Towards low suspension thermal noise of cryogenic torsion pendulums with crystalline fibres

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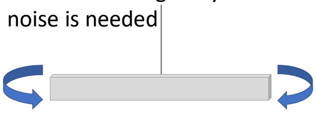
Abstract

Suspension thermal noise is a significant noise source for torsion pendulums. Two ways to reduce it is to utilize cryogenic temperatures and crystalline fibres. We record our progress here in utilising both in tandem to achieve low suspension noise levels, with an eye on achieving high Q for use in TOrsion Bar Antenna (TOBA), a proposed gravitational wave detector aimed at 0.1-10 Hz.

Background

Torsion pendulums

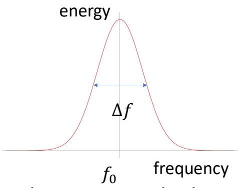
- Removes (or at least minimise) the influence of Earth's gravity
- For precision experiments, low thermal noise is needed



Introduction

Thermal noise

- Originates from mechanical loss
- Fundamental limitation of mechanical systems
- Thermal noise $\propto \sqrt{T/Q}$
  - T is temperature
  - Q is a mechanical loss parameter (The Q factor)



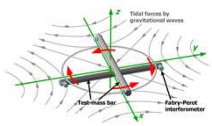
Q factor

- The Q factor is an dimensionless parameter that characterises the loss of energy in a system, and is inversely proportional to the square of thermal noise
- Defined by the resonance frequency divided by the width of the resonance peak in frequency space, $Q = \frac{f_0}{\Delta f}$
- Highly dependent on many variables, including setup, temperature and material

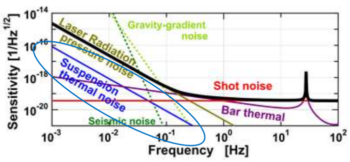
Motivating experiment

Torsion Bar Antenna (TOBA)[1]

- A proposed gravitational wave detector made up of two torsion bars
- Main advantage is higher sensitivity at lower frequencies (0.1 – 10 Hz) than LIGO, Virgo, KAGRA
- Goal of $\boldsymbol{Q \gtrsim 10^8}$ at 4 K



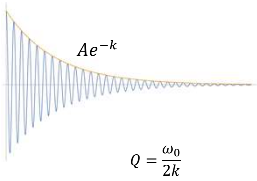
Schematic of a TOBA. The bars experience differential torque from gravitational waves [1]



Estimated noise floor for TOBA, at 4K (with cryogenic cooling) [1]

Measurement of torsional Q factor

- Q factor is measured by the ringdown of the system at resonance.
- The decay envelop is related to the Q factor



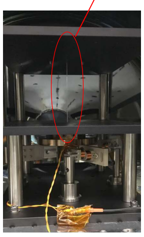
$$Q = \frac{\omega_0}{2k}$$

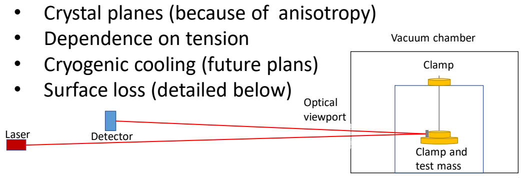
Candidate material selection for suspension

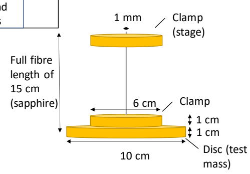
- Sapphire selected for its high intrinsic Q
  - High bulk Q both at room ($\sim 10^8$) [2] and cryogenic temperatures ($\sim 10^9$) [3]

Experiment overview

- Measurement of torsional Q of crystalline fibres
  - Lack of measurement data from crystalline wires
  - Current measurements do not show high enough Q [4]
  - Study frequencies around 0.1 – 10 Hz (TOBA)
- Parameters to study include
  - Crystal planes (because of anisotropy)
  - Dependence on tension
  - Cryogenic cooling (future plans)
  - Surface loss (detailed below)







Experimental setup

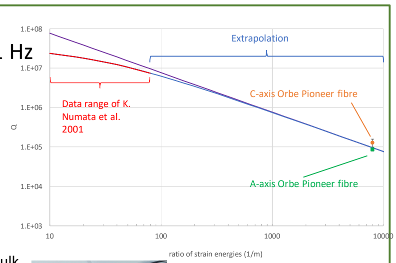
- Optical lever used to collect data
- Initial excitation via coil-coil actuators

Previous results

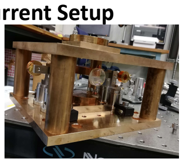
- Maximum of Q = 1.3x10^5 at 1.31 Hz
- Consistent with surface loss dominated Q
- Relationship given by the following equation:

$$\frac{1}{Q_{measured}} \sim \frac{1}{Q_{material}} + \phi_{surface} h \underbrace{\frac{\int_S \epsilon^2 dS}{\int_V \epsilon^2 dV}}_{}$$

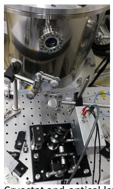
ratio of strain energies stored between surface and bulk



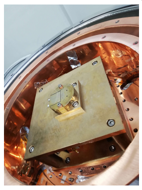
Current Setup



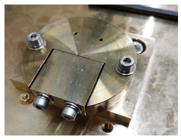
Stage outside cryostat



Cryostat and optical lever



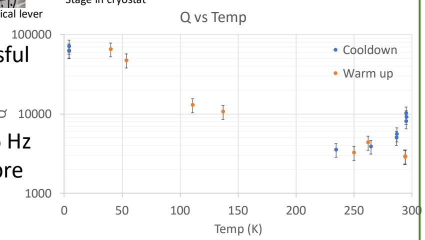
Stage in cryostat



Close up on clamp

Current results

- Cryogenic cooling was successful
- Q generally increases at lower temps
- Peaks at 4K at Q = 6.5x10^4 at 6 Hz
- C-axis sapphire, 1 mm thick fibre
- However, measured Q was much lower than room temperature results of the previous setup
- No direct temperature sensor on fibre, so temps given would be an underestimate on cooldown and an overestimate on warm up



Results seem to be clamp loss limited

- The Q values for this setup are all lower than the room temp values measured with the previous setup, which reached a maximum of 1.3x10^5 at 1.31 Hz, using the same batch of fibres sourced from Orbe Pioneer
- Increase in Q at lower temps could be due to increase in clamp strength from thermal contraction mismatch between sapphire and copper beryllium (clamp)
- Clamp loss Q is possibly dependent on resonance frequency. Previous results have indicated that it was dependent on pendulum mass

Future work

- Primary focus: Figure out and eliminate the cause for low Q (most probable candidate: Clamp loss)
- Test direct bonding
- Test different materials (e.g. silicon)
- Test for surface loss via diameter dependence
  - Quantify surface quality improvements required
- Polishing and annealing

Conclusion

- Figure of merit in reducing mechanical loss is Q
- Trying to reach high Q for use in torsion pendulum precision experiments
- Cryogenic cooling and measurement was achieved, but currently having abnormally low Q, as compared with the previous setup
- Main focus currently is getting the Q back to pervious levels
- Improvement of surface quality to improve Q

References

1. M. Ando et al., *Physics Review Letters*, 2010
2. S. Rowan et al., *Physics Letters A*, 2000
3. V. B. Braginsky, V. P. Mitrofanov, and V. I. Panov, *Systems with Small Dissipation*, 1985
4. M. Bantel, R. Newman, *Journal of Alloys and Compounds*, 2000
5. K. Numata et al., *Physics Letters A*, 2001
6. P. R. Saulson, *Physics Review D*, 1990