A QUICK, CONVENIENT METHOD FOR MEASURING LOOP GAIN

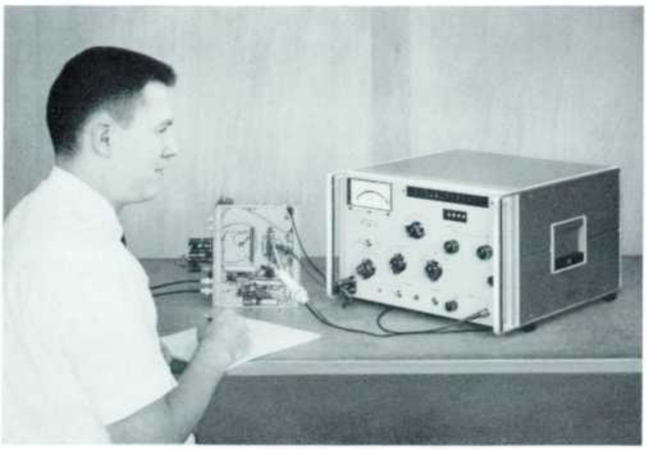

Fig. 1. *By using an -hp- AC-21F clip-on probe to couple signal output from -hp- Models 302A or 310A Wave Analyzer into feedback loop, loop gains can be measured easily and without breaking loop.*

CONVENTIONALLY, measurements of loop gain $A\beta$ are made by opening the feedback loop and then measuring the output obtained in response to a known input. Difficulties arise here, though, because the simulated load impedance must duplicate the impedance presented to the output stage when the loop is closed, and auxiliary bias sources must be added if dc feedback is employed.

New techniques now allow measurement of loop gain with the loop closed, providing rapid, easily-obtained results[1]. These measurements are made with the *-hp-* AC-21F current probe for signal injection, and either the *-hp-* 302A or 310A wave analyzer for signal measurement. The current probe, used inversely to its usual current-sensing function, serves as a coupling transformer for feeding the driving signal into the system, simply by being clipped around a circuit lead. Values of $A\beta$ over a wide range of frequencies and magnitudes, including $A\beta$ less than unity, are readily obtained. In addition, the phase angle of $A\beta$ at frequencies near gain crossover is easily determined.

THEORETICAL CONSIDERATIONS

Insertion of an isolated voltage source in series with the signal path of a feedback system does not alter the characteristics of the feedback loop, an ideal voltage source having zero series impedance and no shunt conductances to ground. Voltages

[1] B. M. Oliver and C. O. Forge, private communication.

WAVE ANALYZER

(Continued from page 4)

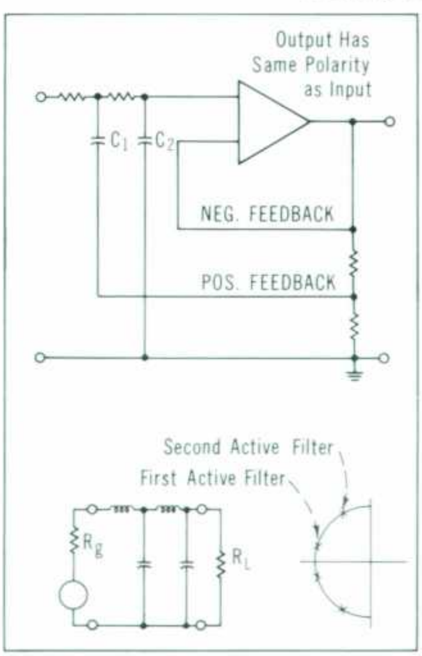

Fig. 8. *Passband of new analyzer is shaped using active filter (top) which minimizes shielding problems. Two filters are cascaded (below) to achieve sharp cut-off. Passband is made maximally flat by placing poles on semicircle in complex frequency plane.*

of course, that frequencies of less than a few cycles per second are attenuated. When translated back to the original IF frequency, the overall passband has a notch at 3 Mc, the notch being less than 1 cps wide at the 3 db points. The notch enables a signal to be tuned precisely to band center for precision frequency measurement. The discriminator, on the other hand, locks on to the edge of the notch so that a harmonic component is not attenuated by the notch during amplitude measurement.

ACKNOWLEDGMENTS

Members of the design team for the *-hp-* 310A were Richard Van Saun, Richard Raven, Richard Osgood, and the undersigned. We are all grateful for the suggestions and ideas of Brunton Bauer, Paul Stoft, Dr. B. M. Oliver, and others.

