Improved Low Frequency Performance of a Geophone

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Poster Map

Title

Introduction

Conventional Geophone

Capacitive Geophone

Conclusions
Objective

- Develop an Affordable, Robust Broadband Seismometer with Resolution Comparable to the Earth’s Seismic Noise

- Enhance the Ability of Seismometer Arrays to Detect Low Frequency Signals
Seismometer Information Flow

Acceleration Input ➔ Mechanical System ➔ Relative Motion ➔ Electrical System ➔ Output Voltage
A Conventional Geophone: OYO Geospace 4.5 Hz GS-11D
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*
Total Sensitivity

- At Low Frequency, Measurement of Proof Mass Velocity Reduces Sensitivity
- At High Frequency, Mechanical System Reduces Sensitivity
Circuitry Noise

Typical Circuit

Output Voltage Noise Spectral Density

100x Amplifier

Peak Caused By Resonance
Conventional Geophone Resolution

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

- Poorer Resolution at Low Frequency caused by Reduced Sensitivity
- Resolution worse than Fundamental Limit

An Improved Seismometer: A Capacitive Geophone

• Use a Commercial, Off The Shelf Geophone as the Mechanical System

• Improve Low Frequency Sensitivity by Capacitively Measuring Proof Mass Displacement with only Simple, External Modifications
Photos

Capacitive Geophone

Guralp CMG-40T and Capacitive Geophone
Capacitive Hardware

Circuit Model

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

\( a = \text{Balanced Gap} \approx 250 \mu m \)

\( A = \text{Area} = 3.4 \times 10^{-4} \text{ m}^2 \)

\( C_{\text{NOMINAL}} = 12.1 \text{pF} \)

Additional Housing

Fixed Electrodes

Moving Electrode

Insulation

33.37 mm

39.37 mm
Electrical System Overview

$V_{BR}$ is a Sine Wave at the Same Frequency as $V_{SIN}$ with Amplitude Modulated by $y$. The Lock-In Amplifier Demodulates the Signal to Produce an Output that is Proportional to the Displacement of the Proof Mass.
Preamplifier Circuit

**Symbols and Equations:**

- $f_{\text{SIN}} = 100\text{kHz}$
- $V_{\text{SIN}} = 3.8V_{\text{pk}}$
- $f_c = \frac{1}{2\pi RC} \approx 600\text{Hz}$
Preamplifier Circuit Sensitivity

Exact Solution: Voltage Amplitude is a Linear Function of Displacement

\[
V_{IN} = \left( V_{SIN} - [-V_{SIN}] \right) \left( \frac{1}{sC_A} \frac{1}{sC_B} \right) - V_{SIN} \left( 1 + \frac{10k\Omega}{1k\Omega} \right)
\]

\[
V_{IN} = V_{SIN} \left( \frac{sC_B - sC_A}{sC_B + sC_A} \right) \quad (11)
\]

\[
V_{IN} = V_{SIN} \left( \frac{1/a - y - 1/a + y}{1/a - y + 1/a + y} \right) \quad (11)
\]

\[
V_{IN} = V_{SIN} \frac{y}{a} \quad (11) = 1.7 \times 10^5 \left[ \frac{V}{m} \right] y[m]
\]
Demodulator

- Demodulator Output is Directly Proportional to the Amplitude of the Input at the Reference Frequency.
- In the Frequency Domain, Low Frequency Amplitude Variations Appear as Signals Near the Reference Frequency. The Demodulator Shifts These Signals Back to Low Frequency.
Demodulator Sensitivity

\[ V_{OUT} = \frac{10V}{5(10^{-3})V} \frac{1}{\sqrt{2}}|V_{IN}|_{pk} = 1414|V_{IN}|_{pk} \]

Electrical Sensitivity

\[ V_{OUT} = (1414)1.7 \times 10^5 \left[ \frac{V}{m} \right] y[m] = 2.3(10^8) \left[ \frac{V}{m} \right] y[m] \]
Total Sensitivity

- **Constant Sensitivity At Low Frequency** since Output is Proportional to Proof Mass **Displacement**

![Graph showing Geophone Sensitivity vs Frequency]

- Capacitive
- Conventional
Preamplifier Circuitry Noise

Noise Near the Reference Frequency is Mapped to Low Frequencies by Demodulator

- Noise is Constant Amplitude vs. Frequency
- Lock-In Amplification Produces 0.18 mV/√Hz Output Voltage NSD at Low Frequencies
Capacitive Geophone Resolution

Resolution\(\frac{g}{\sqrt{Hz}}\) = \frac{\text{Noise}\[\frac{V}{\sqrt{Hz}}]\]}{\text{Sensitivity}\[\frac{V}{g}\]}

- At Low Frequencies, Resolution is Limited by Thermomechanical Noise, not Circuitry
- Better Resolution at Low Frequencies as a Result of Constant Sensitivity
Clip Level

- Demodulator Output Range ±10V
- Corresponds to 0.040 μm Displacement
Resolution Comparison

USGS LNM: Seismic Noise At Quietest Sites On Earth
Resolution Comparison

• Low Frequency Resolution of a Geophone is Improved by using Capacitive Detection
• Circuitry Noise does not Limit Capacitive Geophone at Low Frequency
• Limits on Resolution of a Capacitive Geophone are Better than the Resolution of a Guralp CMG-40T Broadband Seismometer
# Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Conventional Geophone</th>
<th>Capacitive Geophone</th>
<th>Guralp CMG-40T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resolution</strong></td>
<td>100 ng/√Hz</td>
<td>.1 ng/√Hz</td>
<td>.5 ng/√Hz</td>
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<tr>
<td><strong>Clip Level</strong></td>
<td>90 mg</td>
<td>5 µg</td>
<td>1 mg</td>
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<tr>
<td><strong>Dynamic Range</strong></td>
<td>120 dB</td>
<td>90 dB</td>
<td>130 dB</td>
</tr>
<tr>
<td><strong>Estimated Cost</strong></td>
<td>$50</td>
<td>$500</td>
<td>$10,000</td>
</tr>
</tbody>
</table>
Conclusions

• The Low Frequency Resolution of a Geophone can be Improved by Adding Capacitive Detection
• Capacitive Detection Does Not Improve High Frequency Resolution
• Thermomechanical Noise Sets a Resolution Limit $\approx 0.1 \text{ ng/} \sqrt{\text{Hz}}$ on all Geophone Based Seismometers
Future Work

• Experimentally Validate the Predicted Resolution of a Capacitive Geophone
• Reduce Size by Integrating Electronics onto a Single Printed Circuit Board
• Operate as a Closed Loop Sensor to Increase the Dynamic Range and Tune the Frequency Response