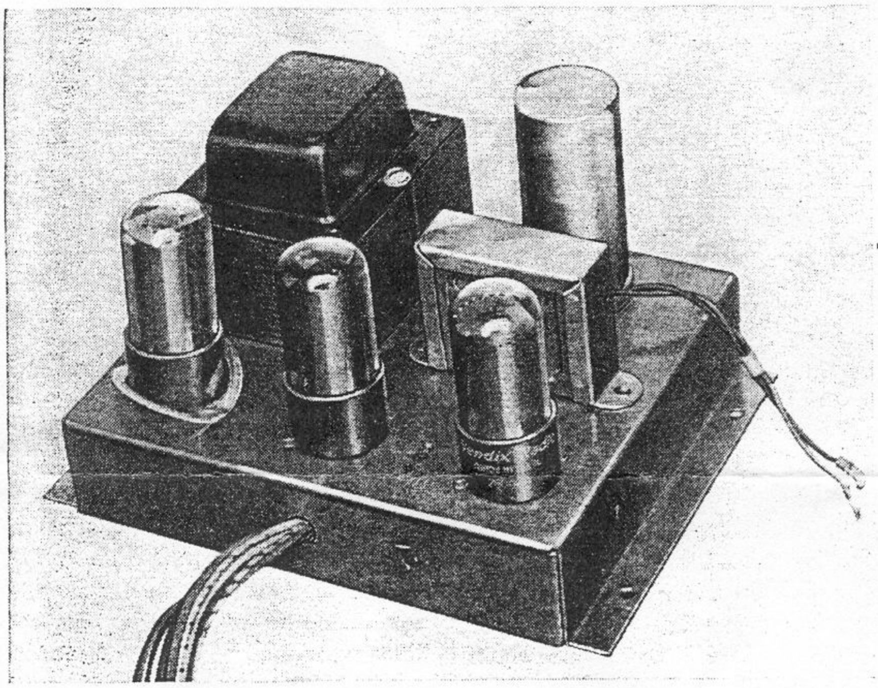
Combining Positive



Experimental output-stage chassis. Unit is capable of 5 watts output with 0.5-percent harmonic distortion at 400-cps. Note small output transformer

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IT HAS BEEN PROVED that the ear can detect as little as 0.5 percent of pentode distortion.[1] To achieve this low degree of distortion in typical pentode amplifiers, approximately 25 db of negative feedback is required. This sacrifice in gain, and the solution of the oscillation problem outside the passband, involve considerable added cost.

It is possible in a two-stage amplifier to approximate the results that would be obtained in a conventional amplifier with 25 db of negative feedback, by using a combination of local positive feedback in the first stage, and a moderate amount of overall negative feedback. The positive feedback has the effect of increasing the gain of the first stage. The general principle of combined feedback has been known for some time.[2]

The block diagram of a two-stage amplifier with combined feedback is shown in Fig. 1. The inherent voltage gains, with no feedback, of the first and second stages, are represented by A_1 and A_2 respectively, for very small signals; B_1 is the feedback ratio of the feedback around the first stage, and B_2 is the overall feedback ratio, for very small signals. The feedback ratio is defined as the ratio of the voltage fed back to the voltage existing at the point from which the feedback is obtained. These are all complex vector quantities, although their phase angles are likely to be very small in the vicinity of the amplifier band center. In the ideal case where there are no phase shifts, A_1 and A_2 are conventionally considered to be positive, and a feedback ratio is positive when the voltage fed back is in phase with the input.

Feedback Equations

The voltage gain is

$$A = \frac{A_1A_2}{1 - A_1B_1 - A_1A_2B_2} = \frac{A_1A_2}{N} \quad (1)$$

N is the vector quantity by which the gain without feedback, A_1A_2, is divided. If B_1 is positive (which would be the case for positive feedback), it has the effect of increasing the gain A; and B_2, if negative, tends to decrease the gain.

