Building a Leveling Device for LISA Ground Tests

Audrey Sederberg
Department of Physics
Harvey Mudd College

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Abstract

In order to reduce noise due to tilt in the ground-based testing on LISA conducted by the Eöt-Wash group at the University of Washington, a level prototype was designed and constructed. It has a range of 125 μm, and its height may be controlled through a PID-based feedback control loop.

1 Motivation

The Laser Interferometer Space Antenna (LISA) will be able to detect gravitational waves, lending insight to merging black holes and binary star systems, as well as possibly shedding light on dark matter and the mysteries of the early universe. LISA will consist of three spacecraft in a nearly equilateral triangle, each corner acting individually as an interferometer. These interferometers will need to measure changes in arm length to an accuracy of 20 picometers. To achieve such precision, it is necessary to understand all the possible small-scale interactions that could cause the test masses to shift. These interactions include patch effects, outgassing of metals, charge accumulation, radiometer impurities, and gravitational forces; currently unknown or underestimated effects may also prove important. The Eöt-Wash group is carrying out ground-based testing to investigate these interactions.

A torsion balance test is sensitive in the appropriate range of frequencies to provide useful information on interactions that may occur on LISA. In the Eöt-Wash experiment, a translatable rectangular surface is brought within millimeters of the test pendulum, a flat rectangular

plate suspended by a delicate fiber. Interactions between these two surfaces cause the fiber to twist, which is then measured. One source of unwanted signal is from any tilt in the platform upon which the apparatus sits. A highly sensitive level detector and feedback-controlled level is necessary to eliminate this tilt. This paper describes the design and function of a level prototype.

2 Level Design

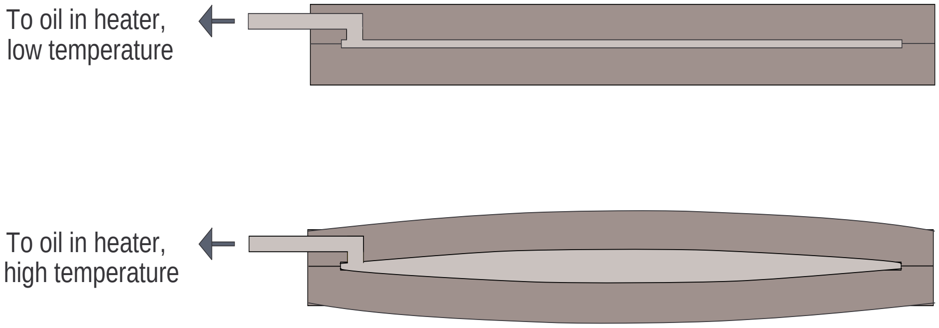

Figure 1: Control of pancake height. Deflection is greatly exaggerated.

The basic set-up involves a platform resting on three legs. A tilt sensor on top of the platform will give information on the platform's tilt. Using the data, the height of two of the three legs can be adjusted to correct the tilt. The purpose of this project has been to design adjustable feet, henceforth called pancakes, for these two legs.

The pancakes are hollow disks filled with oil. Figure 1 shows how the height of the pancakes is adjusted. The oil feeds into the pancake through a tube that leads to a reservoir of temperature-controlled oil. As the temperature of the oil rises, the oil expands. The expansion of oil in the heater will force more oil into the pancake, resulting in a deflection of the pancake top. Cooling the oil causes it to contract and thus decrease the deflection in the pancake.

The pancake actually consists of two disks fixed together about their circumference. A single disk is shown top-down and in profile in Figure 2. The deflection δ of one disk, clamped at the edges is

