The Loop Test Board permits the loop gain of FBV instruments to be measured without having to break the feedback loop. This allows the loop to continue to maintain control of the boom centering while measurements are being made.

In addition to the Test Board, a cable is needed to connect it to the Electronics Board of the seismometer under test. The cable has identical 5-pin Molex connectors on both ends, pin 1 connected to pin 1, 2 to 2, etc. It both provides power to the test board and connects the test signals to the FBV Electronics Board. If desired, header JP2 on the test board may be omitted and the cable wired directly to the board. **Note! In the first batch of boards dated 11-30-2011 pins 4 & 5 are reversed. Reverse the wires 4 & 5 on one end of the jumper cable or board damage will occur. Boards Rev. 2.0 and later use the proper straight-through cable.** To measure loop performance, the jumper connecting pins 1 and 2 of JP2 of the instrument’s electronics board should be removed and the Loop Test Board connected to JP2 by means of the cable.

The board is designed to accept two different styles of signal connectors as desired by the builder. Provisions are made for either BNC connections or miniature terminal strips, with additional test terminals available for scope probes.
While being measured, the instrument should be well shielded from drafts, but a pressure case should not be necessary.

A sine wave source capable of providing signal frequencies from 1-100Hz is connected to the Osc pins, and an oscilloscope, meter or, for low frequencies, A/D inputs, are connected to the Loop Out and Loop In terminals. Although the board's oscillator input is differential, it is assumed that one of the oscillator terminals will be grounded.

Whereas measuring from 0.1 to 1000Hz may be informative, the most useful measurements will be made near the gain-crossover frequency, the frequency at which \( V_{out} \) and \( V_{in} \) become the same. So you might want to start with the oscillator set to around 30 Hz. Gradually increase the signal level until there are good, easily measurable sine waves at Loop In and Loop Out. If either signal becomes distorted, possibly exhibiting a tall spike at the peak, reduce the oscillator voltage until both sine waves are clean. The test board can handle oscillator signals up to \( \sim 14 \) V peak, though \( 5V \) is a probably a good signal level, and possibly somewhat lower as the frequency is taken above 30 Hz.

The loop gain at the test frequency is given by \( V_{out} / V_{in} \). And the frequency at which \( V_{out} = V_{in} \equiv V \) will be the gain crossover frequency, which will also approximate the high-frequency corner of the instrument response.

The loop phase may be computed from the values of \( V_{osc} \), \( V_{out} \) and \( V_{in} \).

\[
\text{Loop Phase} = \cos^{-1}\left(\frac{V_{out}^2 + V_{in}^2 - V_{osc}^2}{2 V_{out} V_{in}}\right) - 180 \text{ deg.} \quad (\text{where} \ \cos^{-1} \text{ represents the arccosine function in degrees}).
\]

So, at gain crossover where \( V_{out} = V_{in} \equiv V \), the loop phase will be \( \cos^{-1}(1 - (V_{osc}^2/2V^2)) \) -180 degrees, and the phase margin, which is the difference between the loop phase and -180 degrees, is just \( \cos^{-1}(1 - (V_{osc}^2/2V^2)) \). The phase margin should be greater than 45 degrees in order to avoid too large a peak in the velocity response at the gain crossover frequency, with the additional possibility that the loop might start to oscillate as a result of circuit parameter changes or mechanical resonances.

For additional insight, a log-log plot of Loop Gain vs frequency (Bode plot) will tell much about how the loop is performing. Note that there will be a significant peak in the loop gain at the 3-4 second free period of the spring mass, which provides an excellent way of confirming its frequency.

If the gain crossover frequency is significantly different from 30Hz, it should be corrected by raising or lowering the overall loop gain curve. This may be done by changing the value of \( R2 \) at the input of U1A. When its value is raised, both the loop gain and the gain crossover frequency will be lowered.
## Parts List  FBV Loop Test Board  Rev. 2.0

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**Total:** $49.67
A QUICK, CONVENIENT METHOD FOR MEASURING LOOP GAIN

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 impedance 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. These measurements are made with the -hp- AC-2IF current probe for signal injection, and either the -hp- 302 A or 310 A 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

\[ C. M. Oliver and C. O. Forge, private communication. \]
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 \( \beta \) 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 \( \beta \) when traveling around the loop, \( E_2 = A\beta E_1 \) (1)

The voltage source \( E \) is simply:
\[
E = \frac{Z_1 + Z_2}{Z_1} E_2, \quad (2)
\]
or\[
E = \frac{Z_1 + Z_2}{Z_1} A\beta E_1 \quad (3)
\]

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 \( E_2 \), however, causes voltages \( E_1 \) and \( E_L \) to be established by the reaction of the feedback loop.

