Acoustic and Vibration Control in Vacuum: A Case Study

John Lawall

National Institute of Standards and Technology

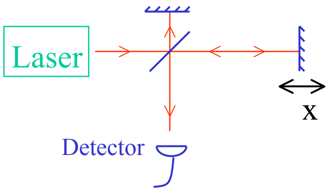
Gaithersburg, MD

1/14/03

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?

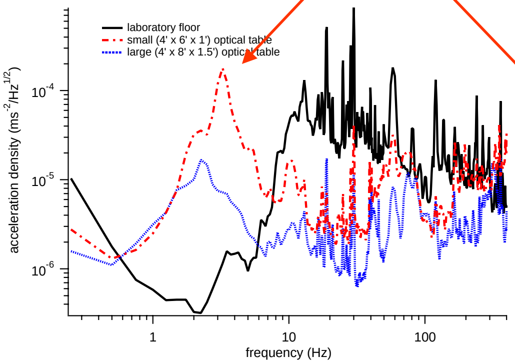
- Passive resonant system
- Sealed enclosure
- Vacuum

How well does it work? What are the tradeoffs?

- Accelerometer
- Fabry-Perot interferometer

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

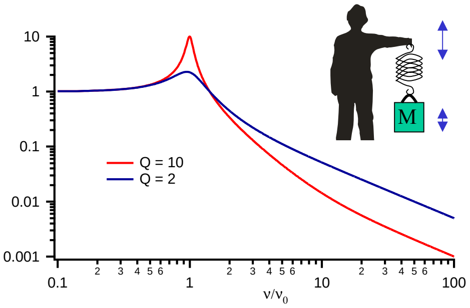
Transfer function for single resonance

$$\nu < \nu_0 : 1$$

$$\nu = \nu_0 : Q$$

$$\sqrt{2}\,\nu_0 < \nu < Q\,\nu_0 : \frac{1}{(\nu/\nu_0)^2}$$

$$Q\,\nu_0 < \nu : \frac{1}{Q\nu/\nu_0}$$



Attenuate frequencies above ~ $\sqrt{2}\,\nu_0$ => **Low resonant frequency desired**

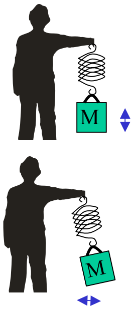
Amplify frequencies near ν_0 by ~ Q => Low Q desired

Attenuation **40 dB/decade** below $Q\,\nu_0$ }

Attenuation **20 dB/decade** above $Q\,\nu_0$ } => 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: (pendulum) $$\nu_{0H} = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

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

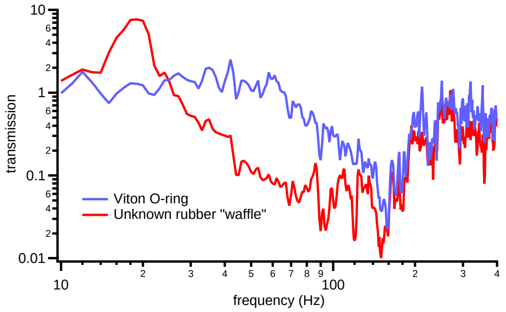
dL	ν_0
1 mm	16 Hz
1 cm	5 Hz
10 cm	1.6 Hz
1 m	0.5 Hz

Resonance below
~ 1 Hz requires lots
of headroom

- 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!

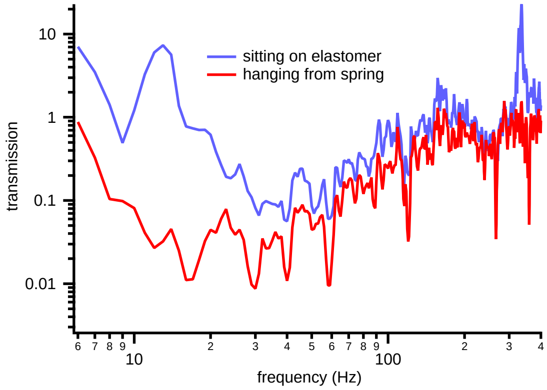
Early experimental comparisons: Elastomers