—Stanley McCarthy

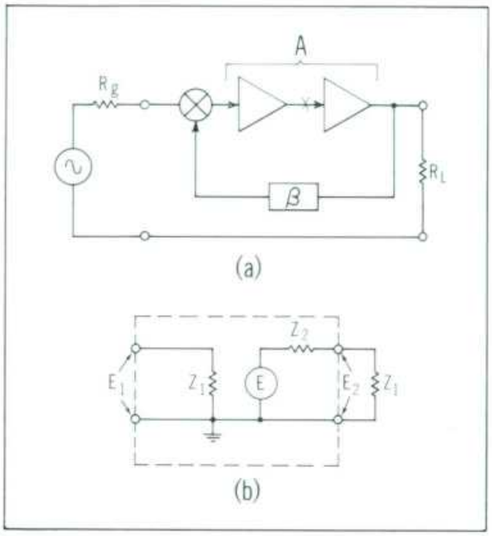

Fig. 2. *(left) (a) Diagram of basic feedback amplifier. (b) Alternate representation of (a).*

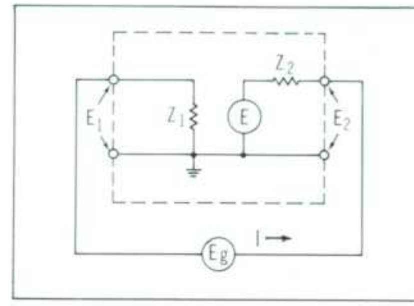

Fig. 4. *Circuit representation when voltage is injected into loop.*

are established, however, which allow $A\beta$ to be determined directly. To understand how $A\beta$ can be measured in this manner, consider the feedback amplifier shown in Fig. 2(a). The amplifier has the normal generator and load impedances connected and the loop is opened at some convenient point (not necessarily in the β circuit). A duplicate of the impedance Z_1, measured when looking into the system at the break point, is connected to the new output, as shown in Fig. 2(b).

Since E_1 is modified by both A and β when traveling around the loop,

$$E_2 = A\beta\, E_1 \tag{1}$$

The voltage source E is simply:

$$E \doteq \frac{Z_1 + Z_2}{Z_1} E_2, \tag{2}$$

$$\text{or, } E \doteq \frac{Z_1 + Z_2}{Z_1} A\beta\, E_1 \tag{3}$$

Now consider the situation in Fig. 4. Here, the loop is closed and a voltage source is connected in series with it. This represents the normally closed feedback loop since no additional impedances have been introduced. The disturbance created by the presence of the voltage E_g, however, causes voltages E_1 and E_2 to be established by the reaction of the feedback loop.

The voltage on the output side of the generator is:

$$E_2 = IZ_2 + E \tag{4}$$

The current may be expressed as:

$$I = E_1/Z_1 \tag{5}$$

Substituting equations (5) and (3) for I and E respectively in equation (4) yields:

$$E_2 = \frac{E_1}{Z_1} Z_2 + \frac{Z_1 + Z_2}{Z_1} A\beta E_1 \tag{6}$$

If $Z_2 << Z_1$ then $E_2 = A\beta\, E_1$, as in equation (1), even though E_g has been added to the circuit. Thus,

$$A\beta = E_2/E_1 \tag{7}$$

Thus it is seen that simply by introduction of the voltage E_g in series with the loop, two voltages E_1 and E_2 are established which determine $A\beta$ directly.

Fig. 3. *-hp- AC-21F clip-on probe, normally used for sampling ac current, is used in loop gain measurements to inject signal from Analyzer into loop.*

The voltage source E_g may be placed at any point in the loop where the signal is confined to a single path and where $Z_2 << Z_1$. The load and generator impedances normally used with the amplifier should be connected to the normal output and input terminals.

The amplitude of E_g must be small enough to avoid saturation in any of the active elements and consequently, either E_1 or E_2 will be quite low. Sensitive wave analyzers, such as the *-hp-* Models 302A or 310A (see article on page 1), are well-suited to making $A\beta$ measurements involving these small signals. Narrow bandwidths insure a high degree of noise and spurious signal rejection. The signal available from the wave analyzer operating in the BFO mode can be used for E_g, so that both source and measurement circuits are tuned simultaneously.