The voltage on the output side of the generator is:
\[
E_2 = |Z_2 + E| \quad (4)
\]
The current may be expressed as:
\[
I = E_1/Z_1 \quad (5)
\]
Substituting equations (5) and (3) for \( I \) and \( E \) respectively in equation (4) yields:
\[
E_2 = \frac{E_1}{Z_1} Z_2 + \frac{Z_1 + Z_2}{Z_1} A\beta E_1 \quad (6)
\]
If \( Z_2 << Z_1 \) then \( E_2 = A\beta E_1 \), as in equation (1), even though \( E_2 \) has been added to the circuit. Thus,
\[
A\beta = E_2/E_1 \quad (7)
\]
Thus it is seen that simply by introduction of the voltage \( E_2 \) in series with the loop, two voltages \( E_1 \) and \( E_2 \) are established which determine \( A\beta \) directly.
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 $Z_l << Z_1$. 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 $E_h$, 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 $\Omega$ 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.

**PRACTICAL EXAMPLE**

The loop gain of the amplifier shown in Fig. 5 was measured with this technique, $E_h$ being inserted at point A. At this point, $Z_2$ was calculated to be no more than 400 $\Omega$ and $Z_1$ was about 10,000 $\Omega$. 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, $E_g$ 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: $E_h = E_1 + E_2$. 

![Fig. 5. Circuit of amplifier on which loop gain was measured using technique described in text.](image)

![Fig. 6. Loop gain characteristic measured on amplifier of Fig. 5.](image)
E₁ and E₂ are measured directly and E₃ 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 \( 2Z₂ << Z₁ \). A similar measurement technique, the dual of the voltage technique, applies when \( Z₂ >> Z₁ \). 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 \( l₂ \) is established.

Referring to Fig. 8:

\[ E₁ = -l₁ Z₁ \quad (8) \]
\[ E₂ = l₂ Z₂ + E \quad (9) \]

Substitution of equation (3) gives:

\[ E₂ = l₂ Z₂ \left[ \frac{Z₁ + Z₄}{Z₁} \right] A β E₁ \quad (10) \]

Since \( E₂ = E₁ \), equations (8) and (10) may be combined:

\[ -l₁ Z₁ = l₂ Z₂ \left[ \frac{Z₁ + Z₄}{Z₁} \right] A β l₁ Z₁ \quad (11) \]

If \( Z₂ >> Z₁ \):

Then \( A β = l₂/l₁ \quad (12) \)

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 \( Z₁ \).

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, \( Z₃ \) is the output impedance of an amplifier with local emitter feedback, approximately one megohm, and the input impedance of the following emitter is about 270Ω which meets the requirement that \( Z₂ >> Z₁ \).

A current source was simulated by connecting a 10K resistor (\( >> Z₁ \)) in series with the wave analyzer’s BFO output. The current probe sensed each current \( I₂ \) and \( I₁ \), 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 \( A β \) obtained by the voltage source method was only 0.3 db.

Since \( I₂ = I₁ + l₄ \), a vector diagram may be constructed to find the phase angle of \( A β \), 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:

\[ Z_{th} = Z_{α} \left[ \frac{1 - A β_{α}}{1 + A β_{α}} \right] \quad (13) \]

where:

\[ Z_{th} = \text{impedance observed when normal feedback is present,} \]
\[ A β_{α} = \text{loop gain with nodes shorted together, and} \]
\[ A β_{α} = \text{loop gain when no external admittance is connected between the nodes.} \]

At dc, two nodes usually can be found where \( A β_{α} \) or \( A β_{α} = 0 \) and where \( Z_{th} \) can be calculated. Then, by connecting a current source between the nodes, and noting the voltage change, \( Z_{th} \) 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, \( Z_{th} \) 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, \( Z_{th} \) is the same as the collector load resistance (22k). If point C were grounded, \( A β_{α} \) would be zero and if it were left ungrounded, \( A β_{α} \) would equal \( A β \), the normal loop gain. Substituting these values in equation (13) yields:

\[ 11,000 = 22,000 \left[ \frac{1}{1 + A β} \right] \]

from which,

\[ A β = \frac{22,000}{11,000} - 1 = 1 \]

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