Active and Passive Damping for Seismic Isolating Suspensions

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Abstract

Gravitational wave detectors have limited sensitivity due to sources of noise. In order to measure the gravitational wave strain in an arm of the interferometer, the total length of the arm must be long enough to measure these small changes in space-time. One limiting source of noise is ground motion, which limits readings in the low frequency range. The signal from a gravitational wave will not be able to be distinguished from the noise floor. The goal of my project is to investigate methods of mitigating and controlling the motion on an optic. The output optics in the AEI 10 m prototype [1] use a (HAM-Horizontal Access Module) HAM-Relay Triple Suspension (HRTS) for optics to mechanically isolate them from ground motion. BOSEMs (Birmingham Optical Sensor and Electro-Magneitc Actuators) are placed on the first stage of the HRTS to actively damp seismic noise in six degrees of freedom using active feedback loops. This paper explores the usage of active and passive damping on the HRTS to isolate the a test mass from ground motion.

1 Introduction

In 1916 Albert Einstein published his General theory of relativity and one consequence of this was that energy is carried away in the form of Gravitational waves from accelerating objects in space. Gravitational waves are ripples in spacetime that carry information about the objects in our universe. In 2015 the first ever gravitational wave signal was detected, proving Einstein's theory correct and marking the beginning of a new field of science. Current generation Gravitational wave detectors are Michelson interferometers that detect strain over the total length of their arms. When a gravitational wave signal reaches Earth, the small amount of energy these waves carry squeeze and contract space-time; consequently, detectors must be extremely sensitive to strain. However, having a sensitive detector means that it is sensitive to signals from sources on Earth. All unwanted motion or uncertainty makes up the noise floor of a detector. The goal of experiments such as the AEI 10 m prototype [1] is to improve current and future generations of Gravitational Wave detectors by minimizing the effects of noise.
One future prospect of the 10m prototype group is to incorporate balanced homodyne detection into the detector, to follow the current next steps of LIGO (Laser Interferometer Gravitational-wave Observatory) and future upgrade of the current gravitational wave detectors (GWD), in order to reach readings below the standard quantum limit [2]. In balanced homodyne detection, ground motion noise can limit sensitivity, to minimize this effect, the mirrors must be suspended.
Damping is necessary to decrease the motion on the suspension when it is inside of vacuum, as mechanical damping from the triple suspension is not sufficient to extract energy and decrease motion on a resonance of the system. The goal of my project at the AEI 10 m prototype is to explore active versus passive damping by characterizing the motion in all six degrees of freedom in comparison to a modeled suspension.

2 Setup and Procedure

2.1 HRTS Overview

The HAM Relay Triple Suspension (HRTS) [4] was designed to mechanically isolate the ground motion in each degree of freedom from the top mass to the bottom mass. In order to mechanically characterize this design with active and passive damping, we built an HRTS to suspend a 3" mirror 1 and an HRTS to suspend a 4" mirror. The purpose of these suspensions is to test different methods of damping and find the resonances of both systems, before these are adopted by the 10 m prototype configuration for balanced homodyne detection.
The first stage of this triple pendulum system is suspended by two cantilever blades and wires that isolate vertical motion, this is the first degree of isolation from ground motion that has coupled to the cage. The blades have a young's modulus of 190 GPa[4], when there is vertical motion present there is a force applied onto the blades causing them to behave as springs and bend accordingly. The first mass now has one stage of vertical isolation that is transferred to the following stages via sets of stainless steel wires. This is the location for all the actuation and one of the two locations of seismic sensing. The actuation must be placed higher in the chain of the HRTS as to not introduce any electromagnetic noise onto the bottom mass, the second location of sensing. In order to determine the center of mass for the first stage, there is a large set screw that can be positioned to balance the mass in the front-back plane. The center of mass of each stage should be exactly in the center to ensure any degree of freedom does not cross-couple to another. The second stage of vertical isolation is on the first mass cascading down towards the penultimate mass (PUM) from 4 cantilever blades and 4 thinner wires. The PUM has multiple locations for adjusting the center of mass by adding or removing heavy washers or moving a smaller set screw forward or backward. The last set of two wires are attached to the PUM and wrap around the bottom of the final stage creating the appearance of 4 wires. On either side of the final stage there are stainless steel prisms where the wires are held steadily in place on these sharp edges. There is a model in Matlab developed at the University of Glasgow [7] to predict the transfer functions, moments of inertia, and damping for the 3" and 4" HRTS designs. The HRTS design was adapted into the current design by the AEI, this model is applicable for the original and adapted design. The model will be used to compare our suspensions to those with perfect assembly.

