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Quality Testing Optically Contacted Bonds for LIGO Voyager

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Motivation

LIGO’s test masses are currently made of many fused silica parts

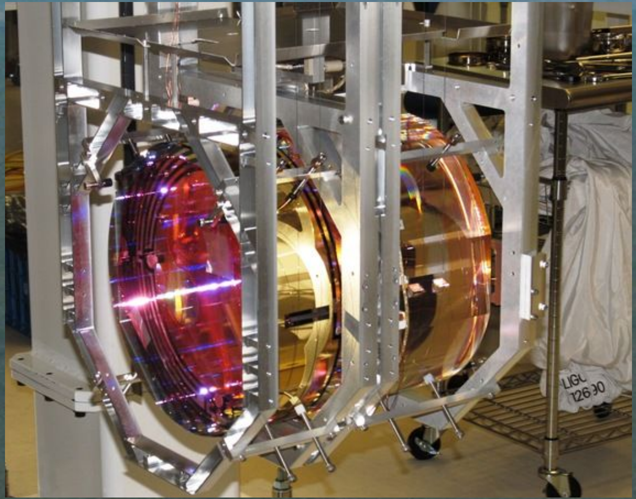


Image of one of LIGO’s test masses from Caltech/MIT/LIGO Lab

Image of LIGO Hanford from Caltech/MIT/LIGO Lab

The test masses are suspended by ribbons and made out of several smaller pieces which contributes to suspension thermal noise

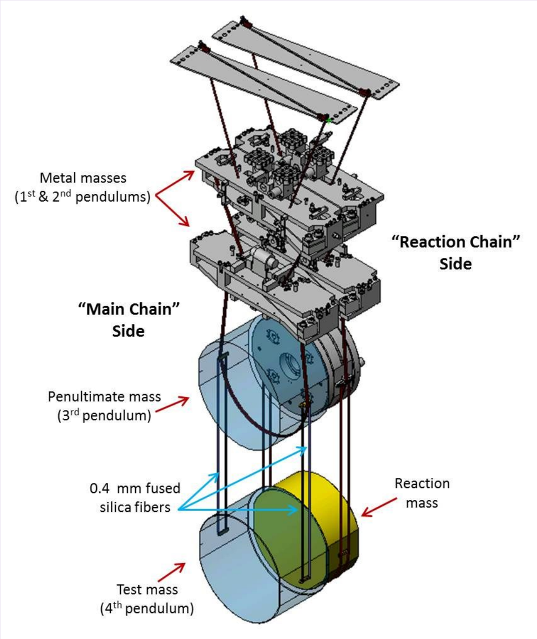


Image of a LIGO quad from IGR, University of Glasgow

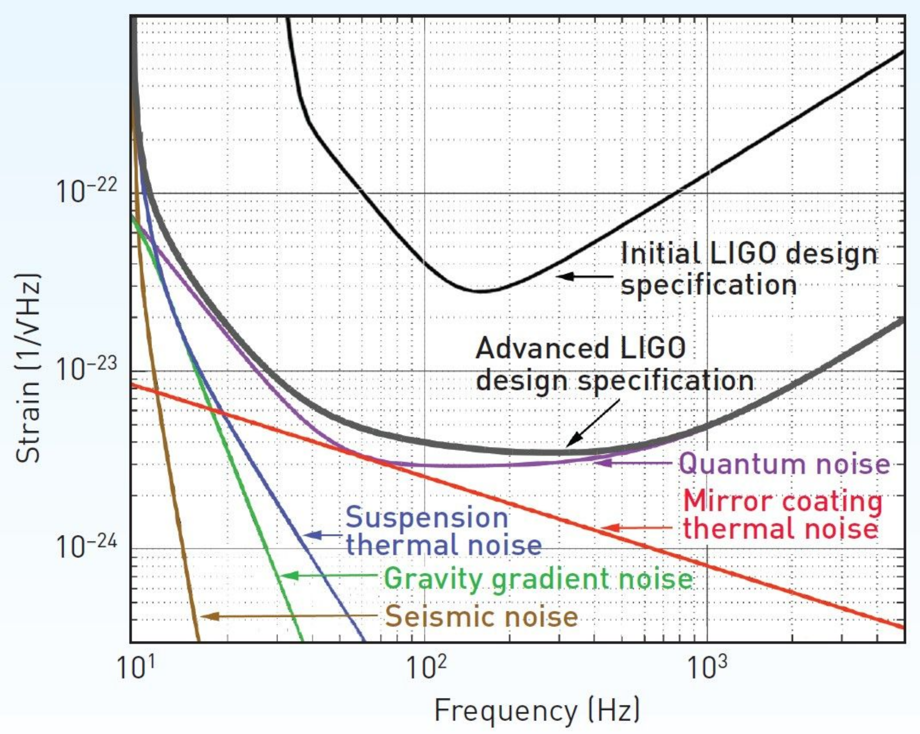


Image of Advanced LIGO principal noise sources as a function of frequency from optica-opn.org

Thermal noise limits the sensitivity of the detector as described by the fluctuation dissipation theorem