$$\delta = \frac{3PR^4(1-\mu^2)}{16Ed^3},$$

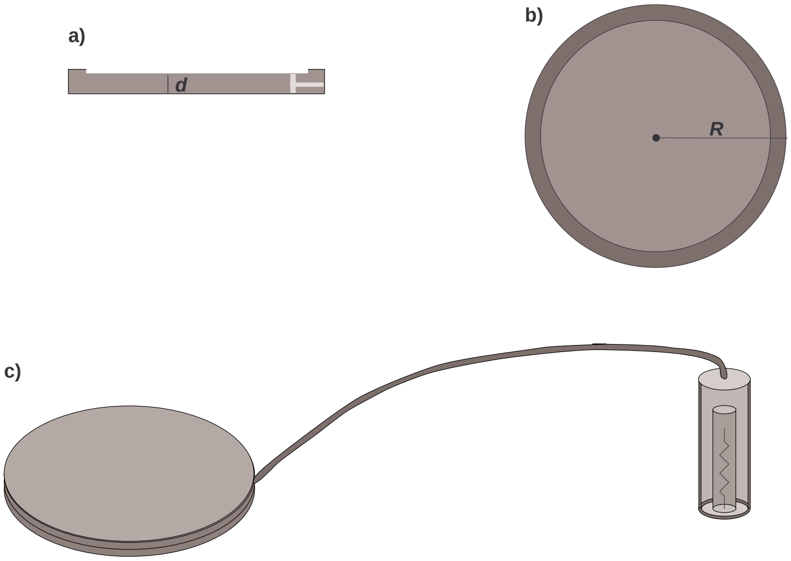

Figure 2: Schematic of pancake construction: a)cross-sectional view of half of pancake; b)top-down contour drawing of pancake; c)pancake and heater connection.

where P is the pressure on the disk; R is the radius of the cavity in the pancake; μ is Poisson's ratio, about 0.3 for metals; E is the elasticity modulus; and d is the thickness of the disk. For a desired range of 50 μm, the pressure in an unloaded pancake ranges from 20 psi (for a stainless steel disk 12 cm in diameter and 0.3 cm thick) to 80 psi (for a brass disk 12 cm in diameter and 0.6 cm thick).

3 The Heater

The heater is constructed from a brass rod 11 cm in length and 2.5 cm in diameter. It is hollowed to a depth of 10 cm and diameter of 2 cm. The resistive heating unit is inserted through the open top. A hole is drilled through the bottom to allow the insertion of the copper tube. The volume of the heater was chosen so that the expansion ΔV of a volume V of oil under a change in temperature ΔT, given approximately by

$$\Delta V = \alpha V \Delta T$$

where α is the thermal expansion coefficient, would correspond to the change in volume in the pancake due to deflection. To find the

volume change in a disk deflected by 25μm, the deflected volume is estimated to be a spherical cap, which has volume

$$\frac{\pi}{6}(3\delta^2 + R^2).$$

4 Testing the Prototypes

Before the prototype could be tested, the entire system had to be evacuated and then filled with oil. This was an iterative process in which the pancake and heater were alternately put under vacuum and opened to an oil reservoir. To facilitate the easy removal of all remaining air in they system, the pancake and heater were kept at a lower elevation than the vacuum pumping apparatus. Without this step, it was far more difficult, if not impossible, to remove all air.

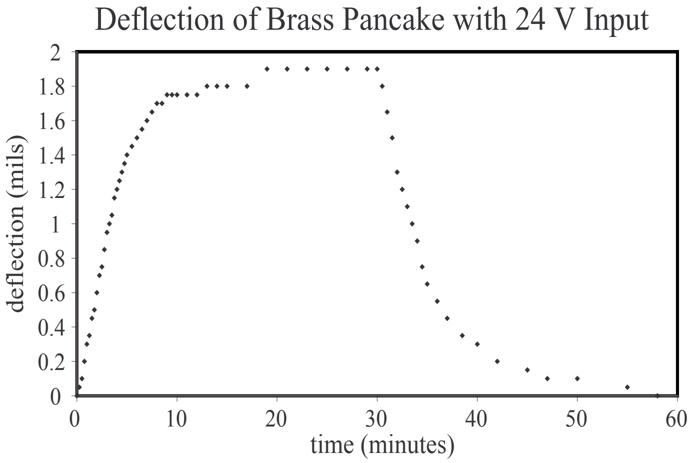

Figure 3: Trial at 24 V. The time to equilibrium was 15-20 minutes. (1 mil = 25.4 μm)

Initially, the copper tubing leading from the pancake to the heater was 3 m in length. This was to prevent the pancake from warming with the heater. It is highly important that the pancake not warm up since this would add to the thermal noise in the experiment; removing the heater sufficiently far away easily solves this problem. However, because the copper tubing used had a small inner diameter, this length made it difficult to completely evacuate the system. It was not until the tube was shortened to 0.5 m that the prototype functioned. Future designs may include larger tubing or stainless steel tubing, which has thinner walls and lower heat conductivity than copper tubing.

