Novel FEEDBACK LOOP Stabilizes

Performance of audio generator is independent of load or transistor parameters.

AUDIO OSCILLATORS usually have an oscillator section followed by an amplifier to isolate load variations. More efficient use of components can result when the oscillator and amplifier circuits are combined to form a single oscillator stage with sufficient power to drive the load directly. However, load variations must then be considered in the design.

Transistor circuits have the advantages of good reliability, small size, and low power dissipation, but transistors are far less stable than vacuum tubes with respect to temperature changes, operating-point and supply voltage variations.

Extensive negative feedback is used in this circuit both to minimize the effects of the unstable transistor characteristics and to make the oscillator independent of load variations. With this feedback the amplifier gain mainly depends on stable resistors. The result is low distortion and excellent amplitude and frequency stability.

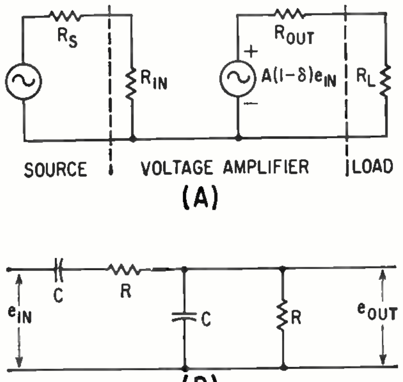
OPTIMUM LOOP GAIN — The performance of a feedback amplifier is usually equated with the ratio of open-loop gain to closed-loop gain, and this leads to the notion that the more loop gain, the better. This is partially true for tube circuits, which closely approach ideal voltage amplifiers, but it can be misleading with transistor amplifiers.

To illustrate the point, consider a voltage amplifier, represented by

LOOP MAKES THE DIFFERENCE

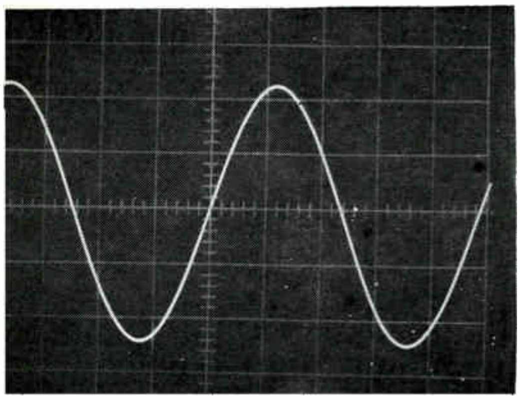
In this generator a negative feedback loop stabilizes not only the oscillator, but the amplifier as well. Using a feedback loop as an amplifier stabilizer is not new; but using a loop to stabilize the oscillator-amplifier combination is, as far as we know, a new approach.

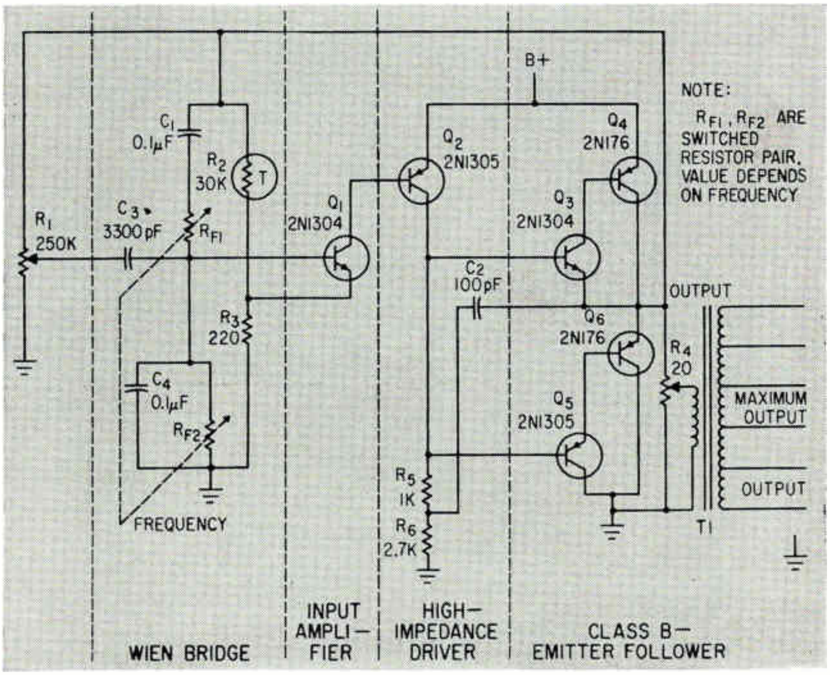
One side advantage of the oscillator with optimum feedback: it can be manufactured cheaply. Its output is largely independent of transistor parameters and transistor sorting is unnecessary



EQUIVALENT *circuit of a voltage amplifier with feedback for frequencies not near resonance (A). Frequency determining part of Wien-bridge oscillator used in the audio generator—(B)—Fig. 1*

OUTPUT WAVEFORM *of the oscillator shows no detectable crossover distortion*





COMPLETE CIRCUIT *diagram of the oscillator-amplifier; the negative feedback path goes from the output, to thermistor R_2 and resistor R_3—Fig. 2*