2.1.1 HRTS Wires

The assembly of the HRTS requires a gentle and precise hand to place the wires. Thinner than a strand of hair at 75 μm and smaller, the wires are difficult to see and can easily become kinked. Prior to the assembly, the wires are placed into a wire jig designed by the 10 m Prototype team for pre-tensioning. The wires are clamped into place so that there is little tolerance between the end of the stainless steel clamps and the launching point of the wire, this is to ensure the length is precise. When installing the wires a counter weight must be placed on the PUM upper wire

clamps to ensure the center of mass stays between the wires. Kinks in the wires will introduce thermal noise in the system that will couple to the bottom mass.

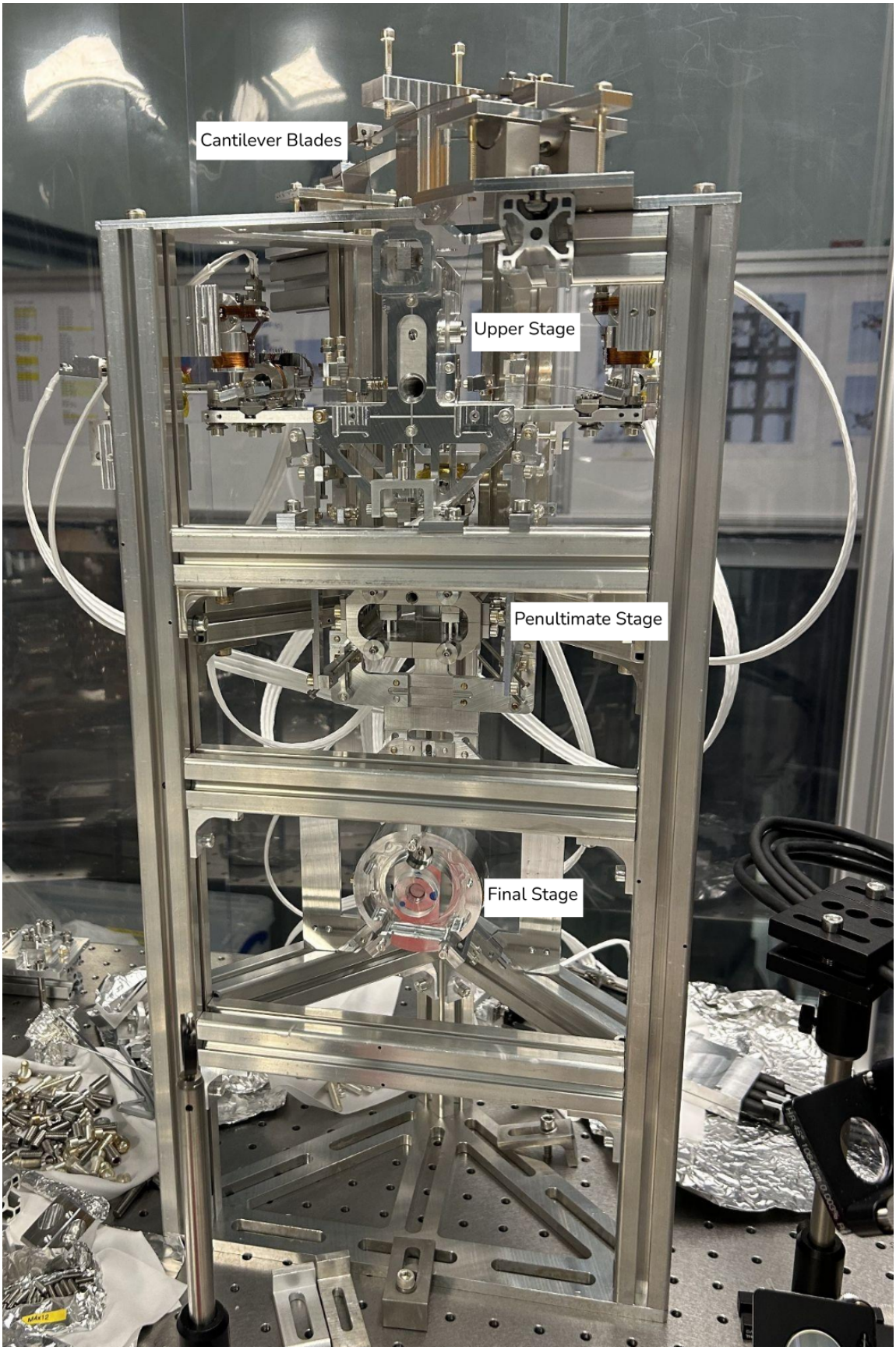


Figure 1: HRTS final construction design for a 3" mirror, with six BOSEMs installed to actuate and sense motion in all six degrees of freedom.

