Experimental Search for Avalanches of Entangled Dislocations as a Source of Dissipation and Mechanical Noise

A Thesis Defense

Presented By, **Morgan Shaner**

To the Department of Physics and Astronomy

CAL STATE LA
CALIFORNIA STATE UNIVERSITY, LOS ANGELES

LSC

Outline

- The Problem
- Dislocation Theory
- Section 1: SOC Experiment
  - Kimball and Lovell
  - Experiment
  - Initial Results
  - Future Improvements
- Glassy Metals as a Possible Replacement Material
- Conclusion
- Acknowledgements

The Problem

- Recent measurements using highly sensitive instruments have shown increased dissipation and the appearance of random low frequency noise in metal flexures.
- These devices include, but are not limited to, seismic attenuators for Gravitational Wave Observatories, seismometers and perhaps instruments measuring of the gravitational constant.
- Hindering the measurements made with these flexures and seismic isolation systems

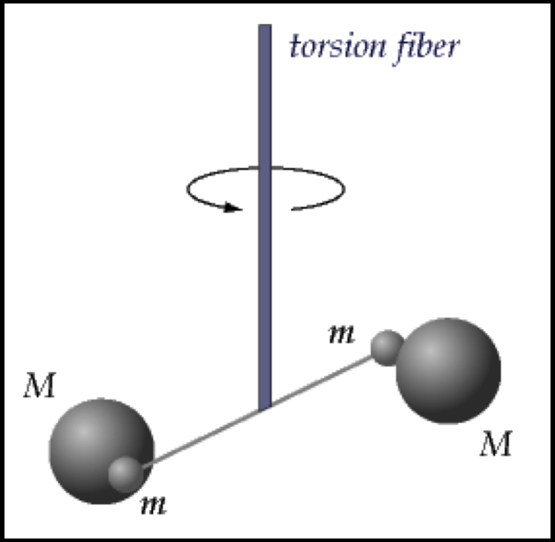
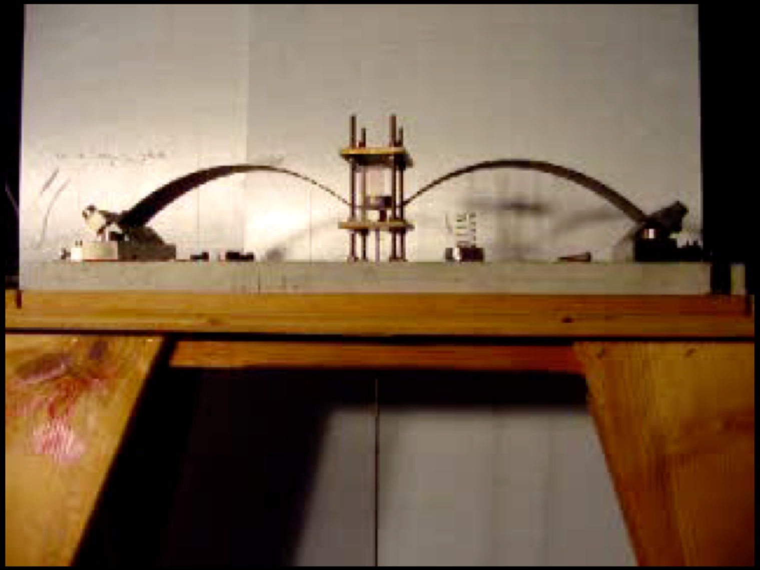


Image Credit: Kossi Physics



[1] Unaccounted source of systematic errors in measurements of the Newtonian gravitational constant G. R. DeSalvo, Phys (2015)
[2] Passive, Nonlinear, Mechanical Structures for Seismic Attenuation. R. DeSalvo, Journal of Computational and Nonlinear Dynamics (2007)

LIGO (Laser Interferometer Gravitational Wave Observatory)

Image Credit: LIGO/MIT/Caltech/Virgo

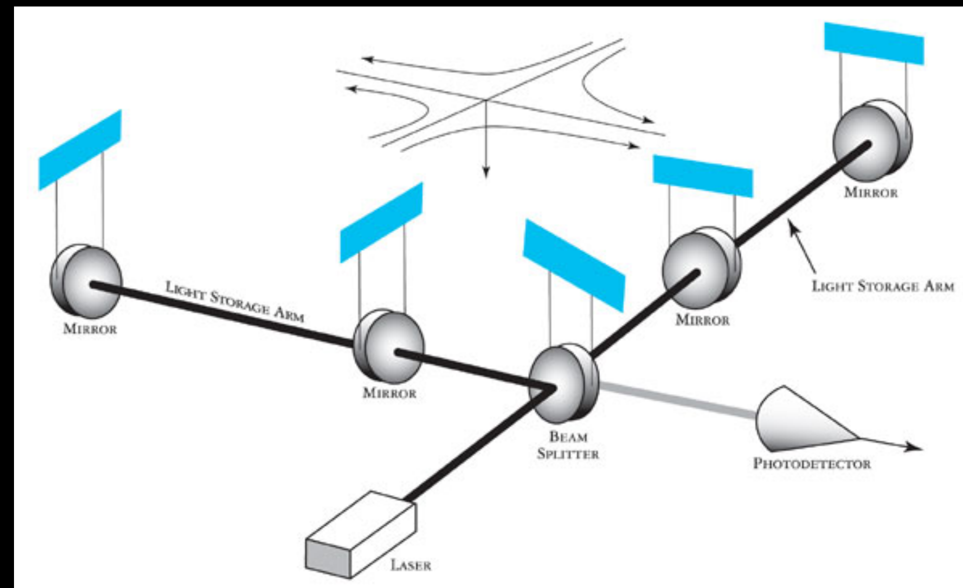
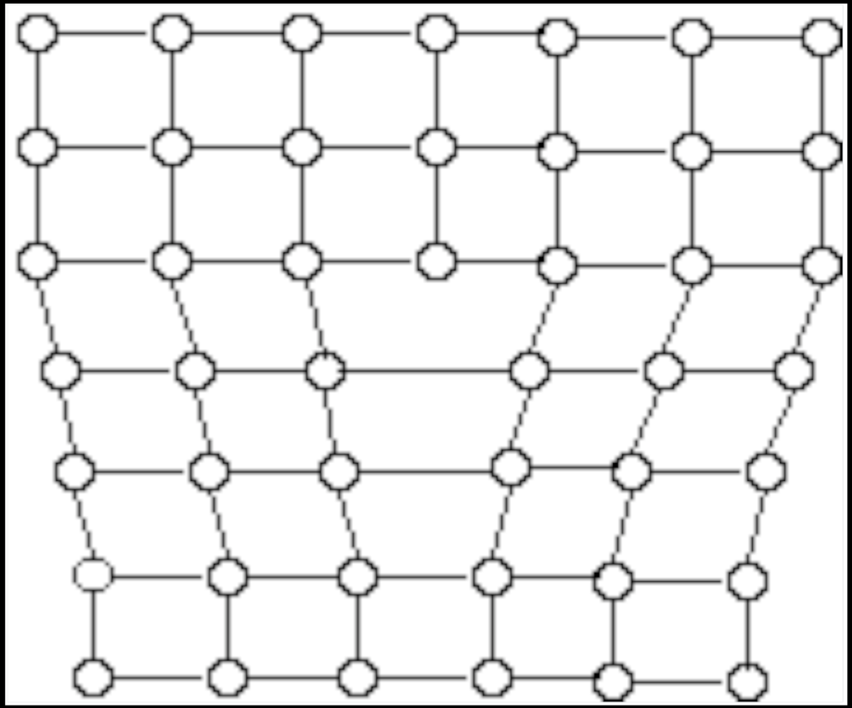


Image Credit: LIGO

Capable of measuring changes in the length of the 4 km cavity arm a trillion times smaller than the width of a strand of hair.

Where is this dissipation coming from?

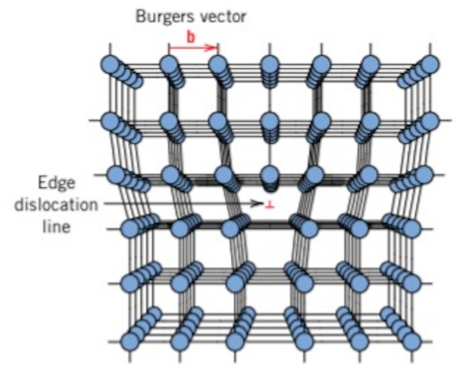
The source of low frequency noise detected in gravitational wave seismic attenuation systems is thought to originate from the dislocations in the metal's crystalline structure at the microscopic level.

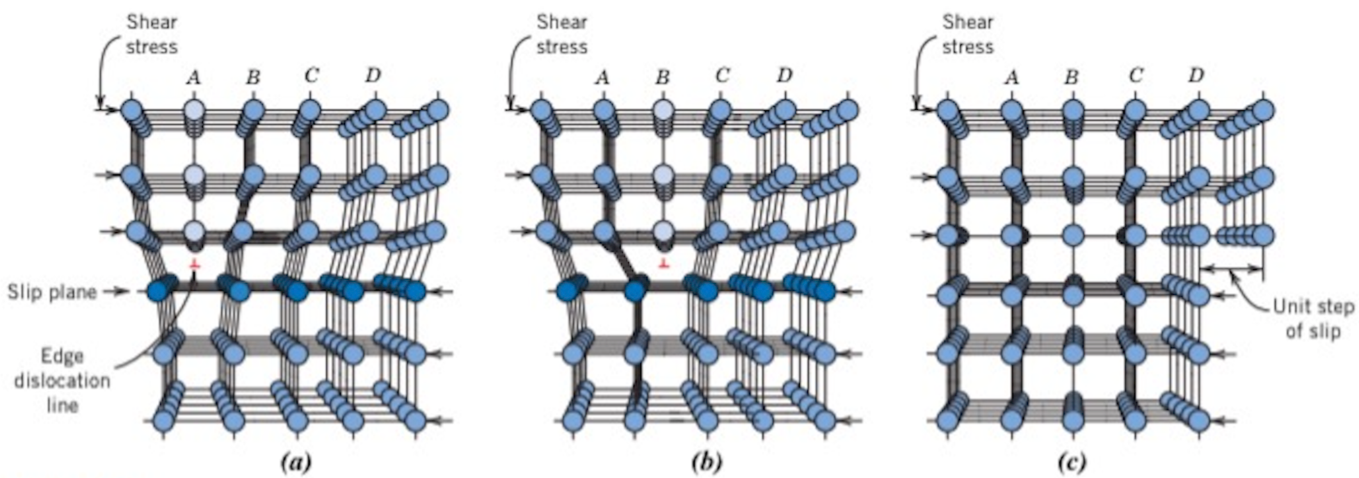


[3] A. Granato and K. Lücke. Theory of Mechanical Damping Due to Dislocations. Journal of Applied Physics 27, 583 (1956); https://doi.org/10.1063/1.1722436

Edge Dislocations

Dislocation is a defect in the crystal's atomic structure. Here we discuss edge dislocations, represented by the half plane in the image.

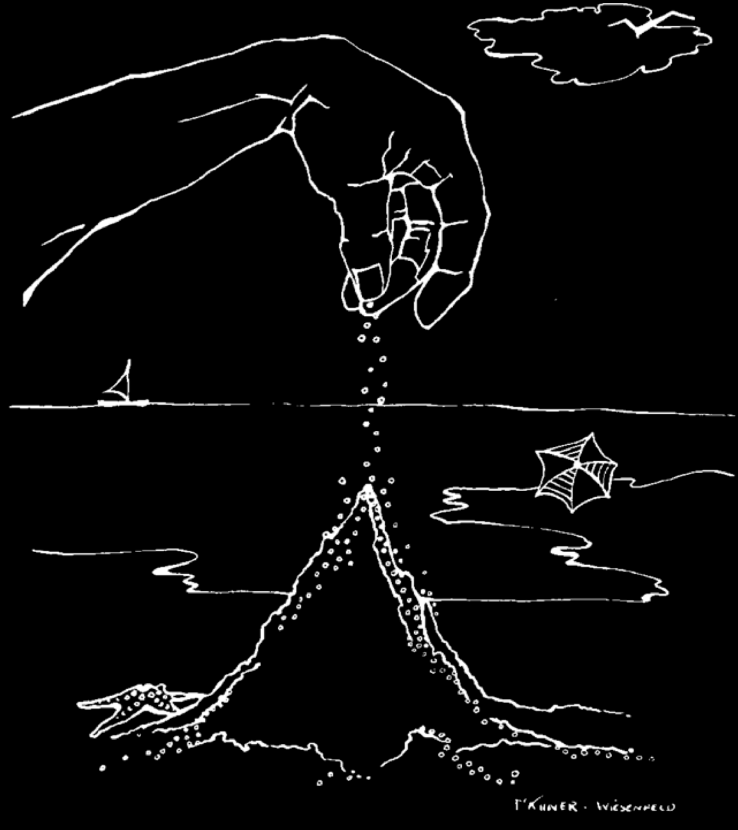




[4] The role of Self Organized Criticality in elasticity of metallic springs: Observations of a new dissipation regime. R. DeSalvo, A. DiCintio, M. Lundin, Eur. Phys. J. (2011)

[5] W. D. Callister and D. G. Rethwisch, Materials Science and Engineering: an Introduction, Wiley, 2014.

Self-Organized Criticality



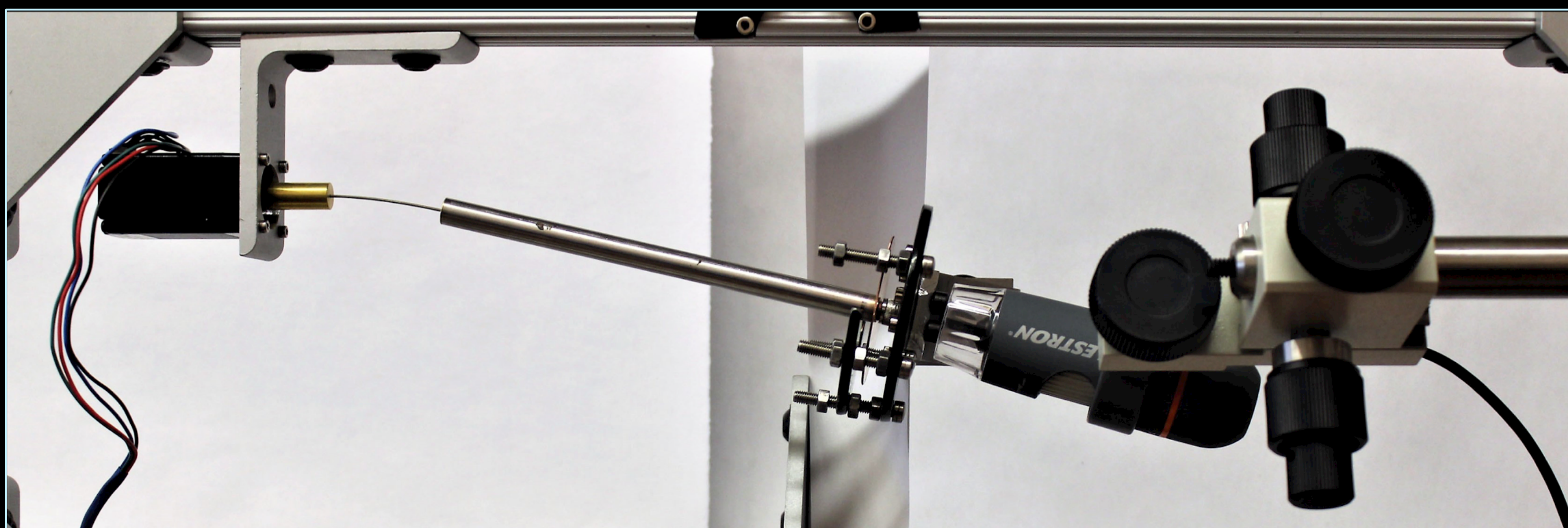
"The ***canonical example*** *of SOC is a pile of sand. A sand pile exhibits punctuated equilibrium behavior, where periods of stasis are interrupted by intermittent sand slides. The sand slides, or* ***avalanches****, are caused by a domino effect, in which* ***a single grain of sand pushes one or more other grains and causes them to topple****. In turn, those* ***grains****, not gradual change,* ***make the link between quantitative and qualitative behavior****, and form the basis for emergent phenomena"*

[6] Per Bak. *How Nature Works: the science of self-organized criticality*. Springer, New York (1996).

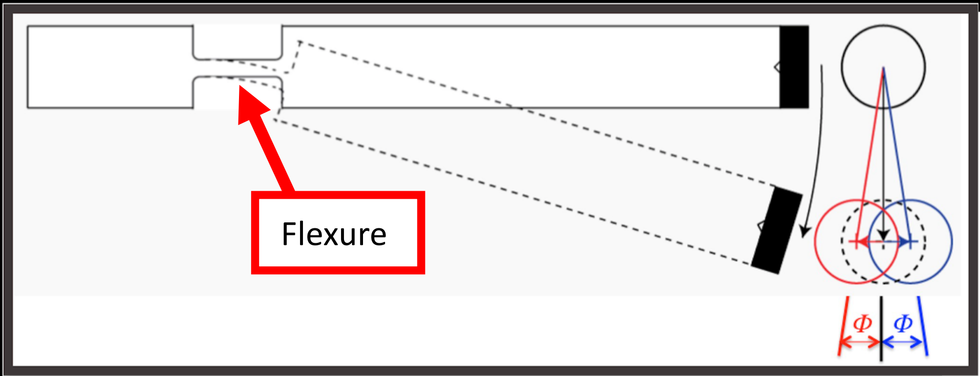
Summary of Theory

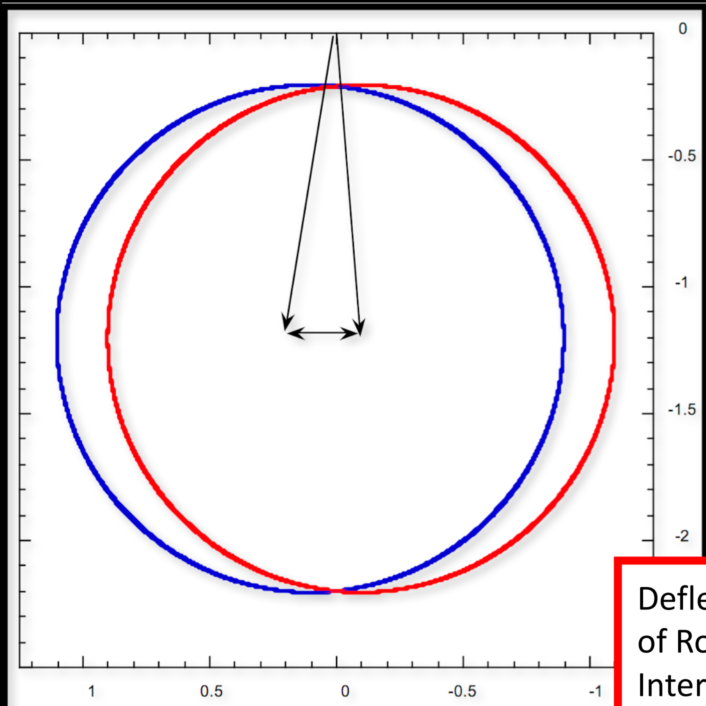
- These microscopic defects have macroscopic effects
- Dislocations are highly prominent in all metals
- High carbon steels and maraging steel are to be explored first because studies have already been conducted on these materials and shown equilibrium point fluctuations below 0.5 Hz where the dislocations are able to entangle and create a complex structure.
- On the macroscopic side this would appear as a shift in flexure's equilibrium point.