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



- 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

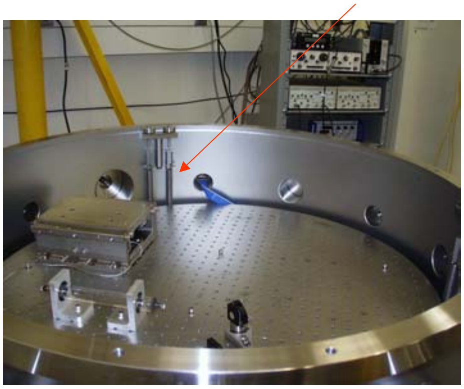


- Lower resonant frequency (larger vertical dL) gives suspension from springs **vastly better performance**
- Above 40 Hz, acoustic disturbances take over

The “Flying Saucer”: An optical breadboard in a can

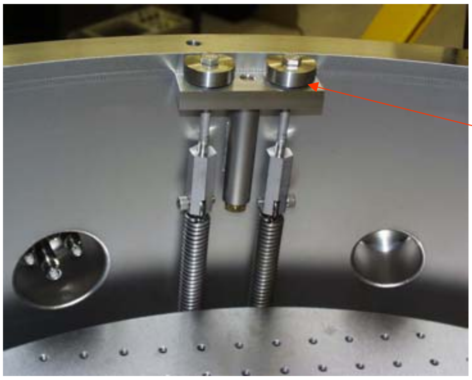
~ 1 meter

Breadboard suspended from springs



Chamber supported on three air-spring legs

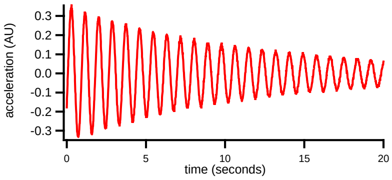
Detail of springs



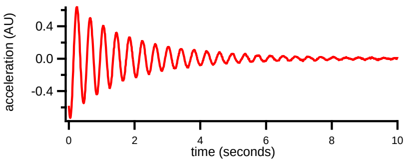
- Steel springs
- Damped with Buna-N rubber of square cross-section inside
- O-rings provide additional isolation in series
- Length under tension: 175 mm

O-rings and Buna-N damp high-ν acoustic wave propagation down spring

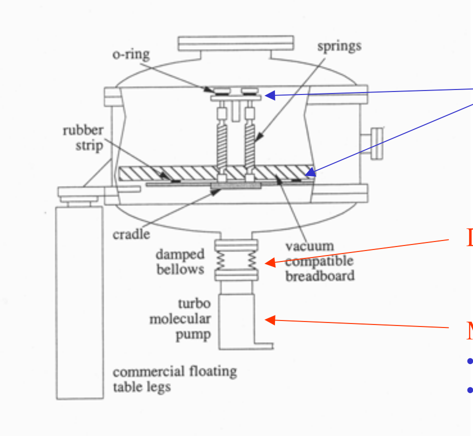
Horizontal: $\nu_0 = 1.2$ Hz, Q = 37



Vertical: $\nu_0 = 2.5$ Hz, Q = 13



Vacuum pumping



Springs and elastomer attenuate pump vibrations

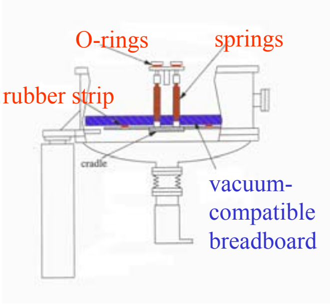
Damped bellows

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)