The series impedance introduced into the test circuit by the clip-on ac current probe is approximately 0.01 Ω shunted by 1 microhenry, and shunt impedance is only about 2 pf. When driven by the wave analyzer, the voltage produced in the test circuit is about 10 mv, a convenient level.

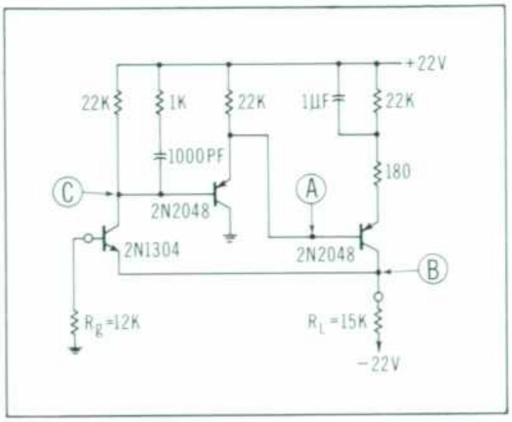

Fig. 5. Circuit of amplifier on which loop gain was measured using technique described in text.

PRACTICAL EXAMPLE

The loop gain of the amplifier shown in Fig. 5 was measured with this technique, E_g being inserted at point A. At this point, Z_2 was calculated to be no more than 400 Ω and Z_1 was about 10,000 Ω. The requirement that $Z_2 << Z_1$ is satisfied here. The plot of measured loop gain versus frequency is shown in Fig. 6.

To read loop gain directly in db units, E_2 is set to the 0 db level on the analyzer by adjusting the amplitude of E_g. E_1 consequently is measured in negative db units and, when the sign is reversed, these readings represent $A\beta$ in db.

Note that loop gains of less than unity (below 0 db) are easily measured. In this case, the 0 db reference is set to E_1 and then E_2 represents the value of $A\beta$ in db units.

Measurement of $A\beta$ values less than unity can be useful. For instance, if the circuit is not stable when the loop is closed, resistive attenuation may be introduced somewhere in the loop to avoid oscillations. The relative values of $A\beta$ then are measured and when plotted, the reasons for instability may be determined.

The phase angle of $A\beta$ is readily determined through construction of a vector diagram, as shown in Fig. 7. This is merely a graphical depiction of the relation: $E_2 = E_1 + E_g$.

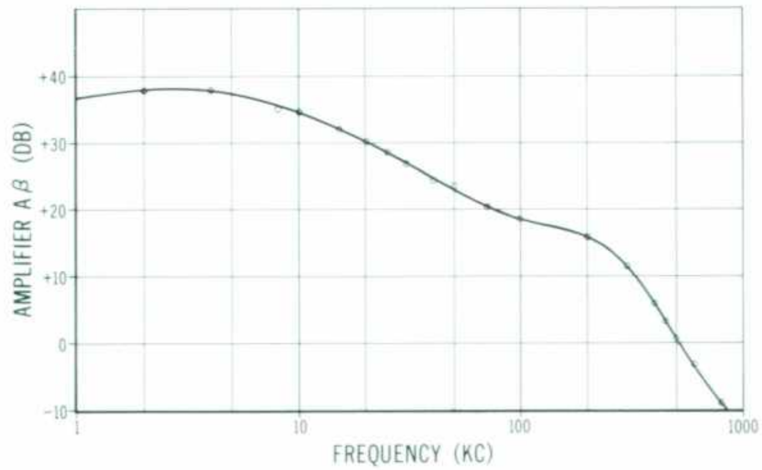

Fig. 6. Loop gain characteristic measured on amplifier of Fig. 5.

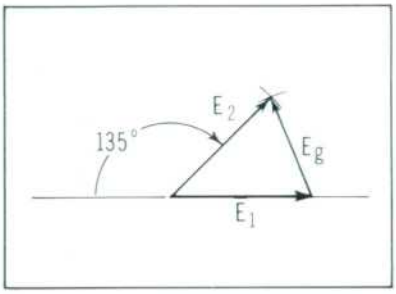

Fig. 7. *Phase angle of loop is easily determined by constructing basic diagram.*

E_2 and E_1 are measured directly and E_g is measured by shorting the voltmeter input leads together and clipping the current probe around them. For negative feedback, the phase angle usually is measured from the −180 degree reference.

