Enhanced performance for a force-feedback seismometer

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This discusses a revision to the feedback branches of the STM-8 vertical seismometer design which may have some advantages in improving its operation. There were several factors which motivated my interest in creating this design, relating specifically to the STM-8 although the circuit should do well when applied to any feedback design.

1. Provide more dynamic range (particularly at DC) for the coil driving circuit.

   The present range can be approximated by taking Ri = 107k in parallel with Rp = 581k. The combination is about 90k; so with 9 volts available that is about 100 micro amps max. At 13 N/A, the maximum force available is 1.3 milli Newtons. If the current capability could be increased to 10 ma. the feedback force could reach approximately 2.6% of the gravitational force on the seismic mass of 0.5 Kg, assuming the force feedback coil exerts 13 N/A. This would allow the loop to counteract a ±2.5% change in the spring force or more than 10º instrument tilt. This is approximately 100x the static correction available in the original design.

2. Provide a better point to sum the proportional, integral and derivative feedback signals.

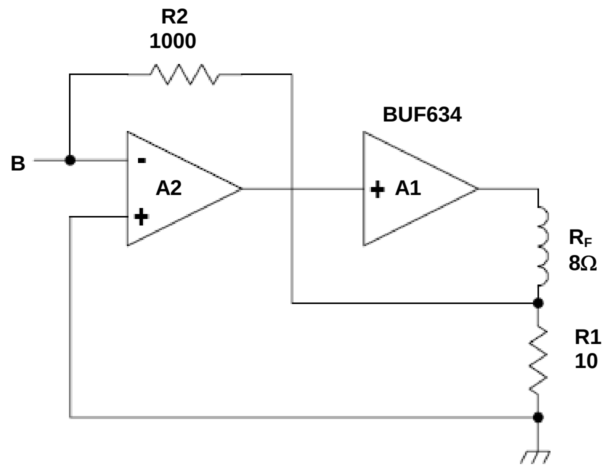
   The original concept was to use the relatively low resistance, low inductance (8 ohm) feedback coil, as the summing point for the three feedback paths. In order for the currents to sum properly the impedance of the summing point must be low relative to the circuit elements providing the currents being summed, however at higher frequencies the derivative feedback branch impedance is getting fairly low relative to the 8 ohm coil. Also, the output current capability of the op-amp driving the derivative branch may be a limiting factor at high frequencies.

3. Allow smaller capacitor values in the differential and integral branches.

   There is presently a 1:1 relationship between the currents in the PDI feedback branches and the coil current (they are directly connected). Adding an effective current gain of 100 would permit the P/D/I component impedances to be increased by a factor of 100 with no other effects on the loop. This, in turn, would reduce the capacitor values by a factor of 100, allowing the use of polypropylene capacitors of reasonable physical size, to replace the aluminum electrolytics.

4. Modify the integrator feedback branch to work substantially down to zero frequency.

Proposed Driver Circuit:



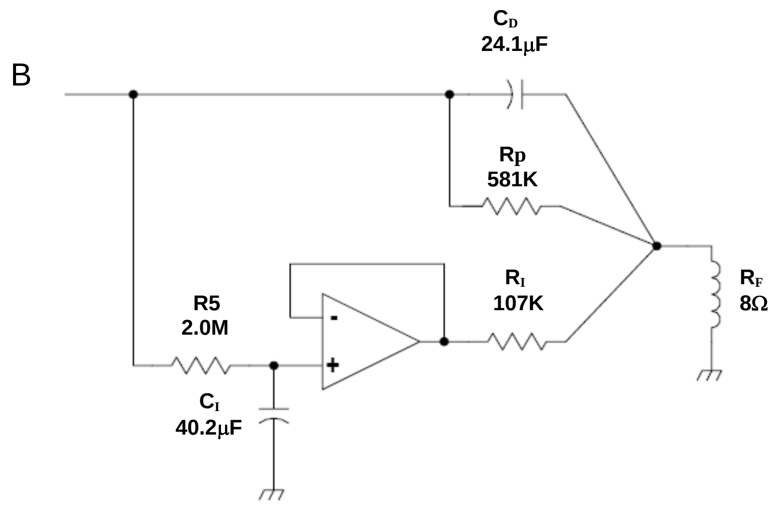
In this circuit, the feedback coil is assumed to be 8 ohms. R1 is a 10 ohm wire wound resistor. A1 is a buffer amp which should have reasonable output current capability, at least 5-10mA with 9v supplies. If using the BUF634, which can supply 250mA, it may also be necessary to add a 100Ω 1W resistor in series with its output to limit the maximum current to 76mA so as not to overload the power supplies. The existing power supply regulators should be examined to be sure that they can handle any additional current.

