A CRYOGENIC TORSION PENDULUM: PROGRESS REPORT

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Abstract

A cryogenic torsion pendulum for gravitational experiments is being refined at its remote operation site near Richland, Washington. Features of the apparatus include: four stages of temperature control, angular readout of the pendulum about three orthogonal axes, and remote operation capability. Currently we are testing the apparatus with a nominally symmetric pendulum suspended from a 25 μm dia Al5056 fiber. Since installing the apparatus in June 1999, we have been testing and fine tuning the instruments and software. Most recently, Dec 1999, magnetic shielding was added reducing the eddy current damping of the pendulum by $\sim 10^3$. Magnetic contamination of the test pendulum, with a net magnetic dipole moment of $\sim 6 \times 10^{-9}$ N m T^{-1}, served in measuring the effectiveness of the shielding.

1 Apparatus

In 1993 we began developing cryogenic torsion pendulums for future use in gravitation experiments. Some advantages leading us to investigate cryogenic torsion pendulums include: reduced thermal noise, reduced temperature sensitivity, improved temperature control, and improved fiber characteristics. Our analysis of the potential performance of cryogenic torsion pendulums has been published elsewhere [1, 2, 3].

A scale drawing of our current instrument is shown in figure 1. A pendulum operates in an evacuated insert within a 3 m tall dewar. The dewar is mounted on a turntable driven by a stepper motor enabling us to change its orientation or to excite torsional oscillations of the pendulum. The dewar accommodates about 95 liters of cryogenic liquid with a 6 day and 24 day holding time for LHe and LN_2 respectively.

Figure 2 shows a scale drawing of the lower portion of the insert where the pendulum is housed. The vacuum chamber (27 cm ID, 79 cm tall) provides spacious room for the pendulum, autocollimators, and temperature control components. For a typical pendulum size ~45 mm width, all components are at least 60 mm from the pendulum; additionally, the mass distribution about the pendulum was designed to be nearly azimuthally symmetric, reducing gravitational gradients about the pendulum.

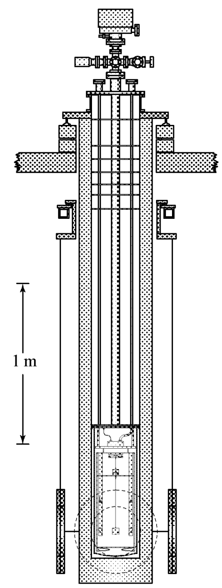

Figure 1: The cryogenic insert within the dewar, and suspended source mass rings to be used in a measurement of G [4].

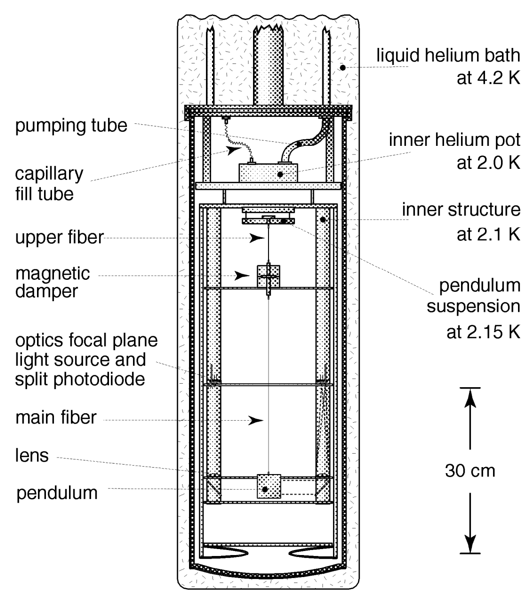

Figure 2: The inner chamber housing the pendulum.