Audio Oscillator

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Circuit is economical because transistors need not be preselected

the equivalent circuit of Fig. 1A. The voltage gain of the amplifier in this circuit is approximately equal to the theoretical gain A less an error term $A\epsilon$

$$\frac{e_{out}}{e_{in}} \cong A\,(1 - \epsilon) \qquad (1)$$

$$\epsilon = \delta + \frac{R_s}{R_{in}} + \frac{R_{out}}{R_L} \quad \text{if } \epsilon \ll 1 \qquad (2)$$

where R_{in} = the input resistance, $A\,(1 - \delta)\,e_{in}$ = a controlled voltage source, A = the ratio of feedback resistors, R_{out} = the output resistance, R_s = the source resistance and R_L = the load resistance. The positive feedback in an oscillator alters this picture at resonant frequency, but becomes less important at other frequencies. It is usually unimportant at the frequencies of the distortion and noise components, so it is valid to consider the amplifier separately.

Since each of the error terms is a function of the nonlinear and variable characteristics of transistors, each should be as small as possible; an optimum amplifier minimizes the three error terms. Thus, by increasing the loop gain, one or more of the terms may decrease but the most important term may be left large.

Consider designing a high impedance emitter follower circuit. The input impedance of one stage is $R_{in} = \beta R_L$. If three stages are cascaded the overall current gain increases to $\beta_1\,\beta_2\,\beta_3$. However, the collector impedance of the first stage shunts and limits the input impedance to a few megohms; and much higher input impedance with less loop gain can be realized.

PRACTICAL DESIGN—A practical example of optimum feedback amplifier design is seen in the General Radio type 1311-A audio oscillator. The frequency-determining part of its Wien-bridge network is shown in Fig. 1B. The voltage transfer ratio can be written as

$$\frac{e_{out}}{e_{in}} = \frac{1}{3 + j\left(\frac{f_0}{f} - \frac{f}{f_0}\right)} \qquad (3)$$

where $f_o = 1/2\pi RC$ which becomes equal to $\frac{1}{3}$ at the resonant frequency f_o. To form an oscillator, the overall system gain must be unity; therefore, the associated amplifier must have a voltage gain of +3. This figure is the gain, A, in Eq. 1. The input resistance, R_{in}, should be much higher than the source resistance, R_s, presented by the network, and the output resistance, R_{out}, should be much lower than the load resistance, R_L.

The circuit shown in Fig. 2 is a schematic diagram of the oscillator circuit. The negative feedback path consists of a thermistor, R_2, and a resistor, R_3. The thermistor, a small bead unit sealed in an evacuated bulb, limits the amplitude of oscillation at a point where the amplifier gain is +3. The complete amplifier is direct-coupled with d-c feedback for good bias stability. Phase-compensation networks are used to insure high-frequency stability as is common in most high-performance feedback circuits.

The power level desired indicated the use of a class-B output stage. To eliminate the crossover distortion without the use of temperature-sensitive bias networks usually associated with class-B circuits, the output stage is driven from a high-impedance driver. This technique is based on the fact that the current gain of a transistor is reasonably constant at low currents, whereas transconductance drops rapidly at low input voltages because of nonlinear input resistance.

The complementary output circuit has a single-ended output and eliminates the need for a closely coupled output transformer.

The single-ended input eliminates the need for a phase splitter or driver transformer. The collector of Q_2 forms the high-impedance source for driving the output stage. The capacitor C_2 keeps both ends of the collector resistor, R_5 at roughly the same potential, so it will appear in the circuit as a high impedance.

The characteristics of the complete amplifier are $R_{in} \cong$ 10 megohms, $R_{out} \cong$ 5 milliohms, and $\delta \cong 0.4 \times 10^{-3}$.

The source impedance presented to the amplifier from the frequency network varies from 15,000 ohms to 80 ohms, depending on the position of the frequency switch, and is 800 ohms at 1 Kc. The load impedance (R_L) reflected by the output transformer at full load is about 6 ohms. Using these values in Eq. 3, the overall error with which the gain ratio differs from ratio of the two feedback resistors is less than

$$\epsilon \approx 0.4 \times 10^{-3} + 0.1 \times 10^{-3} + 0.8 \times 10^{-3} = 1.3 \times 10^{-3}$$

The gain of the amplifier is 99.9 percent dependent on the ratio of resistors, and 0.1 percent dependent on active devices. As a result, variations in the characteristics of transistors due to temperature and line-voltage changes and to aging result only in extremely small changes in the overall characteristics of the oscillator. A frequency is typically changed less than ±0.01 percent by a ±10 percent change in line voltage. The effective nonlinearities in the transistors are similarly attenuated, so that the harmonic distortion caused by the amplifier is less than 0.1 percent under these conditions. At low frequencies, the transformer and the time constant of the thermistor add some distortion, while at high frequencies some added distortion is caused by the decreasing current gain of the power transistors.

BIBLIOGRAPHY

J. R. Macdonald, "Nonlinear Distortion Reduction by Complementary Distortion," *IRE Trans on Audio*, Vol. AU-7 No. 5, September-October, 1959.

J. J. Faran and R. G. Fulks, High-Impedance Drive for the Elimination of Crossover Distortion," *IRE Trans on Audio*, Vol. AU-10 No. 4, July-August, 1962.