parameter	value
total height	635mm
total width	330mm
total depth	205mm
mirror to floor	220mm
total mass	9.0kg
upper mass	739g
penultimate mass	789g
test mass	291g
wire radius m1	75μm
wire length m1	0.115m
wire radius m1 to m2	50μm
wire length m1 to m2	0.115m
wire radius m2 to m3	25μm
wire length m2 to m3	0.16m

Table 1: The estimated dimensions for the HRTS holding a 3" mirror.

2.2 Sensing and Actuation

2.2.1 BOSEMs

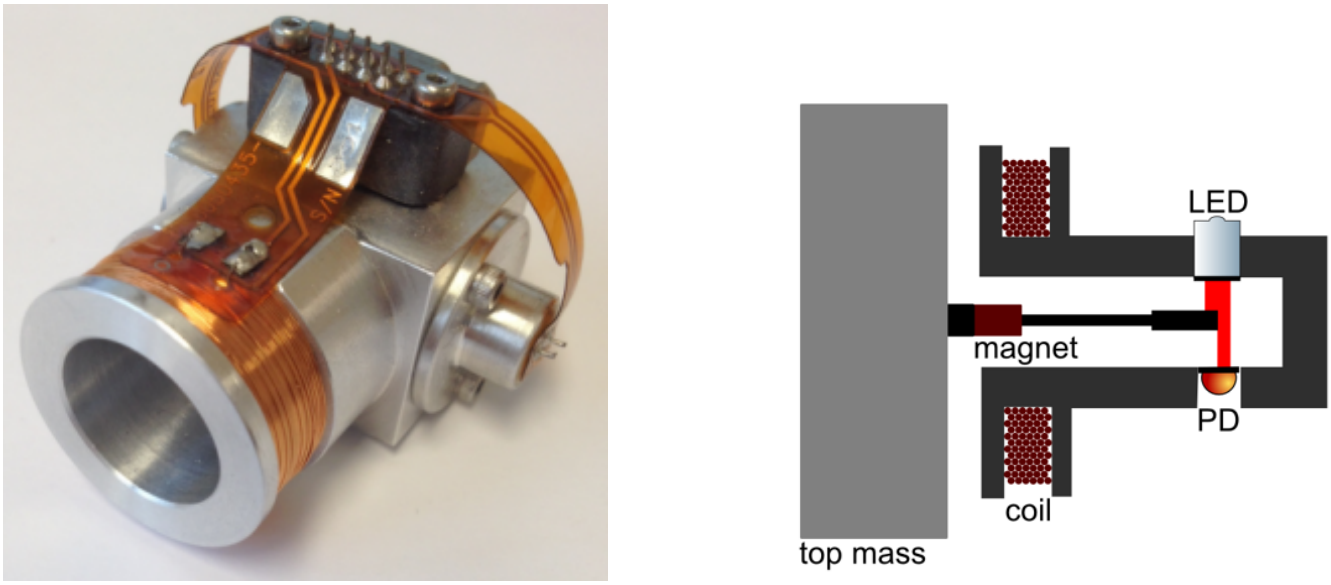


Figure 2: BOSEM[1] used for active damping and sensing motion on the upper mass of the HRTS. The coil is used to externally send actuation to the suspension when placed in vacuum. The LED and photodiode pair will read out position, velocity, and acceleration of the upper mass in one direction. The degree of freedom that the BOSEM is capable of sensing is dependent on its positioning on the upper mass.