The SOC Experiment



Kimball and Lovell: Measurement of Loss Angle





Deflection of Center of Rotation Due to Internal Friction

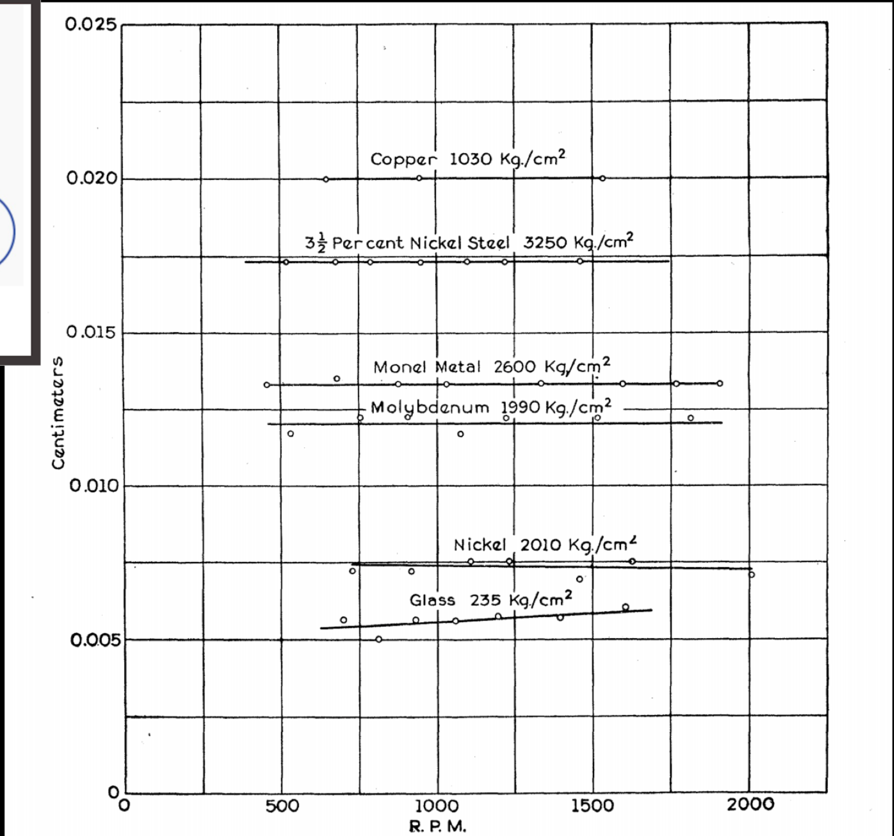
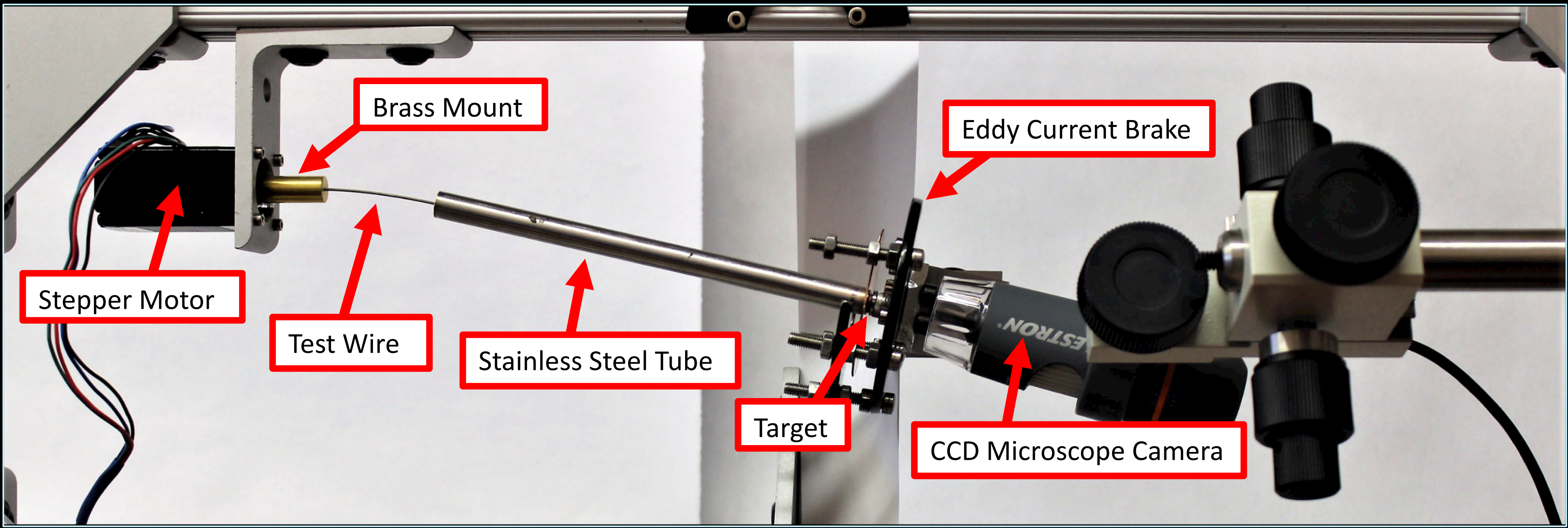


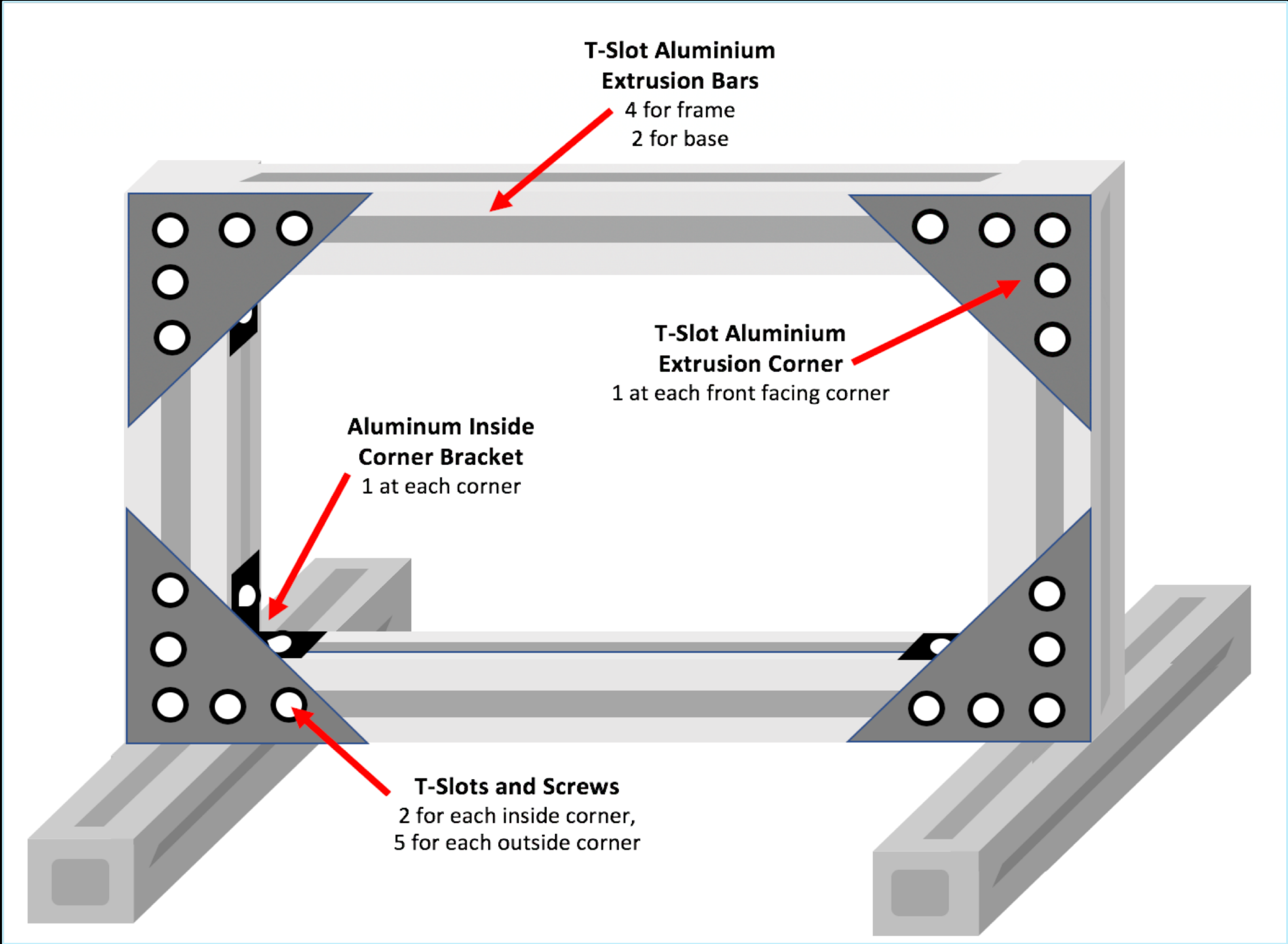
Fig. 6. Curves of sideways deflection at end of shaft plotted against speed of rotation for several different materials.

[5] ***Internal Friction in Solids.*** **A. Kimball, D. Lovell, Phys. (1927)**

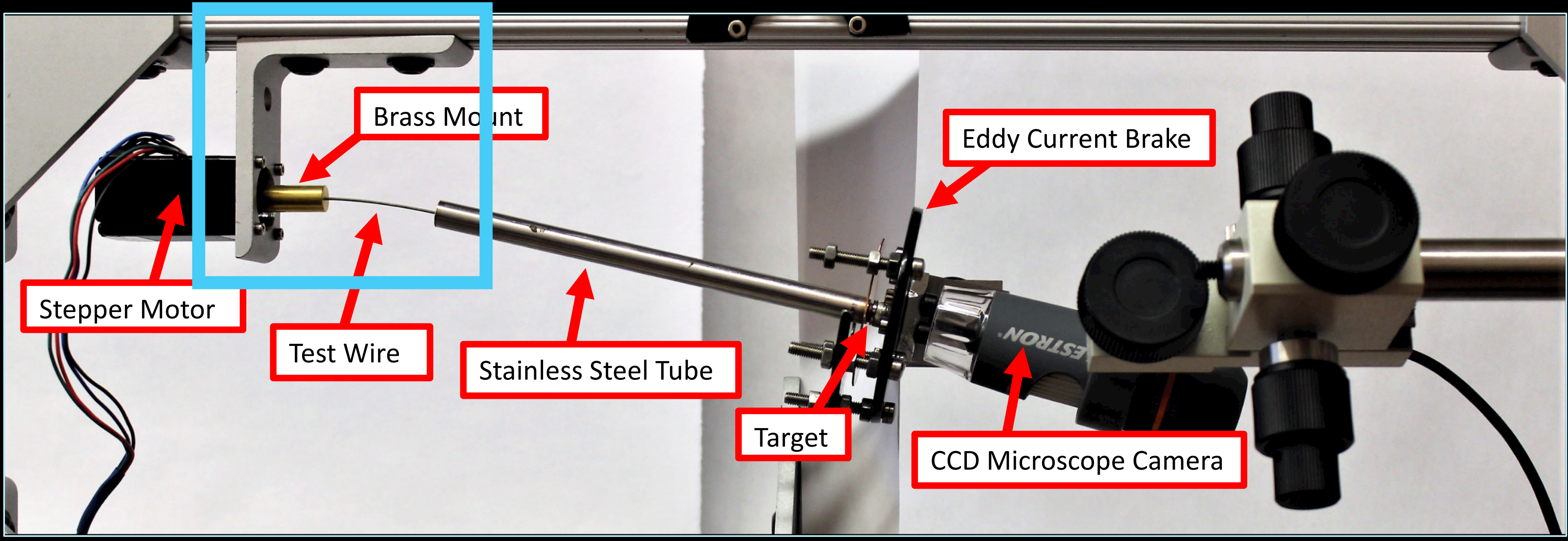
The Experiment



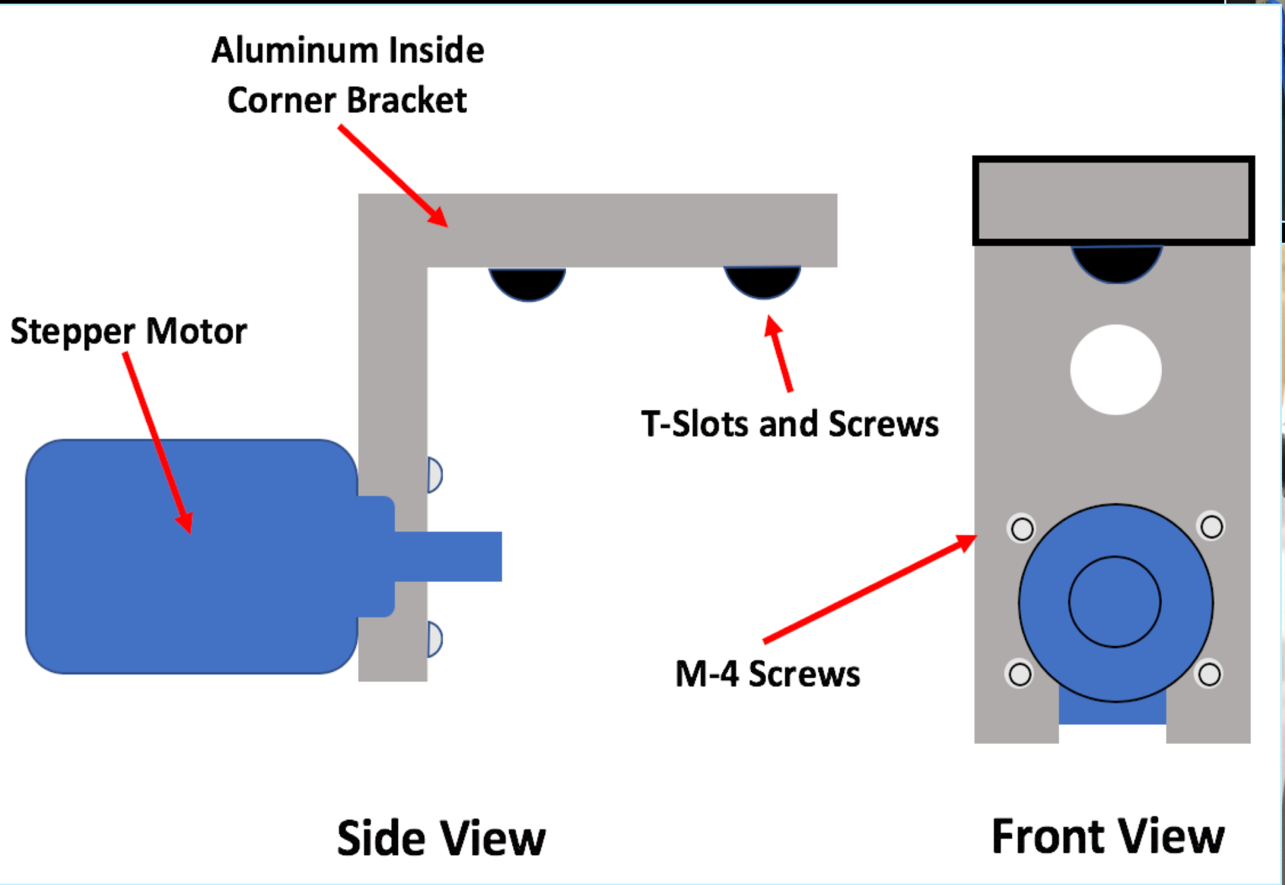
Main Frame

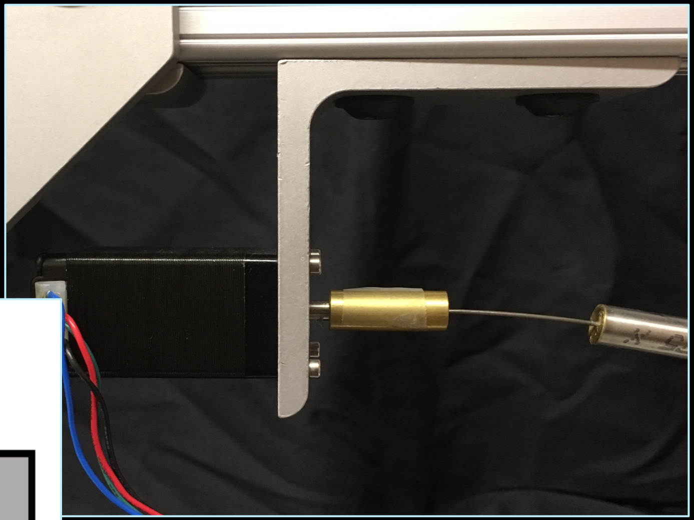

T-Slot Aluminium Extrusion Bars
4 for frame
2 for base
T-Slot Aluminium Extrusion Corner
1 at each front facing corner
Aluminum Inside Corner Bracket
1 at each corner
T-Slots and Screws
2 for each inside corner,
5 for each outside corner

