TOWARDS COUPLED MAGNETOMETERS FOR ULTRA-SENSITIVE METROLOGY

Fabricating and Measuring the Resonant Frequency of Oscillators using Analog Signal Processing

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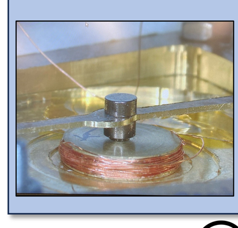
VISUAL ABSTRACT

1) Engineering Workflow

Fabricate Magnetic Sensor
Involves CAD, parameterizing, machining, precision assembly



Parameters:
W: width
L: length
t: thickness

Measure Resonant Frequency
Find the device's maximum amplitude of oscillation.

Result: Magnetic Sensing Oscillator
Measures inputs through shifts in frequency.

2) Data Collection Model

Connecting the Device to a Lock-in Amplifier
BNC cables, soldering wires

Filter Out the Noise
Phase sensitive detection & transformers

Sweep the frequency of the reference waveform

Display amplitude versus frequency

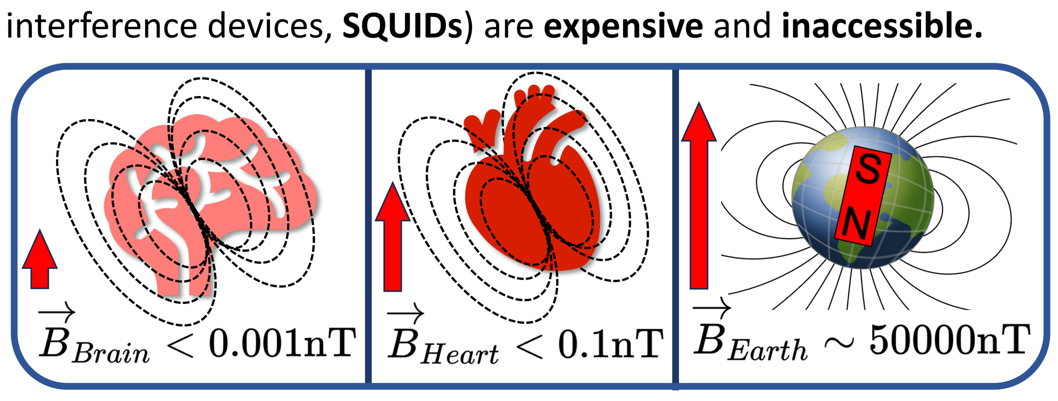
INTRODUCTION

PRECISION METROLOGY

Science of measurement focused on the accuracy and repeatability of measurements at a delicate level.

Magnetometer application in biomedical settings (e.g. cardiac imaging via motion of charged ions in the heart with magnetic field of ~100pT).

THE ENGINEERING PROBLEM: Methods of measuring signals at this scale, (e.g. **atomic magnetometers** & superconducting quantum interference devices, **SQUIDs**) are **expensive** and **inaccessible.**



Coupled Oscillator

Transduces input into a shift in **oscillation frequency:** essential for **high sensitivity measurement** (*i.e.,* Gain) (Bouche 2024).

$$G = -\frac{1}{4\pi}\frac{F_C''(d_{eq})}{\Delta f_{min} k^{3/2} m^{1/2}}\frac{1}{(1+F_C'(d_{eq})/k)^{3/2}}$$

Allows for **noise reduction tactics** such **as phase locking** & **signal amplification**. Noise: mechanical, electrical, geomagnetic.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Key Equation: Resonance frequency (f) modeling the mechanics and signal the oscillator gives while utilizing Hooke's law.

Coupled oscillators could be **a novel approach** for measurements down to hundreds of zeptonewtons (10^{-21} N).

RESEARCH OBJECTIVES

RESEARCH QUESTION: Can a coupled oscillator be fabricated with the sensitivity to **pickup small signals** using **magnetic sensing**?

GOAL: Work towards **proof of concept** of a coupled oscillator for sensitive metrology.