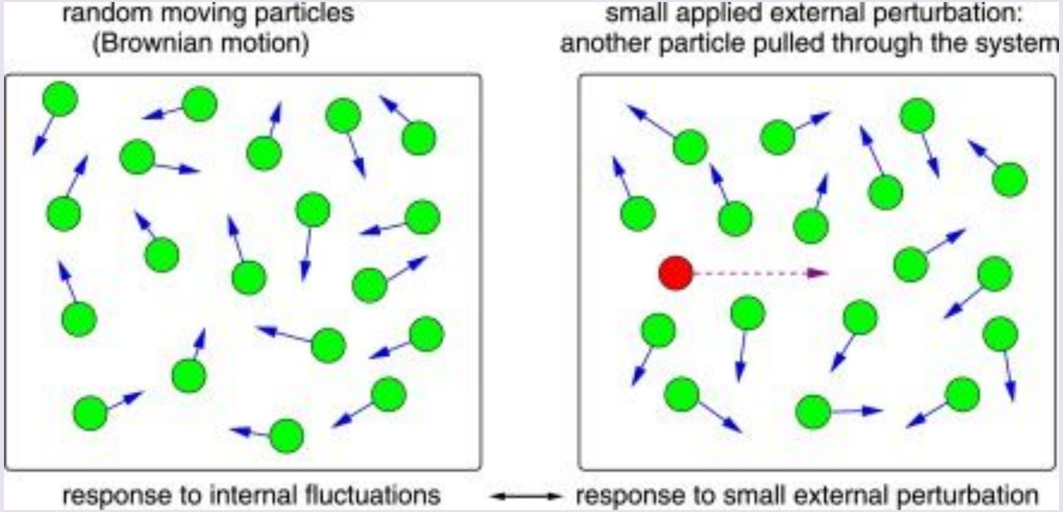


Image of a particle's response to fluctuations from ScienceDirect.com

Heat dissipation through the interfaces of the mirror parts is a source of fluctuation which causes the mirrors to vibrate

Optically contacted silicon is thought to have low thermal noise but has yet to be tested

