Improving the Performance of a Geophone through Capacitive Position Sensing and Feedback

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Abstract

• The seismological community would like an affordable, broadband seismometer.

• A geophone is an affordable seismometer used for high frequency measurements.

• Modifying a geophone to sense proof mass position capacitively enables its use in low frequency applications.

• A capacitive geophone requires feedback to maintain its high frequency capability.
Low Frequency Seismology

• The Earth acts as a low pass filter.
• Only the low frequency components of a seismic signal will travel great distances.
  – Information about the deep structure of the Earth can be obtained from studying low frequency signals.
  – Low frequency signals are used for studying global seismicity.
## Commercial Seismometers

<table>
<thead>
<tr>
<th>Type</th>
<th>Streckeisen</th>
<th>Guralp</th>
<th>Geophone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>8.33mHz-50Hz</td>
<td>33mHz-50Hz</td>
<td>4.5Hz-400 Hz</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01 ng/√Hz</td>
<td>1 ng/√Hz</td>
<td>1 ng/√Hz</td>
</tr>
<tr>
<td>Price</td>
<td>$20,000</td>
<td>$10,000</td>
<td>$50</td>
</tr>
</tbody>
</table>

- A $500, 33mHz-50Hz seismometer with a resolution of 1 ng/√Hz would add another price-performance point to the currently available instrumentation options.
A New Broadband Seismometer: The Capacitive Geophone

• The existing mechanical system of a geophone provides the basis of the seismometer.

• **Capacitively** measuring coil displacement yields excellent low frequency sensitivity and resolution.

• A capacitive geophone can be made for under $200.
Conventional Geophone

Acceleration Input → Mechanical System → Relative Motion → Electrical System → Output Voltage

Schematic

Cross-section

Leaf Spring
Geophone Housing
Cylinder
Coil
Magnet
Mechanical Sensitivity

- Acceleration Causes Relative Motion Between the Coil and the Housing
- Constant Sensitivity Below the Resonant Frequency
Electrical Sensitivity

- **Inductively** Measure Motion of the Coil Relative to the Magnetic Field

- Output Voltage Proportional to the Proof Mass Velocity

![Graph showing electrical sensitivity vs frequency](image)
Total Sensitivity

- At Low Frequency, Measurement of Proof Mass Velocity Reduces Sensitivity
- At High Frequency, Mechanical System Reduces Sensitivity
Conventional Geophone Resolution

\[
\text{Resolution}\left[ \frac{g}{\sqrt{\text{Hz}}} \right] = \frac{\text{Noise}\left[ \frac{V}{\sqrt{\text{Hz}}} \right]}{\text{Sensitivity}\left[ \frac{V}{g} \right]}
\]

- Poor resolution at low frequency is caused by reduced sensitivity.
Capacitive Hardware

Circuit Model

\[ C = \frac{\varepsilon \varepsilon_0 A}{a - y} \]

\[ C = \frac{\varepsilon \varepsilon_0 A}{a + y} \]

Fixed Electrodes

Moving Electrode

Insulation

Additional Housing

\[ a = \text{Balanced Gap} \approx 250 \mu \text{m} \]

\[ A = \text{Area} = 3.4 \times 10^{-4} \text{ m}^2 \]

\[ C_{\text{NOMINAL}} = 12.1 \text{pF} \]
Capacitive Electrical System

- $V_{BR}$ is a sine wave at the drive frequency with amplitude and phase modulated by $y$.
- A Lock-In Amplifier demodulates $V_{BR}$ and outputs the amplitude and phase of the signal.
Phase Proportional to Position

Predicted

Measured

Sensitivity = $2.66 \times 10^7$ V/m
Operate with Integral Feedback

\[ \frac{1}{s^2 + 240s + 45000} \]

- Integral feedback applies forces at frequencies below the range of interest to keep the coil centered and the gaps balanced.
Sensitivity with Integral Feedback

- **Constant Sensitivity At Low Frequency** since Output is Proportional to Proof Mass *Displacement*
- **Attenuation at very Low Frequencies** caused by Integral Control
Capacitive Geophone Resolution

- The resolution is currently worse than target.
- The likely cause is noise in the biasing circuitry.
Add Lead Compensator

- The outer loop extends the bandwidth beyond the mechanical resonant frequency.
Closed Loop Sensitivity

- The bandwidth has been extended to 100 Hz.
- Discrepancies are based at 60 Hz and 180 Hz.
Conclusions

• Modifying a geophone into a capacitive sensor leads to an affordable, broadband seismometer.

• A capacitive geophone has been fabricated based on a 40 Hz geophone.

• Current results are promising, but more testing needs to be performed.

• Future goals include obtaining resolution at the fundamental limits, implementing the modifications on a 4.5 Hz geophone, and measuring phase without a Lock-In amplifier.
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