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Prototype Mirror Suspension for Cryogenic Interferometers

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Contents

Abstract

Gravitational wave astronomy has been a rapid growing field, we use interferometers to detect gravitational waves which give us insight into optically hidden events such as black hole mergers. Since the current noise levels of the Advanced LIGO detectors are reaching to the physical limit, they will soon need detector upgrade. For the successful design of such upgrade, the development of the cryogenic suspension is imperative. The goal of my summer research is to build and test a prototype suspension system. In this article, we will be describing the project "LIGO Voyager" [3] and our goal for the summer to help push the advancement of the current aLIGO to LIGO Voyager by creating a prototype suspension system. This prototype will then be tested in air, vacuum ,and at cryogenic temperatures specifically looking at the dynamical and cooling performance. Our Test results are feedback to the modification of the suspension design for Mariner and thus increase the feasibility of the Voyager upgrade.

2 Introduction Gravitational Waves

The first detection of Gravitational Waves (GW) was on September 14, 2015 by Advance LIGO (aLIGO) detectors [2]. This set forth a foundation for a new field of study: gravitational wave astronomy. GW detectors are probes that will help us understand some of the mysterious of the cosmos, such as providing information about the warping of space time around black holes, exotic nuclear matter in neutron stars, and giving astronomers the ability to see cosmic event that are normally not visible from electromagnetic radiation.

The current LIGO detectors have provided valuable data for the scientific community, but they will soon reach the thermodynamic and quantum mechanical limits of their design. Over the coming years we plan to upgrade the current aLIGO design, so that we lower the quantum noise and the thermal noise from the mirrors. The goal is that with this upgrade we will be able to improve sensitivity by ∼50% and increase the range by a factor of 4∼5 [6]. This upgrade is called LIGO Voyager [3].

For the successful design of the Voyager detector, we need a small scale prototype interferometer for the confirmation of the design principles. Mariner is such a prototype interferometer that is going to be built at the 40 m prototype facility at Caltech. Mariner suspension will employ a silicon test mass, double pendulum design, and will be implanted into a croyostat.

This summer we have planed to build a prototype of the suspension system for Mariner. After we will then be then be putting this system inside of a Cryogenic chamber. Ideally we would like to test our prototype in air, vacuum and at cryo-temperatures (123 K). We will specifically look at the dynamics of our prototype and how the overall system fair while at cryo-temperatures.

3 Motivation

3.1 LIGO Voyager

Due to the current limits of the aLIGO detectors, we would like to advance the sensitivity and range of the current detectors by investigating a different method to improve efficiency. The current plan to help advance aLIGO into the new era of LIGO detectors is the project LIGO Voyager. LIGO Voyager plans to reduce mirror thermal noise and quantum noise by implementing a crystalline silicon test mass, 2um laser wavelength, and Cryogenic cooling of the test masses and the suspensions. The crystalline silicon has been chosen over current and proposed test mass such as fused silica [1], sapphire [5] ,and 10 K silicon [4]. When the crystalline silicon is cool to 123 K it is seen that neither Brownian nor thermo-optic substrate noises should limit detector sensitivity. This test mass will be large and weigh 200 kg it will also affect the sensitivity by having a larger optical spot size, thus reducing the coating thermal noise and it being a heavier test mass will result in less disturbance from radiation pressure forces. A laser of 2 μm wavelength has been chosen due to the silicon test mass being effectively opaque for wavelengths shorter than approximately 1.1 μm. Furthermore, a 2 μm wavelength will have a 14% degradation in coating thermal noise at 2 μm, a higher power recycling gain due to lower loss in the arm cavities, lower loss in the high-finesse, squeezing filter cavity, and reduced backscattering noise (currently limiting all ground-based detectors). The last upgrade for Advance LIGO detectors is to build a cooling system around the test mass and suspension system. My project focuses on the cryogenic suspension system which will help create a successful design of the Voyager detector.