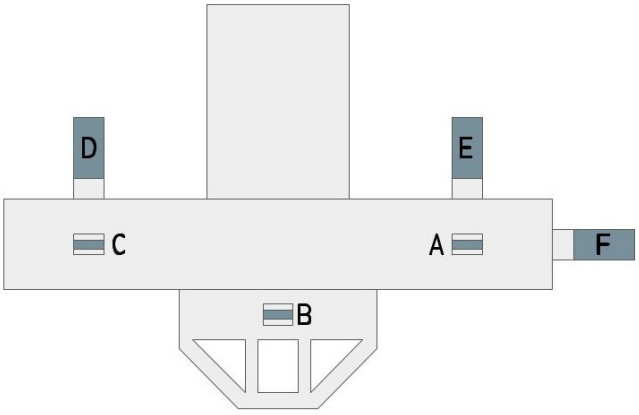


Figure 3: Placement of BOSEMs on a simplified illustration of the upper mass of the HRTS. Where A and C are capable of actuation and sensing longitudinal and yaw motion, B actuates and senses in pitch, F actuates and senses in side, D and E are capable of actuation and sensing in vertical and roll motion.

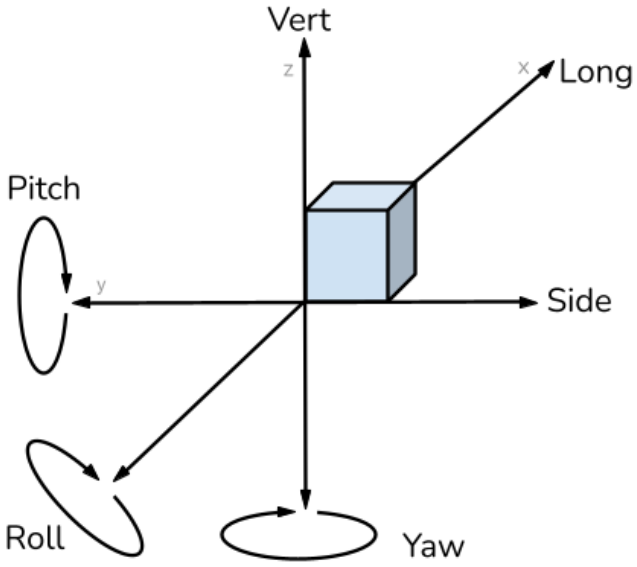


Figure 4: Six Degrees of Freedom in which we will measure motion on the triple suspension.

In order to fully mechanically characterize the HRTS system we can use BOSEMs [6] (Birmingham Optical Sensor and Electro-Magnetic Actuator) to actuate on the upper mass of the suspension, then find how the motion will transfer into the bottom test mass.

The BOSEM design originates from the electrodynamic principle of Faraday's law, where a change in magnetic flux induces a voltage, and the method of shadow sensing to measure motion. The design is as follows in Fig.2, the BOSEM shell houses a photodiode (PD), LED, and a coil. On the upper mass of the HRTS there are six magnets and small flags that are aligned to fit in the center of the BOSEM passing through the LED and PD path. When the upper mass has some motion, the flag will block or show more light onto the PD. The signal from the shadow sensor can be readout to characterize the motion of the suspension and a current can be externally supplied to the coil to excite the upper mass of the suspension.