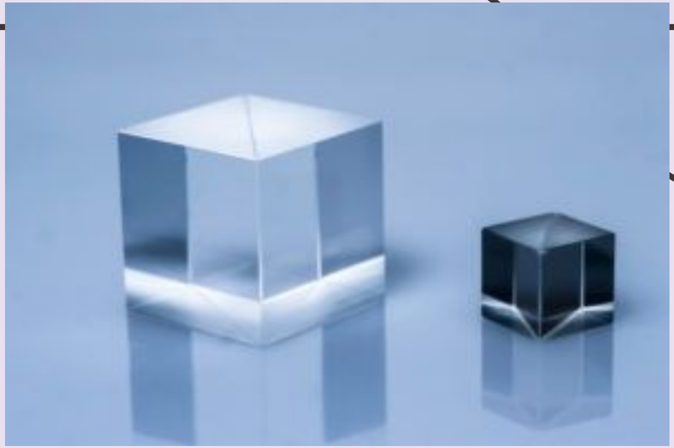


Image of optically contacted glass from solarisoptics.eu

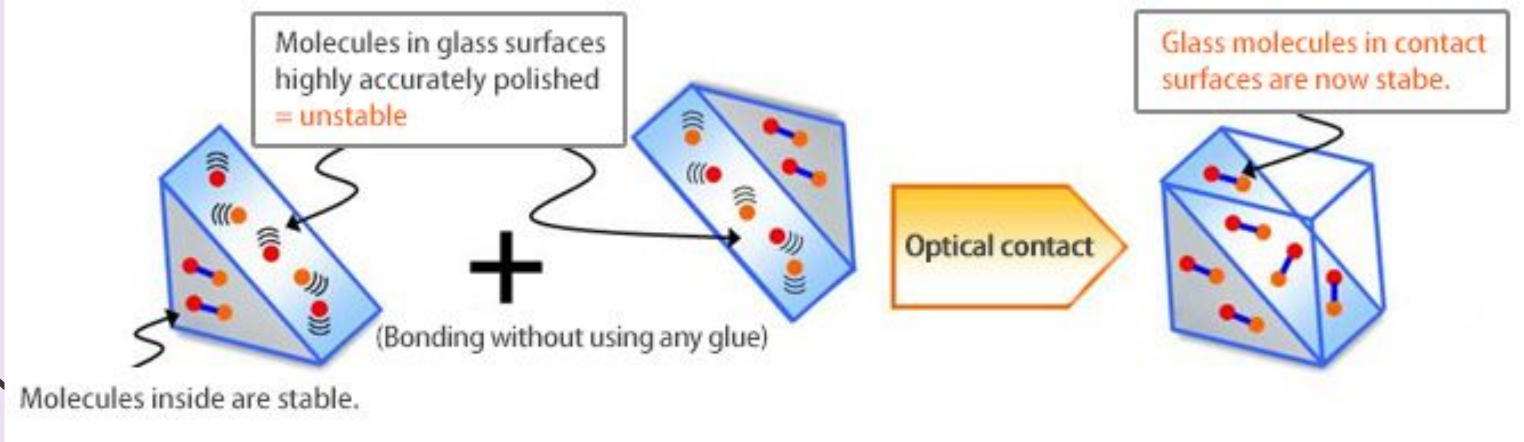
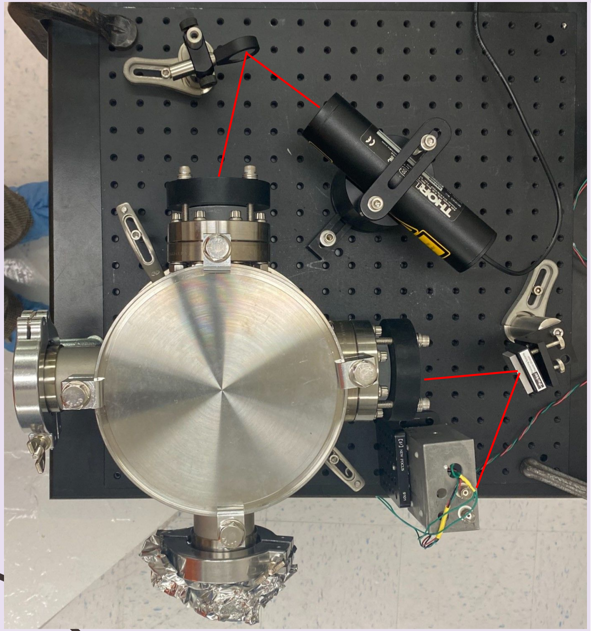
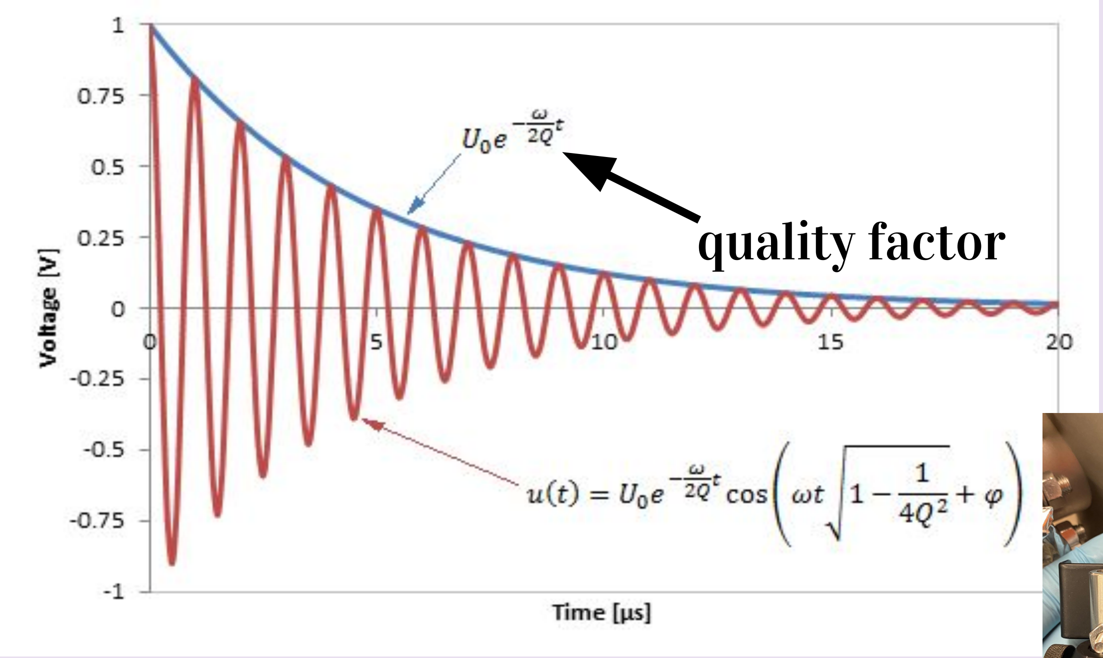


Diagram explaining optically contacting glass from mitsui-om.co.jp

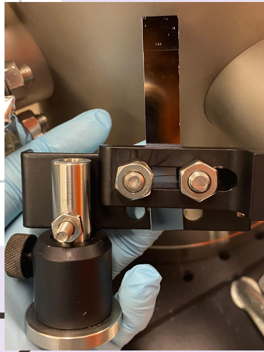
Testing

A high quality factor corresponds to low thermal noise





Graph of a damped oscillation and its fit from giangrandi.ch



How to find the quality factor of a bond…

$$\frac{1}{Q_{system}} = \sum_{i=1}^{n} \frac{E_i}{E_{system}} \frac{1}{Q_i}$$

$$\frac{1}{Q_{system}} = \frac{E_{silicon}}{E_{system}} \frac{1}{Q_{silicon}} + \frac{E_{bond}}{E_{system}} \frac{1}{Q_{bond}}$$

…maximize its energy contribution

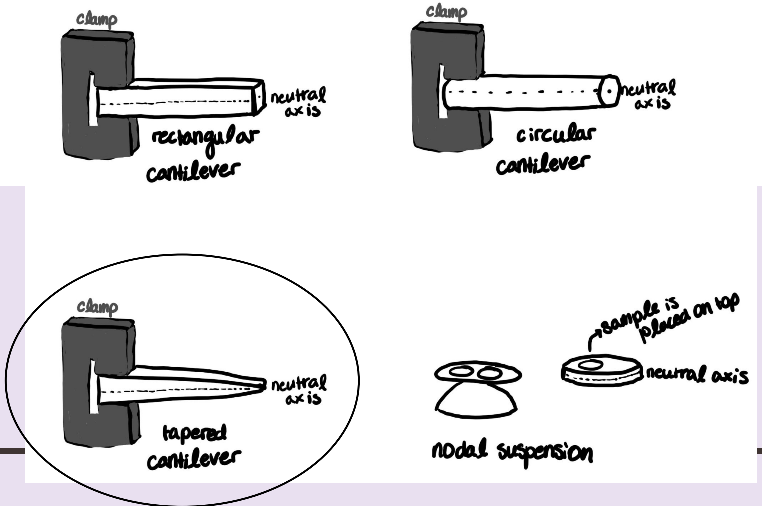
Maximizing the Energy of the Bond: A Geometry Optimization Problem