3.2 Prototype of Mariner suspension

Mariner is an interferometer that will be built at the Caltech 40 m prototype facility. It will use a similar suspension system that is planned for Voyager with simplification. Although Mariner suspension is based on a double pendulum system it is similar to the final quad suspension that will be implemented in LIGO Voyager. Another difference between Voyager and Mariner is that the silicon test mass will be 200 kg in Voyager and 6 kg in Mariner. This prototype allows us to study a suspension system and its dynamics inside of the cryostat, ideas for future designs, and how different components within our suspension system will react to thermal expansion.

As a first article of the Mariner suspension, we are working on the prototype version of the Mariner suspension this summer. This prototype Mariner suspension (Fig.1,2) will be tested in a cryostat ("suspension test cryostat"). The prototype test results will give us excellent feedback for modification of future suspension design for Mariner, and also give us insight into what issues may arise from cooling a suspension system.

4 Structure of the Mariner prorotype suspension

The Mariner suspension consists of the following parts: The frame structure, top suspension plate, suspended masses, earth quake stops, and cryoshields. Each part is described in the subsections below.

- We first start from component preparation for Mariner suspension and the test setup.

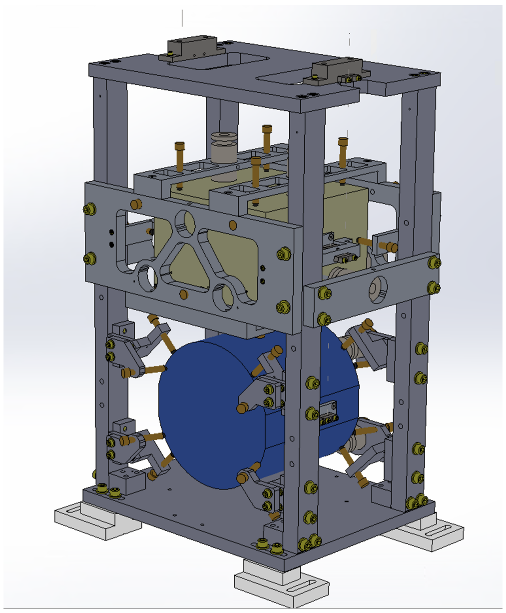

Figure 1: Mariner Suspension Prototype Side View

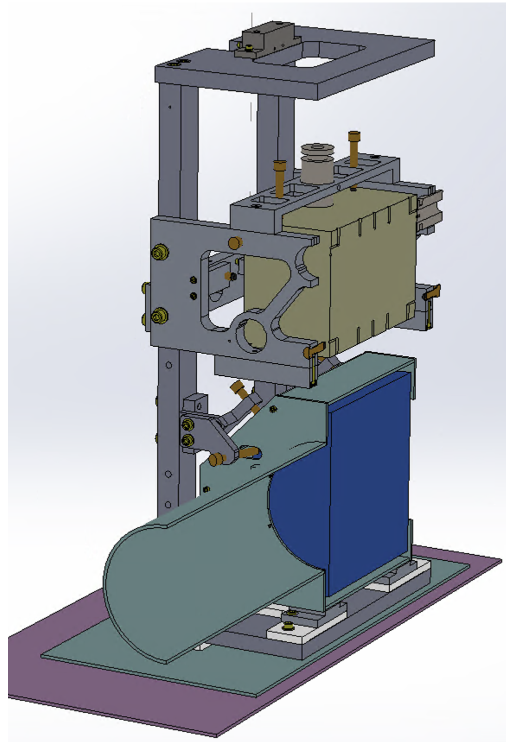

Figure 2: Section view of the Mariner suspension with cryoshields.

This will include the test of the actuator (the traditional LIGO OESM) at room temperature and in a cryostat.

- Test the dynamics of a suspension. This test is going to be done both without and within a cryostat.
- Lastly, we will have a better understanding of how to design a better cryostat for our suspension system. All of this helps with the feasibility to upgrade aLIGO to Voyager.