The summing point B, now connects where the coil was originally connected to the P/D/I elements. The feedback around A2 makes that a very low impedance point into which the currents can be summed with little concern for interaction between their source paths. R2/R1 defines the current gain, so if R2 = 1000 ohms we will have a current gain of 100. Since this portion of the circuit is in the feedback path of the main feedback loop, any changes to it will directly affect the instrument response. To maintain the same instrument response it will therefore be necessary to reduce the current gain elsewhere in the feedback path by a factor of 100. I think that that should be done by a 100x increase in the impedances in the PDI stages, which has the doubly beneficial effects of reducing the capacitor sizes by a factor of 100, and also of increasing the dynamic range of the derivative and integral feedback branches.

Input voltage noise in A1 and A2, and input current noise in A2 will need to be evaluated to assure that they do not increase the instrument noise level.

Frequency compensation of the A1, A2 loop might be necessary to avoid oscillation.

The Original STM-8 Design:



The original circuit had a transfer function from the voltage at 'B' to the current in the feedback coil of:

Derivative + Proportional + Integral

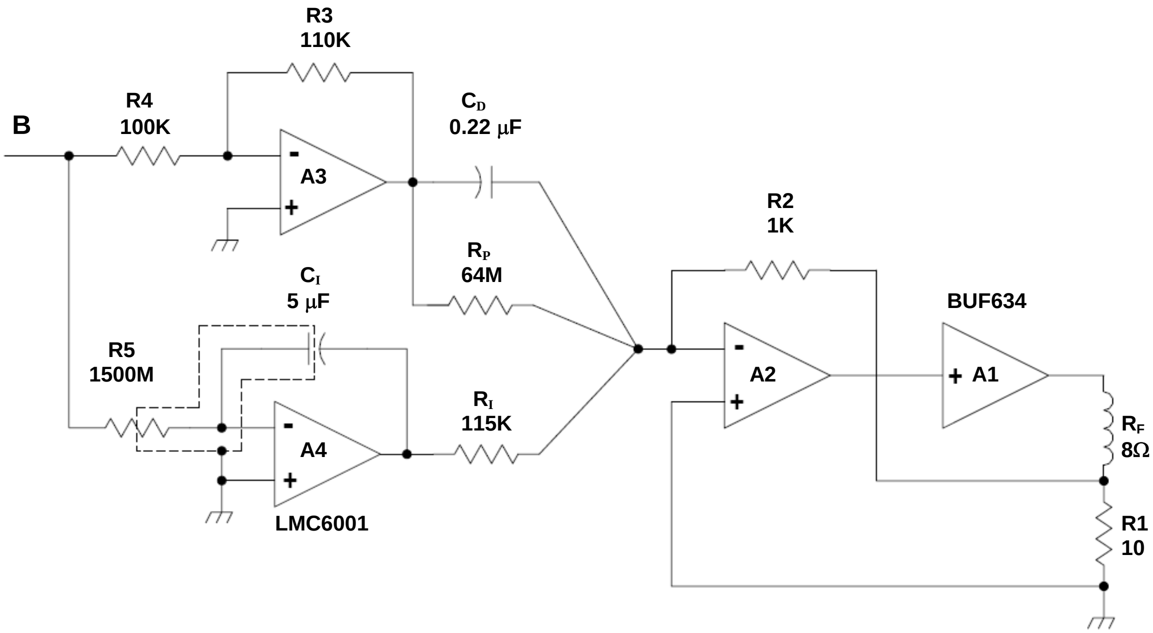
$j\omega C_D/(1+j\omega R_F C_D) + 1/R_P + 1/(R_I(1+j\omega R_5 C_I))$ A/V

Looking at the term for the integral branch, we see that at frequencies well above 0.02Hz, where $\omega R_5 C_I >> 1$ the integral branch transfer function approaches $1/j\omega R_I R_5 C_I$. For frequencies well below 0.02Hz, where $\omega R_5 C_I << 1$ it approaches $1/R_I$, in which case it is no longer acting as an integrator. As discussed elsewhere, we would prefer to have the magnitude of the integral term continue to grow as ω approaches zero, in which case it should look more like $1/j\omega R_I R_5 C_I$ which is characteristic of a true integrator.