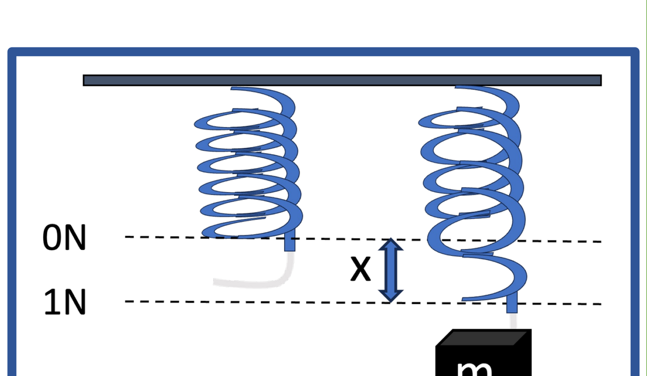
Engineering Design Criteria for Oscillator

LOW COST	PRECISION	ROBUSTNESS
Minimal material needed compared to status quo.	Picks up small inputs such as micro Tesla.	Atmospheric operation and has long lifespan.

WHERE TO START?: Design a resonator and establish parameters on paper than utilize equations such as…

a) **Hooke's law:**

$$\frac{F}{x} = k$$



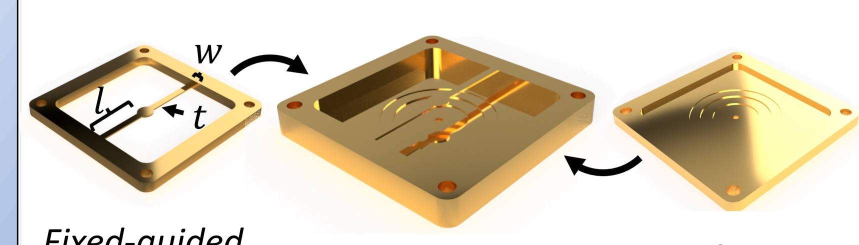
b) **Youngs Modulus**

$$\sigma = E\varepsilon$$

c) Plug into resonant frequency (f) & approximate the result in **MATLAB** and **COMSOL**.

1. DESIGN

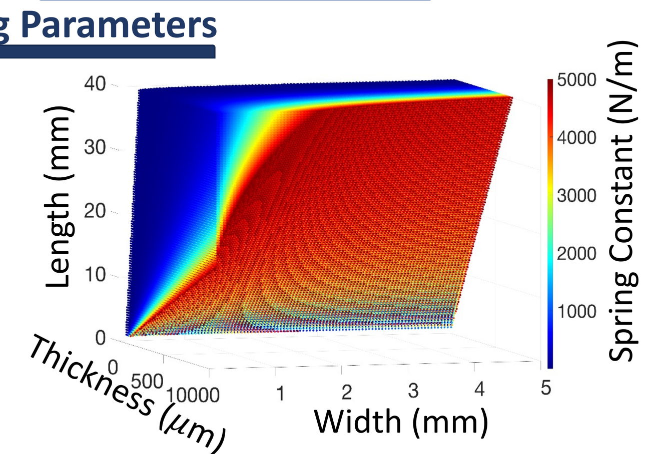
1a) CAD Oscillator Design



1b) Setting Parameters

k – Spring Constant

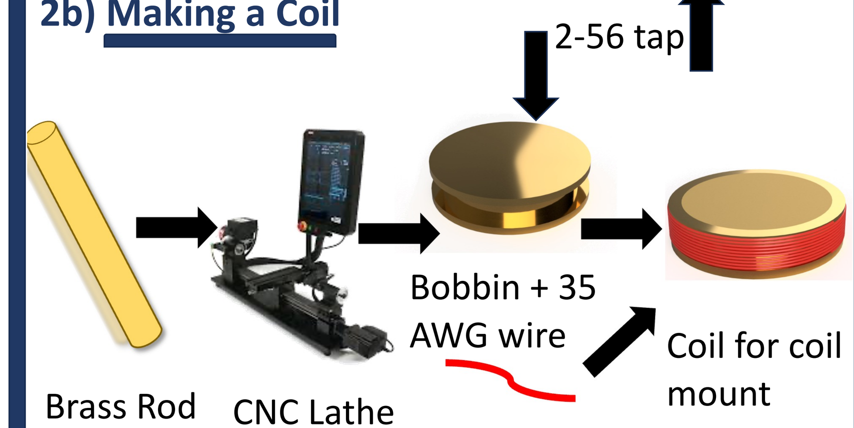
$$k = \frac{Ewt^3}{l^3}$$



2. MANUFACTURE

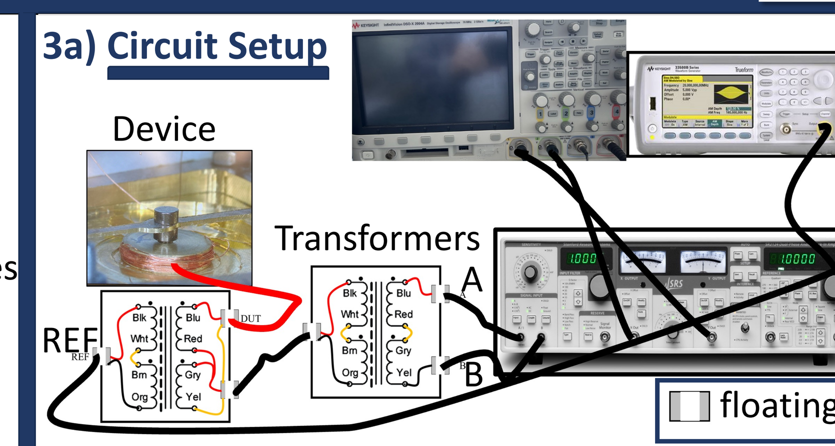
2a) Milling Pieces For Assembly

2b) Making a Coil



3. MEASURING

3a) Circuit Setup

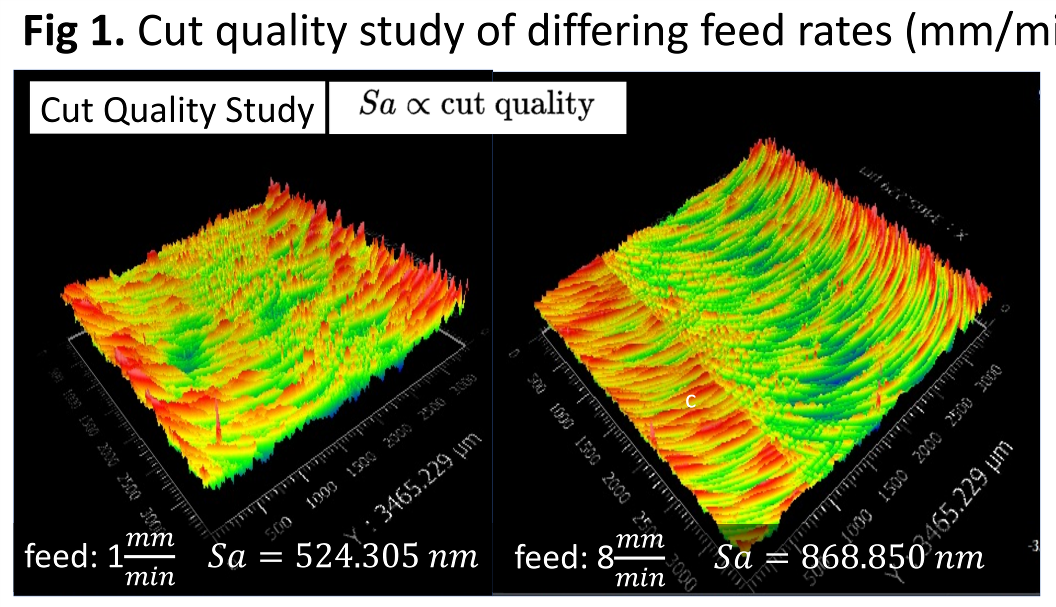


3b) Sweep, Filter, Detect, & Display Data

1. Sweep Frequency
2. Lock-in the signal
3. Display the results

RESULTS

Fig 1. Cut quality study of differing feed rates (mm/min)



Different feed rates (mm/min) and spindle speeds (rpm) were studied prior to manufacturing.

Red/Orange/Yellow = Positive displacement (μm) from base
Green = near/zero displacement (μm) from base (level)
Blue = Negative Displacement (μm) from base

Fig 2. Bode plot of device in a turbomolecular pump (<1.5e-5 torr)

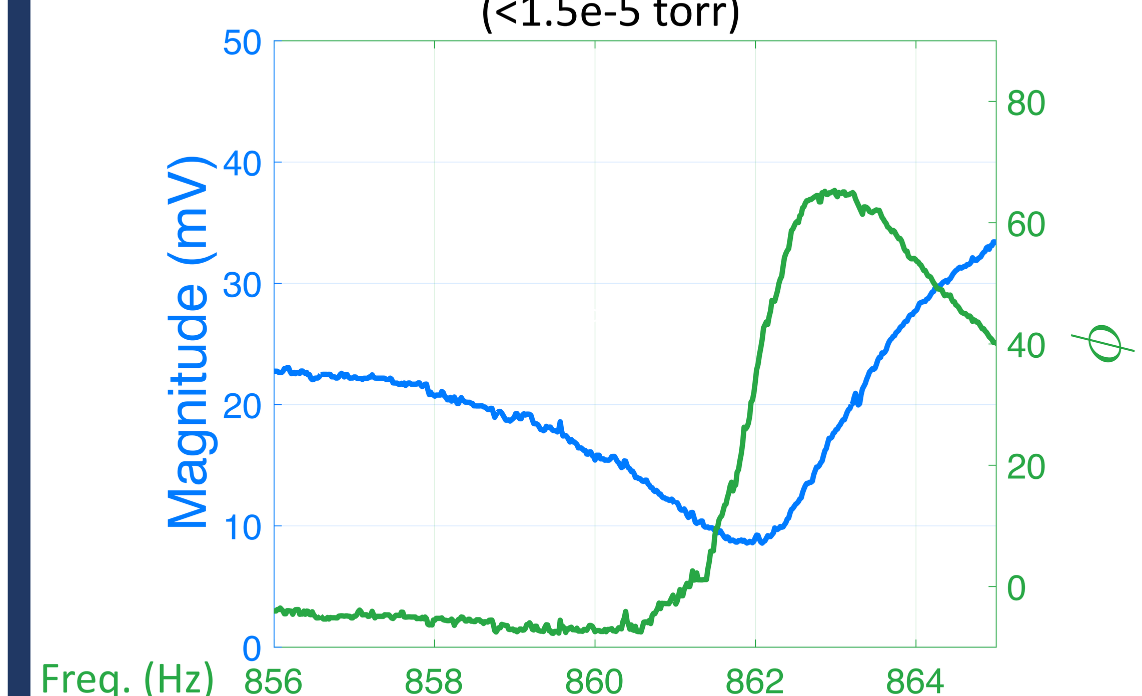


Fig 3. Bode plots of different amounts of magnets (bell jar)