The Experiment

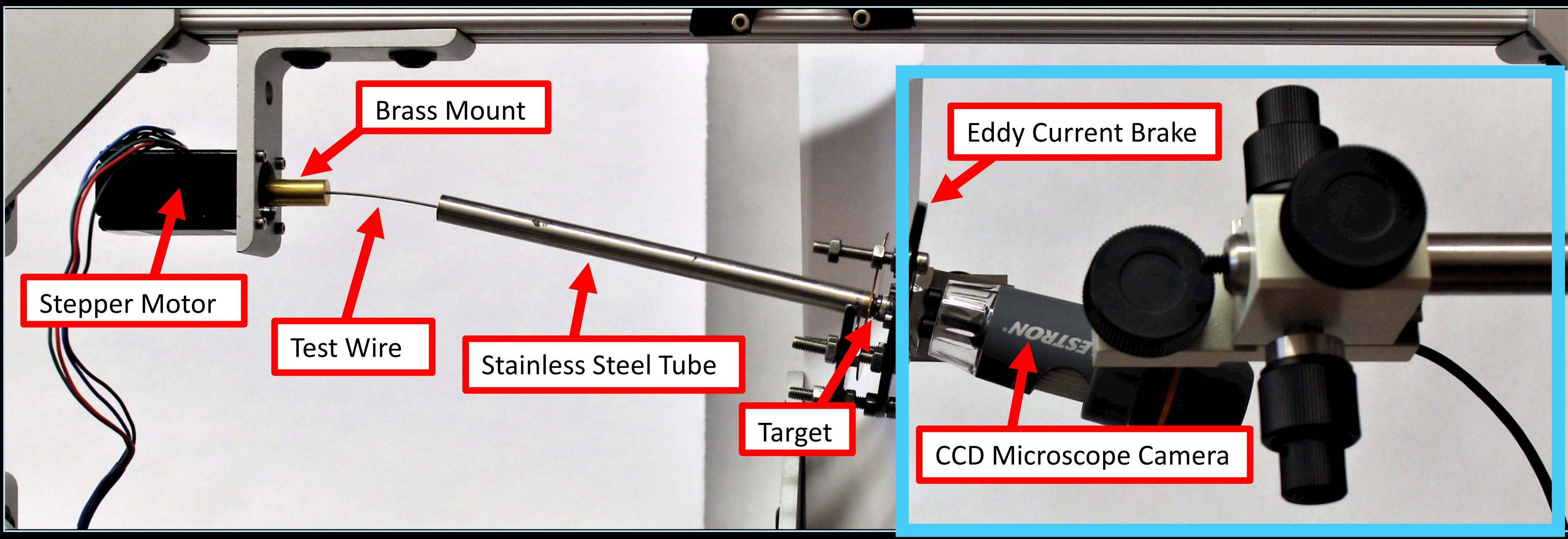


Stepper Motor Mount

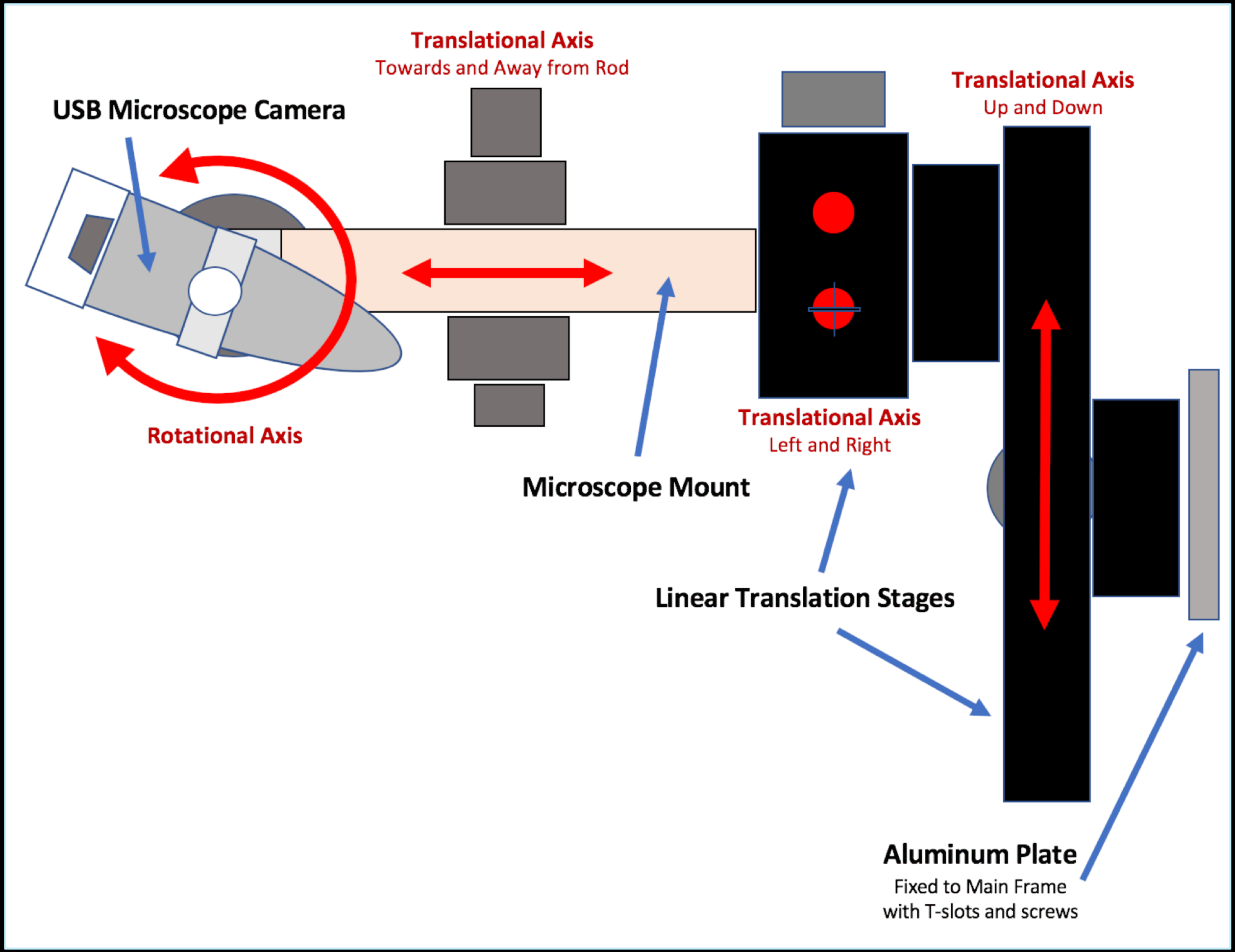




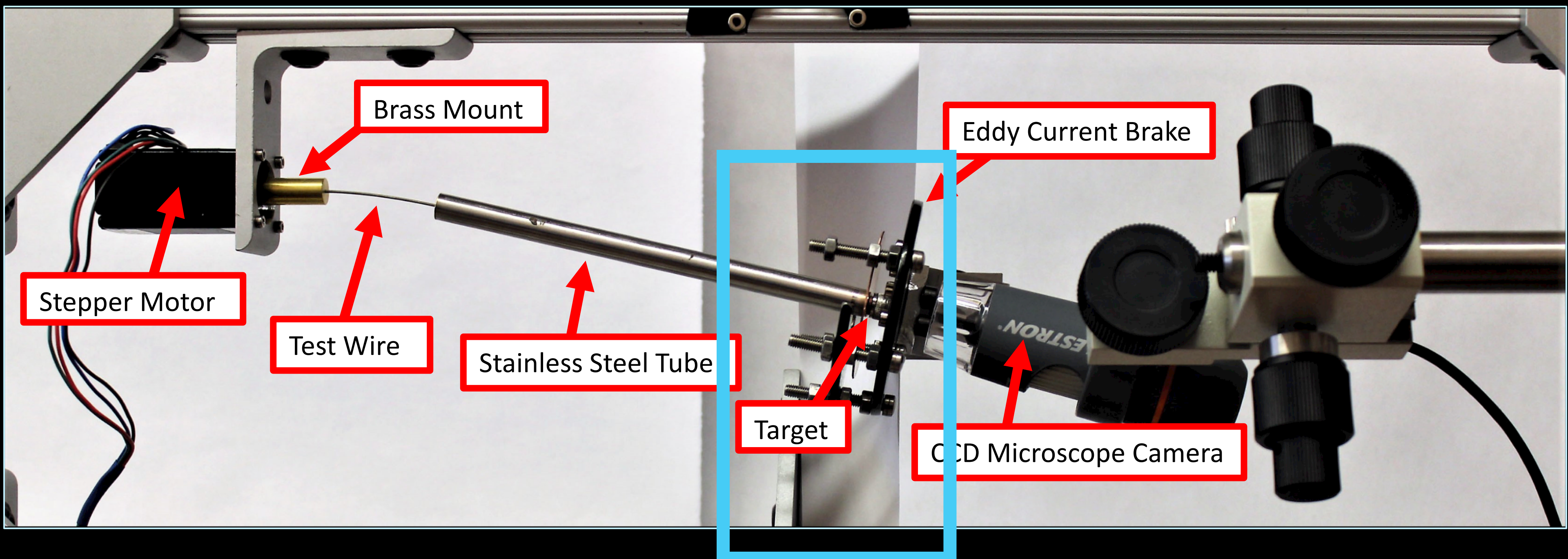
The Experiment



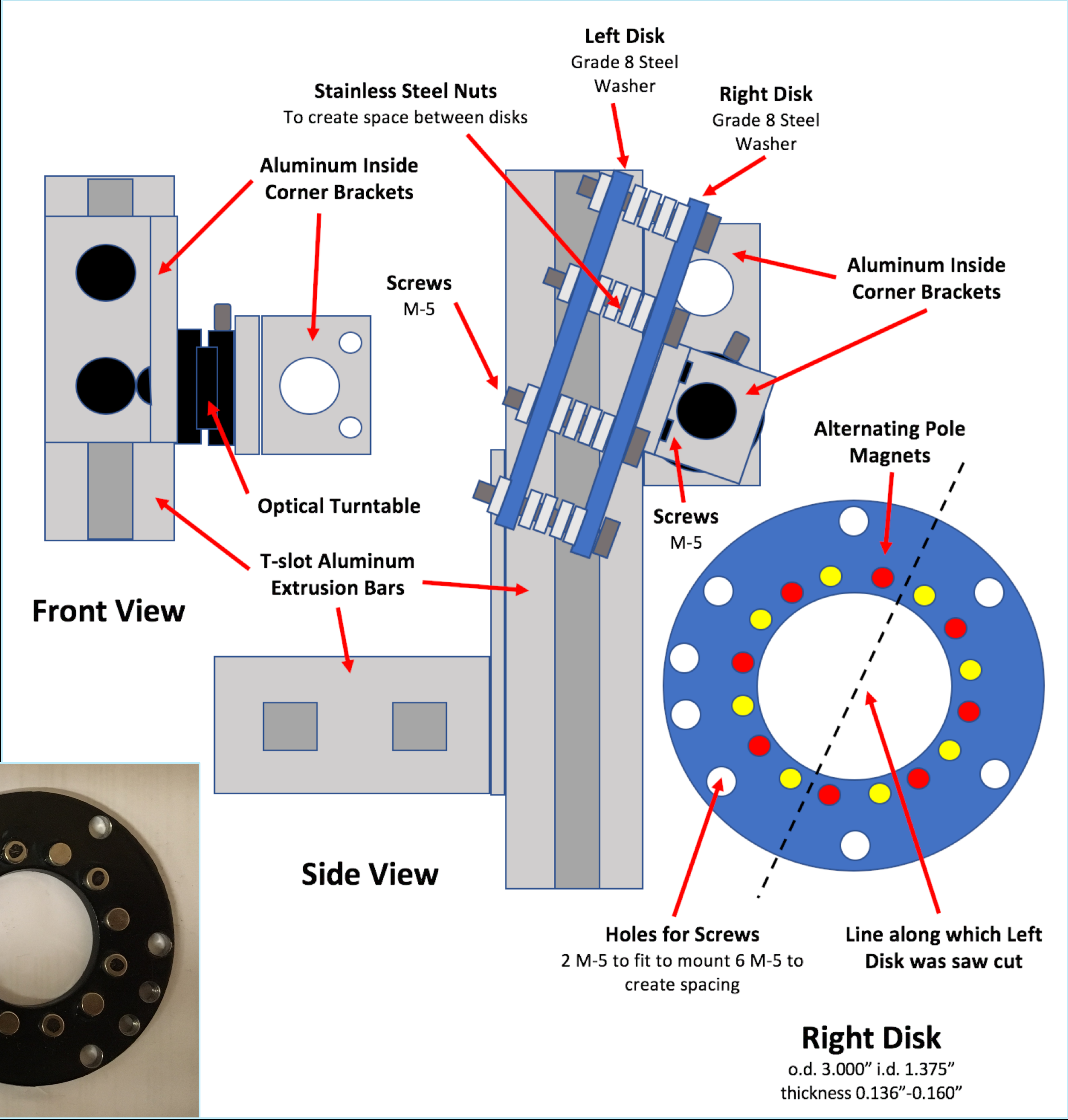
Camera Mount



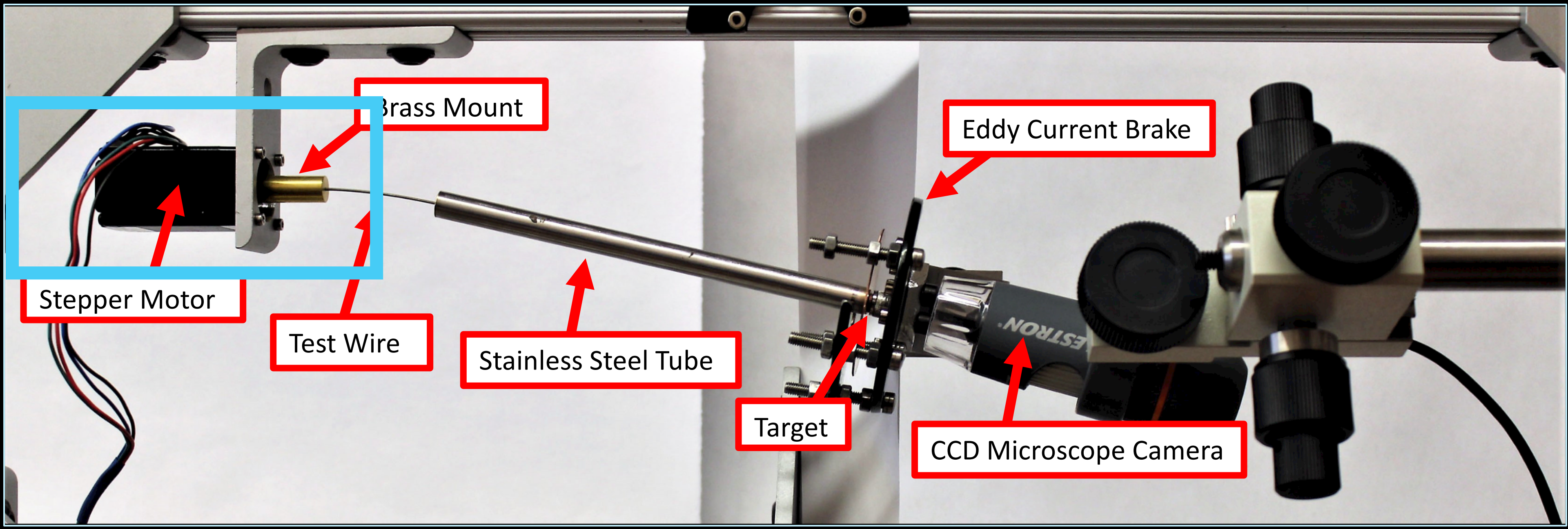
The Experiment



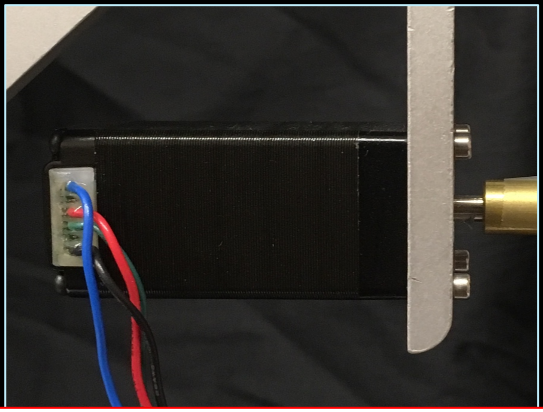
Eddy Current Disk Brake Mount



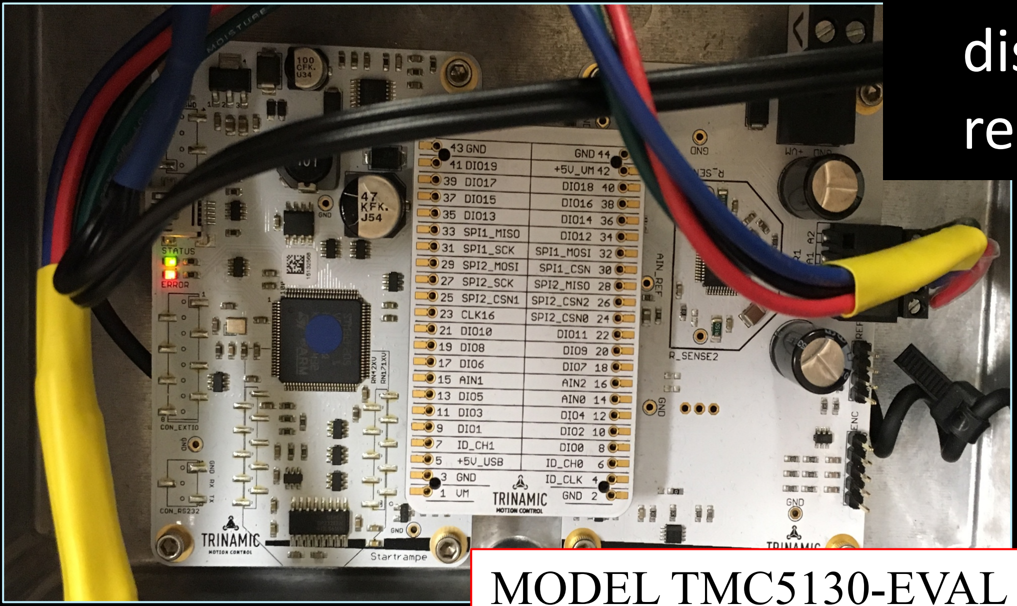
The Experiment



Stepper Motor



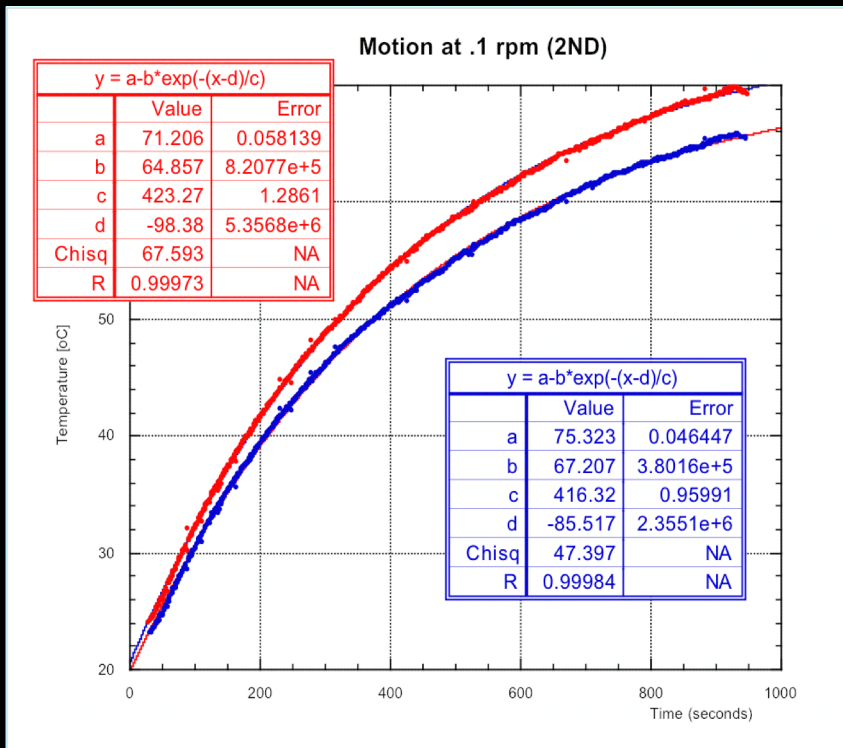
Trinamic MODEL QSH2818-51-07-012



MODEL TMC5130-EVAL

- 200 steps/turn
- 256 microsteps/step
- stepping noise : 51,200 X rotational frequency
- Operating the motor at 0.08 A, creates only 60 mW of power dissipation on the motor resistance of 9 Ω.