A term such as A_1B_1 or $A_1A_2B_2$ is known as a feedback factor. In the ideal case it will be a pure positive or negative quantity, but in the practical case, it will have a phase angle that is the sum of the phase angles of the factors involved. When there is no phase shift in the feedback network itself, the feedback ratio is considered to be a real quantity, and the phase angle of the feedback factor is equal to the sum of the phase angles of the A's involved.

The output impedance Z_2 is

$$Z_2 = Z_L \frac{(1 - A_1B_1)}{N(1 + Z_L/Z_{p2}) - (1 - A_1B_1)} \quad (2)$$

where Z_L and Z_{p2} are the load impedance and inherent output impedance of the output stage. It is seen in the above expression that when the product A_1B_1 is positive, a decrease in the output impedance can result.

The expression for distortion and gain stability is

$$D = \frac{D_1}{N} + D_2\left(\frac{1 - A_1B_1}{N}\right) + D_1D_2\left(\frac{1 - A_1B_1}{N}\right) \quad (3)$$

The inherent gain increments D_1 and D_2 in the first and second stages are caused, for example, by a change in applied static or instantaneous signal electrode voltages, or aging of the tube, and D is the resulting overall gain increment. The parameters D, D_1, and D_2 are each expressed as a fraction of A, A_1, and A_2. Equation 3 also holds if D_1, D_2, and D represent nonlinear distortion.

Regeneration and Distortion

For most purposes, optimum performance is obtained by designing so that the product A_1B_1 over the useful range of frequencies is approximately equal to unity. (If the negative feedback were temporarily removed, the first stage would be in a state of critical regeneration, with a gain approaching infinity.)

and Negative Feedback

Development of simple two-stage audio amplifier using a combination of local positive feedback in first stage and a moderate amount of overall negative feedback to approximate the results obtainable from conventional amplifier with 25 db negative feedback

From Eq. 2, we now obtain zero output impedance, and from Eq. 3 we find that the distortion and gain variation contributed by the final stage, including the output transformer, are reduced to zero. From Eq. 1, the gain becomes $1/-B_2$. In an amplifier using negative feedback only, it would be necessary to provide an infinite amount of feedback gain reduction to obtain these results.[3] Very good results can be obtained even when A_1B_1 departs from unity by ± 20 percent.

It will be seen from Eq. 3 that if A_1B_1 exceeds 2, the distortion introduced by the output stage will actually be greater than that which would be produced by omitting the positive feedback entirely. This shows the unsoundness with large feedback factors of the balanced feedback principle, in which A_1B_1 is made equal to $-A_1A_2B_2$, (N equals unity), since the distortion and gain variation are greater, though reversed in sign, than if no feedback at all were used.

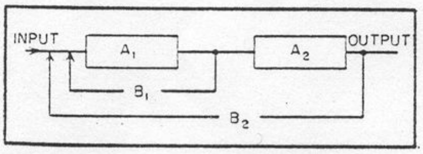


FIG. 1—Notation used for a two-stage amplifier showing two feedback paths

Oscillation

It is apparent from Eq. 1 that the quantity $(A_1B_1 + A_1A_2B_2)$ is analogous to the feedback factor AB in a conventional feedback amplifier, and may be considered to be the effective feedback factor in determining the possibility of oscillation. Thus we can use Nyquist's[4] and Bode's[5] criteria in analyzing any particular case. If, because of phase reversal in the feedback factor, a positive value of unity is assumed at some frequency, Eq. 1 gives a gain value of infinity, indicating oscillation. If the feedback factor is positive and greater than unity, oscillation will usually result, although there are exceptional cases, known as conditional stability[5], where oscillation does not result. However, in good practice it is customary to design so that the feedback factor never assumes a positive value greater than, say, 0.5.