If that can be done, the 1000-second high-pass filter can be removed from the STM-8 output, as its function would be taken over by the improved integral feedback.

Modified design:

Below is a circuit which uses op-amps to improve the derivative and integral branches. Note that in the integrator branch as shown, leakage current at the input of A4 will eventually result in it drifting to its maximum output. However, when this circuit



is incorporated into the main feedback loop, which has substantial loop gain at DC, the feedback will simply adjust the mass position by a small amount, sufficient to exactly offset the leakage current, via R5. Nevertheless, because R5 is so large, the input current variations in A4 must be kept quite small to avoid introducing excessive noise in the loop. The LMC6001 has extremely low input current and current noise.

We can now compare the transfer function from the voltage at 'B' to the current through the feedback coil which is:
Derivative + Proportional + Integral
$110\, j\omega C_D + 110/R_P + 100/(j\omega R5 C_I R_I)$ A/V
Or, applying the indicated component values $24.2\text{E-}6\, j\omega + 1.72\text{E-}6 + 1.16\text{E-}7/j\omega$ A/V

We see that the new circuit now has an integral branch which continues to be effective far below 0.02Hz. Also though not as important, as a result of the new output stage the derivative branch performs better than in the original circuit, which ceased to differentiate above 825Hz, where the impedance of C_D had fallen to 8 Ohms.

We can now compare the new transfer function with the original, evaluated here in the mid-frequency range of 0.02Hz < f < 825 Hz In that range the original transfer function becomes approximately:

$24.1\text{E-}6 j\omega + 1.72\text{E-}6 + 1.16\text{E-}7/j\omega$ A/V

showing that, except for its wider frequency range, the new circuit performs essentially the same as the original, as was intended.

Components:

Some of the components, especially those in the integrator need to be chosen carefully. The leakage resistance of C_I will place a limit on the minimum frequency which can be integrated. Polypropylene capacitors appear to have the best combination of adequately large capacitance combined with very high leakage resistance.

One capacitor suitable for C_I is the Cornell Dublier part# 935C1W5K-F see:
http://www.cde.com/catalogs/935.pdf
which has a leakage time-constant rating of 200,000 seconds. If that were the only limiting factor, it would support an integrator which could integrate down to 0.8 μHz. As of this date it can be obtained as Mouser Electronics part# 5984-100V5-F

Resistor R5 could be the Ohmite (was Victoreen) Slim-Mox series SM108031507FE see:
http://www.ohmite.com/catalog/pdf/v_slimmox.pdf
which is Mouser part# 588-SM108031507FE

The integrator Op-Amp is the National Semiconductor LMC6001AIN See:
http://www.national.com/ds/LM/LMC6001.pdf
which is available from Digi-Key as part# LMC6001AIN-ND

The buffer amplifier is TI part# BUF634P See:
http://www.ti.com/lit/gpn/BUF634
which is Digi-Key part# BUF634P-ND

Integrator leakage currents:

In the integrator circuit, leakage currents over surfaces will likely be the greatest cause of drift, particularly in conditions of high humidity. To combat these, the op-amp input terminal is protected by a guard ground, which is simply a technique for intercepting surface leakages before they can reach the sensitive input node. In practice, this means that pin 2 of the LMC6001 should not be connected to the circuit board, but should be bent up and connected through the air to R5 and C_I For mechanical stability, these parts can be joined at a Teflon stand-off terminal, so long as it is mounted with its base grounded. R5 and C_I are suspended in the air so that they do not touch the circuit board. In addition, grounded guard bands should be placed around the centers of R5 and C_I . This can be done with a loop of #28 wire-wrap wire, which is then painted over with a thin stripe of conductive paint, used both to secure the wire and to provide a continuous electrical contact with the surface.

Other issues:
Two other issues may exist in the STM-8 design, which are not addressed here.

First the displacement amplifier needs about 100x more gain from DC to 0.016 Hz.

Also the carrier frequency of the displacement transducer may need to be raised substantially so that its carrier filter can be moved higher in frequency so as to avoid feedback instability in the 30 Hz region.