4.1 Frame+Thermal Isolating feet

Our prototype frame is 454.4 mm by 304.8 mm. We have implemented stiffening plate to help with stability in our frame. further more we have to deal with thermal isolation between our frame and the outside environment, we plan to use Polyether ether ketone or a low heat transfer plastic.

4.2 Top plate / Wire clamp

The top plate will allow for extra support and hold the wire clamps for the intermediate test mass there are a total of six wire clamps first two are holing the intermediate test mass. The other four are holding the silicon test mass.

4.3 Intermediate mass

The intermediate mass will be made of an aluminium alloy this mass will help with pendulum stability.

4.4 Test mass

The test mass will be made of silicon so that when we cool down our system we get little to no Brownian nor thermo-optic substrate noise.This test mass will weight about 6 kg and 300 mm in diameter.

4.5 OSEMs (Sensor+ Actuator)

The OSEM's are electromagnetic actuators and sensors. The OSEM's use shadow sensor to detect the position of our test mass. There are small magnets that are inserted into the test mass. These then stick out of the test mass so that we can apply various current to our OSEM's which then changes the magnetic field moving the test mass around.

4.6 Earth Quake Stops

There is earth quake stops above and below the test mass so that in case of an earth quake if the strings holding the test mass break we won't damage the mirror since it won't be allowed to fall a great distance.

4.7 Cryogenic Shields

There will be 3 different shields in our system the chamber wall, outer shield, and inner shield.The chamber wall will block off our system from the outside environment. The outer shield will help separate our suspension from most of the open air inside the chamber. The inner shield will in close our suspension to help with the cooling of the suspension and test mass. There is one more shield that we will need which is for our test mass. This shield will have snouts on the ends of our test mass since we need beam to pass through. We are still working on on snout length so this is undetermined.

5 Research Goal

The over all goal is help with the advancement of LIGO and future LIGO detectors. We first need to start with this small scale prototype so that we can get general information and an idea from this model. This will then be implemented into the 40 m lab here at Caltech. Once we are confident with this system we can then bring it to actual LIGO sites.This upgrade is known as Voyager.

5.1 Testing method

The overall goal for my summer research is to set up and test. We are specifically looking into the mechanical dynamics of our prototype. The test items are described below.

Ideally, when that is complete we then would like to build a cryostat around our suspension system then we can test our system in a vacuum and at cryo-temperatures. At first tests are going to be performed in air, then in vacuum environment at room temperature and at cryogenic temperature.

5.2 Testing items

Testing all mechanical and electrical systems of the prototype suspension. This involves checking for full functionality in our coil driver and satellite amp, verifying OSEM's are working properly, and reassuring that the suspension system is properly built. We will also be collecting data from our OSEM's.

This data will be used to map a transfer function that we will be compared to our modeled transfer function. Also, we would like to use our transfer function to implement feedback control to our OSEM actuator so that we can have our test mass as stable as possible.

5.3 Electronics

5.3.1 Coil driver circuit

We are using coil driver board D1100687-v2. The coil driver board is use to driver current through the coil on our OSEM's this produced a magnetic field to push and pull the magnets on our test mass. The coil driver board use operational amplifier to create a differential signal to give a positive or negative voltage through out the coil.

5.3.2 Satellite amp

We are using Satellite amp board D080276-v2. The Satellite amp are used to power the LED and photo-diode inside the OSEM, also we use them to collect information on how the system is reacting. We had to modify the board because at cryo-temperatures our OSEM's will over saturate, so by lowering the trans impedance gain we ideal gave our OSEM some head room so that they don't over saturate.

6 Progress Towards Mariner

Over the 10-week summer we managed to lay down the electrical groundwork for the electromagnetic actuator that will be used in mariner. Unfortunately, due to logistical issues we could not get the part for the mariner suspension in turn I setup the three coil driver board's and four sat amplifier boards. We created two different test to validate that the OSEM's are functioning properly and that our boards are functioning properly.