Estimation to Gain an Intuition

Three different cantilever geometries were analyzed in order to find a suitable energy ratio between the bond and the rest of the silicon wafer. The ratio between shear and bending energy was estimated for the geometries shown in figure 1 using the following equations where M is the moment, I is the moment of inertia, l is the length, E is young's modulus, K is a constant that depends on the geometry (1.11 for circular and 0.5 for rectangular sections), V is the traverse shear force, G is the modulus of rigidity, and A is the cross sectional area.

$$constant\ bending\ energy = \frac{M^2 l}{2EI}$$

$$constant\ traverse\ shear\ energy = \frac{KV^2 l}{2GA}$$



Finite Element Analysis in COMSOL: Pizza Cantilever

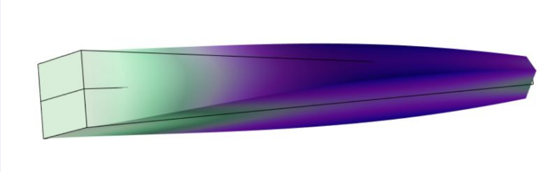
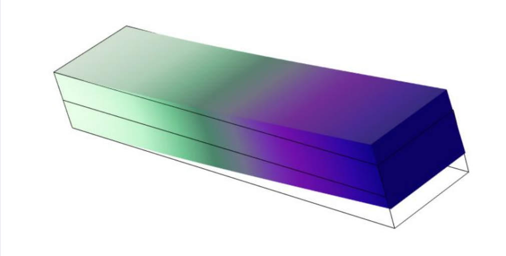


Table 1: Pizza Cantilever Energies.

Eigenfrequency (Hz)	Bulk (N*m)	Shear (N*m)	Total (J)	Shear/Bulk
34557	6.0-13	2.5E-12	1.5E-12	4.2
51994	1.4E-12	5.8E-12	3.6E-12	4.3
1.0385E5	2.8E-12	1.2E-11	7.4E-12	4.3
1.5129E5	5.8E-12	2.8E-11	1.7E-11	4.8
2.1981E5	1.0E-11	4.7E-11	2.8E-11	4.6
* 2.7240E5	2.1E-12	5.6E-10	2.8E-10	270

* is excluded because its shear strain dominates on the edges. We want to maximize the strain at the bond.

Finite Element Analysis in COMSOL: Rectangular Cantilever



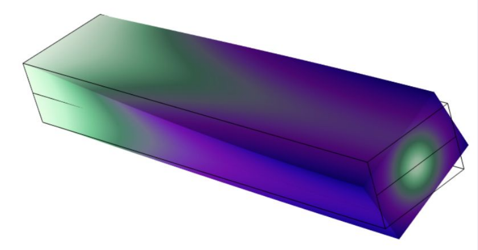
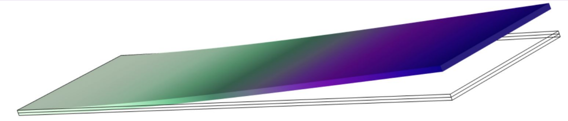


Table 2: Rectangular Cantilever Energies.

Eigenfrequency (Hz)	Bulk (N*m)	Shear (N*m)	Total (J)	Shear/Bulk
20385	2.2E-12	8.6E-12	5.4E-12	3.9
30507	4.8E-12	2.0E-11	1.2E-11	4.2
1.1796E5	7.3E-11	3.3E-10	2.0E-10	4.5
* 1.2326E5	1.4E-12	3.6E-10	1.8E-10	260
1.6250E5	1.3E-10	7.3E-10	4.3E-10	5.4
2.2601E5	5.1E-10	2.1E-9	1.3E-9	4.1

* is excluded because its shear strain dominates on the edges. We want to maximize the strain at the bond.

Finite Element Analysis in COMSOL: Lab Dimensions



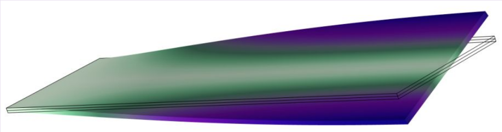


Table 3: Rectangular Cantilever With Lab Dimensions Energies.

Eigenfrequency (Hz)	Bulk (N*m)	Shear (N*m)	Total (J)	Shear/Bulk
1266.0	5.3E-16	1.9E-15	1.2E-15	3.6
7927.1	2.0E-14	7.6E-14	4.8E-14	3.7
* 12012	2.3E-15	1.4E-13	6.9E-14	58
22212	1.6E-13	5.8E-13	3.7E-13	3.6
30433	2.7E-13	1.2E-12	7.4E-13	4.5
36767	3.6E-14	1.2E-12	6.0-13	3.3

Table 4: Pizza Cantilever With Lab Dimensions Energies.

