TorPeDO: A Low Frequency Gravitational Force Sensor

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Abstract. Second generation gravitational wave detectors are likely to be limited by Newtonian Noise at low frequencies. A dual torsion pendulum sensor aimed at exploring low-frequency gravitational-force noise is being studied at the ANU. This sensor is designed to measure local gravitational forces to high precision and will be limited by Newtonian noise. We report on a controls prototype which has been constructed and suspended, along with initial characterisation and testing of the two torsion pendulums. Large weights at the end of each bar reposition the centres of mass to the same point in space external to both bars. Since both bars have a common suspension point, resonant frequency (≈33.4 mHz), and centre of mass, mechanical disturbances and other noise will affect both bars in the same manner, providing a large mechanical common mode rejection.

1. Introduction
Second generation gravitational wave detectors are about to begin taking measurements, with strain sensitivities as low as $3 \times 10^{-24}/\sqrt{Hz}^1$ in the frequency range from 10 Hz to 10 kHz. At lower frequencies these detectors are potentially limited by seismic and atmospherically induced Newtonian Noise\(^2\). To understand and characterise Newtonian Noise, a direct measurement of Newtonian Noise is first required.

The Torsion Pendulum Dual Oscillator (TorPeDO) is a low frequency gravitational force sensor which aims to be limited by Newtonian Noise. The system features two torsion pendulums which are suspended along the same axis of rotation and perpendicular to each other, similar to the TOBA design\(^3\). Local gravity gradient changes cause a differential attraction on the two torsion bars which causes them to rotate in opposite directions. A differential optical measurement is taken between the two torsion bars to measure this. The mechanical configuration is chosen to maximise common mode rejection between the torsion bars. This is achieved by locating the centres of mass of both bars to the same point in space and tuning the torsion bars to the same frequency for most modes.

Other low frequency gravitational forces can be measured by this system, making it useful for early earthquake warning, giving advanced warning over seismometers for an earthquake 50 km away\(^4\). Low frequency systems such as the TorPeDO are of interest for testing theories of semi-classical gravity\(^5\), by looking for a semi-classical resonance offset from the main resonance. A
smaller version of this sensor is also planned for construction to measure quantum radiation pressure noise.

A controls prototype for this sensor has been constructed and suspended. This prototype is currently in air with a static suspension as a proof of concept; to demonstrate our control and measurement method. It will later be placed in vacuum with suspension improvements to lower noise contributions and increase force sensitivity.

2. Prototype Design
The controls prototype for the TorPeDO features two 60 cm long aluminium bars. Large steel weights are positioned at the ends of each bar to reposition the centres of mass to the same point in space, external to both bars. Each bar is suspended by two straight tungsten wires with a separation of 23 mm. This double wire suspension allows for both bars to easily be suspended with the same axis of rotation. While a double wire suspension raises the frequency of the torsional mode, we still achieve a suitably low resonance frequency of roughly 33 mHz for our design. Cavity mirrors are mounted at the end of the bars in line with the centre of mass at a 45° angle. Once the two bars are suspended, these mirrors form 4 linear optical cavities around the perimeter of the system as shown in Figure 1. Figure 2 shows a picture of the constructed prototype at ANU.

![Figure 1. Top down engineering drawing of the controls prototype design](image1.png)

![Figure 2. Photo of the controls prototype suspended at ANU.](image2.png)

The experiment is currently in air, and is limited by environmental disturbances. The prototype will be moved inside vacuum along with an isolated suspension platform to improve sensitivity. A planned upgrade to the prototype will replace the tungsten suspension wires with fused silica, reducing thermal noise levels down to an estimated $10^{-18}/\sqrt{\text{Hz}}$ strain at 1 Hz. After this upgrade, the estimated sensitivity level of the TorPeDO prototype is $10^{-16}/\sqrt{\text{Hz}}$ strain at 1 Hz. The 60 cm bar length TorPeDO prototype is predicted to be sensitive to Newtonian noise below 0.1 Hz.
3. Tuning Masses
Tuning masses are used in the mechanical design to allow for small alterations to be made to physical mass properties of the system. The first set of tuning masses are positioned on top of both bars on either side of the axis of rotation. These masses can be moved up and down along a thread to shift the location of the centre of mass for that bar. This also allows tuning of the pendulum and pitch modes of the bars. A second set of tuning masses are positioned in a hollow channel that runs through the centre of the bar. These masses can be moved inwards and outwards, which changes the moment of inertia of the bars about the torsional axis. This allows for tuning of the torsional frequency of the bars. Correct positioning of these masses allows for the two frequencies to be matched as closely as possible. The frequency matching goal for this prototype is a match to within 1 part in 1000 to achieve the sensitivity goal quoted in the previous section. By mismatching the distance of these tuning masses from the axis of rotation, the centre of mass can also be tuned along the bar axis. The centres of mass must be well tuned to the rotation axis on each bar to minimise coupling from suspension point displacement into yaw rotation. This offset should be reduced to less than 1 mm to prevent this coupling from limiting our sensitivity.

4. Sensing and Actuation
In the current controls prototype, two different systems are used for sensing and actuation. A pair of optical levers and shadow sensors are used to measure rotation of the torsion bars. BOSEM coils are used to actuate and provide feedback to the bars. These systems allow for characterisation of individual bar motion and to control the differential torsional mode.

5. Transfer Functions
Transfer functions have been taken of both bars by driving through the BOSEM actuators with white noise and measuring the response with the optical levers and shadow sensors. Figure 3 shows the transfer functions of both bars measured using the shadow sensors. The low frequency peak on both plots corresponds to the torsional resonance of the bars ($\approx 33$ mHz). The second main feature at $\approx 0.6$ Hz corresponds to the pendulum mode of the bars.

![Figure 3. White noise transfer functions.](image-url)
6. Conclusion and Future Work
A controls prototype of the TorPeDO has been constructed and suspended at ANU. The next stage of this experiment involves further characterisation of the mechanical properties of the prototype, including the tuning range and quality factor of the torsional and pendulum modes. The optical read-out using the arm cavities of the TorPeDO must also be implemented before the system is placed in vacuum.

References
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