Before any of the OSEM test we first validated that our boards are functioning properly. For the coil driver boards we used a function generator, oscilloscope, and multimeter. We induced a sinusoidal signal and use the oscilloscope to verify that the signal was amplified and made it to our output 3. For our sat amp board we just used leds and a multimeter 4.

7 OSEM Scale Verification

For this test we use a 200 g scale to measure the change in weight of a test mass which was a metal block with a Teflon bar and magnet. Also used a OSEM actuator connected to optical lens post and a z-axis caliber. We ran into some issue with this test first issue was our scale was sensitive to air flow in the room, so we use a plastic container to cover our setup this helped with fluctuation in our scale 6, 7.

We test 3 different OSEM's and this gave us a general idea of what our OSEM are doing and how they are working. We see that they do follow what we expect them to do but there was an issue with our calibration so we have to do some post calibration to verify our results and make any conclusions.

8 40 cm Single Pendulum Test

For this test we use the old 40 meter single pendulum suspension and four OSEM's to shake the pendulum to measure the input response and output response of the system with this we measure the transfer function for the pitch, length, and yaw. We verified this result by validating our date to the equation of a pendulum we see that a 40 cm pendulum frequency is at 0.78 Hz and you can see this in our data. We also can see that our length has couple with pitch and yaw resonant frequency 8.