1.1 Optical Readout

Within the cryogenic environment, four independent autocollimators view the pendulum, positioned at 90 degree intervals about the torsion fiber axis. Two of these are portrayed in figure 2. To each autocollimator an optical fiber (62.5 μm dia, 4 m length) delivers light from an LED at room temperature to the focal plane. Light emitted at this point is collimated by a lens 160 mm below then reflected towards the pendulum by a 45° mirror. When the pendulum's mirror face is nearly perpendicular to the incoming light, the light reflected from the pendulum mirror face travels back through the same path and is focused on a two-element PIN split photodiode located near the end of the optical fiber. This returning focused image of the light is $\sim$ 100 μm in diameter. As the pendulum rotates through one of a discrete set of angular regions about 3 mrad wide, the focused image traverses the photodiodes. For two of the autocollimators, the dividing line between the photodiode elements is aligned perpendicular to this traverse path. The zero crossing of the amplified differential signal from the photodiode elements serves to accurately determine the time at which the pendulum had one of a set of discrete azimuthal angular orientations. This zero-crossing time is determined from a 1 MHz 12-bit digitization of the signal referenced to an HP 58503B GPS-steered quartz oscillator clock. These zero-crossing times serve to determine the pendulum's amplitude, frequency, quality factor, and harmonic content.

The two other autocollimators monitor seismically induced tilts of the pendulum in two orthogonal directions. We expect to use this tilt information to correct for tilt-associated errors in the azimuthal timing signal. The tilt autocollimators have their photodiode dividing lines tangent to the traversing path such that the traversing path will lie directly along the dividing line. The focused light image in these tilt autocollimators is blurred to $\sim$ 1 mm diameter giving a larger dynamic range of the tilt signal and making initial alignment easier.

1.2 Temperature Control

Temperature control of the pendulum's environment is maintained in four stages: (1) The vacuum can is maintained at 4.2K by the main helium reservoir, where its vapor pressure is maintained by a PID controller at $\sim$ 1.1 bar. (2) Within the vacuum chamber a 2 kg Al6061 platform supports a helium pot which is pumped to a controlled vapor pressure to maintain it at 2K. (3) Weakly thermally coupled to the 2K platform is a 9.6 kg Al6061 cylindrical thermal shield with plates covering the top and bottom, and thermally anchored within is a 2.6 kg Al6061 frame supporting the pendulum and autocollimators. The shield and frame are maintained at 2.1K by a PID controlled heater. (4) The pendulum hangs from yet another stage (250 g) weakly coupled to the frame and maintained at 2.15K by another PID controlled heater.

Stage four supporting the pendulum is typically controlled to 5 μK rms. However, the dominant temperature variations in the fiber may arise from LED light absorbed by the pendulum ($\sim$ 100 nW). For this reason, the LED's will be activated only during the intervals of a few milliseconds during which they provide useful information.

2 Project Status

The apparatus is operating in a former Nike missile bunker on an arid-lands environmental preserve near Richland, also near LIGO, in Eastern Washington where the microseismic noise power spectrum is about two orders of magnitude less than that at Irvine ($\sim$ 2000 km away). Since initial testing in June 1999, we have operated once with LHe and a few times with LN_2. Setbacks include breakage of the fiber twice, first when a seal within the dewar catastrophically failed resulting in a sudden internal implosion, and second during a LN_2 fill causing vibrations. We are currently on our third fiber.

The torsion oscillator in the apparatus has a fiber made of hardened Al5056 (25 μm dia, 260 mm long) whose breaking strength is 25 g and 34 g at 300K and 77K respectively. The pendulum is made of Al6061-T6 with mass 17 g and moment of inertia 10 g cm^2. It is 16 mm tall with an octagon cross section, having diamond machined mirrors on its eight sides (9 mm width, 16 mm height). The torsion pendulum's oscillation period is about 80 sec and 76 sec at 300K and 77K respectively.

2.1 Eddy Current Damping

For the three similar fibers which have suspended the pendulum, the measured quality factor (Q) was much lower than expected (6 000 and 9 000) compared to previous measurements (22 000 and 350 000) using a 50 μm fiber in an older cryostat at 77K and 4.2K respectively. For a long solid cylindrical conductive pendulum suspended with its symmetry axis vertical, eddy current damping is approximately:

$$Q^{-1} \simeq \frac{B^2\sigma}{2\omega\rho} \tag{1}$$

where B is the magnetic field's horizontal component, and (σ, ω, ρ) are the pendulum's (conductivity, oscillation frequency, density). For our pendulum in the earth's magnetic field a limiting Q is about 7 500. In Dec 1999, after installing and degaussing magnetic shielding on the outside of the dewar, the observed Q at 77K was at an anticipated value of 20 000. Lead foil

(0.125 mm thick) enclosing the vacuum canister, installed in July 1999, should provide additional shielding at 4.2K; this is to be tested Jan 2000.