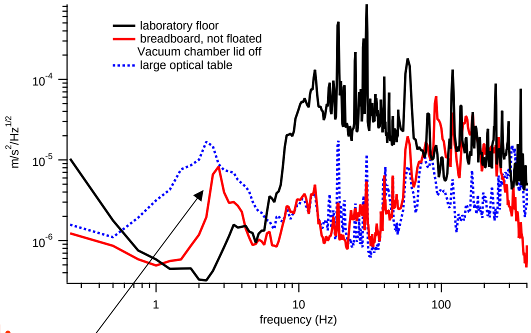


O-rings

springs

rubber strip

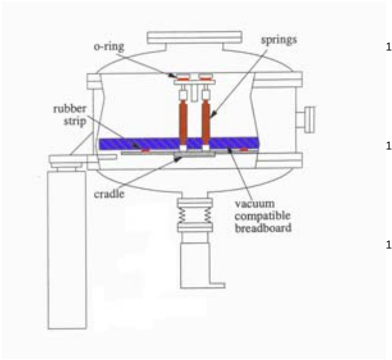
vacuum-compatible breadboard

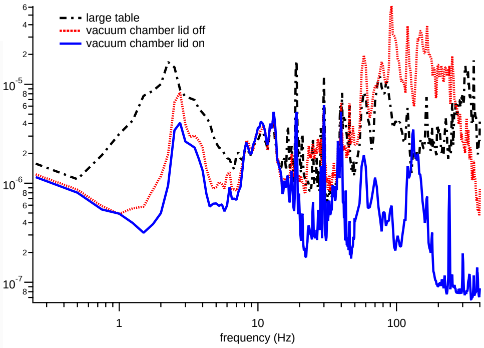


Suspended breadboard:

- 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)

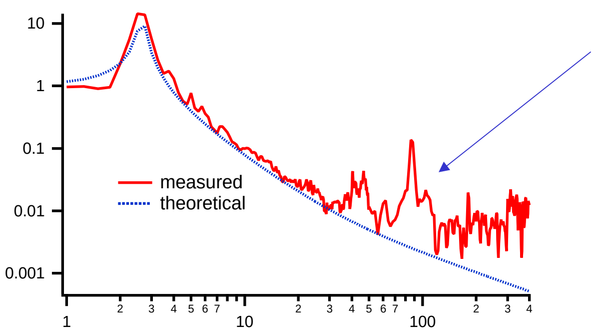




Spring suspension + sealed environment

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

Transfer function of springs

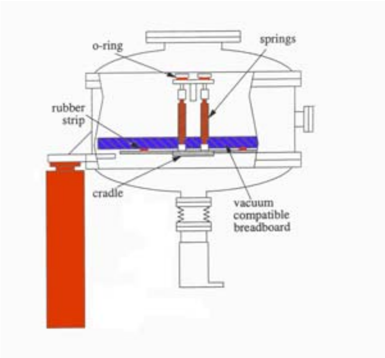


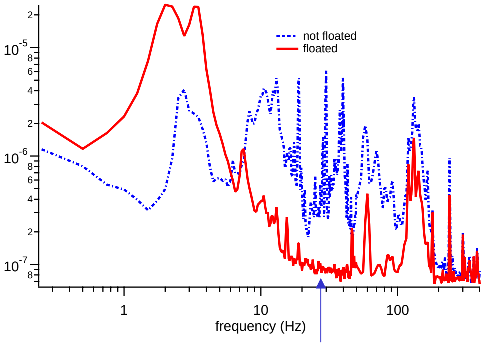
Spring transmits higher frequencies better than simple model predicts

Beware:

Simple model of real-world spring starts to fail at $\nu \sim 10\ \nu_0$

Third step: Float vacuum chamber on air-springs (seismic isolation)



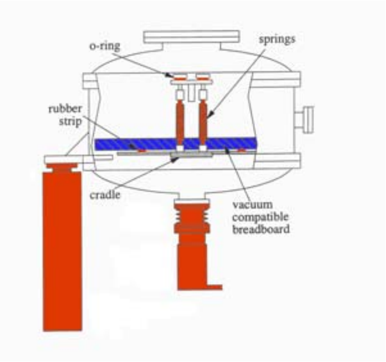


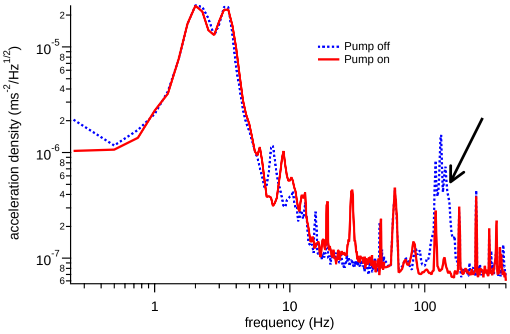
accelerometer noise floor

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!)