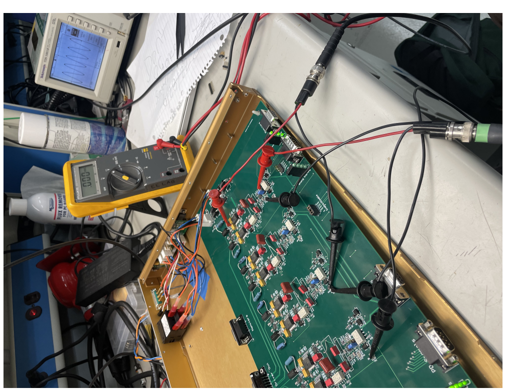

Figure 3: Coil Driver Test Verification

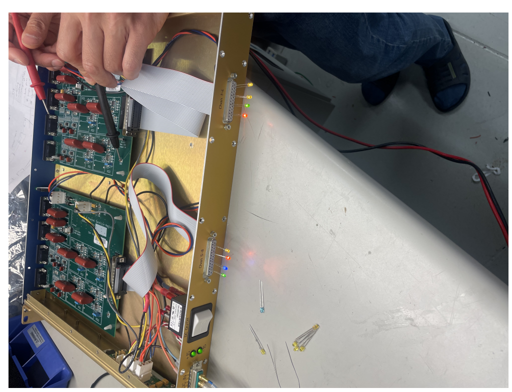

Figure 4: Sat amp Test Verification

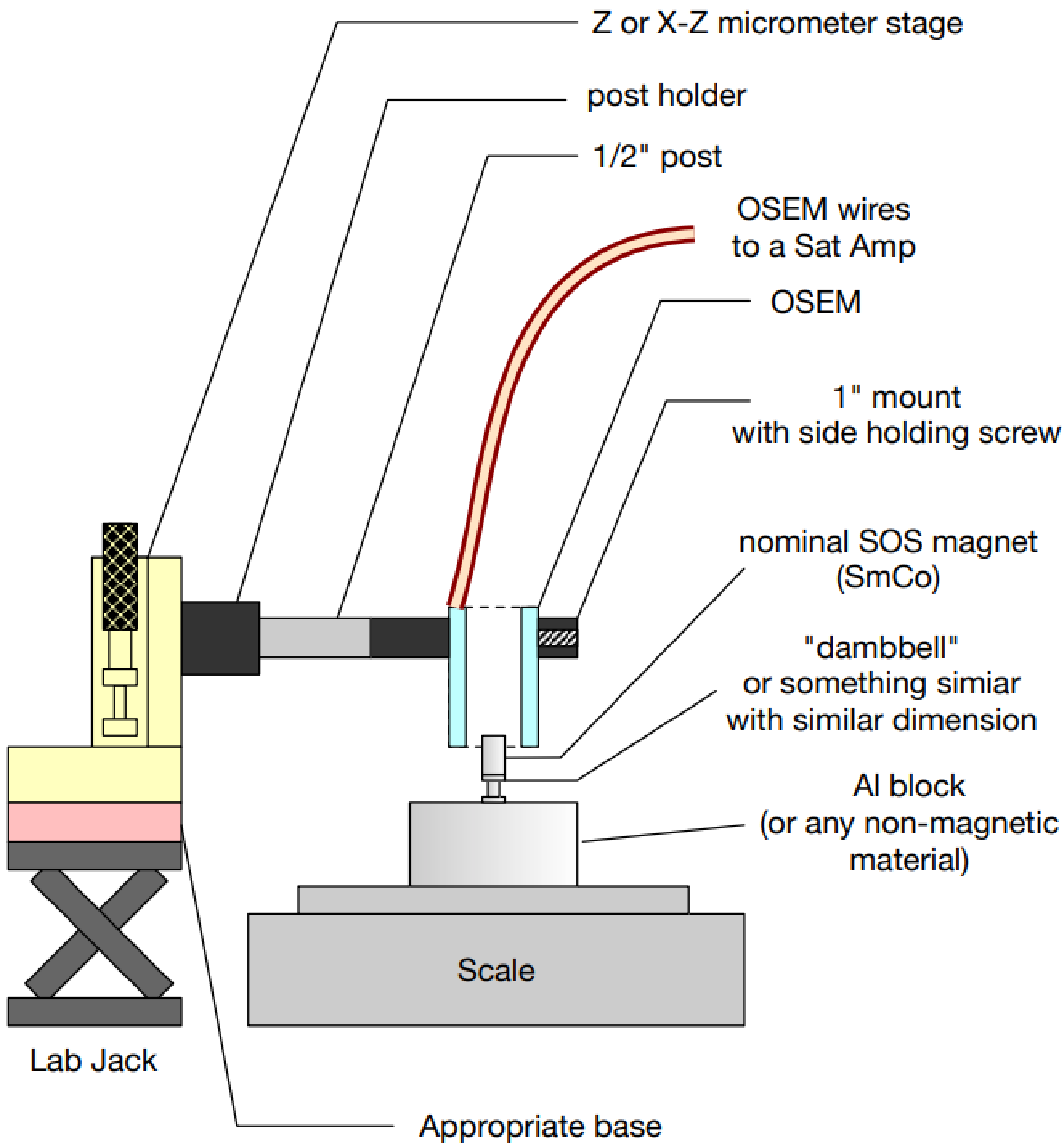

Figure 5: Cartoon Of Test Setup

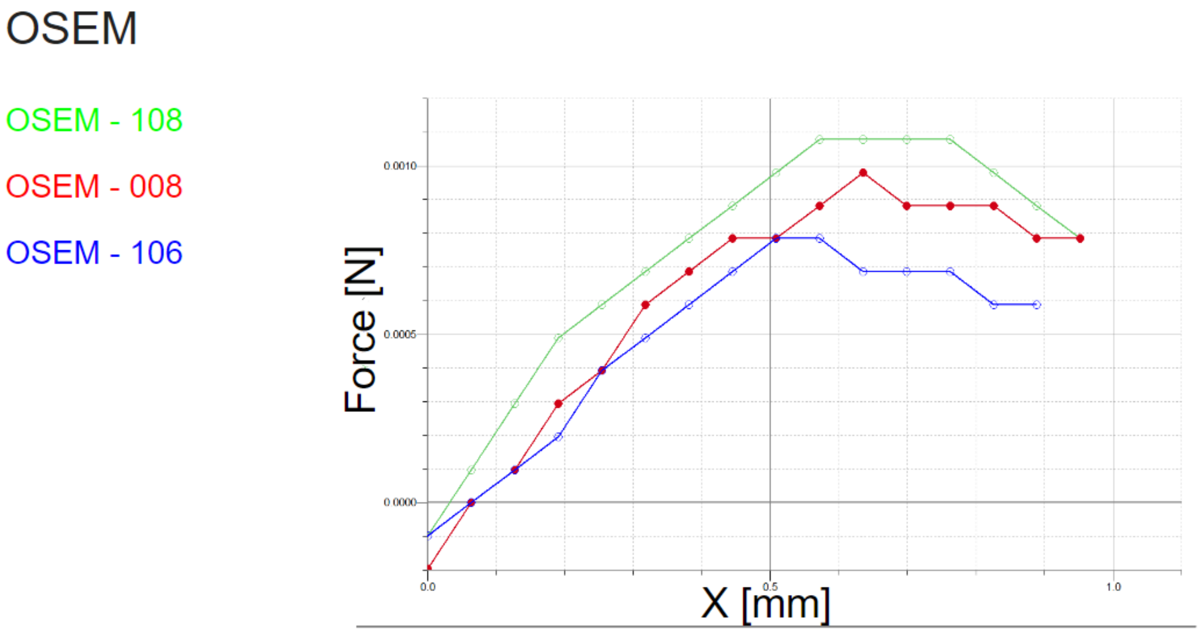

Figure 6: Force Vs. Distance

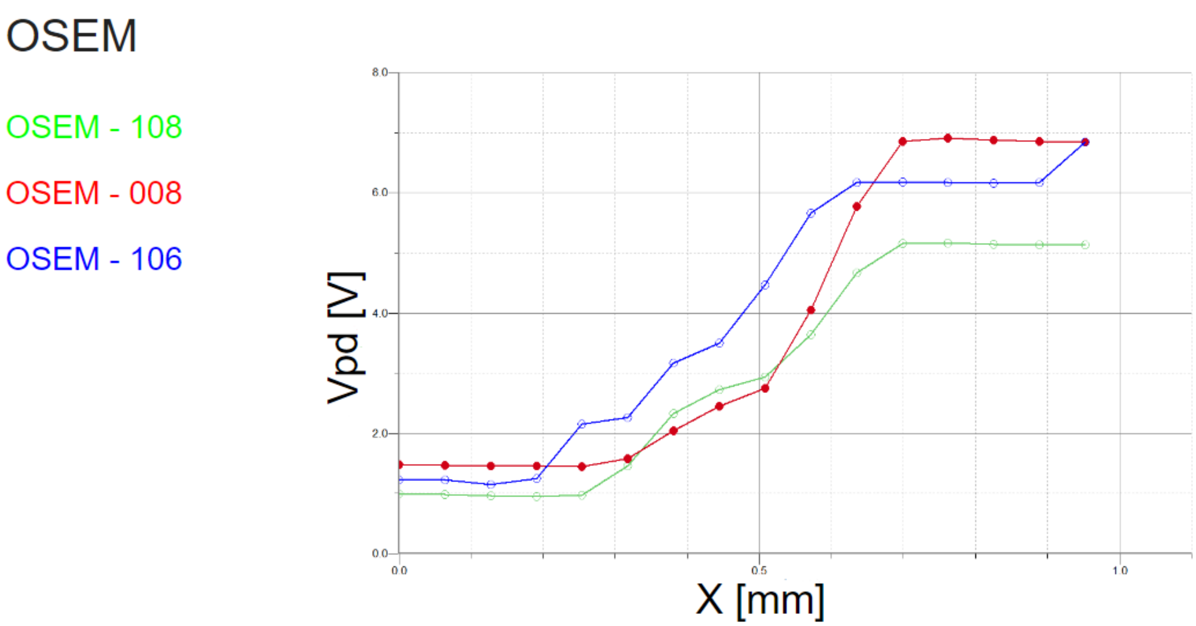

Figure 7: Voltage Vs. distance

9 Conclusion

This Summer I helped in the advancement for the Mariner Project I managed to setup the electrical background for Mariner and proven that the Coil Driver and Sat Amplifier are functioning properly. Using these test we can verify that our OSEM are functioning properly and pushing the pendulum properly. For future test we ideally like to test the actuator in a cryogenic system and on the double pendulum system. After this we can then implement this in the 40 Meter lab to then hopefully we can then devloped a system for futuer LIGO systems.

10 Background/Theory

10.1 Transfer Function

The Transfer function is a complex function that describes the relationship between the input and output of a linear system. To obtain our transfer function we can use our suspension system to model what our transfer function should be. For our simple case of a single pendulum we can model and look at the transfer function.

11 Apendix

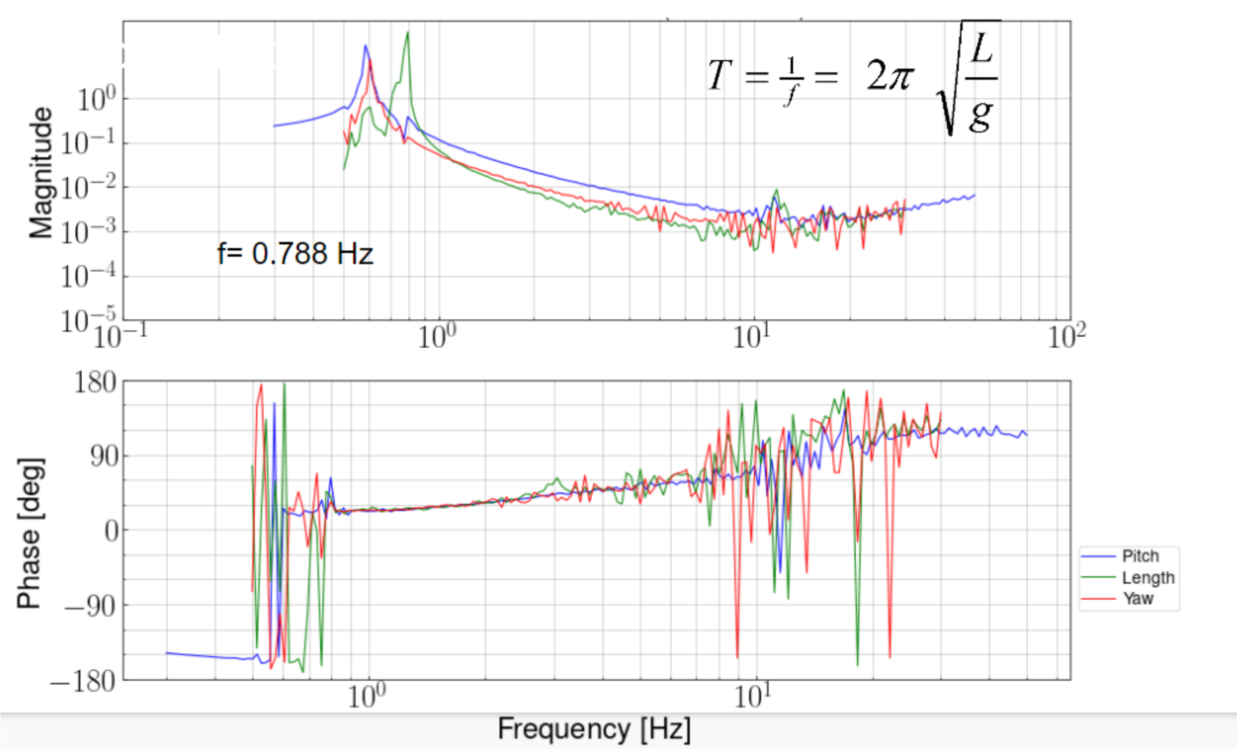

Figure 8: Transfer function of single pendulum

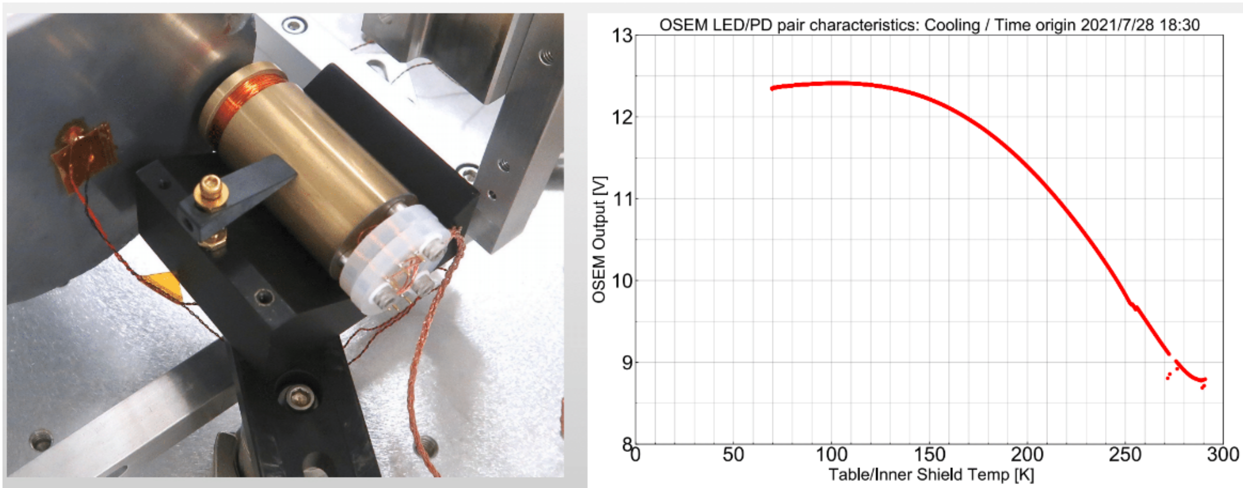

Figure 9: OSEM & Output Readout

A Issues/future Issues

A.1 Scaling issues

A common issue for any system is scaling. Most of the time a system will not work going from 1x to 100x in size. For example, drones specifically looking at quad-copters. I was working on an eVTOL project where we want to create a quad-copter that is capable to transport people but there is a problem when you have a light and nimble drone it is easy for the drone motors to counteract any disturbances such as a gust of wind. For a larger quad-copter if a larger gust of wind hits it will not be able to react fast enough to counteract the disturbance and will then lose control and ultimately end up crashing. So relating this to our prototype model it is something to keep in mind that for one our prototype will be about 500mm for total height and 170mm for stage length while Voyager will eventually be the same height as aLIGO suspension and stage length will be 780mm. Also, the OSEM actuator will have to deal with a larger mass with the silicon test mass weighing 6 kg in our prototype and 200 kg in Voyager.

A.2 Actuator/Sensors

Another concern is how will the OSEM actuators fair overtime being cooled for long periods of time. There has been a preliminary test that has been done on the OSEM actuator. These tests cooled the OSEM to 70K and we saw that there was a 40% increase in readout(Fig.9).

A.3 Wiring and Thermal Expansion

Wiring from within the Cryogenic system may prove to be trouble sum due to the amount of wire needed to be fed into our suspension system. We have some general idea of how the cable will feed through but are still unsure how it will all work out in the end. This issue can be solved while we are building our prototype and the plan is to build our suspension shell first and then start looking at how some of the components will fit. Another issue that we will have to look out for is how thermal expansion will affect our system. Will it cause some of our components to shrike or change the alignment of our test mass?

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