2.2 Magnetic Coupling Measurement

During operation at 77K in Nov 1999, we found evidence for a rotationally periodic torque acting upon the pendulum of the form:

$$0 = I\ddot{\theta} + k\theta + \alpha\cos\theta + \beta\sin\theta \qquad (2)$$

where θ is the pendulum's angular displacement, I is the pendulum's moment of inertia, k is the fiber's torsion constant, and α and β parameterize the periodic torque. The observed magnitude $\sqrt{\alpha^2+\beta^2}$ was $\sim 3\times10^{-13}$ N m or $4.4\times10^{-5}k$. Rotating the entire apparatus by 180 degree changed the signs of α and β, indicating that the source was fixed relative to the lab. A gravitational coupling of this symmetry and magnitude is highly unlikely. However, a very plausible explanation is that the pendulum has a magnetic dipole moment of $\sim 6\times10^{-9}$ N m T^{-1} coupling to the earth's magnetic field. Quite possibly, the contaminating magnetic moment was embedded in a small brass washer when cut in half by a steel tool; this half washer (29 mg) was epoxied to the top of the pendulum to trim the pendulum's balance. After installing the magnetic shielding around the dewar, this rotational periodic torque decreased by a factor of 35.

The torque of eq(2) was inferred by observing the pendulum's motion as a function of time. A general equation describing the pendulum's motion is:

$$\theta(t) = A\sin(\omega t) + c_0 + \sum_{n>1}^{\infty}\left[A_n\cos(n\omega t) + B_n\sin(n\omega t)\right] \qquad (3)$$

An approximate solution[5] to eq(2) in terms of parameters in eq(3) is:

$$c_0 \cong -\frac{\alpha}{k}J_0(A) \qquad (4)$$

$$A_n \cong 2\frac{\alpha}{k}\frac{J_n(A)}{n^2-1} \quad \text{for } n \text{ even} \qquad (5)$$

$$\omega^2 \cong \frac{k}{I}\left[1+\frac{2\beta}{k}\frac{J_1(A)}{A}\right] \qquad (6)$$

$$B_n \cong 2\frac{\beta}{k}\frac{J_n(A)}{n^2-1} \quad \text{for } n \text{ odd} \qquad (7)$$

where A is the pendulum's oscillation amplitude, and the $J_n(A)$'s are Bessel functions. The pendulum's harmonic content was analyzed through the 7th harmonic, thus α and β may each be determined uniquely by any one of four parameters of the pendulum's motion. Figure 3 shows plots of the parameters associated with an $\alpha\cos\theta$ torque as in eq(2).

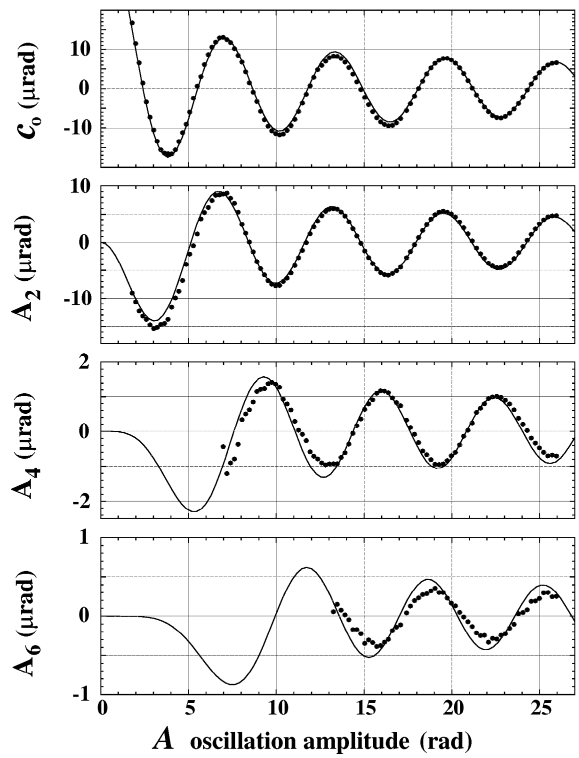

Figure 3: Measured harmonic coefficients in eq(3) versus oscillation amplitude (A). Solid lines are calculated from eq(4) and eq(5) with $\alpha/k = -4.33\times10^{-5}$.

Acknowledgments

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