The six BOSEMs are arranged in alphabetical order on the upper mass as depicted in the illustration Fig.3 that actuate in each of the six degrees of freedom. In order to convert the readings from the shadow sensor into physical interpretations of the degrees of freedom, we must create a conversion matrix for the BOSEM signals to be read through. This matrix is a 6x6 that is multiplied by the BOSEMs to create a sum of signals that is read out as a velocity. This signal is used in the closed control loop for damping, once the resonances are found.

To characterize the suspension, the resonances in every degree of freedom should be known. Using a gaussian white noise excitation over a wide range of frequencies, we can find resonances with damping and without damping to observe changes in the transfer functions from ground displacement to the upper stage motion, and from the upper

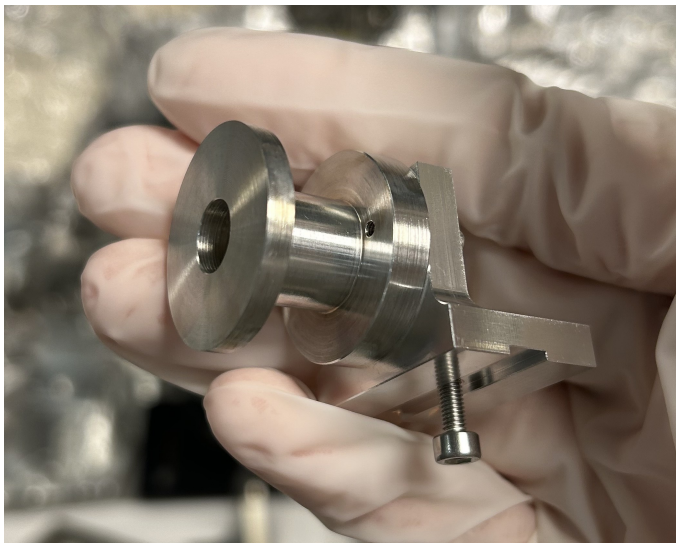


Figure 5: Eddy current damper without actuation coil.

stage motion to the final stage motion. The first iteration of the BOSEM velocity damping used a band pass filter starting with a differentiator at 0 Hz and everywhere else attenuate the high frequency with a zpk. When actuating in a degree of freedom, the signal sent to the BOSEMs must pass through an actuation matrix that determines to which BOSEM the signal is sent. In the case where an individual BOSEM is used, the signal is supplied directly. This loop of sensing and damping actuation is called an active feedback loop that allows us to control the gain on excitation of each BOSEM. For our purposes we want to strongly damp at the resonant frequencies by creating notches at these points in a gain filter.

BOSEMs can be used as both actuators and dampers based on need, however because they are an active system electrical noise can couple in at high frequencies, introducing noise. The BOSEMs are expensive and complicated to manufacture, and require an electrical channel for sensing and actuation signals to be sent. If passive damping is sufficient, then the 10 m prototype team will proceed with this method.

2.2.2 Eddy Current Dampers

$$\epsilon = -N\frac{d\Phi_B}{dt} \tag{1}$$

Eddy current dampers (ECDs) are passive dampers meaning it is not possible to have active control or sensing. The fundamental principle behind these is similar to BOSEMs, here Lenz's law (1) describes the nature of their behavior on the system. Lenz's law states that when there is a change of magnetic flux, there is a current induced to oppose the change. When there is faster motion on the upper mass the ECDs become more effective because Lenz's law is a function of flux over time, this is also known as velocity damping.

The ECD design is more simple and cheap to produce than the BOSEM. However, with this design, it is impossible to select specific frequencies to damp. The ECDs sacrifice the high frequency band sensitivity where gravitational wave signals can be found [1]. It is possible to add a coil to the current ECD design for actuation, however, sensing motion is not possible compared to a BOSEM.

For our test, an ECD is positioned on the upper mass in three positions replacing BOSEMs D, E, and F. Long, pitch, and yaw motion most directly affects the readings on the final mass, the BOSEMs we want to keep are the ones that can actuate in these degrees of freedom. In principle, we can place an ECD in the locations of the BOSEMs to read out the same measurements to compare the quality factors and effectiveness of damping.

The ECD design is similar to the BOSEM without the shadow sensor. The installation is similar as well, the ECD replace the positions of the BOSEMs on the upper mass and the flags are removed from their position on the magnet.

2.2.3 Optical Lever

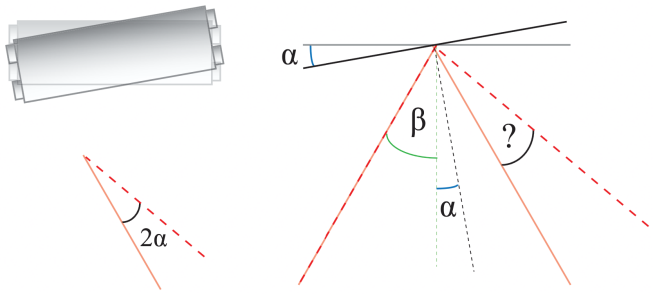


Figure 6: [3]. (The angle α in which yaw motion is excited contributes a change in laser position β on the final stage mirror.

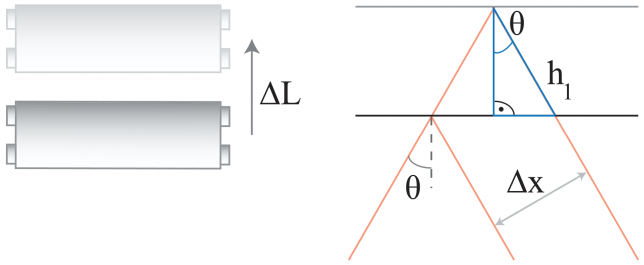


Figure 7: [3] (The ΔL in which longitudinal motion introduces some uncertainty in the position Δx of the laser on the final stage mirror.

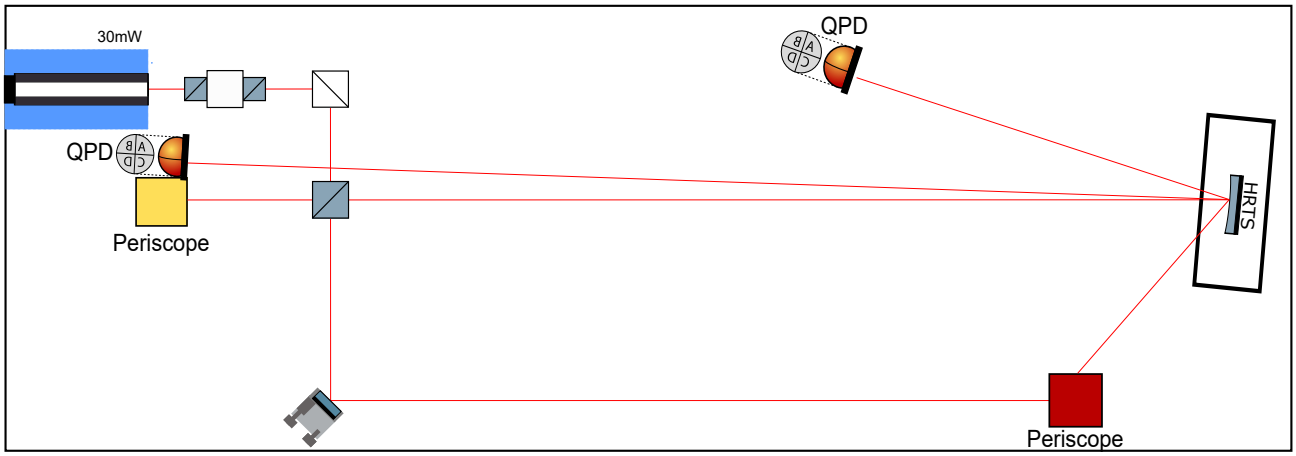


Figure 8: Optical levers layout for sensing motion on the third stage of the HRTS. The height of the final stage mirrors were higher than the laser beam path, to steer beam upwards to the proper height to be centered on the mirror. Periscopes are more mechanically stable than optical posts with long poles, so their resonant frequencies are higher. In the optical lever set up, they used closest to the final stage mirror.

