Acoustic and Vibration Control in Vacuum: A Case Study

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Environmental Isolation for Interferometry: a Laboratory Physicist’s approach
Not a vibration expert!

Required an environment to explore ultra-high accuracy optical interferometry:

- 5 cm displacements $x$ measured in pm
- Air turbulence intolerable
- Real-time mechanical control
- Mechanical servo bandwidth: >100 Hz

Learned a lot that may be useful!
What disturbances are present?

- Seismic: Frequencies below 100 Hz
- Acoustic: Frequencies above 15 Hz
- Built-in: Turbomolecular pump

How will we deal with them?

- Passive resonant system
- Sealed enclosure
- Vacuum

How well does it work? What are the tradeoffs?

- Accelerometer
- Fabry-Perot interferometer

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Isolation Provided by Optical Tables

- Measured with ultra-sensitive accelerometer
- Bandwidth: 400 Hz

**Basement floor:**
- Quieter than optical tables for frequencies below 6 Hz!
- Minimum vibration at ~ 2 Hz

**Small optical table:**
- Small table outperforms floor above 7.5 Hz
- Resonance at 3.3 Hz

**Large optical table:**
- Large table outperforms floor above 6 Hz
- Outperforms small table for all frequencies
- Resonance at 2.3 Hz
Vibration isolation with a passive resonant system

Transfer function for single resonance

\[ \nu < \nu_0 : \frac{1}{\nu} \]
\[ \nu = \nu_0 : Q \]
\[ \sqrt{2} \nu_0 < \nu < Q \nu_0 : \frac{1}{(\nu/\nu_0)^{1/2}} \]
\[ Q \nu_0 < \nu : \frac{1}{(\nu/\nu_0)} \]

Attenuate frequencies above \( \sim \sqrt{2} \nu_0 \) \( \Rightarrow \) Low resonant frequency desired
Amplify frequencies near \( \nu_0 \) by \( \sim Q \) \( \Rightarrow \) Low Q desired
Attenuation 40 dB/decade below \( Q \nu_0 \) \{ \Rightarrow \) High Q desired
Attenuation 20 dB/decade above \( Q \nu_0 \) \{ \Rightarrow \) High Q desired

Optical tables: Resonances 2.3 – 3.3 Hz
Attenuation up to 60 dB/decade

What sets the resonance frequencies?

Vertical oscillation frequency:
\[ \nu_{0v} = \frac{1}{2\pi} \sqrt{\frac{g}{dL}} \] (dL: Amount spring stretches under load)

Horizontal oscillation frequency:
\[ \nu_{0h} = \frac{1}{2\pi} \sqrt{\frac{g}{L}} \]

Key to reducing the resonant frequency is to have more height available

<table>
<thead>
<tr>
<th>dL</th>
<th>( \nu_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>16 Hz</td>
</tr>
<tr>
<td>1 cm</td>
<td>5 Hz</td>
</tr>
<tr>
<td>10 cm</td>
<td>1.6 Hz</td>
</tr>
<tr>
<td>1 m</td>
<td>0.5 Hz</td>
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</tbody>
</table>

• Just sitting on an elastomer pad cannot give especially good isolation, no matter how “good” the elastomer is!
• Applications requiring \( \nu_0 < 1 \) Hz should consider active feedback. This is complicated, especially in all six degrees of freedom!
Early experimental comparisons: Elastomers

- Support aluminum plate on elastomers
- Compare acceleration to that of floor

![Graph showing transmission vs. frequency for Viton O-ring and Unknown rubber “waffle”](image)

- Trade low Q (viton) against better suppression at high frequencies
- Resonance at 19 Hz ⇔ Rubber compressed ~ 0.7 mm
- Above 150 Hz, acoustic disturbances take over

Elastomers under compression vs. Springs in suspension

![Graph showing transmission vs. frequency for sitting on elastomer and hanging from spring](image)

- Lower resonant frequency (larger vertical dL) gives suspension from springs
  vastly better performance
- Above 40 Hz, acoustic disturbances take over
The “Flying Saucer”: An optical breadboard in a can

~ 1 meter

Breadboard suspended from springs

Chamber supported on three air-spring legs

Detail of springs

- Steel springs
- Damped with Buna-N rubber of square cross-section inside
- O-rings provide additional isolation in series
- Length under tension: 175 mm