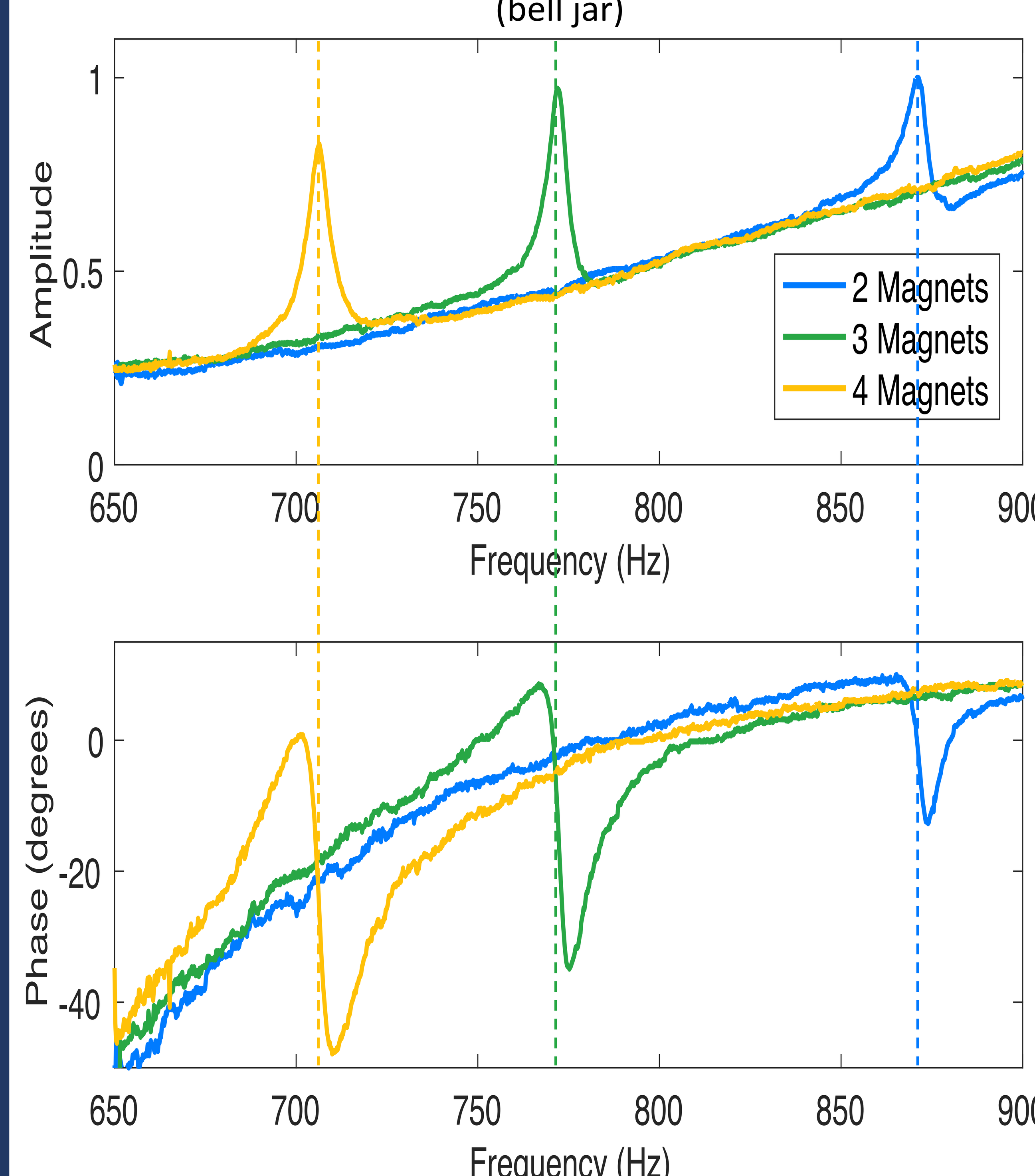


Fig 4. COMSOL simulated frequencies of the main mode with different magnets

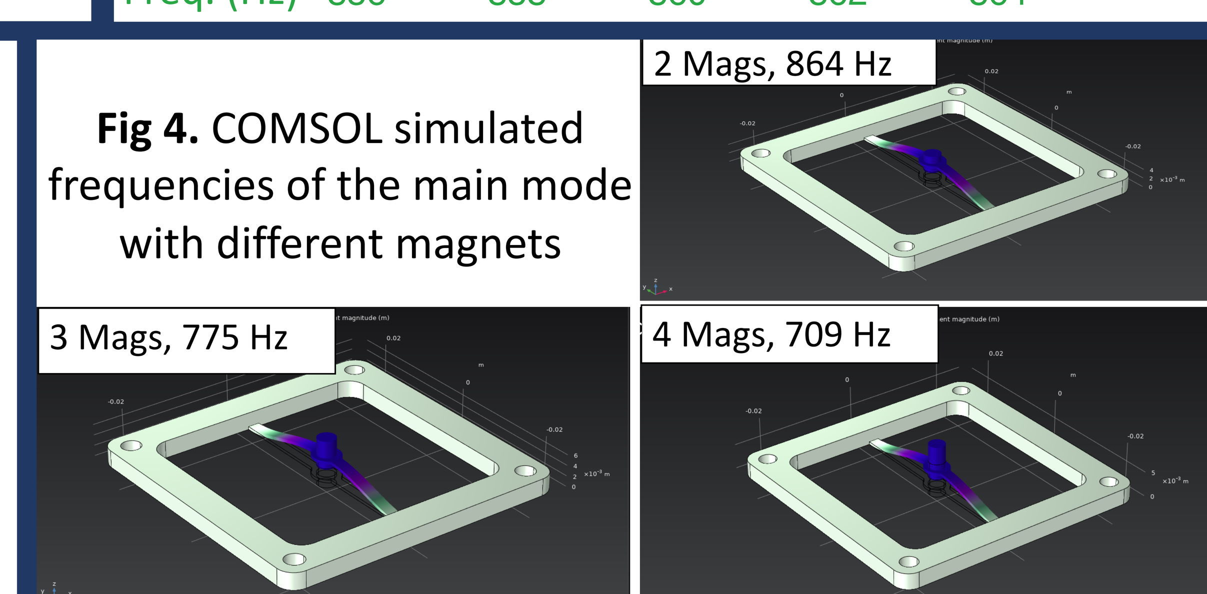
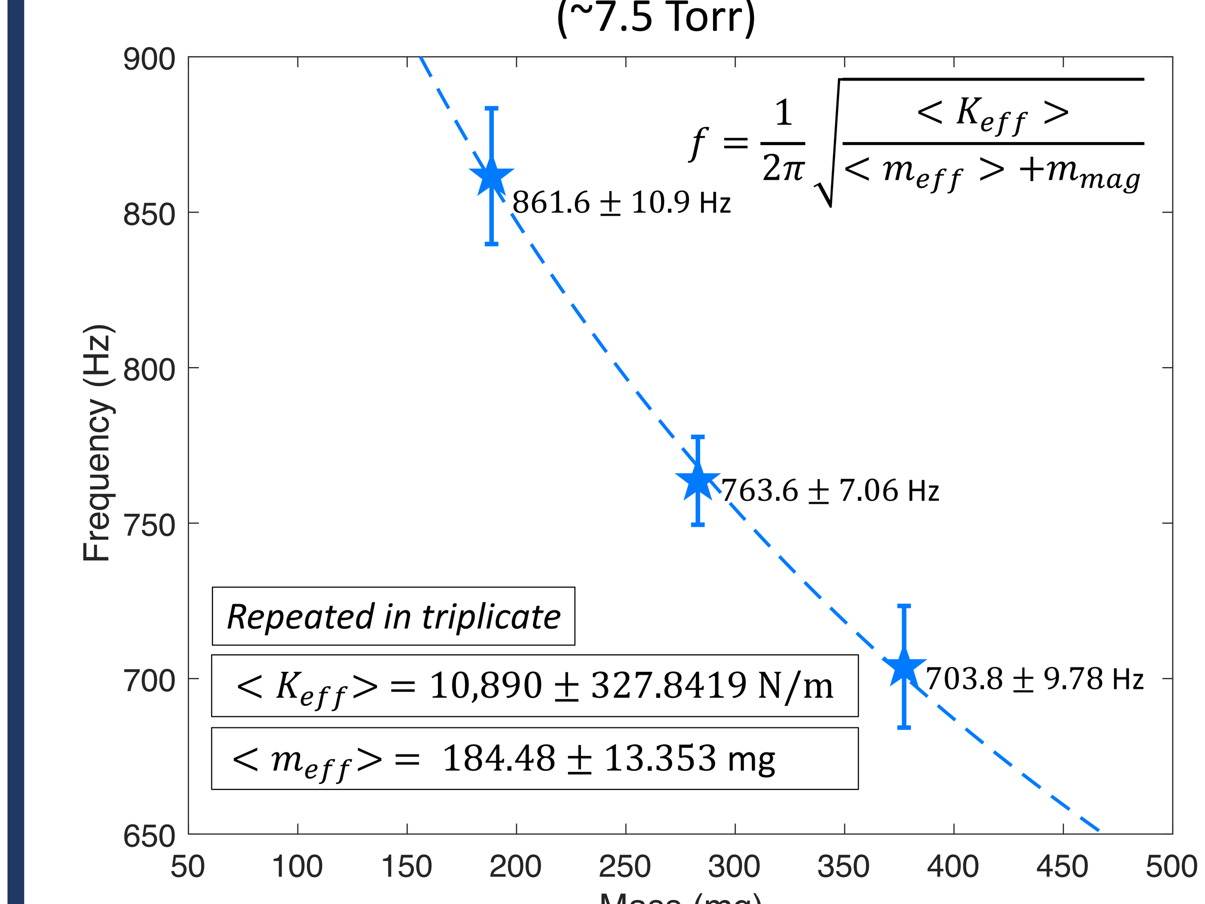
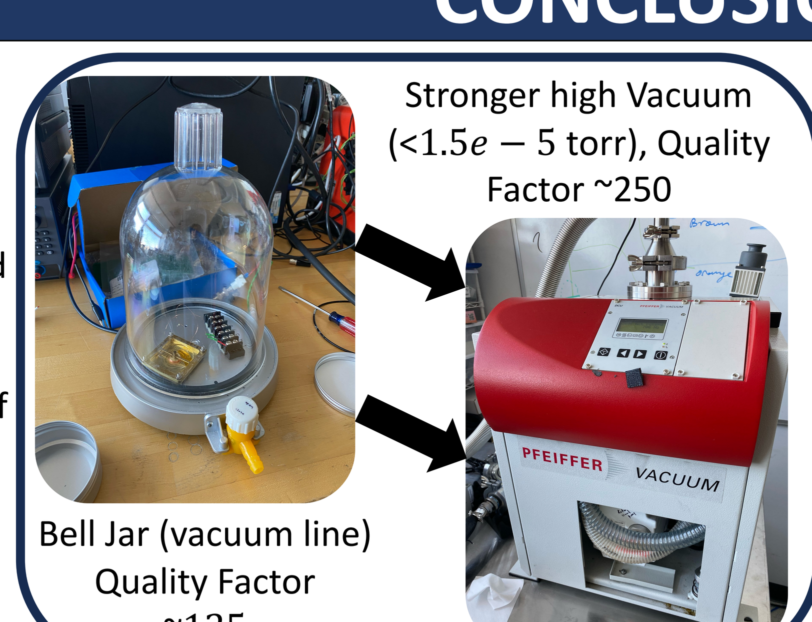