Since the effective feedback factor $(A_1B_1 + A_1A_2B_2)$ must be held to a value less than plus unity at all frequencies to avoid oscillation, then if A_1B_1 equals plus unity, the negative feedback factor $A_1A_2B_2$ must never become zero or positive. This requirement cannot be met; in fact, the asymptotic phase shift in a loop containing a two-stage resistance-coupled amplifier and the primary and secondary of an output transformer is at least 270 degrees at very high frequencies with a resistance load. Thus it becomes necessary to cause A_1B_1 to assume a value other than unity at frequencies where $A_1A_2B_2$ is positive. A phase shift must be introduced into the feedback transmission network which, in conjunction with the phase shift in A_1, actually reverses the phase of A_1B_1 at very high and very low frequencies, so that it becomes negative feedback, although its amplitude is then very small. The local feedback factor A_1B_1 may now tend to oppose rather than aid oscillation at extreme frequencies where $A_1A_2B_2$ is positive, although A_1B_1 is still essentially positive and nearly unity

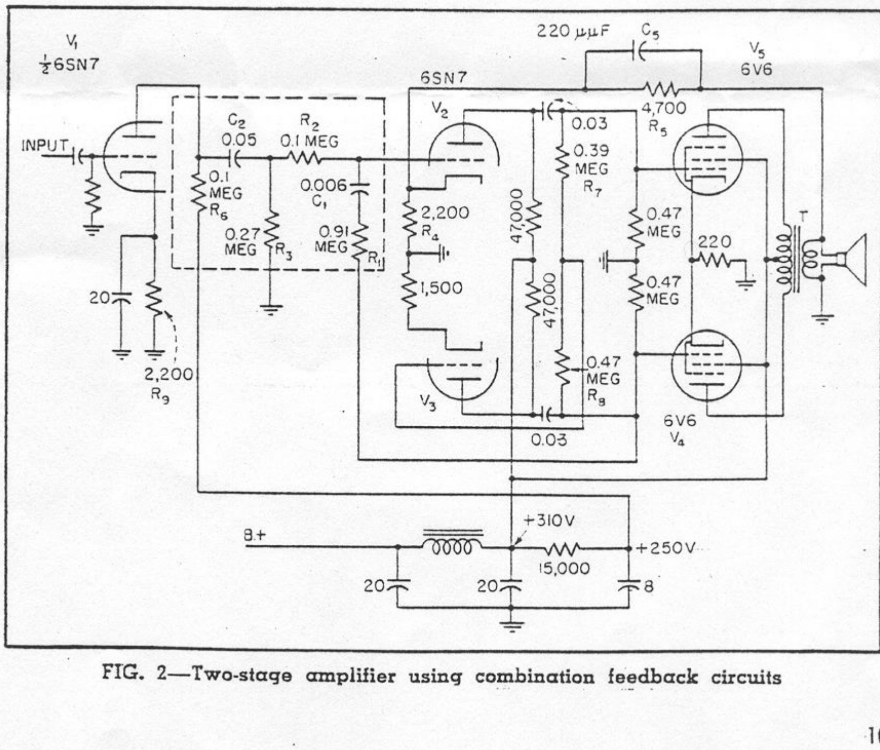


FIG. 2—Two-stage amplifier using combination feedback circuits

Table I—Distortion Figures for Various Combinations of Operating Conditions

Harmonic Distortion — 8 watts into 3.9-ohm speaker load

Harmonic	Frequency in Cps: 100 %	100 Db	400 %	400 Db	1,000 %	1,000 Db
2	0.12	58	0.2	54	0.17	55
3	0.09	61	0.24	52	0.32	50
4	0.04	68	0.045	67	0.036	69
5	0.034	69	0.017	75	0.04	68
6	0.002	94	0.003	90	0.02	74
7	<0.001	—	<0.001	—	0.006	84
8	—	—	—	—	0.006	84
9	—	—	—	—	<0.001	—
10	—	—	—	—	0.012	78
11	—	—	—	—	<0.001	—

Harmonic Distortion—3.9-ohm load

Harmonic	50 Cps, 5 watts %	50 Cps, 5 watts Db	2 Kc, 4 watts %	2 Kc, 4 watts Db
2	0.7	43	0.1	60
3	0.88	41	0.23	53
4	0.03	70	0.006	84
5	0.08	62	0.02	74
6	0.01	80	0.002	94
7	0.02	74	0.008	82
8	0.004	88	—	—
9	0.002	94	—	—
10	0.002	94	—	—

