuit of E_o-constant system for source-impedance analysis.

$$Z_{s2} = R_g + R_f - \frac{A\ (R_g\beta + R_{f2})}{1 + A\beta} \tag{21}$$

E_C-CONSTANT SYSTEM

This system is capable of a greater range of control than the E_o-constant system which has been described. Another obvious advantage over the E_o-constant system lies in its ability to permit a constant amount of negative feedback to be maintained around the amplifier regardless of the setting of the damping control. Hence, amplifier distortion is not a function of control adjustment. The circuit configuration is shown in Fig. 3.

CIRCUIT ANALYSIS

It can be seen from Fig. 3 that the bridge is arranged so that the arm of potentiometer R_3 can sample at one end of its travel, position 1, a negative feedback voltage that is 100% proportional to load current. At the other end of its travel, position 2, the arm samples combined negative voltage-proportional and positive current-proportional feedback voltages. If the value of current feedback resistor, R_{f1}, is selected to introduce the amount of negative feedback required by the amplifier design, and if the difference between the negative voltage feedback introduced by the voltage divider consisting of resistors R_1 and R_2 and the positive current feedback introduced by resistor R_{f2} is made to have a net negative phasing and is equal in amplitude to the voltage developed across resistor R_{f1}, the gain, A', of the loaded amplifier will then remain independent of the position of the arm of potentiometer R_3.

GAIN ANALYSIS

The assumptions made in the analysis of the E_o-constant system are also applicable to the analyses which follow. Equations 4 and 5 also apply.

Pure negative current feedback is introduced when the slider of R_3 is in position 1. The total feedback voltage is

$$E_{fb} = IR_{f1} \tag{22}$$

and

$$E_{fb} = -AE\lambda_1 \tag{23}$$

where λ_1 is the feedback factor in position 1. Combining eqs. 4, 22, and 23,

$$\lambda_1 = \frac{R_{f1}}{R_g + Z_l + R_f} \tag{24}$$

Combined negative voltage and positive current feedback is introduced when the slider of R_3 is in position 2. The total feedback voltage is

$$E_{fb} = I(Z_l + R_f)\beta - IR_{f2} \tag{25}$$

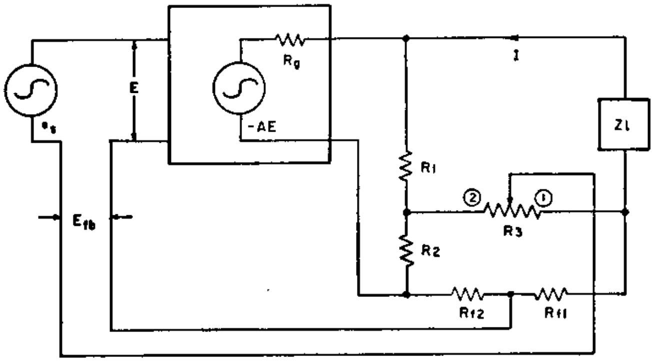

FIG. 3. Equivalent circuit of E_c-constant system for gain analysis.

and
$$E_{fb} = -AE\lambda_2 \tag{26}$$

where λ_2 is the feedback factor in position 2. Combining eqs. 4, 25, and 26,

$$\lambda_2 = -\frac{(Z_l + R_f)\beta - R_{f2}}{R_g + Z_l + R_f} \tag{27}$$

The values for λ_1 and λ_2 given by eqs. 24 and 27 may be substituted in general gain eq. 3 for determination of gain, A', of the amplifier.

To make the gain, A', remain constant as the slider of R_3 is moved from position 1 to position 2, make

$$\lambda_1 = \lambda_2 \tag{28}$$

Combining eqs. 24 and 27, we see that

$$R_{f1} = (Z_l + R_f)\beta - R_{f2} \tag{29}$$

or

$$\beta = \frac{R_{f1} + R_{f2}}{Z_l + R_f} \tag{30}$$

This can be stated in final form giving all parameters as

$$R_2 = \frac{R_1(R_{f1} + R_{f2})}{Z_l} \tag{31}$$

Inspection of eqs. 2 and 3 will indicate that the change in output voltage throughout control rotation under *no load* will be the same for an equivalent *DF* range as that for the *loaded* E_o-constant system, or 9.5 db for a range covering +2 to -2.

SOURCE IMPEDANCE ANALYSIS

Figure 4 shows the equivalent circuit of Fig. 3 with signal input terminals shorted and a current generator substituted for the load. The assumptions are the same as in the gain analysis. The voltage developed across the current generator is given by eq. 15:

$$E_1 = IR_g - AE + IR_f \quad (15$$

The slider of R_3 is set at position 1 to introduce pur negative current feedback. The voltage, E, fed back t the input, is

$$E = -IR_{f1} \quad (32$$

Combining eq. 32 with eq. 15 and solving for E_1/I,

$$Z_{s1} = R_g + R_{f2} + AR_{f1} \quad (33$$

When the slider of R_3 is set at position 2, the combine negative voltage-proportional and positive current-propo tional voltages that are fed back can be expressed as

$$E = (IR_g - AE)\beta + IR_{f2} \tag{34}$$

Combining eqs. 34 and 15 and finding E_1/I,

$$Z_{s2} = R_g + R_f - \frac{A(R_g\beta + R_{f2})}{1 + A\beta} \tag{35}$$

which is, as may be expected, the same expression obtaine for the source impedance of the E_o-constant system with th slider of R_3 in this position.

CONCLUSIONS

The foregoing presentation, in the author's view, indicates that the E_c-constant system is superior to the E_o-constant system on the following points:

1. System distortion remains constant and is independen of damping control adjustment.
2. With load connected the output-voltage level does no vary with damping control setting.
3. The range of source-resistance control is greater fo the same values of the parameters R_{f1} and R_{f2}. This i an important consideration inasmuch as a finite fraction of the amplifier power output is dissipated in th current feedback resistors.

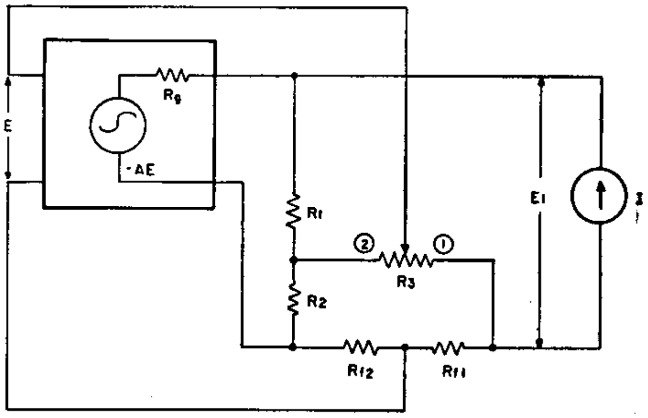

FIG. 4. Equivalent circuit of E_c-constant system for source-impedance analysis.

The only possible objection to the E_c-constant system as compared with the E_o-constant system is that the former provides no means to equalize for speaker response. However, such equalization must of necessity be a compromise if a single fixed network is employed. It has been found from experience that, in general, any such equalization that is required may be readily introduced by use of the bass tone control. More precise equalization, such as is obtainable with an insertion device having a variable inflection frequency, may be desirable in some cases; however, such a need is dependent on the characteristics of the loudspeaker system.

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