Stepper Motor Heating



Thermalizes to:

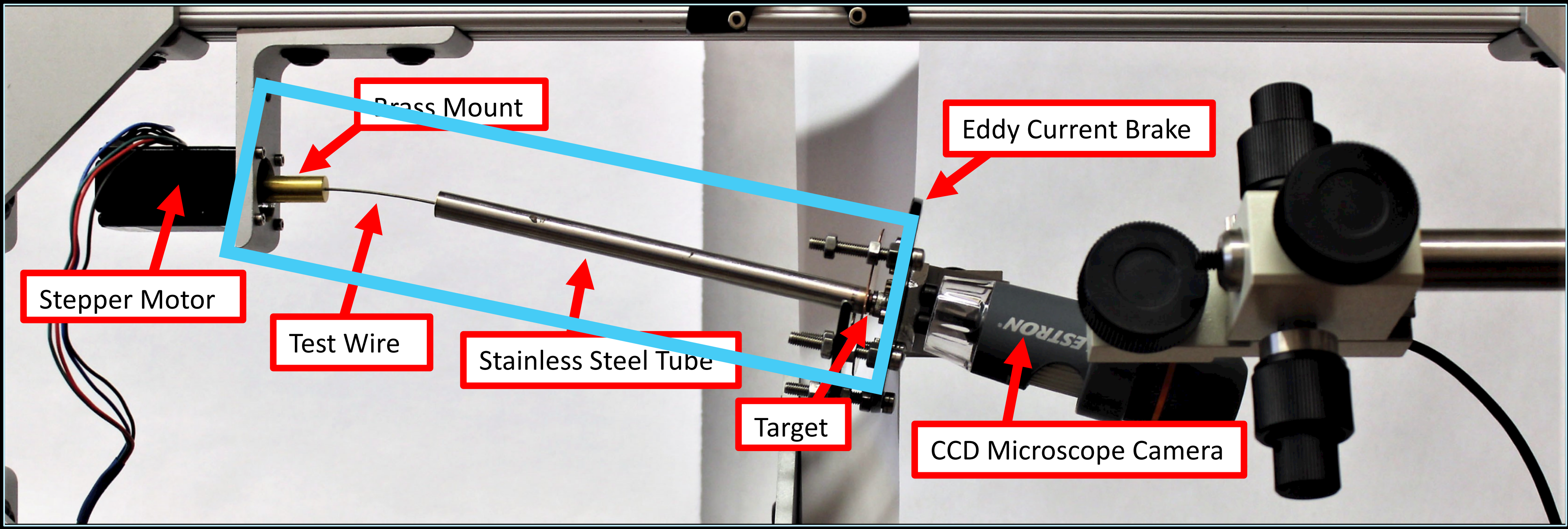
$T_1 = 71.21 \pm 0.06\ ^oC$

$T_2 = 75.32 \pm 0.05\ ^oC$

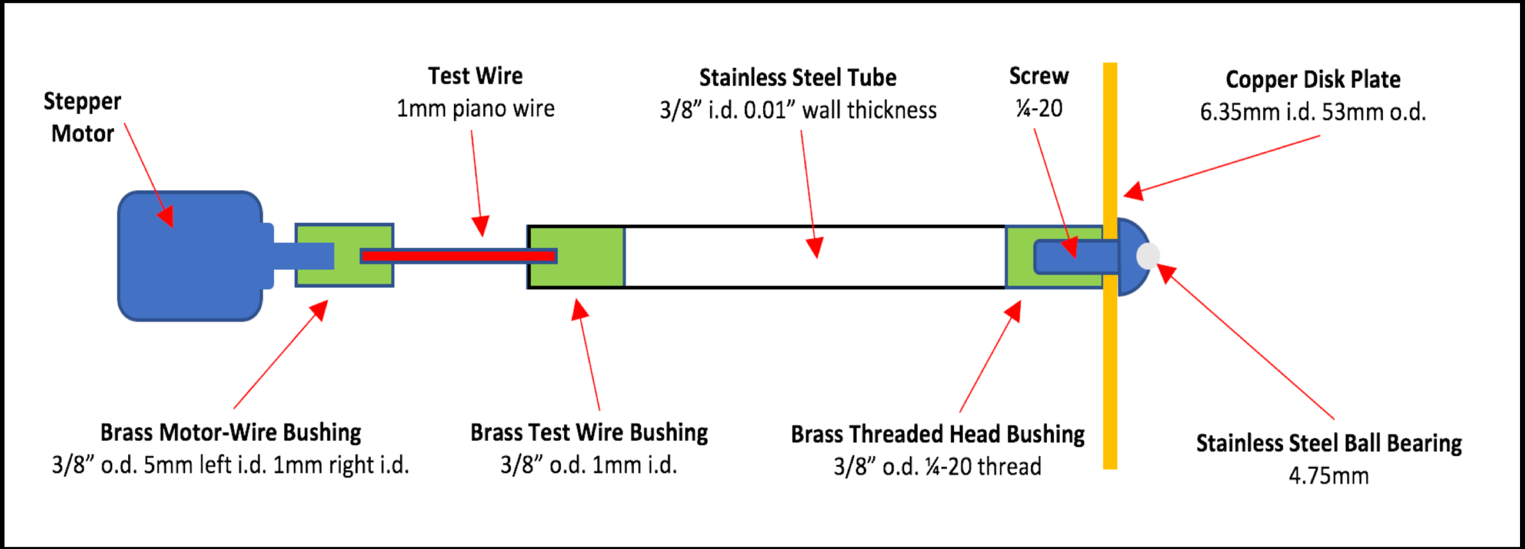
(50 ^oC ⇧ T_{room})

Thermalization (5τ) within 34.7 - 35.2 minutes

The Experiment



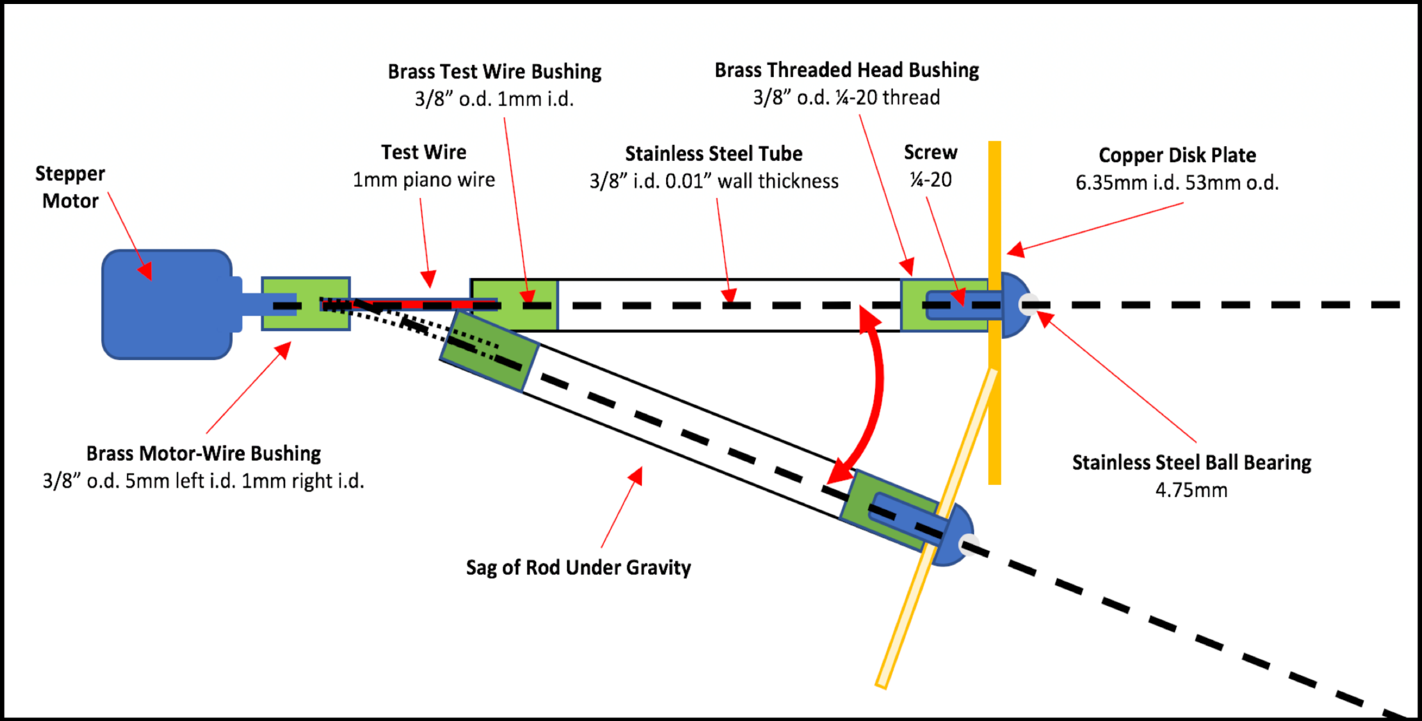
Rod Design



The flexure stress level can be changed multiple ways:

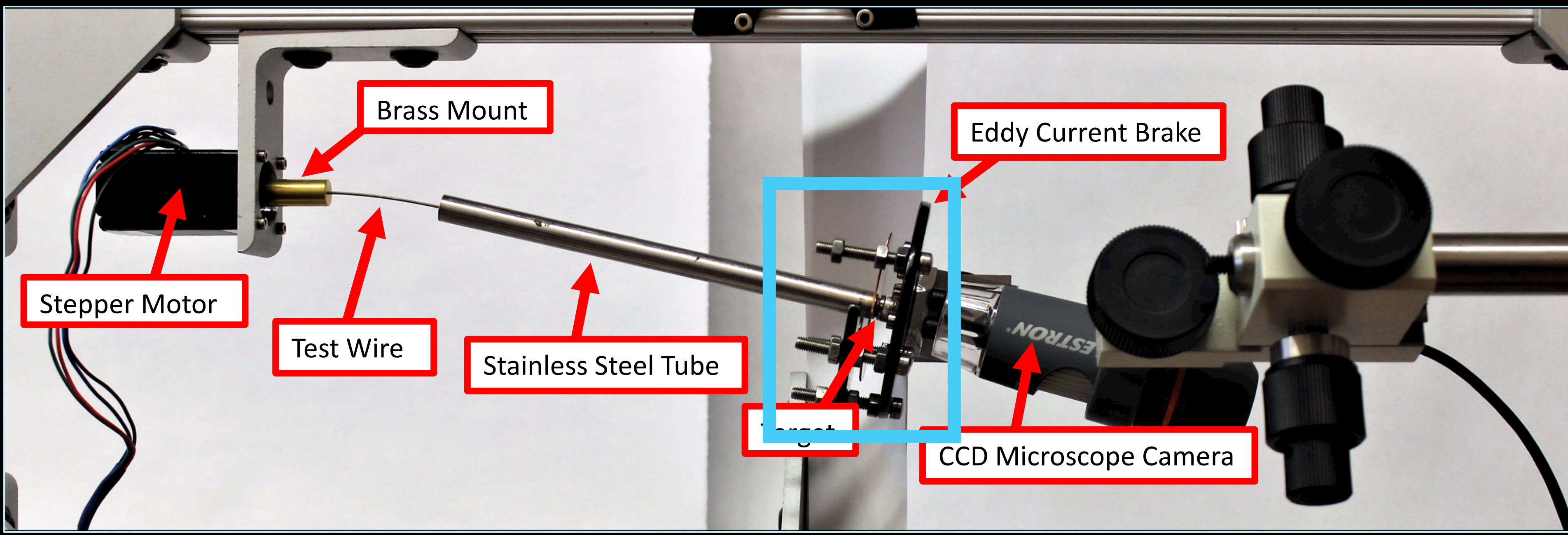
- Changing the mass of the copper disk
- Changing the length of the tube
- Tilting the frame, thus changing the angle of the force applied by gravity
- Changing the flexure diameter

Rod Design



High carbon steel, copper-beryllium, tungsten and maraging steel were chosen to study first because they exhibit excess losses

The Experiment



Eddy Current Vibration Damper

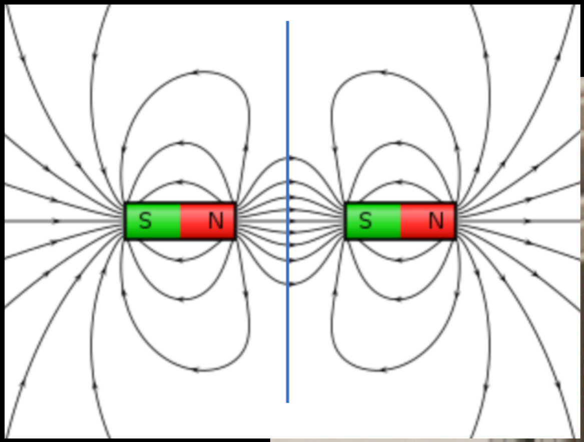
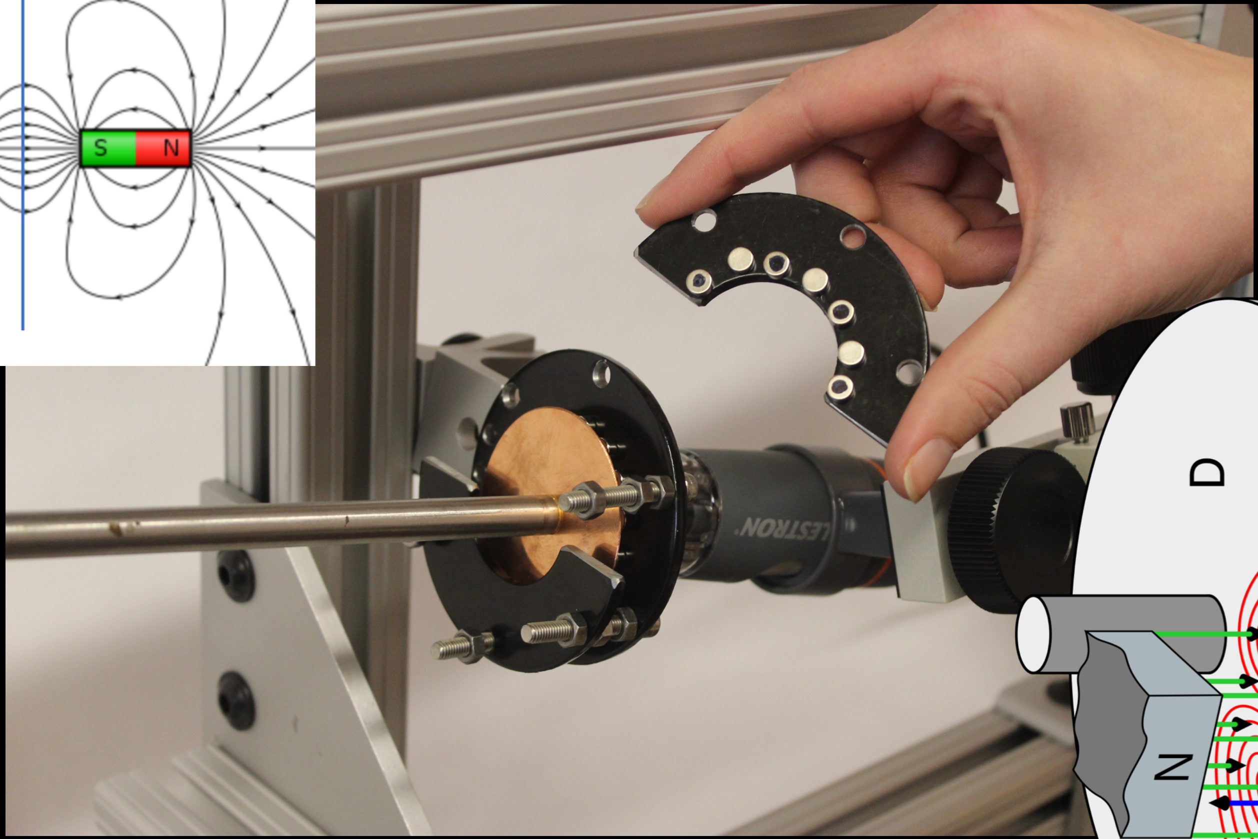