Percent Harmonic Distortion—8 watts into 3.9 ohms at 100 cps

Harmonic	No feedback	Negative feedback	Pos-neg feedback
2	0.6	0.07	0.12
3	6.0	2.2	0.094
4	0.15	0.01	0.04
5	0.6	0.08	0.034
6	0.2	0.08	0.002
7	0.2	0.04	<0.001

Percent Harmonic Distortion—8 watts into 3.9 ohms at 400 cps

Harmonic	No feedback	Negative feedback	Pos-neg feedback
2	1.4	0.3	0.2
3	7.0	2.4	0.24
4	0.6	0.1	0.045
5	1.2	0.08	0.017
6	0.14	0.02	<0.001
7	0.27	0.02	<0.001

Percent Intermodulation Distortion—8 watts into 3.9 ohms, 4 to 1 voltage ratio at 60 and 100 cps

Frequency	No feedback	Negative feedback	Pos-neg feedback
	60 Cps		
2 kc	—	—	1.4
7 kc	40	8.0	1.9
12 kc	—	—	2.2
	100 Cps		
2 kc	—	6.6	0.52
7 kc	—	5.8	0.84
12 kc	—	6.1	1.0

throughout the band of useful frequencies.

The amplifier of Fig. 2 incorporates positive and negative feedback. It is otherwise conventional, using self-bias throughout, and a highly degenerative self-balancing phase inverter. The output transformer is small, having a $\frac{3}{4} \times \frac{3}{4}$-inch stack. The copper efficiency is about 80 percent.

The overall negative feedback is obtained from the secondary of the output transformer T, and is fed through R_5 to the cathode of V_2. Shunt capacitor C_5 affords some feedback phase correction at very high frequencies. The feedback gain reduction is 9 db, and becomes 11 db with the positive feedback disconnected.

The positive feedback is obtained from the grid of V_4, and is fed through R_1 and C_1 to the grid of tube V_2. The positive feedback voltage is developed primarily across R_2 and C_2, since the plate resistance of V_1 is relatively small, and the input resistance of the grid of V_2 is high. The positive feedback is designed so that, with the negative feedback disconnected, V_2 will be near oscillation or oscillating weakly. Since the voltage gain of the stage V_2 is approximately 10, about one-tenth of the voltage on the grid of V_4 is fed back to the grid of V_2. The resistance of R_1 is therefore made about nine times that of R_2, and C_2 has about nine times the capacitance of C_1. Thus the phase and amplitude of the positive feedback is maintained flat over the range of audio frequencies. Because of the highly degenerative nature of the phase inverter, the balance is not appreciably affected by the additional load of the positive feedback network.

Some phase shift in the positive feedback is obtained at extreme frequencies in the stages V_2 and V_3 due to electrode and stray capacitances, and due to the blocking capacitors. The input capacitance of the grid of V_2 causes a further phase shift, so that the polarity of the product A_1B_1 reverses from positive to negative at extremely high frequencies. The input capacitance of V_2 is primarily dynamic, due to feedback through its grid-plate capacitance[6], at very high frequencies where the overall feedback is positive or small.

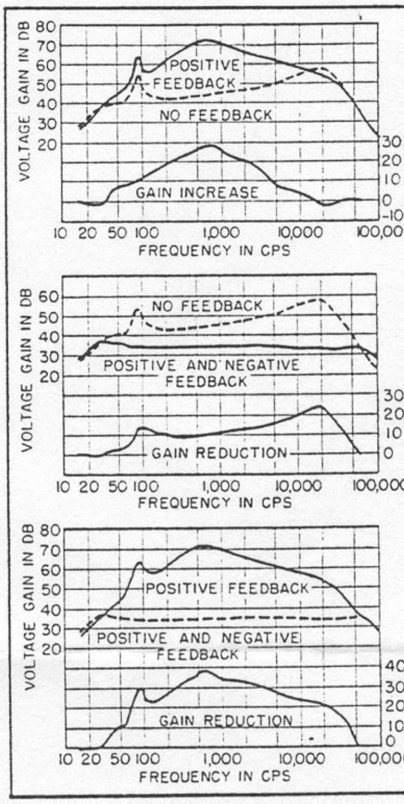


FIG. 3—Amplifier response curves for various types of feedback with 0.5-watt input to a 3.9-ohm loudspeaker load