Fig 5. Statistical analysis of differing masses in a bell jar (~7.5 Torr)



CONCLUSIONS

- Slower feed rates lowers roughness (feed rate ∝ Sa).
- This tested the concept of a magnetometer, next step is coupling this oscillator to applied magnetic field.
- A higher driving amplitude enhances **signal-to-noise ratio** of measurement.
- Back calculation of mass and spring constant were repeatable within error of 7% and 3% respectively (Fig. 5).

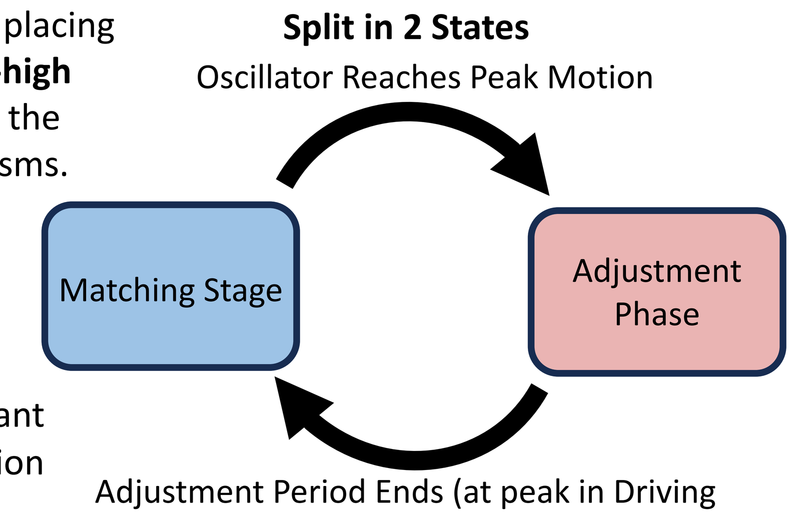


Future work entails improving the quality factor by placing the device in a **ultra-high vacuum** to decouple the dampening mechanisms.

Allows for a **phase-locked loop** to track resonant frequency changes.

Detect shift in resonant frequency as a function of applied magnetic field.

Phase-Locked Loop
Split in 2 States



KEY REFERENCES

[1] Ian Bouche, Josh Javor, Abhishek Som, David K. Campbell, David J. Bishop; Zeptonewton and attotesla per centimeter metrology with coupled oscillators. *Chaos* 1 July 2024; 34 (7): 073133. https://doi.org/10.1063/5.0205663

[2] Javor, J., Stange, A., Pollock, C., Fuhr, N., & Bishop, D. J. (2019). 100pTcm Sensitive MEMS Resonant Magnetometer from a Commercial Accelerometer. *arXiv preprint arXiv:1911.10250*.

[3] Liu, C. (2006). Foundations of MEMS.