Image Credit: physbot



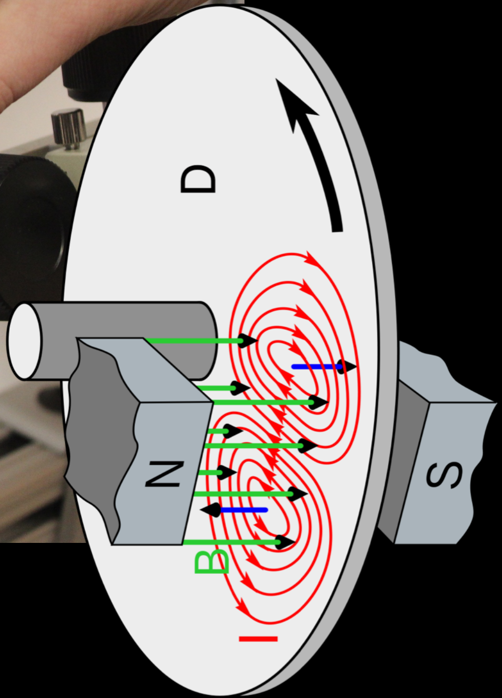
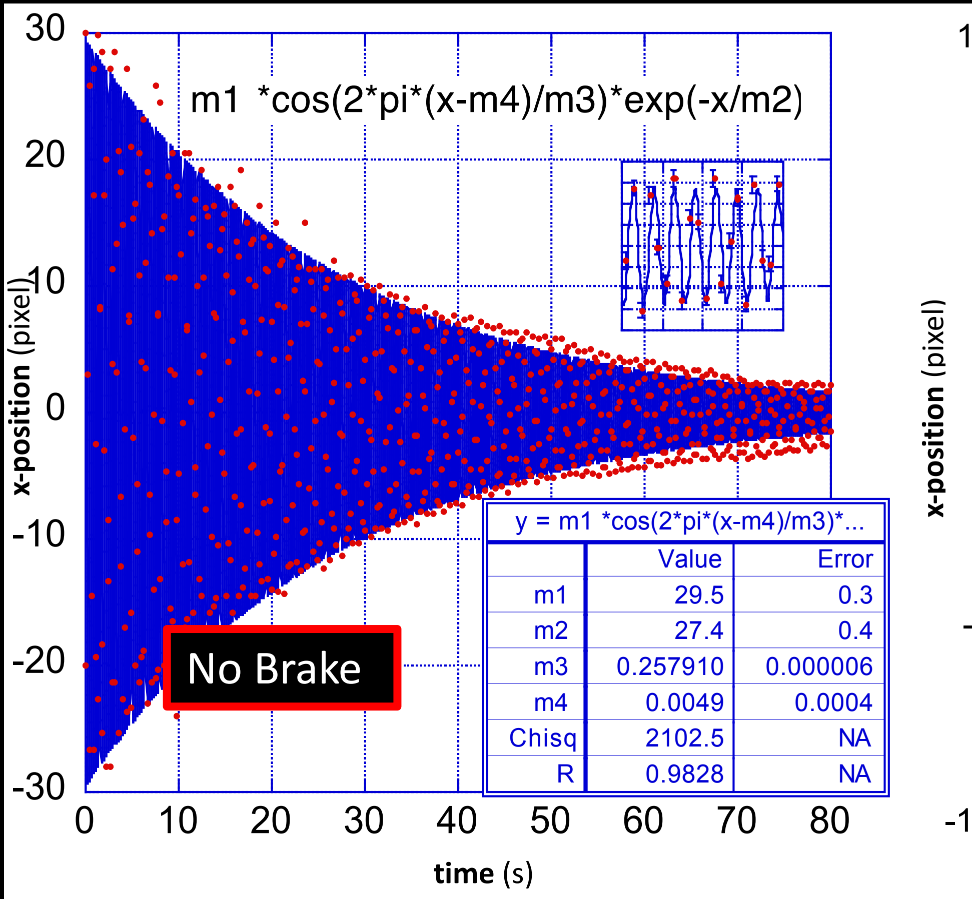
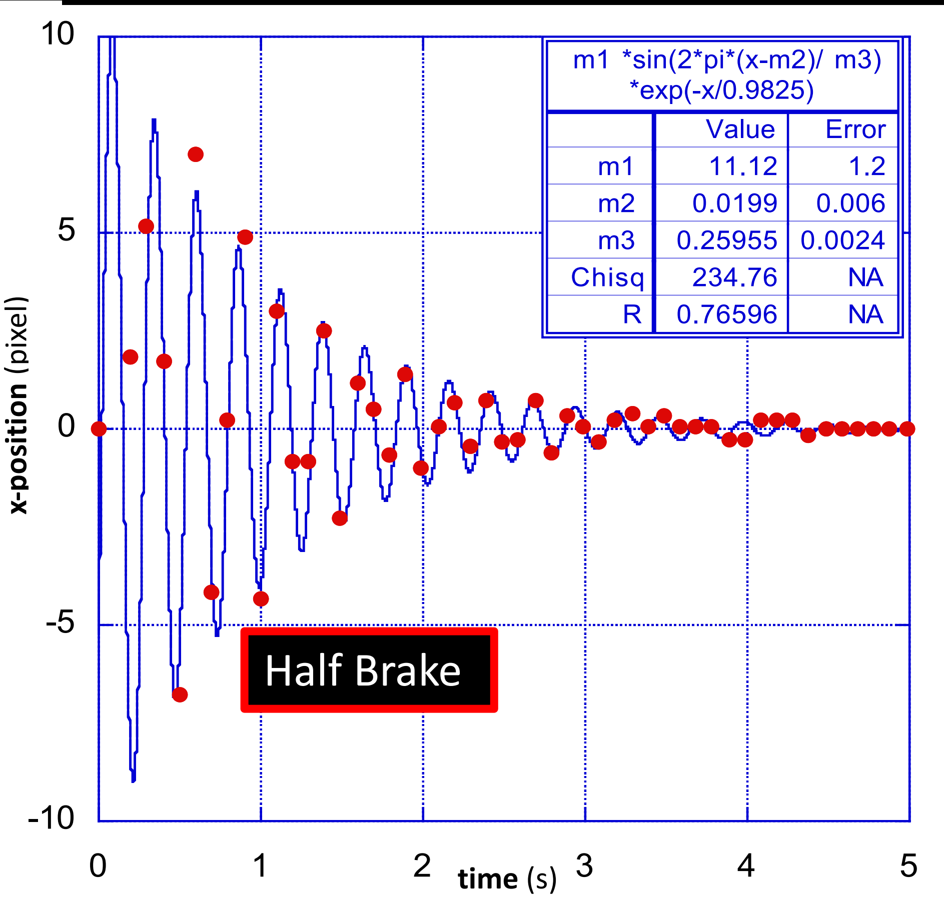


Image Credit: Wikipedia

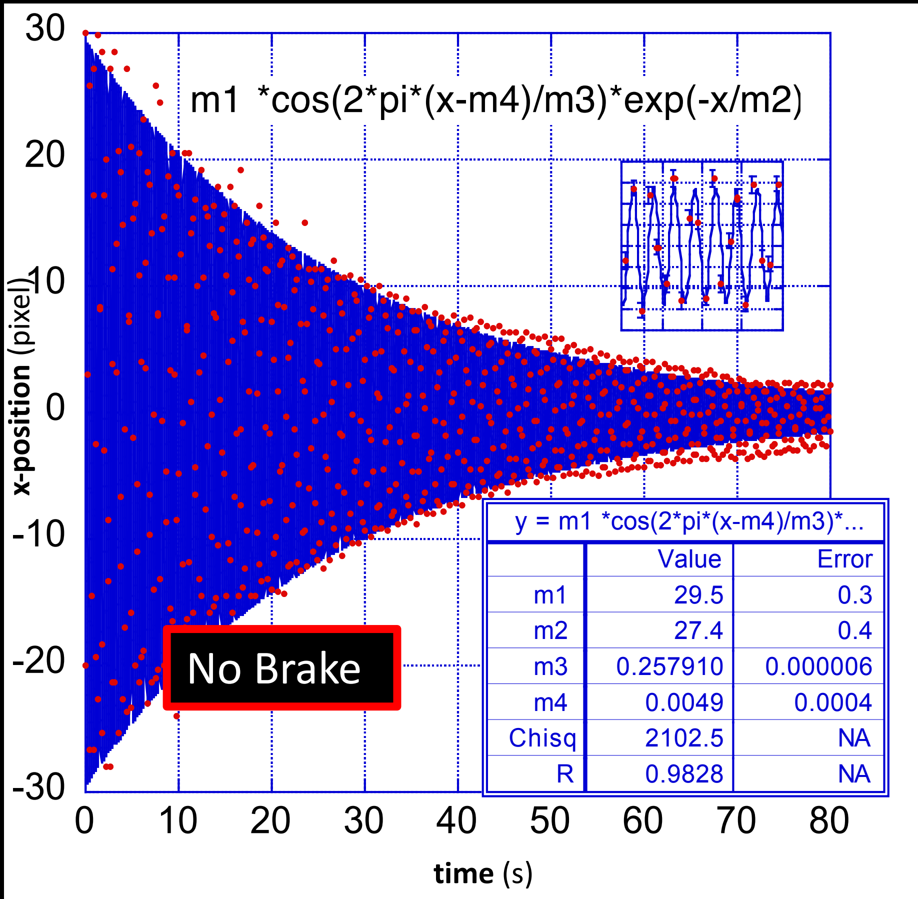


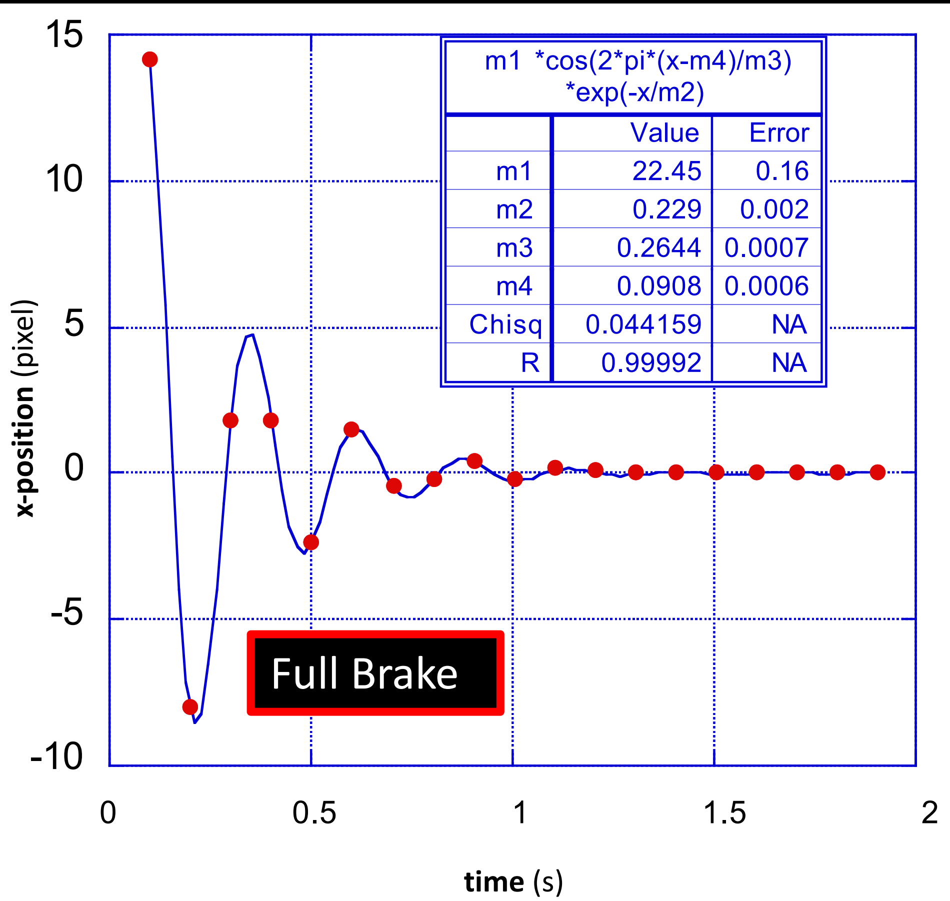


$$\omega = \frac{2\pi}{T} = \frac{2\pi}{0.257910} = 24.362 \pm 0.004\ Hz$$

$$Q = \frac{\tau\omega}{2\pi} = \frac{(27.4\ )(24.362)}{2\pi} = 106.2 \pm 0.2$$

$$\phi = \tan^{-1}\frac{1}{Q} = \tan^{-1}\frac{1}{106.2} = 9.42 \pm 0.02 \text{ milli-radians}$$





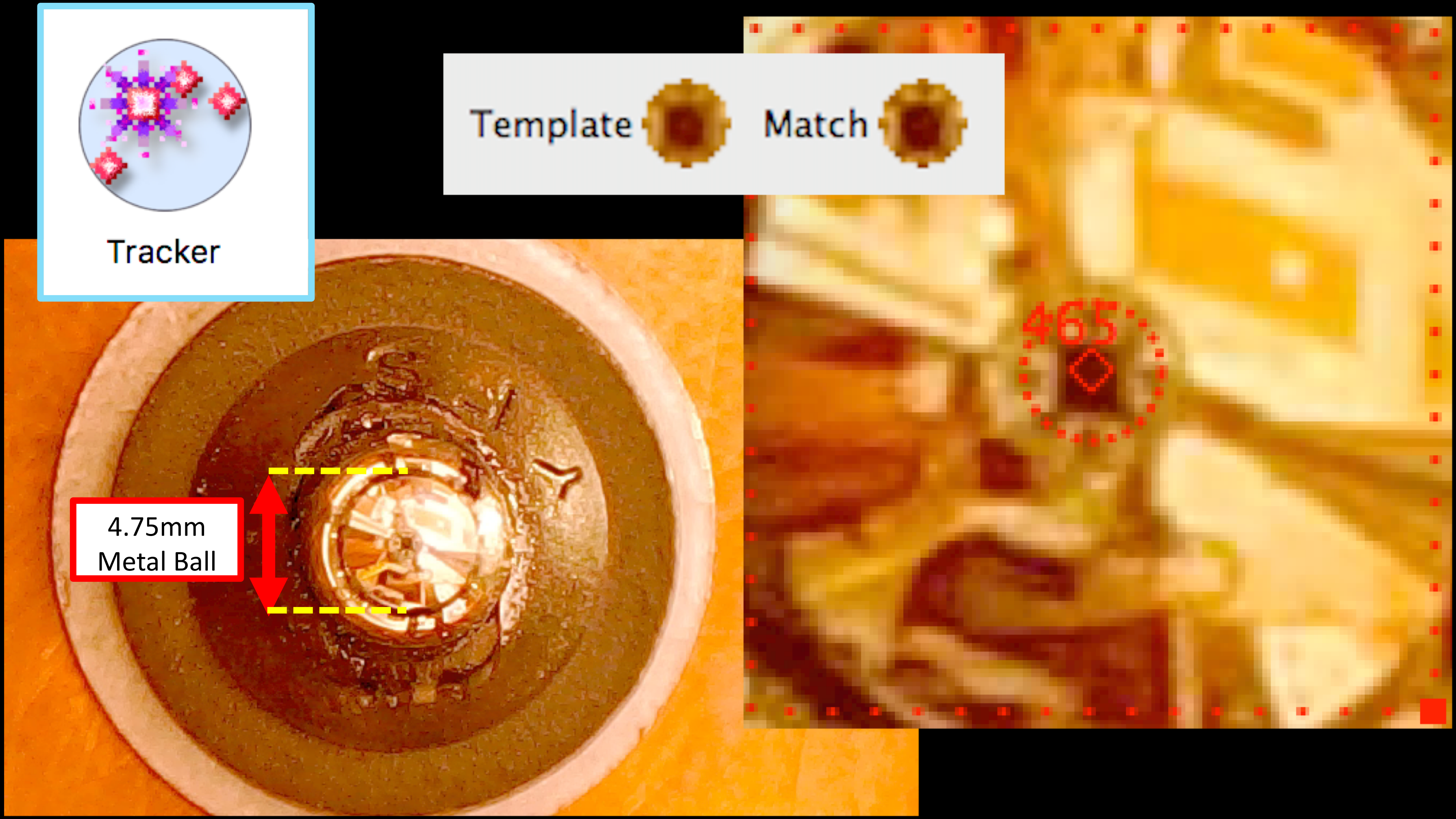
Minimal Frequency Shift with Damper

	T[s]	δT[s]	ω [Hz]	δω [Hz]	Δω [Hz]
No damper	0.257910	0.000006	24.362	0.004	----
Half damper	0.260	0.002	24	1	-0.36
Full damper	0.2644	0.0007	23.8	0.4	-0.60

Achieve almost critical damping!

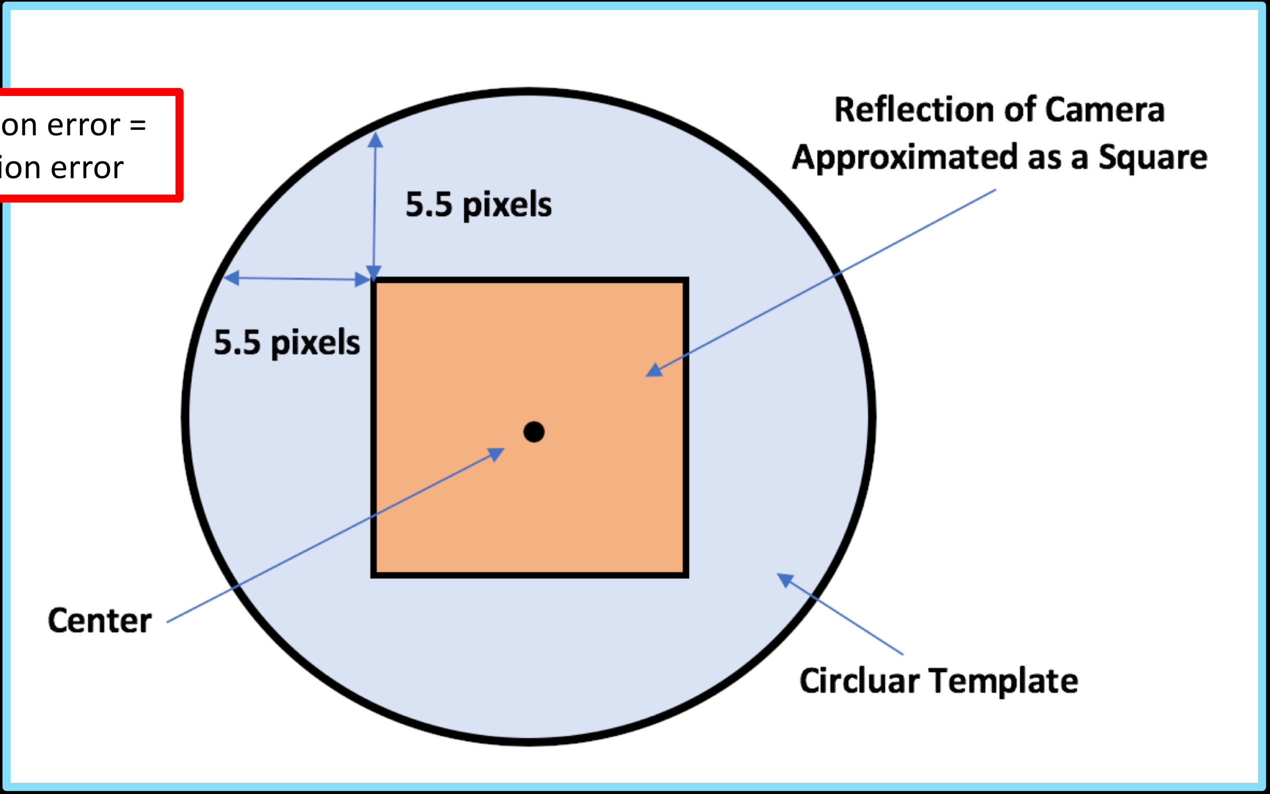
Initial Results

Tracking the Target



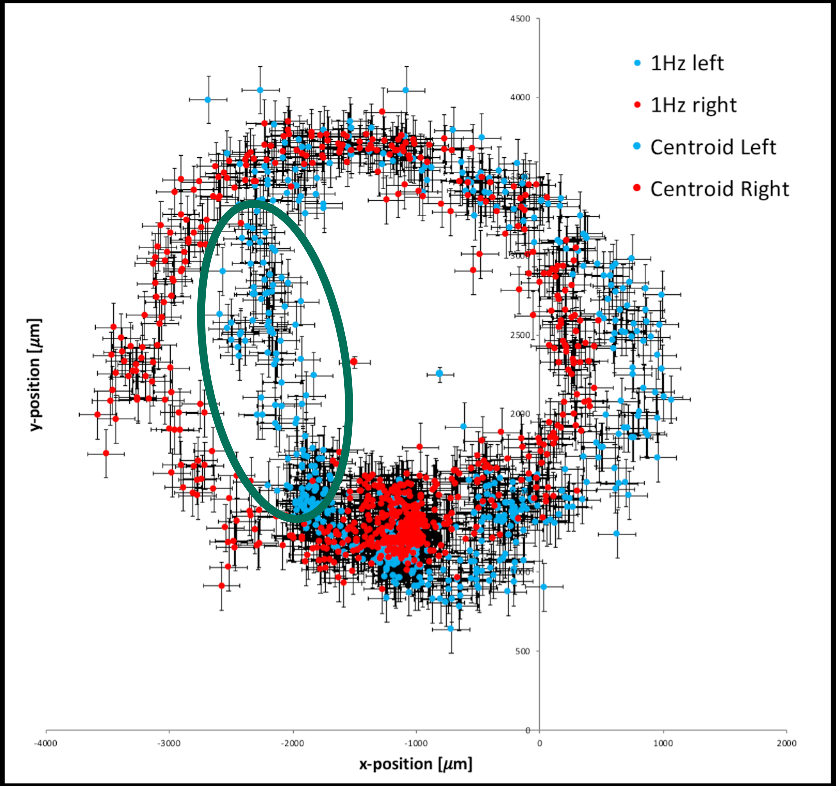
Tracking Error

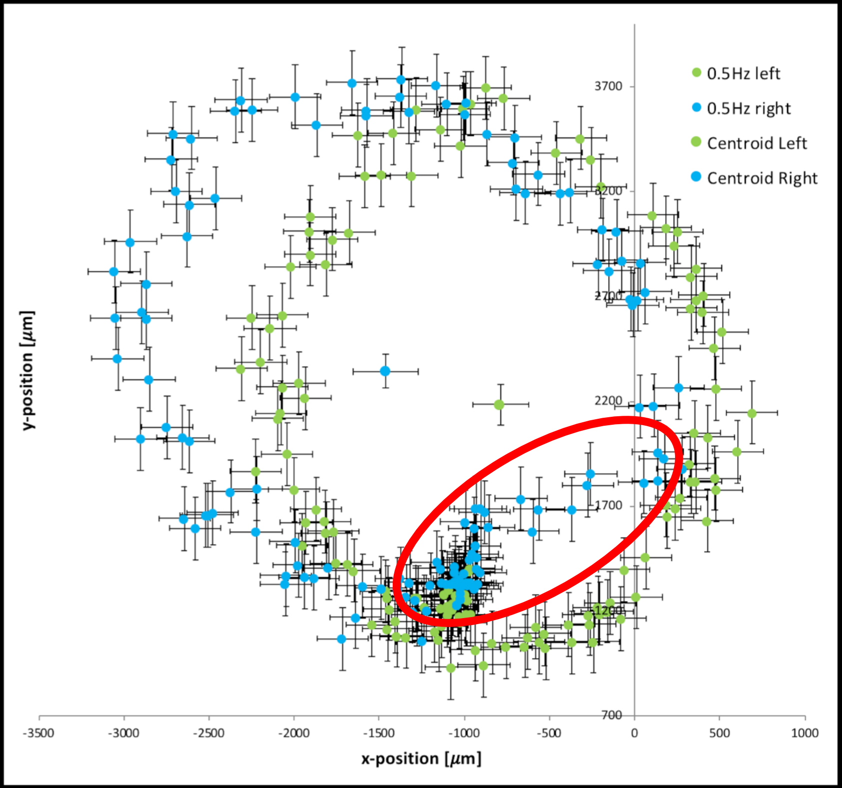
5.5 pixel position error = 151μm position error



Box always stays inside the circular template, so the maximum distance the center can move is 5.5 pixels.

The Raw Data



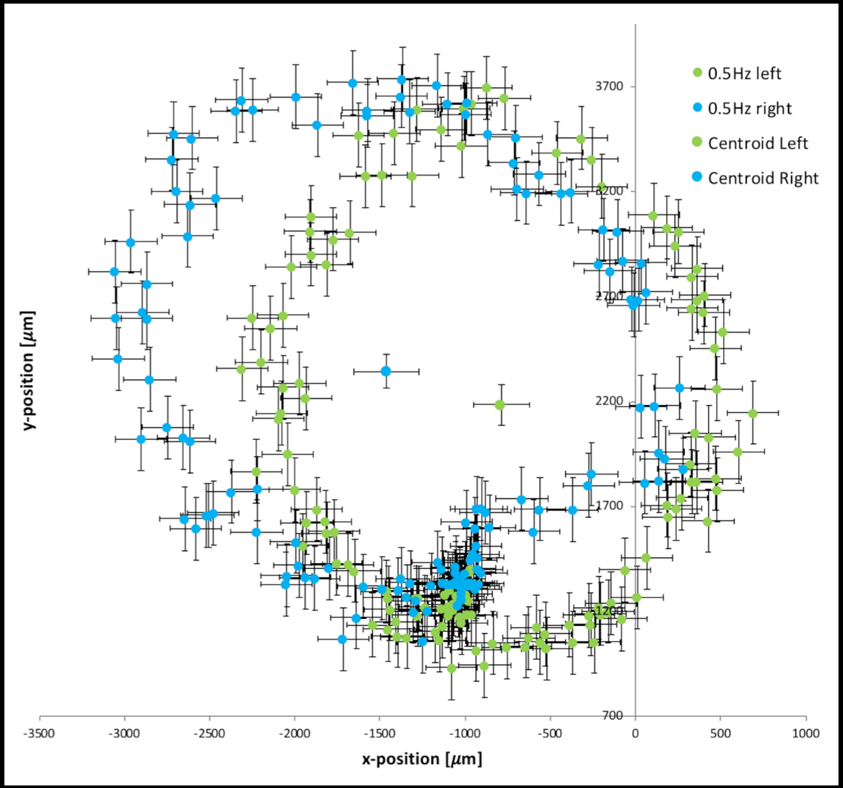


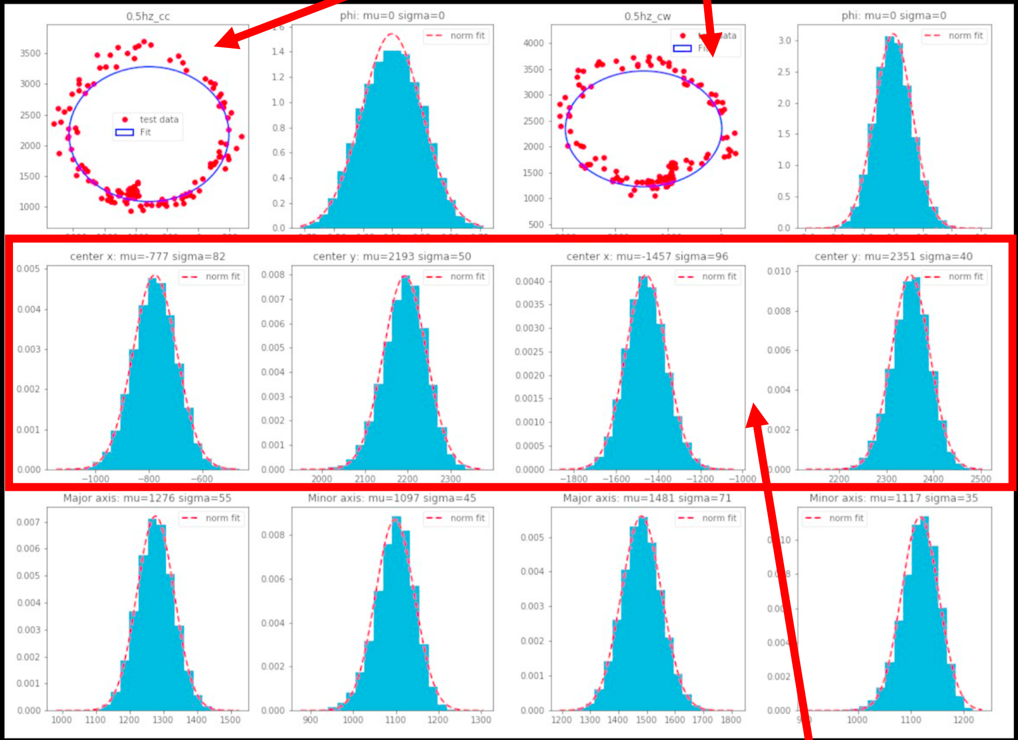
Suspicion: Contact with Eddy Current Brake and Noise from Gluing Sample in Brass Bushings

Finding the Center of Rotation

Fit in Python to obtain ellipse centroids

Blue = Fit, Red = Data



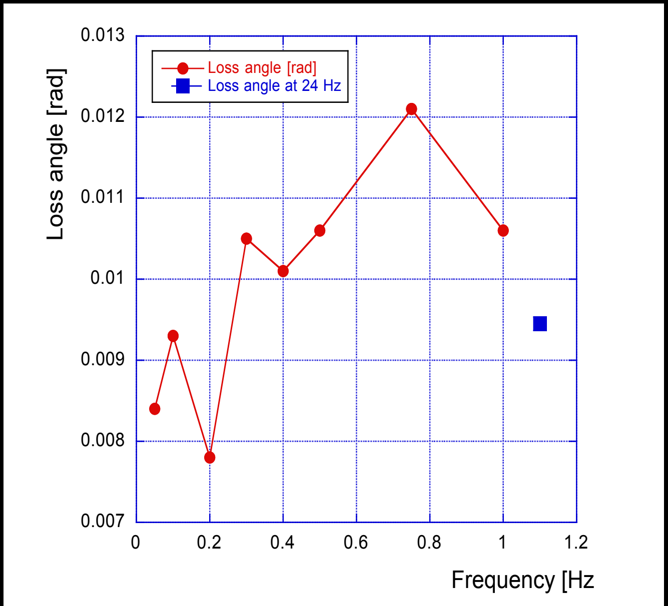


Centroid Positions and σ error

Polynomial Curve Fit using Bootstrapping Method

Initial Results

Frequency [Hz]		x [μm]	σx [μm]	y [μm]	σy [μm]	Δx [μm]	Δy [μm]	Magnitude [μm]	ϕ [radians]	Δϕ [radians]
0.05	clockwise	-705.0431204	17.38480948	2128.065546	16.17022022	-515.4567176	200.6335374	553.1269692	0.0084	0.0003
	counterclockwise	-1220.499838	21.66846895	2328.699083	14.78041749					
0.1	clockwise	-769.2187676	25.32793474	2162.614483	22.90867762	-580.4559033	193.2897986	611.79245	0.0093	0.0003
	counterclockwise	-1349.674671	32.3064157	2355.904281	20.64387386					
0.2	clockwise	-787.0012455	39.29380679	2210.593728	32.24326905	-497.9756569	124.4197428	513.2835739	0.0078	0.0002
	counterclockwise	-1284.976902	50.14229887	2335.013471	27.82479315					
0.3	clockwise	-757.0990577	59.75417122	2218.878636	40.11274887	-684.850828	109.7125948	693.5830953	0.0105	0.0003
	counterclockwise	-1441.949886	70.40102238	2328.591231	31.9400132					
0.4	clockwise	-785.0183955	73.91538813	2218.748387	50.77154644	-655.8207983	133.4556213	669.2617741	0.0101	0.0003
	counterclockwise	-1440.839194	84.71509025	2352.204008	36.92898495					
0.5	clockwise	-778.0979354	81.98026427	2193.572453	50.22247348	-679.7097049	157.7705196	697.7799222	0.0106	0.0003
	counterclockwise	-1457.80764	97.19698283	2351.342972	40.96974107					
0.75	clockwise	-675.856223	135.6713026	2176.615235	59.87064878	-795.1191666	97.25833473	801.0453625	0.0121	0.0004
	counterclockwise	-1470.97539	151.2326711	2273.87357	45.94170071					
1	clockwise	-800.5543475	54.47301304	2254.329266	23.91432305	-694.7015838	74.77637231	698.7143883	0.0106	0.0003
	counterclockwise	-1495.255931	62.9999566	2329.105638	20.06448893					



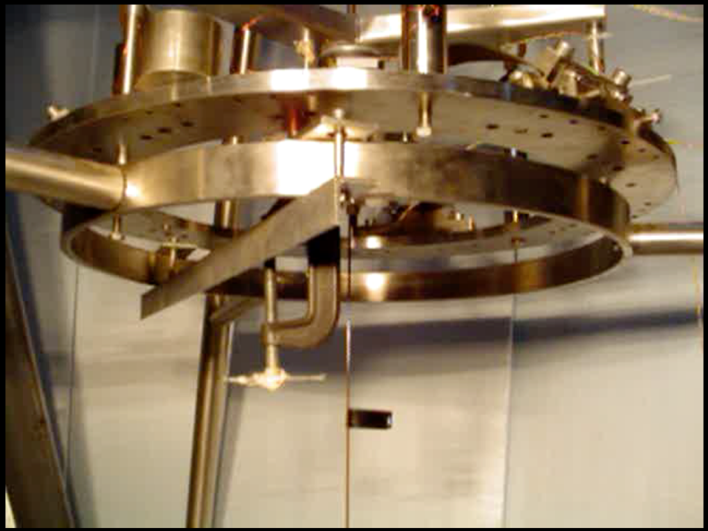
Average: 9.9 ± 0.3 mili-radians
Expected: 9.42 ± 0.02 mili-radians

Difference of 5%

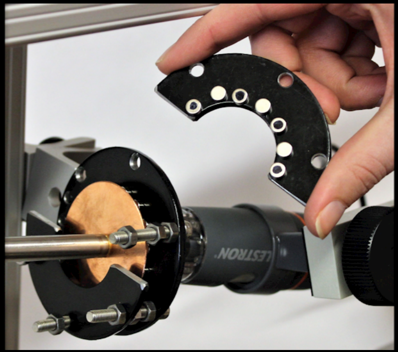
Mild Steel, Cold Rolled (Kimball and Lovell): 1.57 mili-radians

Almost a trend, which may be due to the heating of the test wire from the motor.

Future Improvements



- Suspend from a GAS Filter
- Stabilize Temperature
- Position Measurement Precision
- Move to a collet mount for fastening the test-wire
- Eddy Current Brake Modifications
- Move to a higher quality steel (Maraging)
- Tracking Program



GAS (Geometric Anti-Spring) Filter

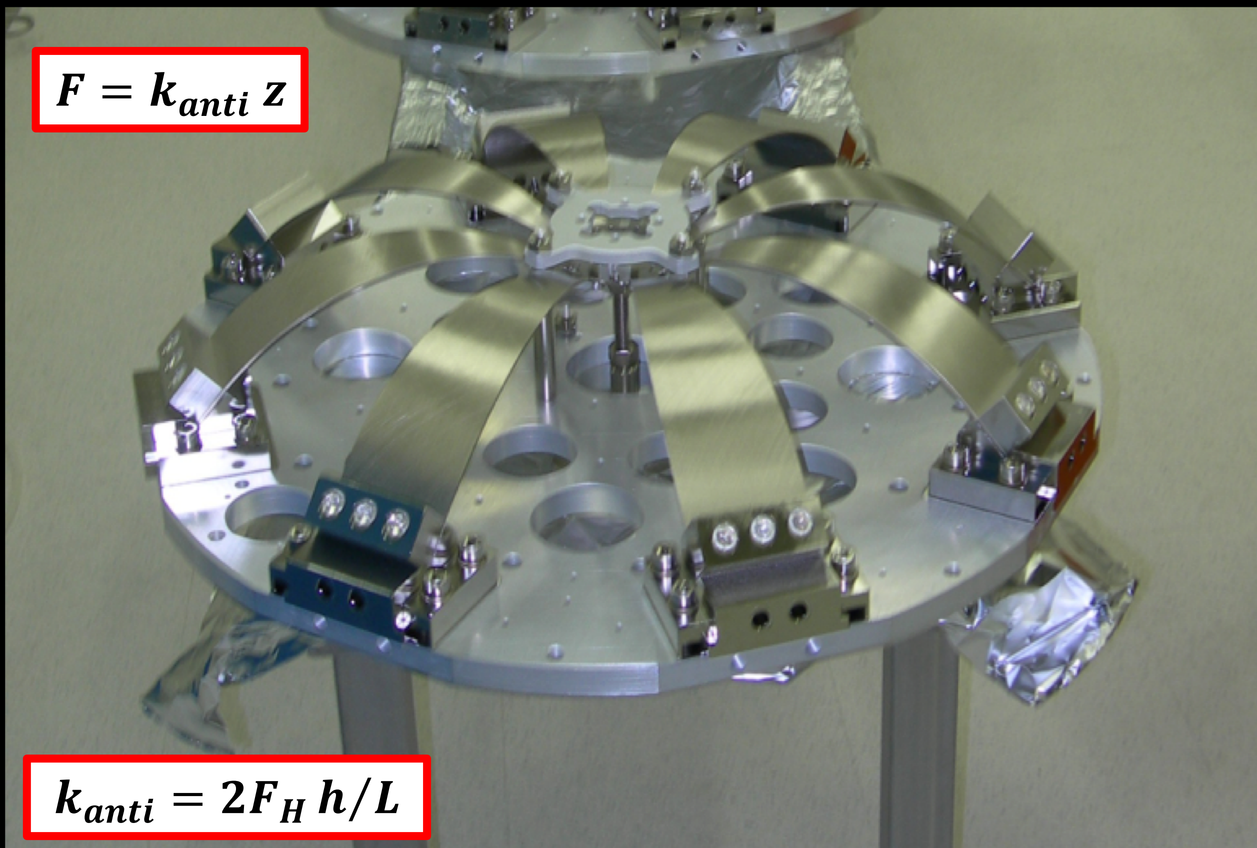


Image Credit: LIGO

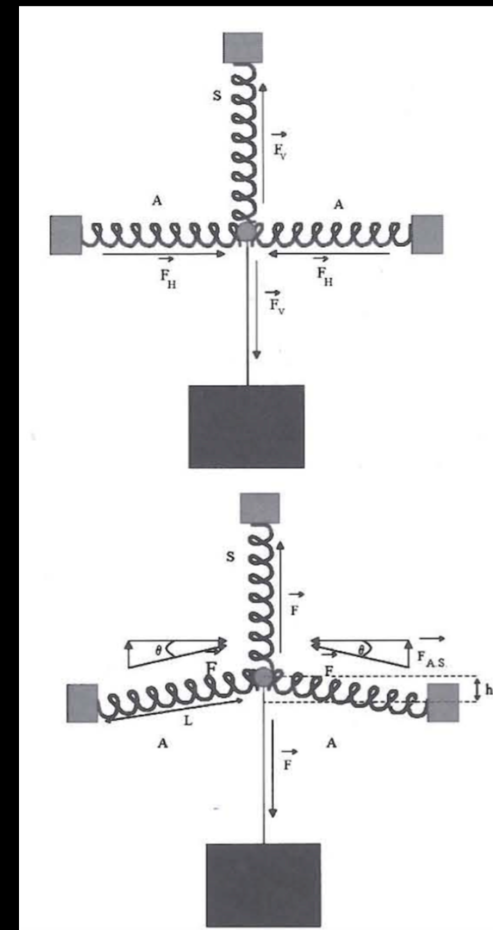


Image Credit: DeSalvo

Stabilize Temperature

- **Styrofoam Box**, isolate experiment
- **Heat Sink**, draw heat away from experiment
- **Water-cooling system**, keep the system at a stable temperature

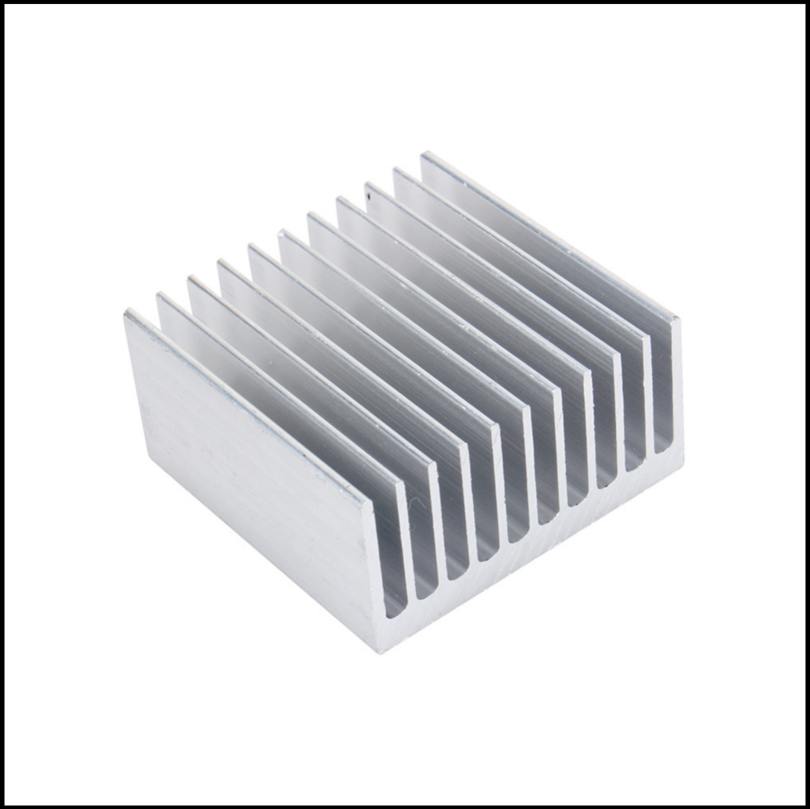
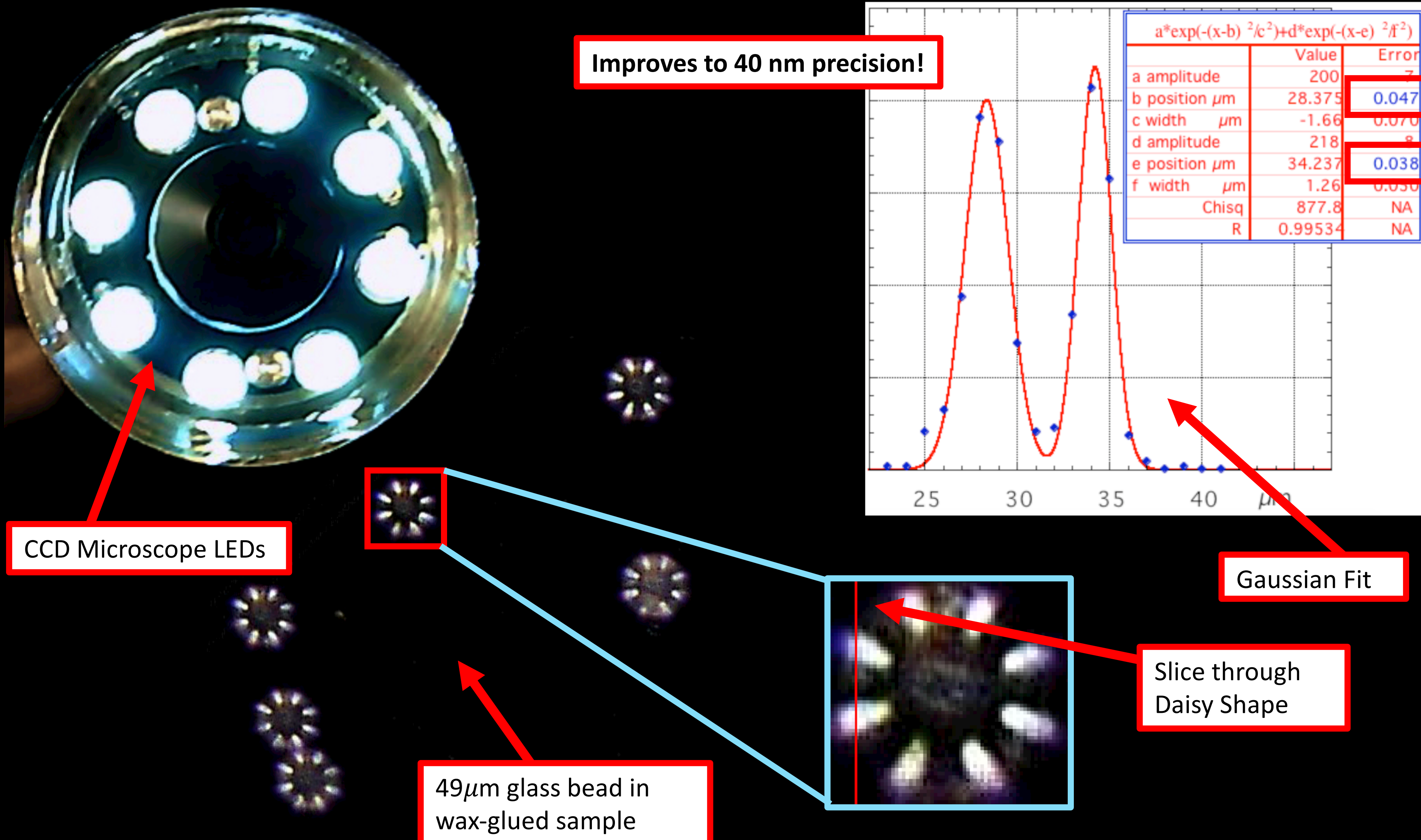
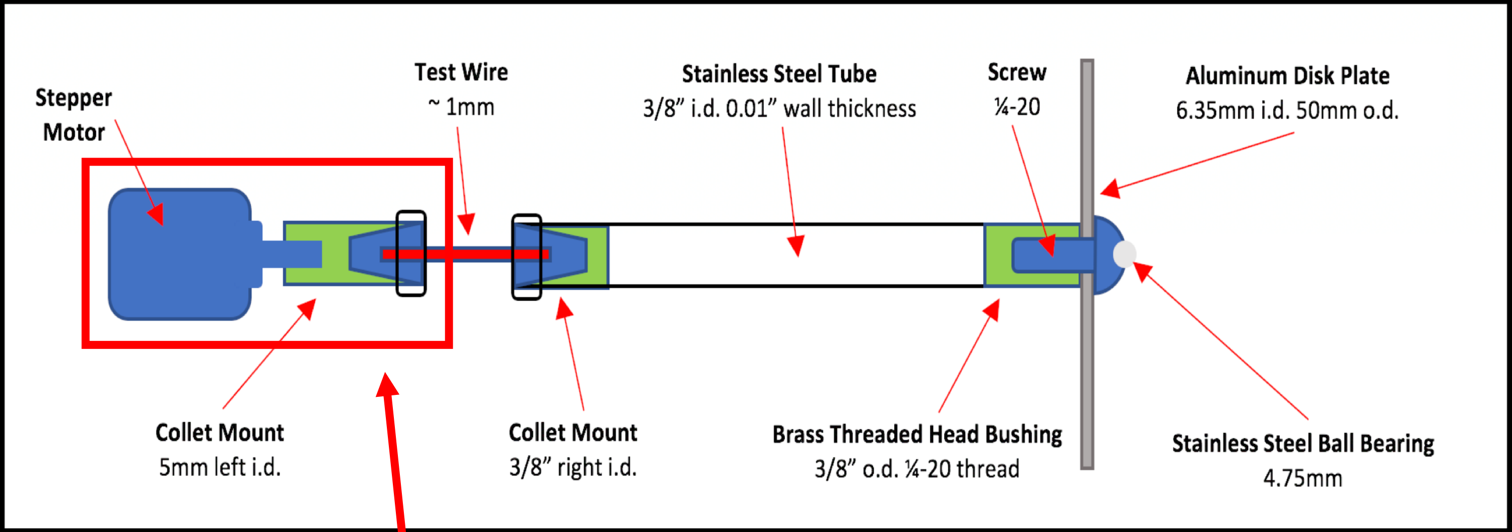


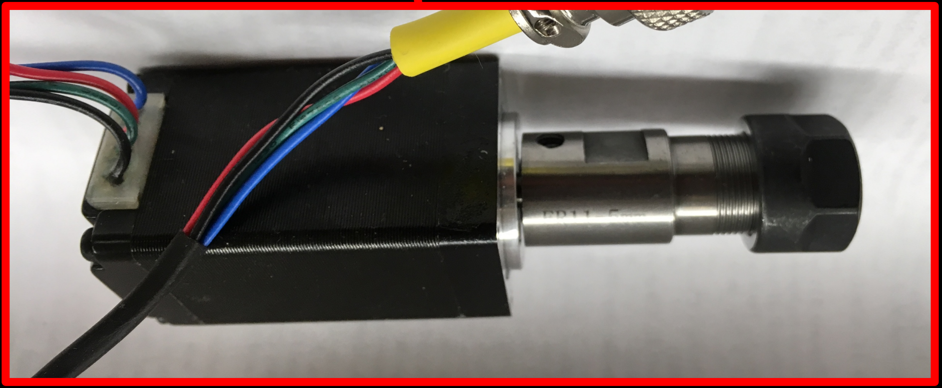
Image Credit: AliExpress

Position Measurement Precision



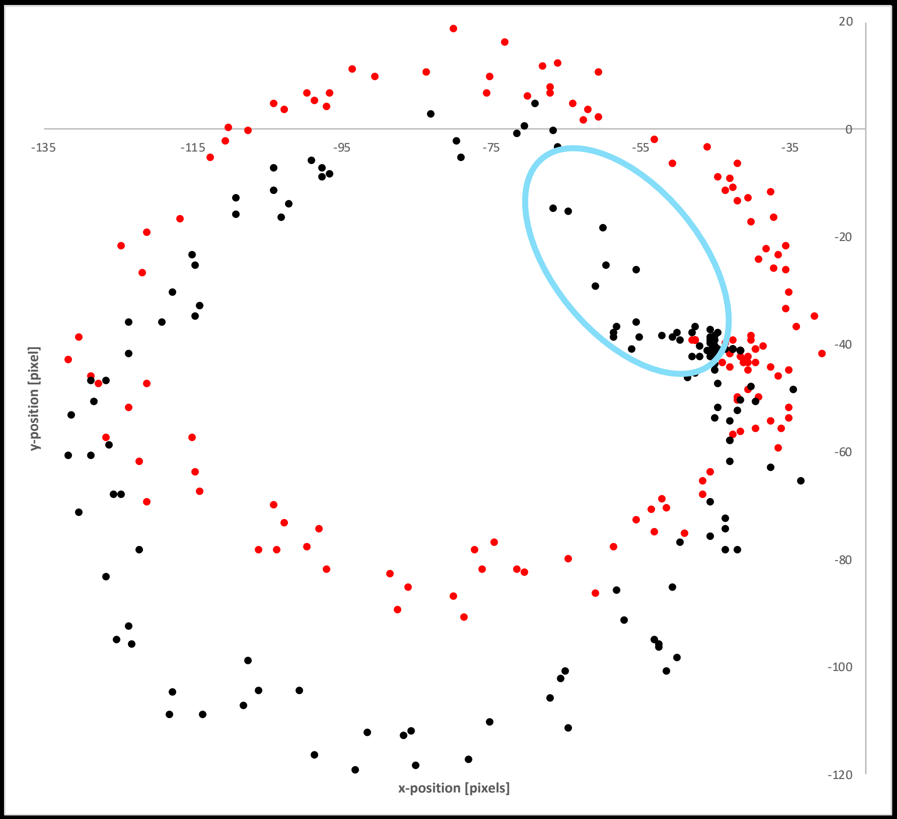
New Collet Mount Design



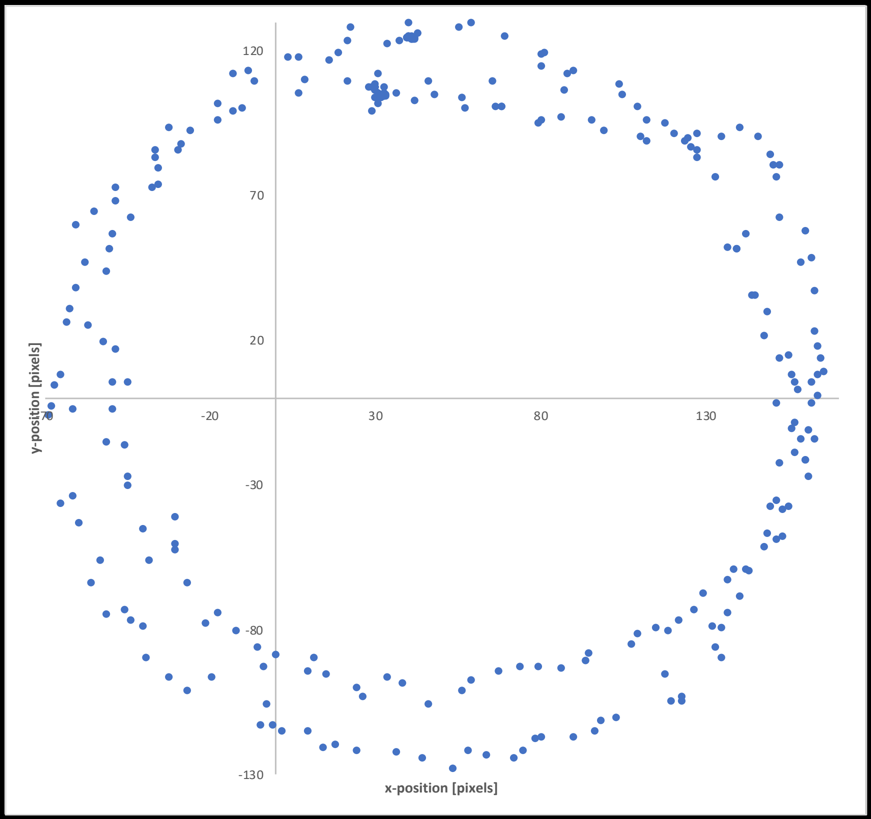


Will remove the problem with the glue

Eddy Current Brake Modifications



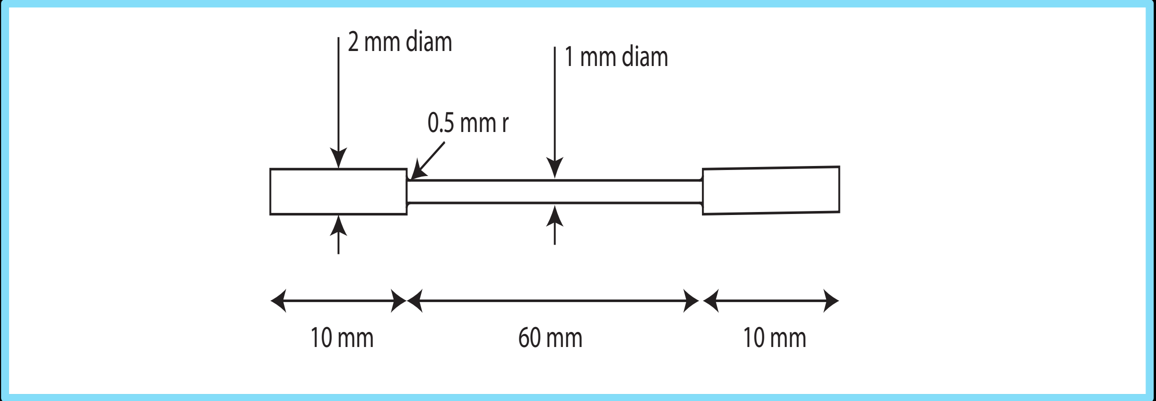
Nuts as Spacers



Stainless Steel Tube as Spacers

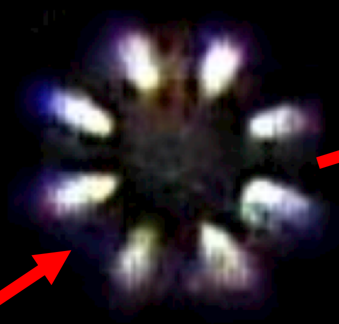
Already given the disk more space to rotate. Next step, testing Aluminum vs. Copper to damp vibrations.

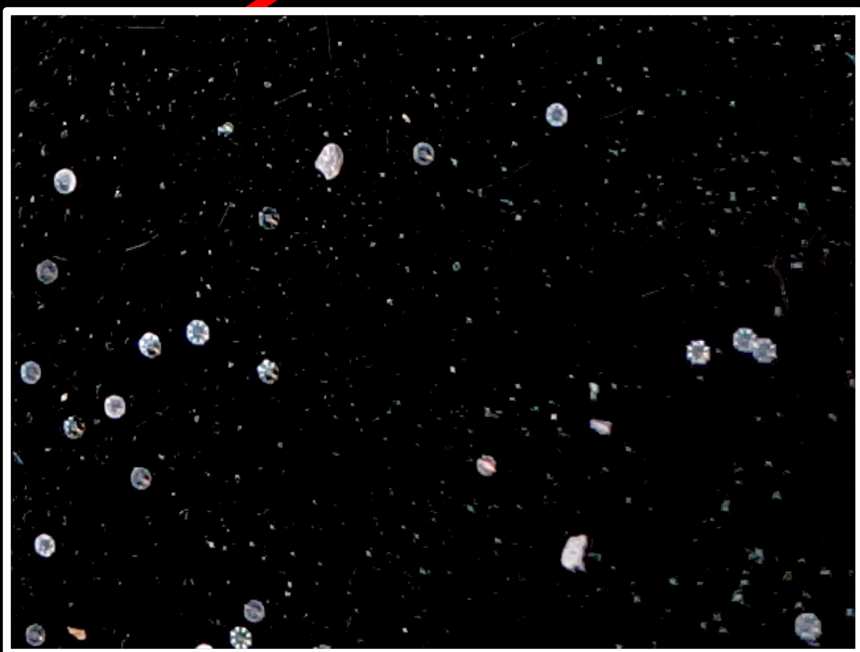
New Test Wire

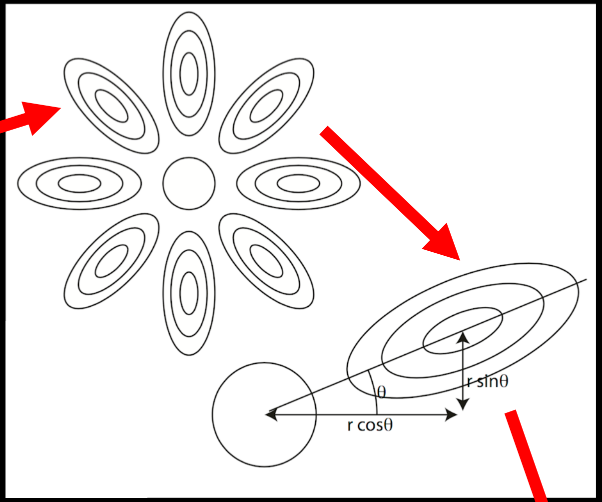


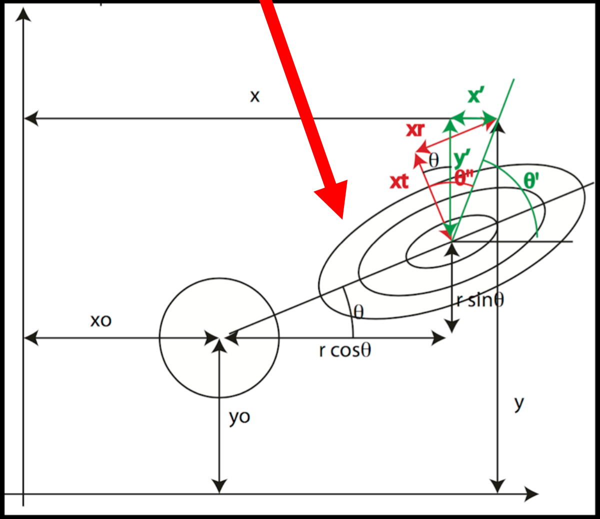
Design for the Maraging test wires.

Tracking Program (In the works)



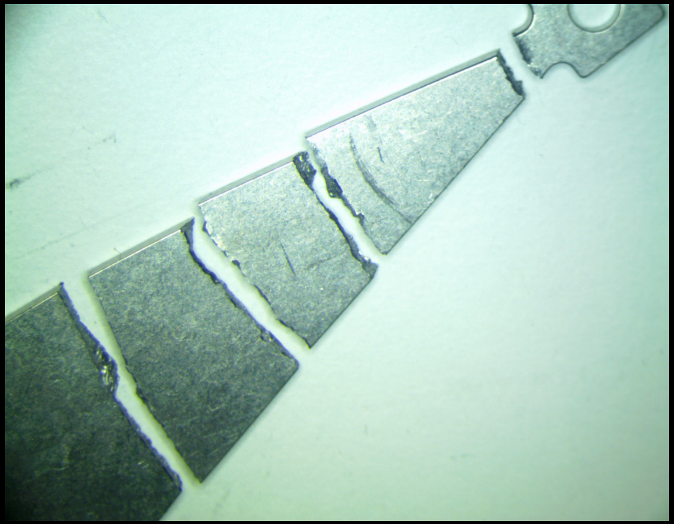






74% success rate with a 94% correlation threshold using stop motion tracking of a single daisy

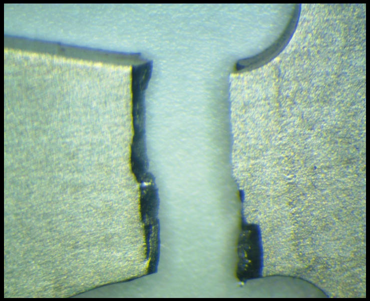
Glassy Metals as a Possible Replacement Material



Glassy metals have no crystalline structure and therefore no dislocations. Therefore, they are free of all dislocation-mediated loss mechanisms, both the traditional Granato-Lücke and the anomalous mechanism investigated here.

Chose to study Vitreloy 105

Failure! Both sets of glassy blades shattered.



- The two remaining blades were taken back to the grinding company and ground to a smaller thickness. Tests were performed at lower load, but the data has yet to be analyzed. While the thinner blades do not carry the desired load, the measurements may give insight into the material's low frequency behavior.
- Different kinds of glassy metals, including lab grade vitrelloy 105 are being considered.

[7] Towards a commercial metallic glass technology. W. L. Johnson, TMS BMG-Symposium, Nashville (Feb. 2016)

Outline

- The Problem
- Dislocation Theory
- Section 1: SOC Experiment
  - Kimball and Lovell
  - Experiment
  - Initial Results
  - Future Improvements
- Glassy Metals as a Possible Replacement Material
- Conclusion
- Acknowledgements

Conclusion

Have shown that the measurement of loss angle is possible with the current experimental set-up, however, our results are most likely from the glued sample. With the improvements outlined and funding, we should be able to see the strange effects caused by SOC behavior of the dislocations within the crystal structure.

Although testing the Vitreloy 105 blades along side the Maraging blades was a failure, the experiment is ready for future testing and should provide useful information for determining the low frequency behavior of the glassy material in comparison with the Maraging Steel.

Acknowledgements

- Dr. Riccardo DeSalvo
- Dr. Marina Mondin and Samavarti Gallardo
- Nicole Araya, Hope Hamamoto, and Greta O'Dea.
- Caleb Schrebies
- William Johnson
- Montana State University's ICAL Laboratory
- CSULA machinists Dave and Blake
- Production Lapping
- My colleagues: Bo Truong, Ronald Melendrez, Alexander Kass, Michael Goff, Seth Linker, and Lamar Glover
- This research was conducted within the LIGO scientific collaboration and the thesis has a the following DCC number: P1800114.

THANK YOU!

Section 2: Glassy Metals as a Possible Replacement Material

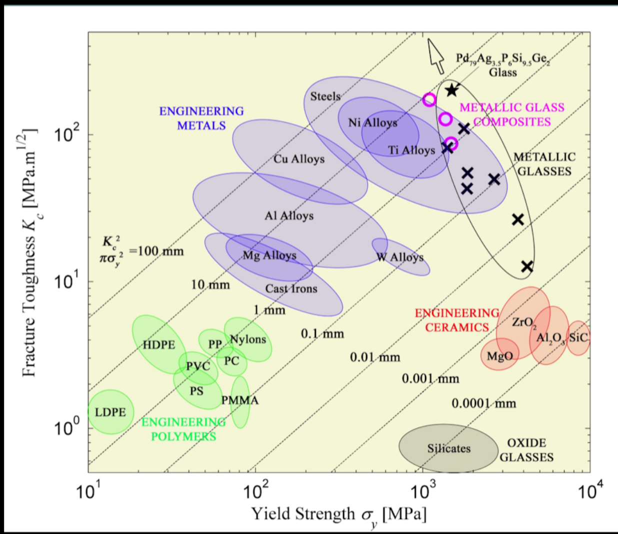
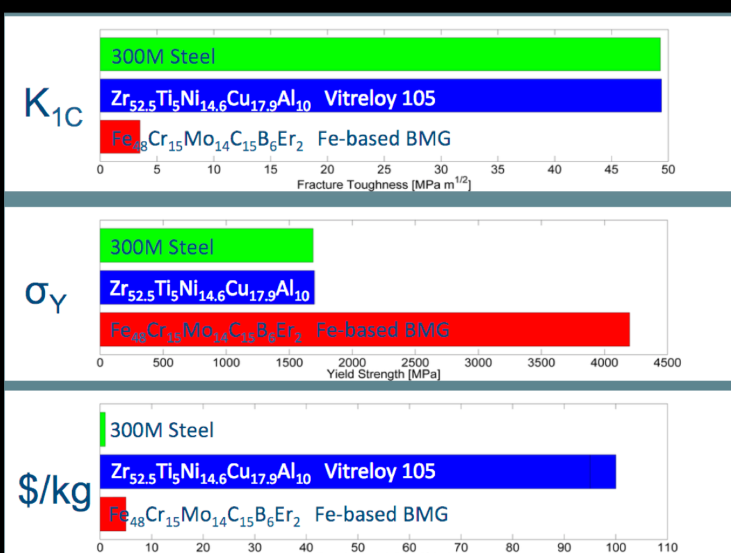


Image Credit: Bill Johnson



Glassy metals have no crystalline structure and therefore no dislocations. Therefore, they are free of all dislocation-mediated loss mechanisms, both the traditional Granato-Lücke and the anomalous mechanism investigated here.

Chose to study Vitreloy 105

[7] Towards a commercial metallic glass technology. W. L. Johnson, TMS BMG-Symposium, Nashville (Feb. 2016)

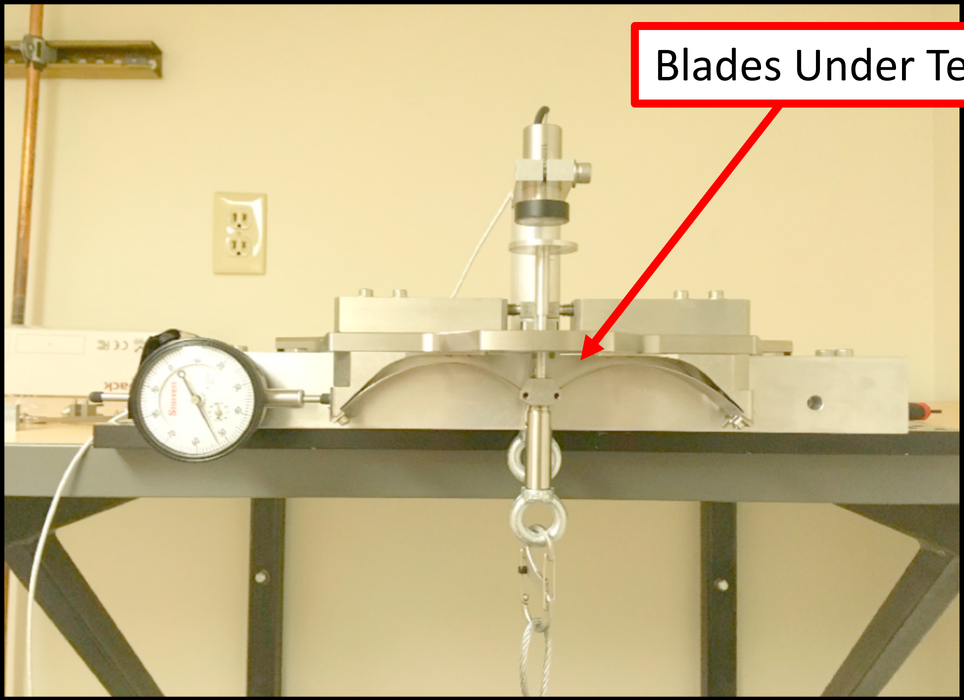
The Goal

The research and development goal for this project was:

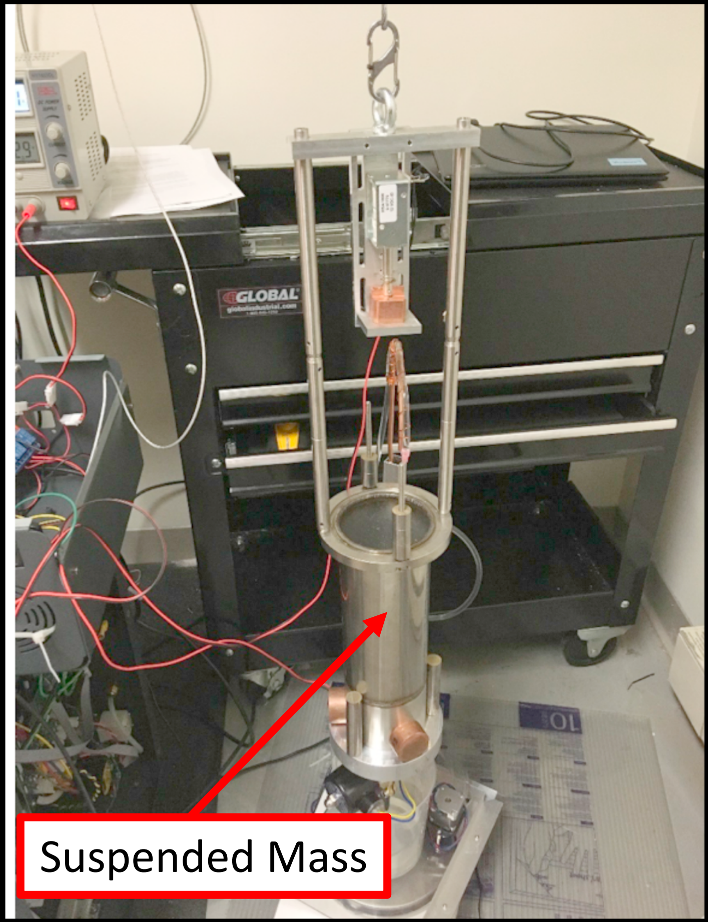
to test the low frequency behavior of commercially produced LM105 blades alongside maraging steel blades to determine if this material removes the low frequency instability noise in the GAS filter set-up.

If fruitful, this research will provide a replacement material to produce a new generation of sensitive devices able to detect gravitational signals from more massive black-hole mergers.

The Experiment



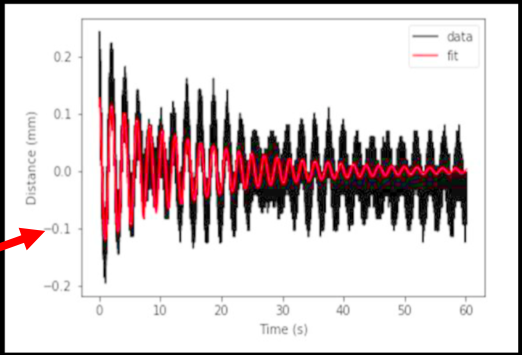
Blades Under Test



Suspended Mass

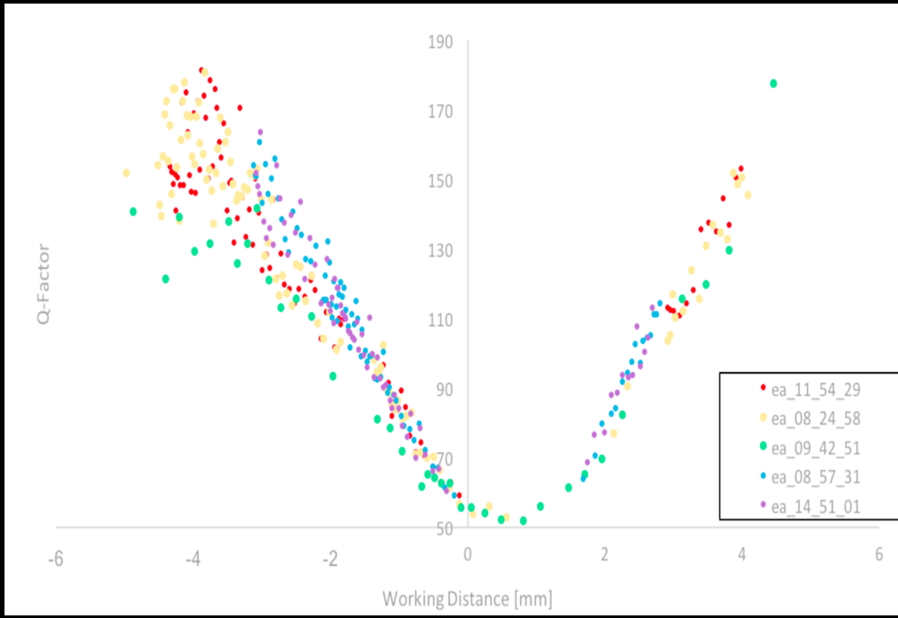
Studied the Q-Factor of the blades as they were tuned.

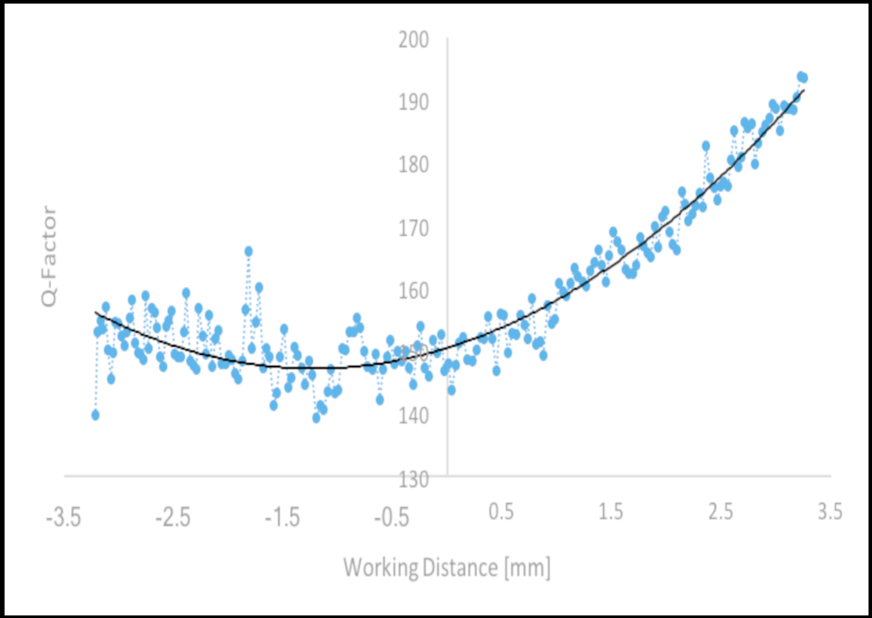
Beat Frequencies when resonant frequency of the blades matched the resonant frequency of the pendulum



Results

Failure! Both sets of glassy blades shattered.





Maraging

Vitreloy 105 (LM105)

We were able to obtain some data with one set before removal to insert spacers to allow for further compression.

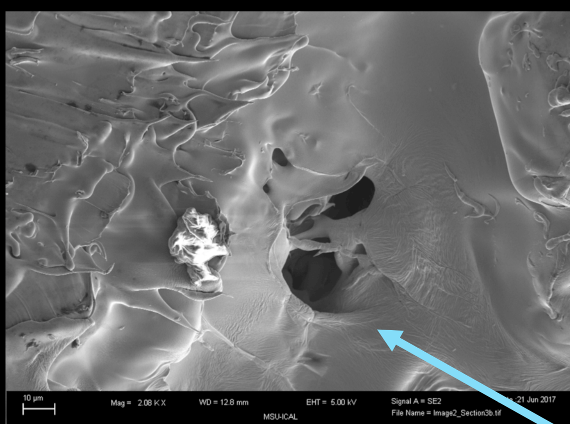
MONTANA INSTRUMENTS®
COLD SCIENCE MADE SIMPLE

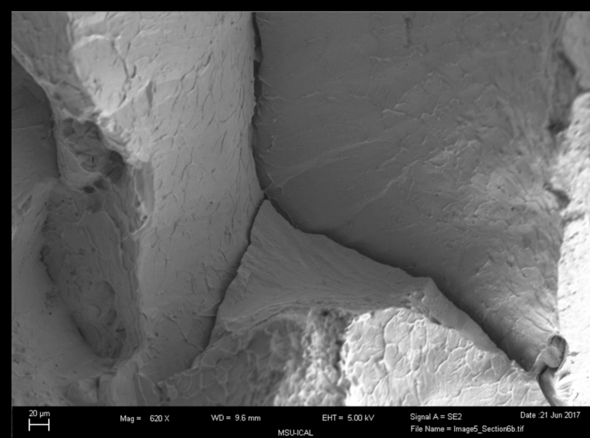
Why They Broke

$$R_{\text{critical}} = \frac{{K_{1C}}^2}{\pi {\sigma_y}^2}$$

Two Possibilities:

- The LM105 purchased was not good quality (the fracture toughness was much less than predicted).
- Impurities (i.e. crystals, cracks, pockets of gas) formed during the casting process were larger than $R_{critical}$ (the smallest a defect can be before causing catastrophic failure) and caused the material to shatter before reaching its yield point.





Evidence of gaseous pockets in the material when studying the crack surfaces under a SEM microscope.

MONTANA INSTRUMENTS
COLD SCIENCE MADE SIMPLE

Future Testing

- A PID loop was optimized for the tuning of the blades using an electromagnetic voice coil and it was able to tune the blades to frequencies below those achieved with the Reynold's Fixture alone. Once fully optimized and integrated this method will allow the exploration of the behavior of the Q-Factor at even lower frequencies, enriching the study already completed here.
- The two remaining blades were taken back to the grinding company and ground to a smaller thickness. Tests were performed at lower load, but the data has yet to be analyzed. While the thinner blades do not carry the desired load, the measurements may give insight into the material's low frequency behavior.
- Different kinds of glassy metals, including lab grade vitrelloy 105 are being considered.