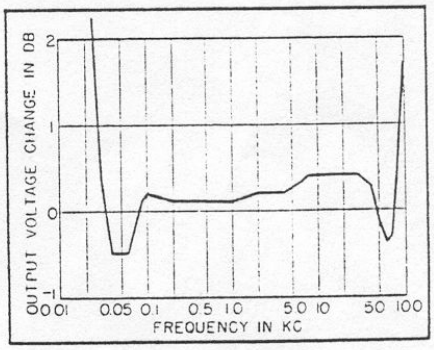


FIG. 4—Voltage regulation in db with 1-volt output into 3.9-ohm loudspeaker load

In some designs, it may be necessary to connect a small capacitor from the grid of V_2 to ground, or to use a more elaborate phase-shift network to obtain a sufficiently rapid phase turnover in the local feedback.

At extremly low frequencies most of the local feedback current flows through R_3 instead of through C_2, so that a phase shift is obtained, which together with the phase-shifting action of the 0.03-μf blocking capacitors in stages V_2 and V_3, is sufficient to cause the desired phase reversal. In practice, the phase reversal frequencies are placed as far outside the desired pass band as good stability permits.

Performance Measurements

Figure 3 permits the determination of the quantities $(1-A_1B_1)$, $(1-A_1B_1-A_1A_2B_2)$, or N, and ratio $(1-A_1B_1-A_1A_2B_2)/(-A_1B_1)$.

Figure 4 indicates a negligibly small output impedance, since the output voltage varies only slightly when the speaker load is disconnected. The regulation of 0.1 db at 400 cycles may be compared with the regulation of 2.7 db that is obtained with the positive feedback disconnected (11 db of negative feedback remaining) or the regulation of 19 db that is obtained with no feedback.

The distortion indicated in Table I would presumably be inaudible even with a wide-range loudspeaker. The intermodulation distortion averages three or four times as much as the harmonic distortion, as would be expected. The table shows that the positive feedback causes a great reduction in distortion.

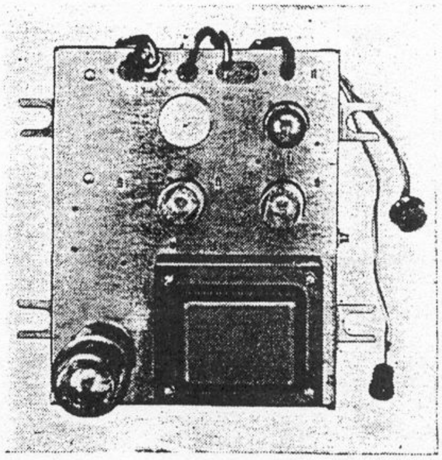
Design Improvements

The amplifier of Fig. 2 is not represented as being the ultimate in design of a positive-negative feedback amplifier, although it seems probable that most major improvements would involve cost increases.

If the negative feedback could be made uniform over a wider frequency range, the local positive feedback could also be made effective over a wider range. A wide-band output transformer would be helpful. Reducing R_1, R_2, R_3 and R_6 and R_9, and increasing C_2 and C_1, will also be helpful. The grid-plate capacitance of V_2 could be largely neutralized by shunting R_1 with a small capacitor of, say, 3 micro-microfarads. The last two measures would reduce the high-frequency phase shift in the overall feedback that is caused by the Miller effect in V_2. Also, R_7 could be shunted with a small capacitor to reduce the phase shift caused by the grid-plate capacitance of V_3. It would also be desirable to replace R_1 by a network having a rapid phase turnover at ultrasonic frequencies and a small phase shift at audio frequencies.