O-rings and Buna-N damp high-$\nu$ acoustic wave propagation down spring

Horizontal: $\nu_0 = 1.2 \, \text{Hz, } Q = 37$

Vertical: $\nu_0 = 2.5 \, \text{Hz, } Q = 13$
Vacuum pumping

Springs and elastomer attenuate pump vibrations

Damped bellows

Maglev turbo pump
- Rotation frequency 820 Hz
- Low-frequency pendulum

- Backing pump suspended from springs in adjoining room
- Roughing line “grounded” in box of lead shot

“Turn on” isolation one step at a time
*First step: Breadboard hanging from springs (seismic isolation)*

Suspended breadboard:
- Resonance at 2.75 Hz
- Outperforms large optical table below ~ 10 Hz
- Vibration at higher frequencies is partly acoustic
  (Breadboard is a floating drumhead; vacuum chamber open)
Second step: Close lid of vacuum chamber (acoustic isolation)

Spring suspension + sealed environment

- Dramatic suppression of vibration above 20 Hz
- Outperforms large optical table at all frequencies!

Transfer function of springs

Beware:
Simple model of real-world spring starts to fail at $v \sim 10 \nu_0$
**Third step: Float vacuum chamber on air-springs (seismic isolation)**

Spring suspension + sealed environment + air-spring table legs

- Dramatic suppression of noise above 7 Hz: Up to 100 dB/decade
- Noise is added at low frequencies by the additional resonant system
- Much of the noise up to 100 Hz is seismic (NOT all acoustic!)

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**Fourth step: Evacuate chamber (acoustic isolation)**

Spring suspension + Air-spring table legs + Vacuum

Main effect of pumping is to eliminate broad peak at 130 Hz
(acoustic mode of air in chamber)
But how much is that breadboard really wiggling?

\[ |D(\omega)| = \frac{|A(\omega)|}{\omega^2} \]

\[ <D^2> = \int |D(\omega)|^2 \, d\omega \]

\[ Z_{\text{rms}} = 140 \text{ nm} \]

\[ X_{\text{rms}} = 210 \text{ nm} \]

- This motion is almost all at the resonance frequencies (2.5 Hz, 1.2 Hz)
- Completely negligible since light coupled in by fiber

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How much vibration is added by the (maglev turbo) pump?

Let pump spin down without venting chamber

**Vertical**: Peak at 29 Hz
- rms displacement: 15 pm

**Horizontal**: 26 – 76 Hz
- rms displacement: 20 pm

But! Pump rotation frequency is 820 Hz
- Outside bandwidth of accelerometer!
Fabry-Perot Interferometer

Two ultrahigh-reflectivity mirrors mounted on breadboard

- Cavity contracts by 1 ppb:
  - Bandwidth 3.2 kHz
  - Resolution better than 5 fm (size of atomic nucleus!)

- Tunable laser

- Transmission frequencies related to cavity length

Laser locked to cavity (under vacuum):
- Unity gain set at 0.8 Hz
- Rms cavity displacement 2.5 pm above ~ 1 Hz

Sweep cavity length*:
- Full-amplitude swing from length change of ~ 0.1 nm

* In practice the laser frequency is swept to obtain this curve
Pump-induced vibration
Let turbo pump spin down under vacuum and compare FFT

Pump vibration at 820 Hz: 200 fm rms
Mechanical resonance of mirror mount

Second harmonic of pump vibration
at 1640 Hz: 5 fm rms

Completely negligible!

Acoustic decoupling provided by vacuum

Previous experiment in air with chamber closed: Impossible!

Must raise gain by ~100 (unity-gain for servo ~ 680 Hz) in order to maintain error signal in center zone

Much more noise at high frequencies with air
Conclusions from Fabry-Perot interferometer

• Perturbation induced by “static” air far worse than one would guess from accelerometer data

• Maglev pump vibration at rotation frequency negligible (~1000 X smaller than hydrogen atom)

Compare: NIST X-ray interferometer

NIST X-ray interferometer:

• Built in basement under grass (no building overhead)
• Isolated behind double door with acoustic damping material
• Pumped with ion pump

“Flying saucer” is substantially quieter above 5 Hz!
Summary

Set out to construct an environment for optical interferometry

- Global motion: ~200 nm, mostly at ~2 Hz
- Pump-induced motion: ~20 pm, in 26 – 76 Hz window
- Quieter than ion-pumped NIST X-ray interferometer, in a normal laboratory environment
- Robust; pumps down in ~30 minutes

What would we do differently if we were to do it again?

- Suspend from somewhat greater height to lower resonant frequency
- Damp springs with viton instead of Buna-N in search of lower Q

A few more details: