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High-Precision Electrolytic Capacitance Tilt Sensor

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Abstract

Tests of gravitational theory are at the forefront of current physics and astronomy research because Einstein's theory of gravitation, General Relativity, is fundamentally inconsistent with the Standard Model of quantum mechanics. The study of gravity at small but measurable distances will probe new theories that are attempting to incorporate gravity into a consistent framework that includes all four fundamental interactions.[1] Laboratory tests of the gravitational inverse-square law are difficult because of the extreme weakness of gravity as compared to the other forces. At Humboldt State University, we are exploring the nature of short-range gravity at unprecedented levels using a novel parallel-plate torsion pendulum. Limitation and characterization of systematic errors are key factors in such gravitational tests. Due to the well-documented "tilt-twist" effect for torsion pendulums,[2] we need to characterize minuscule oscillations of the inclination of our apparatus. To this end, we are constructing a high-precision, electrolytic capacitance tilt sensor. The sensor is comprised of several aluminum rods partially submerged in a sodium bicarbonate solution. The aluminum rods each act as one side of a capacitor while the solution acts as the other. The dielectric between the rods and the solution is the naturally occurring oxide layer on the aluminum. Using a capacitance bridge circuit, the difference in capacitance between two rods yields a measure of the tilt of the sensor along one axis. As the apparatus' inclination changes, the surface area of the rods in solution also varies, thus changing the output of the bridge circuit. This paper addresses the design and characterization of the tilt sensor, as well as its relevance for short-range tests of gravity.
Keywords: Gravity, Extra Dimensions, Inverse-square Law, Inclinometer, Tilt Sensor

1. Introduction and Motivation

The motivation to study gravity comes from various speculations in theoretical physics that range from the prediction of extra dimensions to gravitational effects concerning dark energy or vacuum energy.[1, 3-5] Many of these scenarios predict that gravity may act anomalously at short ranges. Predictions that gravity gets stronger at short distances come from string theories that model extra dimensions as being "rolled up." At short enough distances these dimensions should be detectable as a deviation from the inverse-square law. Conversely, attempts to explain Dark Energy have given cosmologists reason to believe that gravity may "turn off" at short distances; less than ~0.1mm.[5]

At Humboldt State University, we are constructing a torsion pendulum experiment to test gravity at unprecedented levels in the sub-millimeter regime. An attractor mass modulated at a known frequency near a hanging pendulum induces a measurable twist in the torsion fiber due to the distance dependence of the gravitational interaction and the geometry of the pendulum. The level of twist at the modulation frequency gives a measure of the strength and distance dependence of the gravitational force.

Due to the short distances involved in this experiment and the inherent weakness of the gravitational force, high sensitivity and noise reduction are key requirements for obtaining useful and accurate results. One potential source of systematic error is the "tilt-twist" effect.[2] This effect couples a change in the apparatus' inclination to a twist of the torsion fiber. If the modulation of the apparatus' inclination has a frequency component at the signal frequency, systematic error will result. Such tilt-induced twist modulation could also be misconstrued as a deviation of the inverse-square law. Thus the motivation for construction of a precision tilt sensor arises because knowing the time variation of the inclination of the apparatus is key to characterizing the tilt-twist effect and suppressing its influence on the quality of the data.

2. Brief Explanation of the Short-Range Gravity Experiment

The experiment consists of a "stepped " torsion pendulum and a modulated attractor plate (Figure 1). The pendulum hangs freely, parallel to the attractor plate. The gravitational force is then measured between the attractor plate and the pendulum by measuring the deflection of a laser beam bounced off of the surface of the pendulum. The precision tilt sensor will be mounted to the top of the vacuum chamber and measure its inclination as a function of time. The tilt-twist feedthrough for a typical torsion fiber is roughly 1% - or for an apparatus tilt of 1 microradian, the pendulum will twist 10 nanoradians. For the gravitational experiment, a twist sensitivity on the order of nanoradians is required so the tilt of the apparatus must be known better than the microradian scale at the attractor mass modulation frequency. For a complete description of the apparatus and experimental technique, see reference 6.

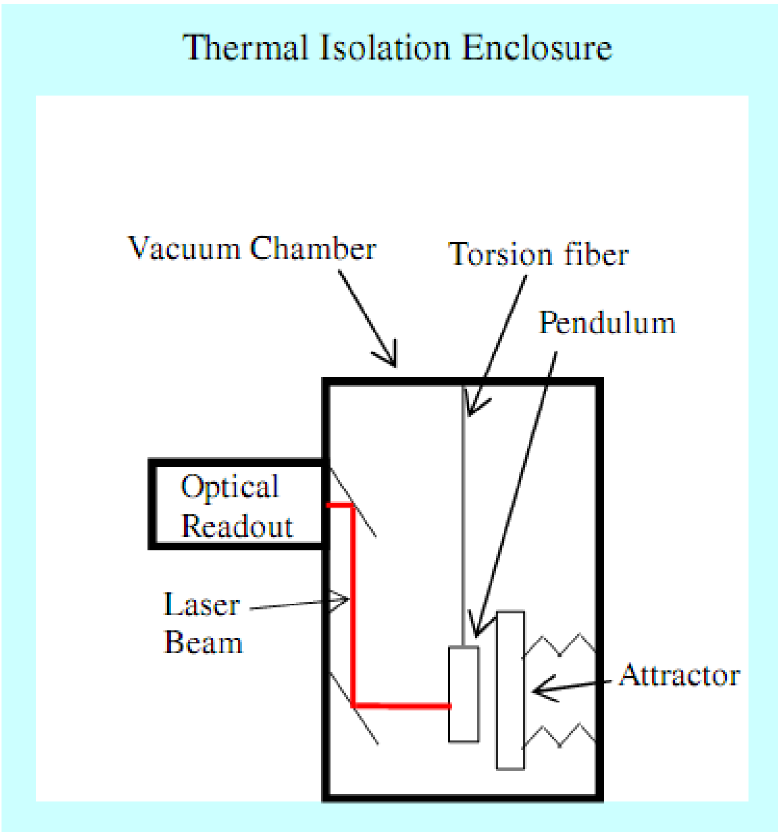

Figure 1: Cross-sectional view of apparatus.

3. Noise Suppression and Error Reduction

Due to the weakness of gravity as compared to electromagnetism and the incredibly close ranges involved in our measurements, many steps have been taken to reduce sources of systematic error.

3.1 vacuum chamber

The experiment will be conducted inside a custom-made high-vacuum chamber. Doing so will avoid any damping of oscillation due to the viscosity of air. Because of an absence of air, there will be limited heat transfer from the pendulum to the attractor plate as well. The chamber is composed of aluminum with ten removable flanges. The roughing and vacuum pumps are Varian SH-110 Dry-Scroll and Varian LP-70 turbomolecular pumps respectively. Preliminary evacuations of the chamber have shown a minimum pressure of lower than 10^{-6} Torr. Given the size of the pendulum, this is well below the needed pressure for the pendulum to be unaffected by the viscosity of air.

3.2 temperature control

Changes in temperature cause length contraction and expansion, especially in metals that have high conductivities. The entire vacuum chamber is therefore surrounded by an insulated enclosure. To further ensure thermal stability, the enclosure is equipped with a programmable thermoelectric temperature controller, TE Technology, Model TC-24-25, which can control temperature within the range -20C to 100C with precision of ± 0.1K.

3.3 pendulum and suspension system

Because the system relies on a hanging pendulum, there is a chance of oscillatory motion due to motion of the suspension point. To counteract such motion in the "simple pendulum" mode, the pendulum will hang from a tungsten fiber that is 20 micrometers in diameter that runs through a cylindrical casing which has a series of magnets. The whole system acts as a magnetic damper exploiting the characteristics of eddy currents to suppress swinging motion of the pendulum. Due to the circular shape of the damper, the torsional motion will not be damped and our data will remain unaffected.

3.4 electrostatic shield

The experiment is taking place both in vacuum and with metal surfaces in close proximity. Even though there will be no intentional potential differences between the metals, virtual particles can arise generating an electric force, a phenomenon known as the Casimir Effect. This force could cause an attraction between the metals leading to false electromagnetic effects that could mask subtleties of the gravitational force. To suppress the Casimir Effect, we will insert a membrane of beryllium copper between the pendulum and the attractor plates. The membrane will act as an electrostatic shield to combat the effects of the Casimir Effect. Patch effects may also introduce unwanted electrical forces that will be screened by this membrane.

3.5 tilt effects

A tilt sensor, or inclinometer, is any device that measures its inclination with respect to the plane perpindicular to local vertical. All inclinometers rely on terrestrial gravity to make their measurements; we have chosen an electrolytic capacitance sensor to make such measurements to ensure that our vacuum chamber is approximately orthogonal to local vertical, and also monitor small variations in the inclination of the apparatus that could detrimetally affect the results obtained via the tilt-twist effect.

4. Tilt Sensor

As mentioned, our experiment involves suspending a torsion pendulum that always hangs vertical in the vacuum chamber; therefore, it is of paramount importance that the chamber is level with respect to the center of the earth and that any tilt fluctuations are measured as accurately as possible. In order to achieve this we are constructing a precision inclinometer to ensure that the chamber is level and to measure any tilt variations due to earthquakes or low-frequency motion of the building floor. Construction and testing are in preliminary stages, but initial sensor design and tests are described below.

4.1 sensor configuration

The sensor is constructed from five rods of aluminum partially immersed in a sodium bicarbonate solution. Each piece of aluminum acts as one side of a capacitor, while the liquid solution acts as the other side. Aluminum forms a natural oxide layer, forming a dielectric layer between the two sides of the capacitor. When a current is sent through the aluminum, the water against it polarizes making a slightly thicker dielectric. Figure 2 shows a trial aluminum electrode submerged in solution.

Four of the rods will be arranged in a cross shape with one rod in the middle acting as a ground reference. Except for surface tension effects, a liquid is always level with respect to local vertical. When the tilt sensor is off-level, the amount of each rod immersed in the liquid will change. The inclinometer will take advantage of this by measuring the differential change in capacitance as the apparatus tilts (see figure 3).

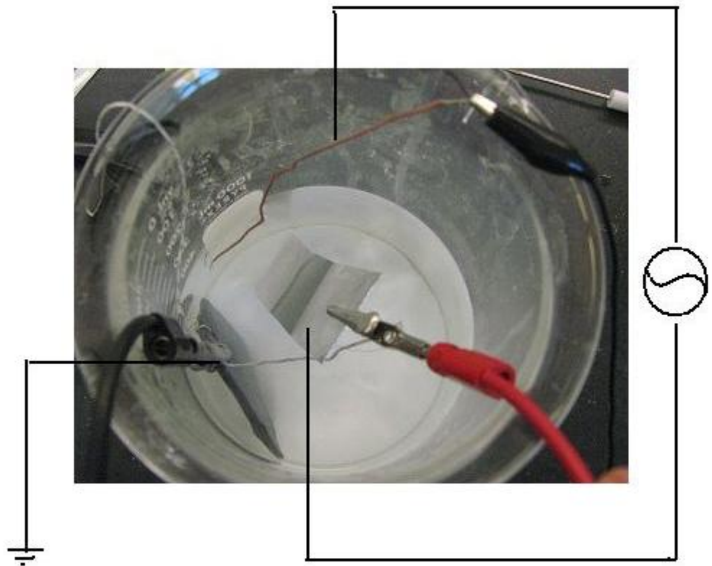

Figure 2: A rudimentary capacitor.

Figure 2 shows a strip of pie plate with roughly $100 mm^2$ immersed as the aluminum electrode and a piece of lead that forms the ground reference.

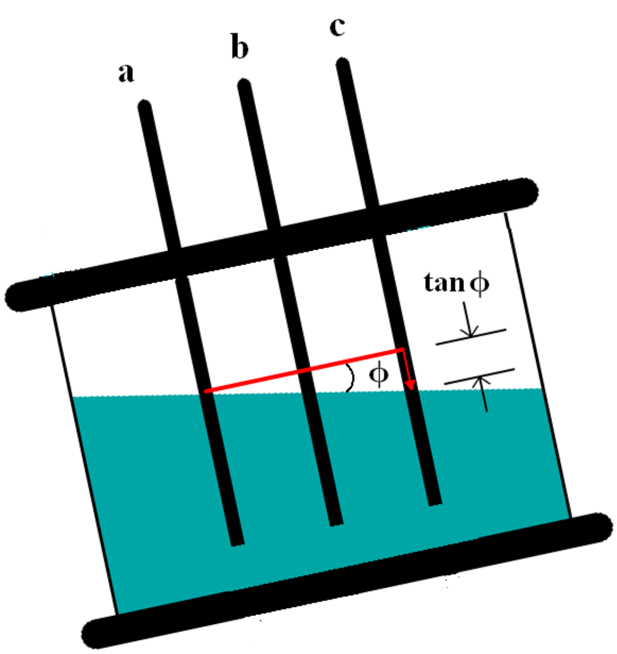

Figure 3: Cross-section of tilt sensor. The solution, always level to local vertical, is the shaded region while a, b, and c, represent aluminum electrodes.

4.2 circuitry

The most obvious circuitry for the device is a capacitance bridge circuit as shown in the Figure 4. After nulling the center voltage, any change in capacitance will produce a voltage change across the center of the bridge. The sign of this output voltage is dependent on the water level going up or down around the electrode. The change in capacitance will then go into a LabView data acquisition system, programmed to sample the output voltage periodically.

By applying a known tilt to the sensor, the circuit will be calibrated such that the tiny deviation in voltage away from null can be interpreted correctly as a tilt of the apparatus. Then, using simple geometry, we will be able to tell how the water level has changed and in what direction the tilt has occurred.

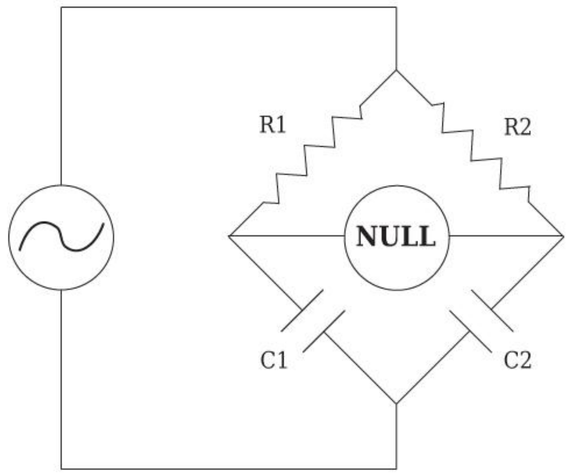

Figure 4: Capacitance bridge circuit.

4.3 analysis

After calibration, the output voltage signal from the sensor will go into LabVIEW, which will be programmed to interpret the changes in tilt. The calculations will be based on the geometry of a triangle as shown in Figure 3. The distance between the rods will be known. LabVIEW will measure the change in voltages induced by a change in tilt. After calibrating the sensor by inducing a known tilt, LabVIEW will be able to associate a change in voltage with a length of the rod that has been exposed or submerged. Changes in tilt can be inferred using the procedure outlined below.

According to the geometry shown in Figure 3 for a tilt along one axis, an unknown capacitance can be measured with the bridge circuit using the following equation:

$$\frac{R_1}{X_{C1}} = \frac{R_2}{X_{C2}}, \tag{1}$$

where R1 and R2 are the known resistors and X_{C1} and X_{C2} are the reactances of the known capacitor and the electrolytic capacitor, respectively. When the output voltage is nulled, this statement is true and the measured voltage across the bridge will be zero.

The device will be calibrated such that a deviation from the nulled voltage can be interpreted as a change in inclination. Negative measured voltages will indicate tilt in one direction while positive voltages will indicate tilt in the opposite direction. Once a change in voltage is measured, we can invoke trigonometric functions to understand exactly what tilt changes have occurred:

$$\tan\phi = \frac{\Delta c}{\overline{ab}}. \tag{2}$$

In the above equation, $\overline{\mathrm{ac}}$ is the distance between electrodes a and c, and Δc is the excess exposed distance of electrode c, as shown in Figure 3. Solving for the the tilt angle, ϕ,

$$\phi = \tan^{-1}\left(\frac{\Delta c}{\overline{ab}}\right). \tag{3}$$

This angle will tell the degree of tilt of the aluminum vacuum chamber and will allow for a correct analysis of the information coming out of the optical readout, as well as characterization of possible tilt-twist influence on the data.

4.4 advantages

There are several different types of inclinometers or tilt sensors ranging from liquid bubble sensors, as used in carpentry and photography, to accelerometer based sensors as used in video game controllers. The liquid capacitance sensor has several advantages for our purpose, the main one being that its readout is capable of achieving the required sensitivity (microradian) and it is temperature independent. Any fluctuations in temperature will happen to the whole sensor at once and will not affect differential measurements to first order.

4.5 sensitivity

Initial tests show that the sensor will be able to detect changes in inclination of less than a microradian. Considering that our required twist angle sensitivity is on the order of nanoradians, this is an acceptable level of sensitivity because the tilt-twist coupling is typically about 1% for torsion fibers (one microradian of tilt induces 10 nanoradians of pendulum twist). The limiting factors will be the sensitivity of our equipment and our abilities to adjust the vacuum chamber such that it is level. The building itself may become a limiting factor if it has an unpredictable, inherent changes in inclination over time larger than the microradian scale.