Fourth step: Evacuate chamber (acoustic isolation)

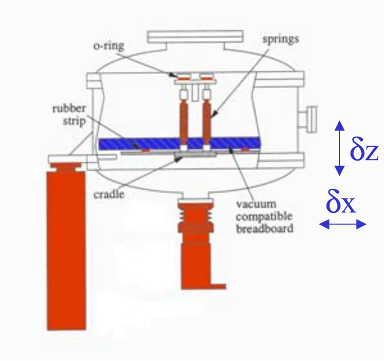




Spring suspension + Air-spring table legs + Vacuum

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_{rms} = 140 nm

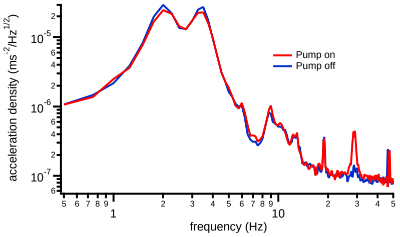
X_{rms} = 210 nm

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

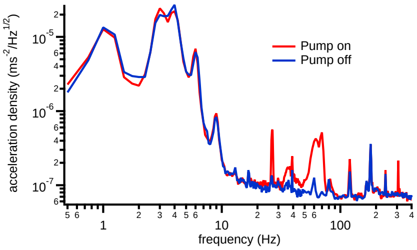
How much vibration is **added** by the (maglev turbo) pump?

Let pump spin down without venting chamber

Vertical: Peak at 29 Hz
rms displacement: 15 pm



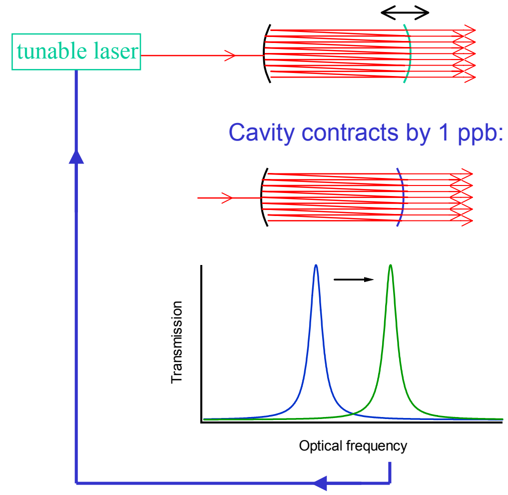
Horizontal: 26 – 76 Hz
rms displacement: 20 pm



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:

Transmission frequencies
related to cavity length

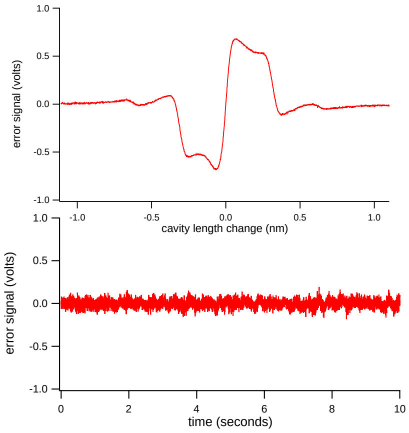
- Bandwidth 3.2 kHz
- Resolution better than 5 fm
  (size of atomic nucleus!)

Fabry-Perot Interferometer

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

Laser locked to cavity
(under vacuum):

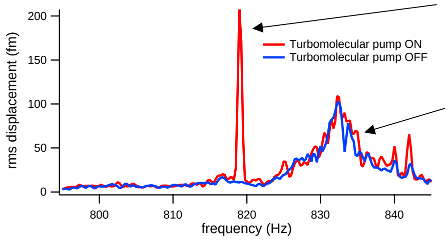
- Unity gain set at 0.8 Hz
- rms cavity displacement
  2.5 pm above ~ 1 Hz



* In practice the laser frequency is swept to obtain this curve

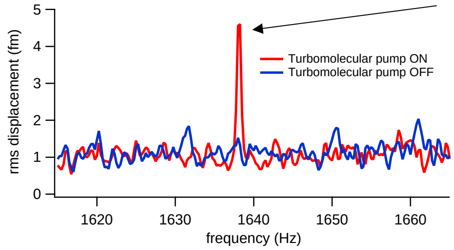
Pump-induced vibration

Let turbo pump spin down under vacuum and compare FFT



Pump vibration at 820 Hz: **200 fm** rms

Mechanical resonance of mirror mount



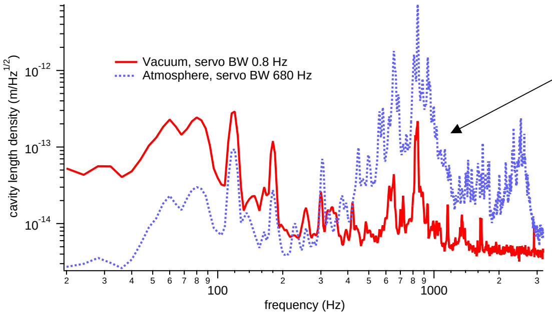
Second harmonic of pump vibration at 1640 Hz: **5 fm** rms

Completely negligible!

Acoustic decoupling provided by vacuum

Previous experiment in **air** with **chamber closed: Impossible!**

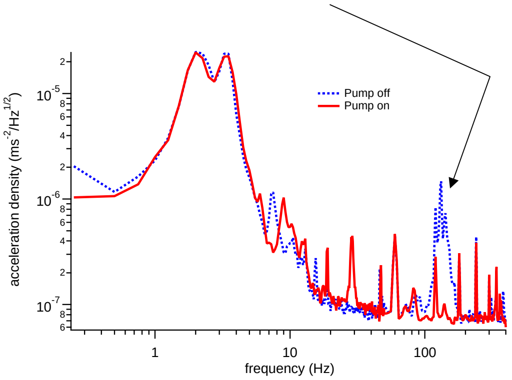
Must raise gain by ~100 (unity-gain for servo ~ 680 Hz) in order to maintain error signal in center zone



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

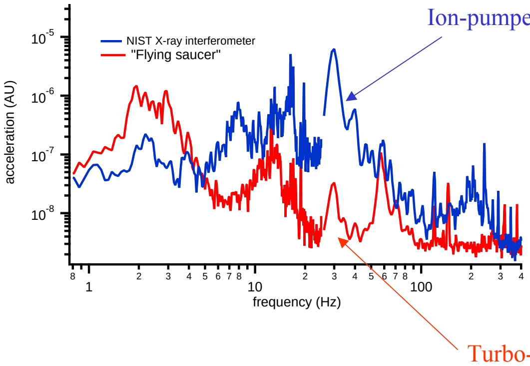


- Maglev pump vibration at rotation frequency negligible (~1000 X smaller than hydrogen atom)

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



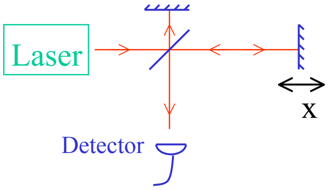
Ion-pumped X-ray interferometer

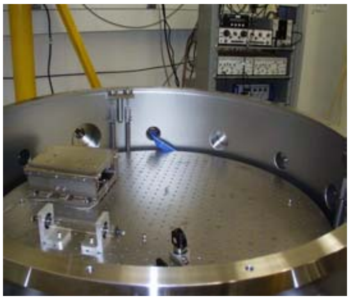
“Flying saucer” is substantially quieter above 5 Hz!

Turbo-pumped “flying saucer”

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:

John Lawall and Ernest Kessler, *Design and evaluation of a simple ultralow vibration vacuum environment*, Review of Scientific Instruments, **73**, 209-215, (2002).