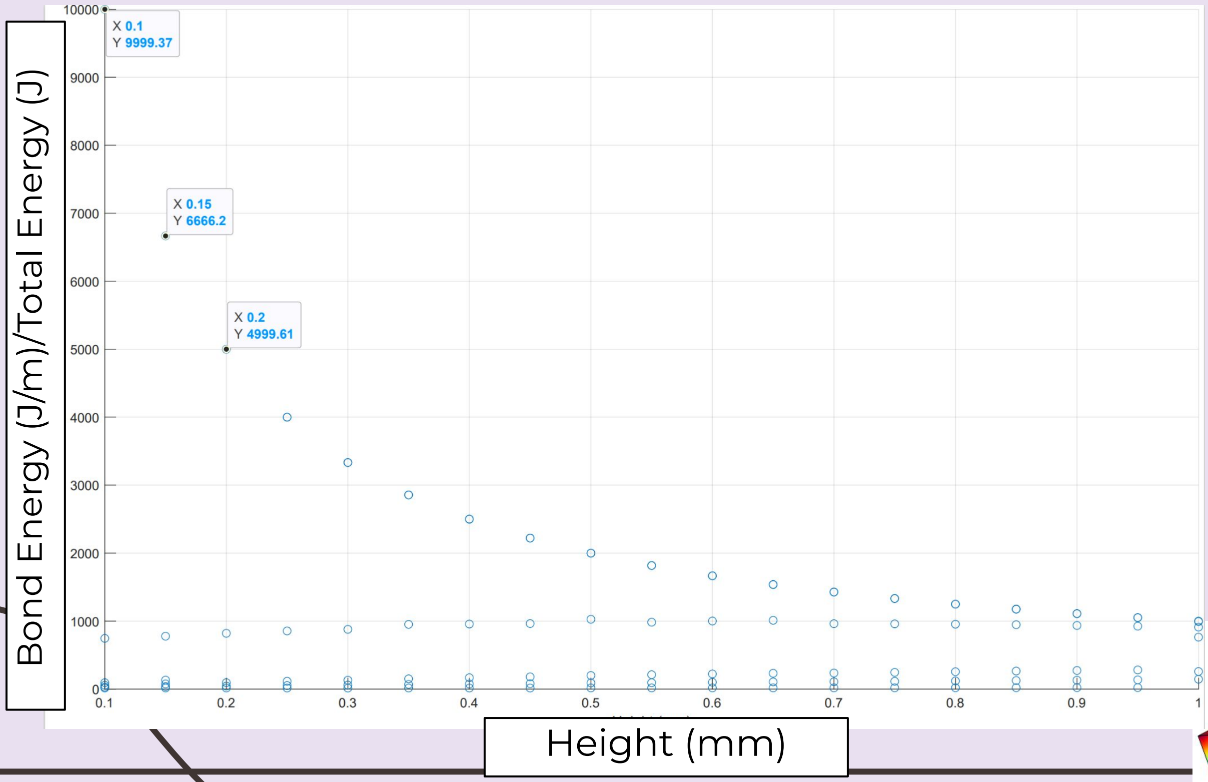
Eigenfrequency (Hz)	Bulk (N*m)	Shear (N*m)	Total (J)	Shear/Bulk
2085.9	1.5E-16	5.9E-16	3.7E-16	4.0
6624.0	8.0E-16	3.2E-15	2.0E-15	4.0
14820	3.4E-15	1.3E-14	8.2E-15	3.9
*25628	2.6E-15	1.9E-13	9.9E-14	75
26899	1.1E-14	4.0E-14	2.5E-14	3.8
42943	2.6E-14	9.8E-14	6.2E-14	3.7

* is excluded because its shear strain dominates on the edges. We want to maximize the strain at the bond.

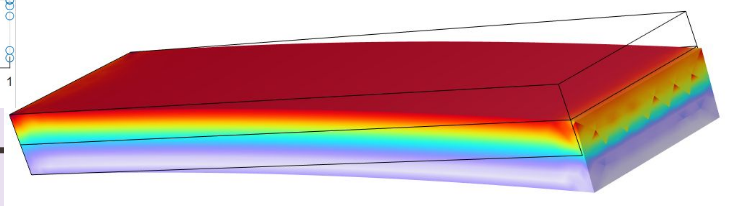
Selecting the Geometry: Results

- The pizza cantilever had a higher shear/bulk ratio than the rectangular cantilever at the frequency I estimated
- The rectangular cantilever had the highest shear/bulk ratio overall
- The ratio was highest when the thickness of the cantilever was minimized

Optimizing the Dimensions

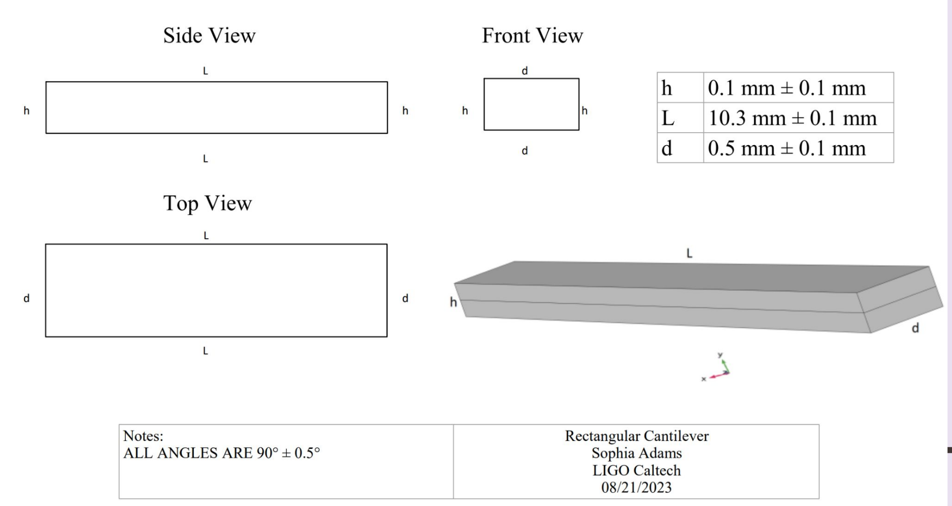


- Added a boundary load and ran a stationary study to find the von Mises stress
- Plotted the shear/bulk ratio and energy per length of the inner surface divided by total energy for different widths/heights/lengths and eigenfrequencies
- Simultaneous parameter estimation with fminsearch