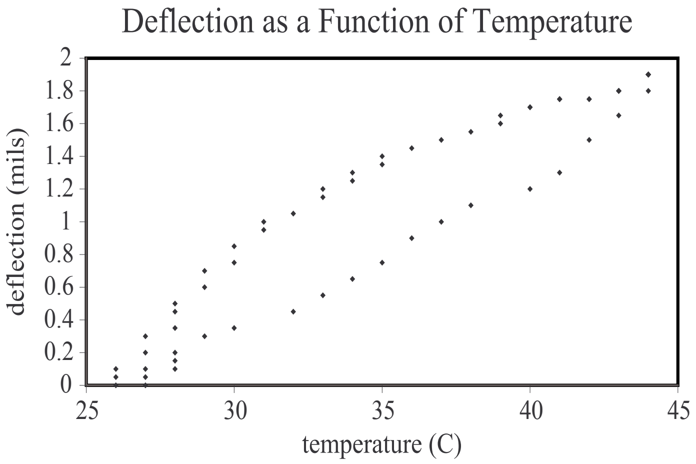

Figure 4: Plot of deflection and temperature relation for the same trial shown in the previous figure. The heating process is the top curve; cooling is the bottom curve.

Once the system was filled, it was straightforward to test. The heater was controlled with a Variac set at voltages ranging from 10 V to 30 V. A sample run is displayed in Figure 3. The pancakes initially deflect quickly and eventually level off at the equilibrium deflection within 15-20 minutes. The maximum deflection on any run was just over 120 μm. Figure 4 shows the relation of deflection to temperature. The temperature appears cooler than expected on the heating curve and warmer than expected on the cooling curve. The reason for this is that temperature was measured on the outside of the heater, which is made of brass, a poor conductor of heat. When the oil is heating, the brass has not yet warmed to the oil temperature, so the temperature measured is cooler than expected. Likewise, as the oil is cooling, the brass does not cool as quickly, so the measured temperature is warmer than expected. Had the oil been measured directly, it is likely there would be no discrepancy in temperatures on the heating and cooling curves.

5 Feedback Control

Using a capacitive measuring device (CMD), built by Todd Wagner, the deflection of a pancake is measured. The CMD works by measuring the capacitances between each of a pair of fixed plates and a moveable plate that is coupled to the pancake's deflection. A computer program takes the differences between these capacitances, which is fed into a feedback loop that implements a Proportional In-

tegral Derivative (PID) algorithm to adjust the power supplied to the heater through pulse width modulation. The PID loop drives the differential capacitance to zero. The program adds a capacitance to the initial capacitance, which effectively changes the zero point and, consequently, the deflection of the pancake where differential capacitance is zero. At this point, only coarse control of the added capacitance has been used. This can adjust the deflection by about 20 μm. There is capability for fine control by using additional registers on the chip, which will improve the precision. A graphical interface program, written by Michael Nickerson, shows the temperature of the computer chip that controls the system and the differential capacitance. The temperature reading decreases sharply when the power to the heater is switched on. This is probably because turning on the solid-state relay, which triggers the power, causes a decrease in the reference voltage used by the temperature sensor, resulting in a change in the temperature reading.

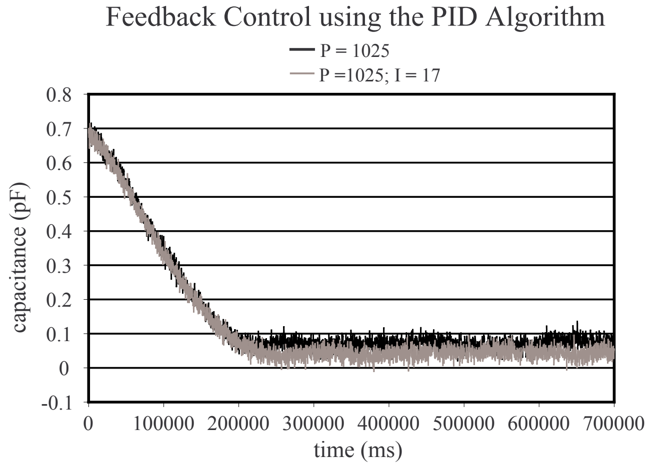

Figure 5: Response to feedback control loop. Target point is 0 pF.

Much remains to be done in the way of calibrating and fine tuning the feedback loop. The gains used on the proportional and integral terms have not yet been optimized, and the derivative term gain has not been tested at all. Initial trials have shown a small offset, 0.04 pF to 0.06 pF, as the loop drives the capacitance to zero. The offset was higher (0.06 pF) when using only the proportional terms than it was when both the proportional and integral terms were used (0.04 pF). A change in capacitance of 0.7 pF results in change in deflection of 60 μm.

6 Conclusion

The pancake has the potential to work well as a leveling device. Currently, it has a range of deflection of 125 μm. Deflection is controlled by a feedback loop to a precision of roughly 20 μm. The next steps for this project are to optimize the gain settings, to implement the fine tuning capabilities of the chip, and to eventually connect it to the rotating tilt sensor.

7 Acknowledgements

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