4.6 challenges

Obvious issues arise due to the evaporation of water and the implications that would have on the capacitance of our system. The evaporation is slowed already by making the liquid more viscous due to the sodium bicarbonate addition. The casing for the sensor will also be designed such that the rods hang from a lid, which can be screwed on. This will allow for minimal evaporation. Should evaporation occur, it will occur at an equal rate across the surface of the water. In other words, one side of the liquid solution will not evaporate faster than the other side. Since the sensor measures the differential change in capacitance of one rod relative to another instead of absolute capacitance, this problem becomes irrelevant.

Another issue that may arise is corrosion of the metal surfaces. The probes will be made of aluminum which has a desirable natural oxide layer that in effect prevents them from oxidizing further. On the other side of the "capacitor" is the solution. Using an aluminum probe to go to ground in the solution would create too many variables in the system, so instead a gold or stainless steel base will be used in the sensor's casing that is equidistant from all of the aluminum rods and connects to ground from the bottom of the casing.

Thermal changes in the surroundings may cause lengthening or contracting of the aluminum rods and therefore in the capacitance. The sensor will be attached to the vacuum chamber and, as previously mentioned, the chamber will be in an insulated, temperature-controlled enclosure. The aluminum rods will not be directly temperature controlled, but because they will all be the same dimension, again, they will change size the same way, thus resulting in no change of the differential capacitance output signal. The saturation of sodium bicarbonate in solution is temperature dependent, but since the apparatus will be temperature controlled, the concentration will remain constant.

In analyzing the circuit output, using the aforementioned capacitance bridge, there was an issue in using an industry capacitor with the electrolytic capacitor. Measurements of the voltage would show a phase lag of 0.6 milliseconds and upwards (see Figure 5). When the “known” capacitor was replaced with another electrolytic capacitor this problem disappeared. While the capacitors in the bridge will be completely electrolytic capacitors, it warrants further investigation as this could pose problems in measurements of the amplitude if the phase lag becomes too large.

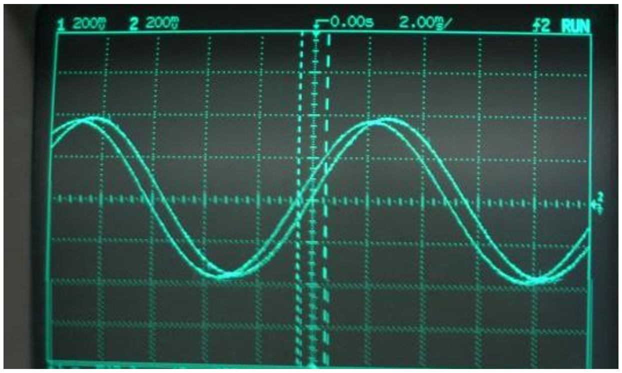

Figure 5: Oscilloscope display of the phase lag.

5. Conclusion and Outlook

Our sensor is still in the development phase, but will be able to provide us with the information needed to characterize any false signals associated with differences in the apparatus's inclination with respect to true local vertical. The gravitational experiments being conducted will be minimally affected by changes in inclination to the vacuum chamber because any associated tilt will be measured, recorded, and appropriate corrections will be applied to the data. Should the building sink in a non-uniform way, the information will be related to the researchers. The sensor along with the other noise reduction techniques will be key in collecting useful and accurate data for short-range tests of gravity.

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7. References

1. N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, "New dimensions at a millimeter to a fermi and superstrings at a TeV," *Phys. Lett.* B **436**, 257 (1998).
2. C.D. Hoyle et al., "Submillimeter tests of the gravitational inverse-square law," *Phys. Rev.* D **70**, 042004 (2004).
3. D.B. Kaplan and M.B. Wise, "Couplings of a light dilaton and violations of. the equivalence principle,"*JHEP* **0008**, 037 (2000).
4. S. Perlmutter et al., "Measurements of W and Λ from 42 high-redshift supernovae," *Astrophys. J.* **517**, 565 (1999).
5. R. Sundrum, "Fat gravitons, the cosmological constant and submillimeter tests," *Phys. Rev.* D **69**, 044014 (2004).
6. Liam J. Furniss, "Extra Dimensions, Dark Energy, and the Gravitational Inverse-Square Law," *Proceedings of The National Conference On Undergraduate Research (NCUR)* (2008)
7. J.A Hunt, "Level sensing of liquids and solids - a review of the technologies," *Sensor Review*, 200-206 (2007)
8. D. Pheifer and W.B. Powell, "The Electrolytic Tilt Sensor – Sensors," *Sensors* - Home Page. 1 May 2000 and 28 Oct. 2008 http://tinyurl.com/dagoly