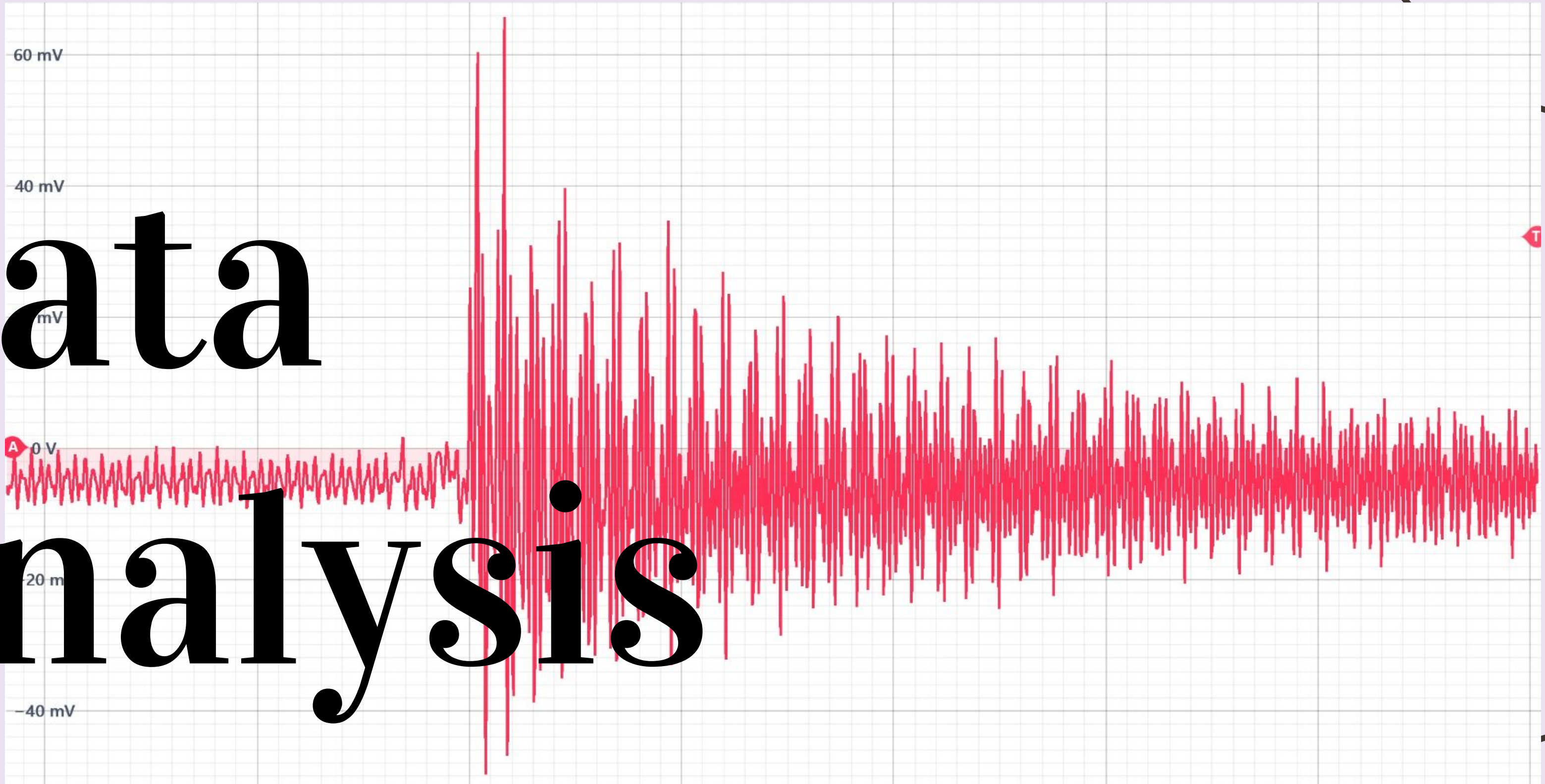


Optimizing the Dimensions: Results

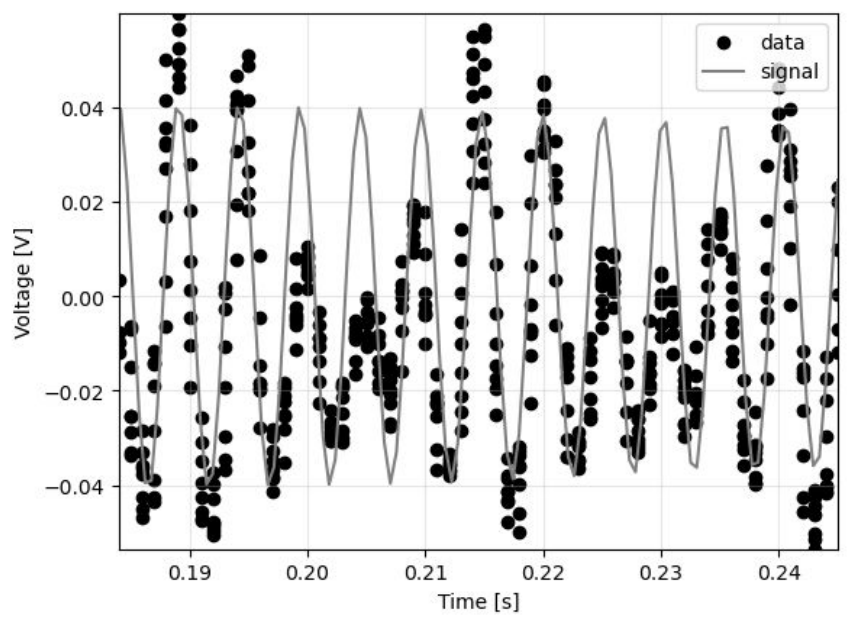
- The stress in the bond was highest when the load was applied normal to the end surface of the cantilever. This was confirmed by an analysis of the eigenfrequencies
- The height of the cantilever should be made as small as possible (in the .1 mm range)
- The width and length should also be minimized but do not have as much of an affect
- The width affected the ratio more and should be 0.5033 mm
- The length should be 1.0313 cm



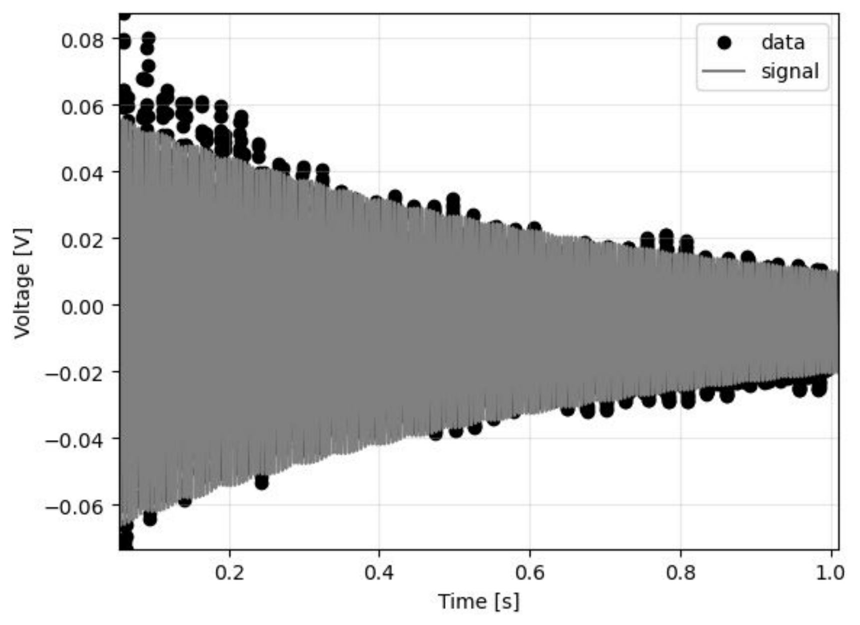
Data Analysis



1. Educated Guess

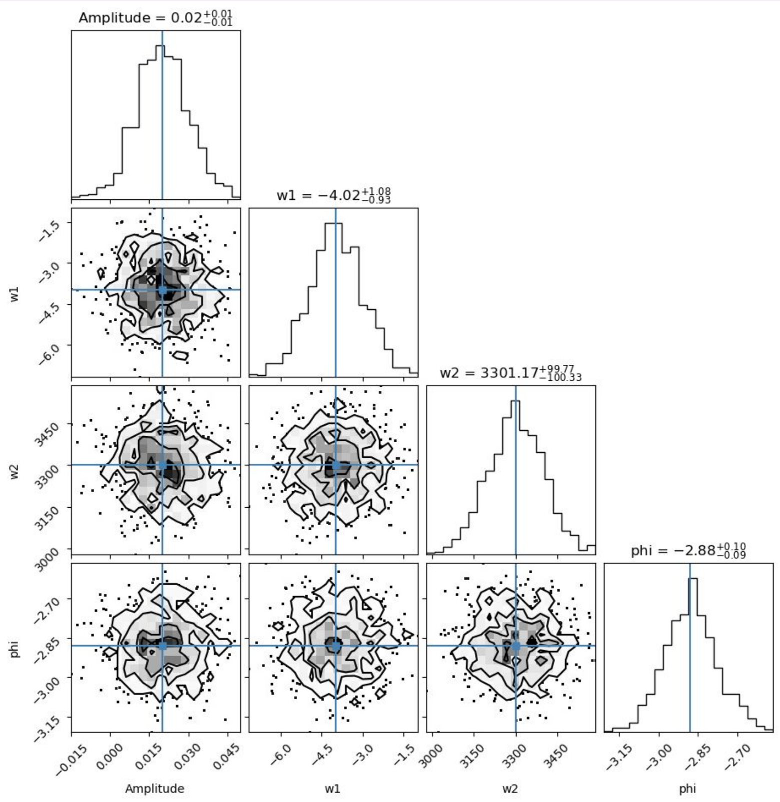


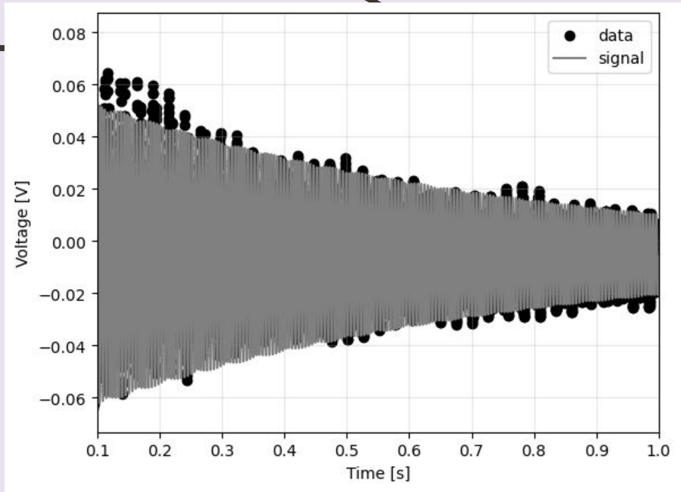
Frequency

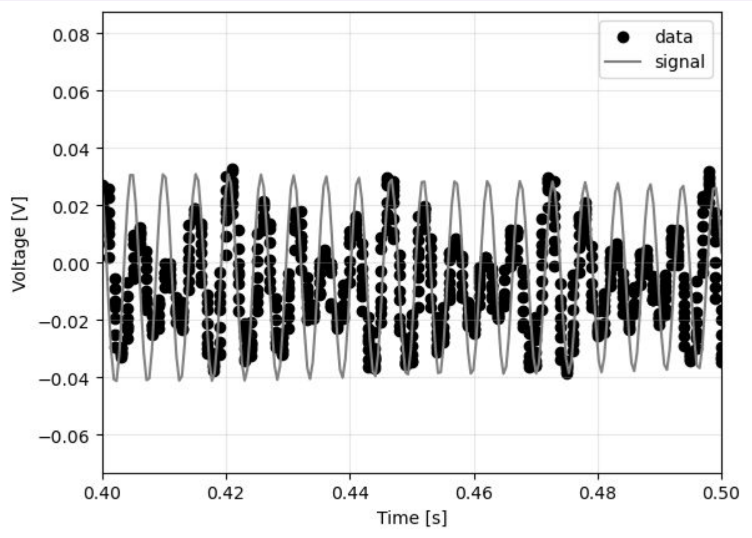


Rate of Decay

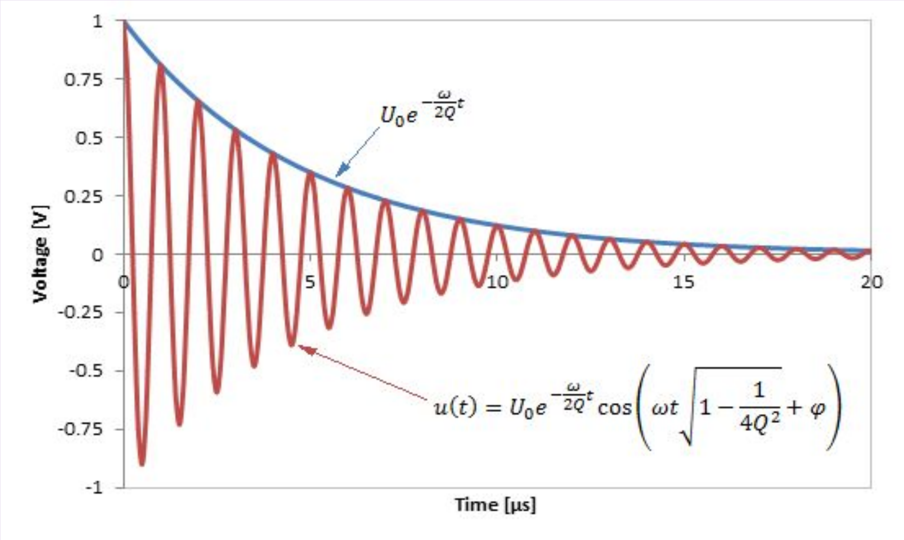
2. Bayesian Monte Carlo Method







3. Calculate Q



$$Q = \frac{\sqrt{\left(\frac{w_2}{w_1}\right)^2 + 1}}{2}$$

$$= 410 \pm 10$$

$$w_1 = -\frac{\omega}{2Q}$$

$$w_2 = \omega\sqrt{1 - \frac{1}{4Q^2}}$$

Summary

01

Problem

How to find the Q of a bond