ALTERNATIVE METHOD

It may not always be possible to find a point where $Z_2 << Z_1$. A similar measurement technique, the dual of the voltage technique, applies when $Z_2 >> Z_1$. The amplifier of Fig. 2 is shown in Fig. 8 with a current source connected from the signal path to ground. As before, the feedback loop is closed but current source I_g causes I_1 and I_2 to be established.

Referring to Fig. 8:

$$E_1 = -I_1 Z_1 \quad (8)$$

$$\text{and } E_2 = I_2 Z_2 + E \quad (9)$$

Substitution of equation (3) gives:

$$E_2 = I_2 Z_2 + \frac{Z_1 + Z_2}{Z_1} A\beta E_1 \quad (10)$$

Since $E_2 = E_1$, equations (8) and (10) may be combined:

$$-I_1 Z_1 = I_2 Z_2 - \frac{Z_1 + Z_2}{Z_1} A\beta I_1 Z_1 \quad (11)$$

If $Z_2 >> Z_1$:

$$\text{Then } A\beta = I_2/I_1 \quad (12)$$

A dual to the first method therefore exists, with currents replacing voltages in the determination of loop gain.

As in the voltage case, the normal input and output load impedances should be connected. The temporary input and output again may be chosen at any point where the signal is confined to one path. A resistor usually is adequate for converting a voltage generator to a current source (a capacitor may be placed in series with the resistor to block dc). In this case, the resistance should be large with respect to Z_1.

This technique was also used to measure the loop gain of the amplifier shown in Fig. 5. Point B was selected as the current node. Here, Z_2 is the output impedance of an amplifier with local emitter feedback, approximately one megohm, and the input impedance of the following emitter is about 270 Ω which meets the requirement that $Z_2 >> Z_1$.

A current source was simulated by connecting a 10K resistor ($>> Z_1$) in series with the wave analyzer's BFO output. The current probe sensed each current I_2 and I_1, supplying a proportional voltage to the input of the wave analyzer (termination of the current probe is not required since only relative measurements are being taken). Using this technique, the maximum deviation from the values of $A\beta$ obtained by the voltage source method was only 0.3 db.

Since $I_2 = I_1 + I_g$, a vector diagram may be constructed to find the phase angle of $A\beta$, as was done in the first method.

DC LOOP GAIN

Another technique, primarily useful for obtaining the dc loop gain, is based upon the equation[2]:

$$Z_{fb} = Z_{nf} \frac{1 - A\beta_{sc}}{1 - A\beta_{oc}} \quad (13)$$

where:

Z_{nf} = impedance between two nodes with A reduced to zero,

Z_{fb} = impedance observed when normal feedback is present,

$A\beta_{sc}$ = loop gain with nodes shorted together, and

$A\beta_{oc}$ = loop gain when no external admittance is connected between the nodes.

[2] T. S. Gray, "Applied Electronics," 2d Ed. p. 587.

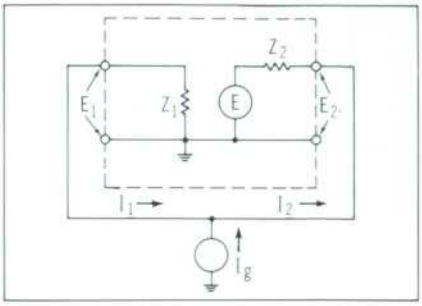

Fig. 8. *Circuit representation when current is injected into loop.*

At dc, two nodes usually can be found where $A\beta_{sc}$ or $A\beta_{oc} = 0$ and where Z_{nf} can be calculated. Then, by connecting a current source between the nodes, and noting the voltage change, Z_{fb} can be calculated from equation (13).

To measure the dc loop gain of the amplifier shown in Fig. 5, a current of 36 μa was injected between point C and ground. A voltage change of 0.4 v at point C was observed. Thus, Z_{fb} is $0.4/36 \times 10^{-6} =$ 11 k. Since the input impedance of the stage connected to this point, and also the output impedance of the previous stage, are very high, Z_{nf} is the same as the collector load resistance (22k). If point C were grounded, $A\beta_{sc}$ would be zero and if it were left ungrounded, $A\beta_{oc}$ would equal $A\beta$, the normal loop gain. Substituting these values in equation (13) yields:

$$11{,}000 = 22{,}000 \frac{1}{1 + A\beta}$$

from which,

$$A\beta = \frac{22{,}000}{11{,}000} - 1 = 1$$

—Philip Spohn