Low-Cost Amplifier

Figure 5 shows the circuit of an economical amplifier. Type 6K6GT output tubes are used, and the current drain is so low that a 5Y3 rectifier is used at less than its rated operating conditions, and with resistance filtering only. The hum is almost inaudible even in a quiet room, being 67 db below maximum level. In production, the output regulation rarely exceeds $\pm$ 0.2 db, and the response is flat over the useful range of frequencies. No production difficulties have arisen, although many many thousands of units have been manufactured, and no special selection of tubes or components has been made. Numerous production units selected at random for test had an average harmonic distortion at 400 cycles of 0.5 percent with 5 watts output. With a shock impulse at the amplifier input, the transient output across the loudspeaker voice coil is negligibly small after the first cycle.



Top view of complete low-cost audio amplifier. Output transformer is mounted beneath the chassis

The photograph of this amplifier shows the output transformer to be small. However, the harmonic distortion in the 60-cps output at five watts is only one percent. The 6SN7GT driver-phase inverter is not shown, as it is located on the tuner chassis of the receiver.

Conclusions

In conclusion, it appears that combined positive and negative feedback offers considerable possibility for improved performance in pentode audio power amplifiers, particularly where cost is an important consideration, and when conventional mass-production techniques are used.

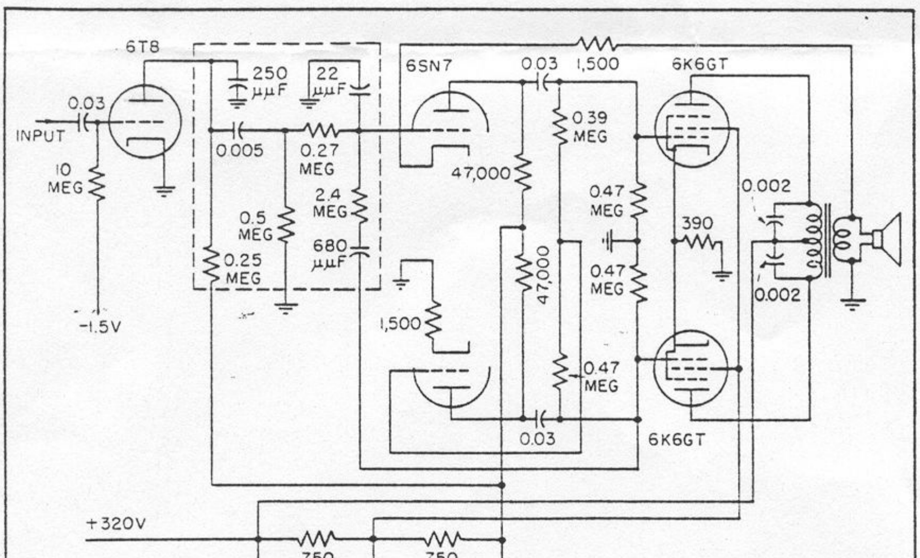


FIG. 5—Complete schematic of a low-cost audio amplifier using combination feedback

REFERENCES

(1) H. F. Olson, "Elements of Acoustical Engineering," Second Edition, D. Van Nostrand Co., Inc., New York, p 488.

(2) F. E. Terman, "Radio Engineers' Handbook," McGraw-Hill Book Co., Inc., New York, First Edition, sec. 5, par. 11.

(3) H. S. Black, Stabilized Feedback Amplifiers, *B.S.T.J.*, Jan. 1934.

(4) H. Nyquist, Regeneration Theory, *B.S.T.J.*, July 1932.

(5) H. W. Bode, Relations between Attenuation and Phase in Feedback Amplifier Design, *B.S.T.J.*, July 1940.

(6) J. M. Miller, Dependence of the Input Impedance of a Three Element Vacuum Tube upon the Load in the Plate Circuit, NBS Scientific Paper 351.