02

Development

Brainstorm possible geometries based on mathematical inference
Geometry optimization using COMSOL
Mechanical drawing

03

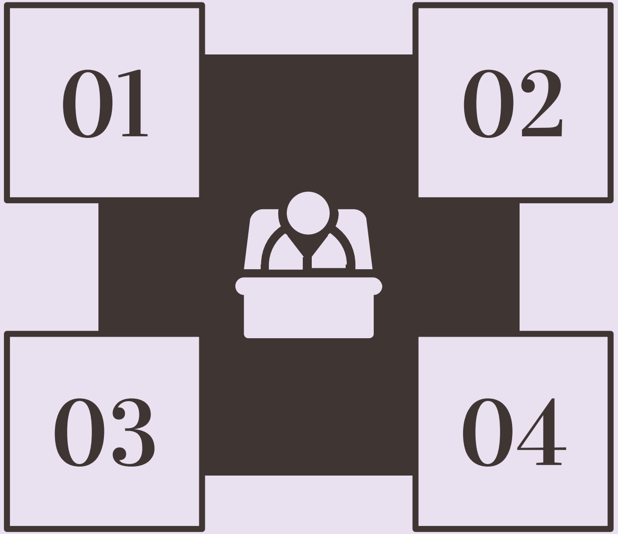
Data Collection and Analysis

Optical engineering to make an optical lever
Parameter estimation using Bayesian inference

Future Work

Test bonded silicon

Test under stress



Cryogenic temperature /vacuum

Model clamp loss

References

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Thanks!

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