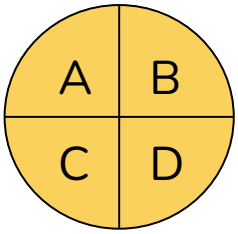


Figure 9: Diagram of QPD used in the optical lever layout. The normalized sum of quadrants is used to find motion in two degrees of freedom.

$$Yaw = \frac{(A+C)-(B+D)}{A+B+C+D} \tag{2}$$

$$Pitch = \frac{(A+B)-(C+D)}{A+B+C+D} \tag{3}$$

parameter	value
l1	1.090m
l2	2.247m
$\theta 1$	47.275°
$\theta 2$	1.595°

$$\Delta x_{long,i} = 2\sin(\theta_i)\Delta L \tag{4}$$

$$\Delta x_{yaw,i} = 2l_i\alpha \tag{5}$$

$$\Delta L = \frac{l_2\Delta x_1 - l_1\Delta x_2}{2(l_2\sin(\theta_1) - l_1\sin(\theta_2))} \tag{6}$$

$$\alpha = \frac{\Delta x_2\sin(\theta_1) - \Delta x_1\sin(\theta_2)}{2(l_2\sin(\theta_1) - l_1\sin(\theta_2))} \tag{7}$$

In order to read the motion on the bottom mass, we use 2 optical levers that are targeted to the final stage suspended mirror. The optical levers will allow us to get a readout in three degrees of freedom that we have chosen to be pitch, yaw, and longitudinal motion.
The design of the optical lever layout is depicted in Fig. 5, one with a large angle and one with a shallow angle. The length of the arms of the large angle optical lever could not be longer due to lack of working space on the optical bench, ideally it would be longer to have more sensitive readings. Since the mirror suspended in the HRTS is taller than the beam path we used periscopes to guide the beam upwards. Using the equations (6) and (7) [3] we can uncouple yaw and longitudinal motion. Now it is possible to find how the motion in the first stage of the HRTS will transfer into the bottom mass.

QPD A QPD or quadrant photodiode illustrated in Fig. 6, allows us to make initial calculations of motion in two degrees of freedom. When the bottom mass moves from seismic activity or actuation, the beam hitting the QPD will move in a mirrored degree of freedom that the bottom mass moves. We can then convert the signal on each quadrant of the QPD into a normalized sum that corresponds to a degree of freedom [3] (2) (3).

2.3 Signal Processing

The complete characterization of the HRTS suspension and the effectiveness of BOSEMs and ECDs can be determined by relating the actuation to the output motion we detect. Transfer functions (8) show a time independent signal response to signal input. For our purposes, it is easiest to visualize this using a bode plot in the frequency domain where we can see the strength of actuation to response.

A resonance is a pole of the transfer function where the actuation in the denominator will be small compared to the motion read out, this will appear as a peak in the bode plot. After reaching a resonance peak the transfer function will drop by $1/f^2$ for every resonance, leading to noise in a high frequency range. A cross-coupling is a zero of the transfer function where the HRTS response is much larger than the actuation. Physically, this can signify when actuation in one degree of freedom does not correspond exclusively to one degree of motion response. A coupling can be caused by the center of mass of each stage of the HRTS not being perfectly centered, the assembly of the HRTS has some misalignment, or the actuation on one of the BOSEMs is stronger than another when two are required for one degree of freedom actuation.

$$H(s) = \frac{Y(s)}{X(s)} \tag{8}$$

$$C_{xy}(s) = \frac{|G_{xy}(s)|^2}{G_{xx}(s)G_{yy}(s)} \tag{9}$$

The coherence of the system's actuation and response is important to determine how much noise is being introduced during actuation. The coherence equation (9) is a normalized cross correlation between two signals in the frequency space. When the response is linear, or without noise, during actuation, the coherence at that frequency will approach 1. This is an indicator of at which frequencies the actuation is strong enough to be distinguished from the noise floor. We have found that the HRTS actuation coherence is with low noise in the 0.6Hz to 5Hz range. When damping a resonance, the coherence becomes higher over that frequency.

3 Results and Discussion

For full characterization of the HRTS system with active and passive damping, the resonances for every degree of freedom were found and compared to a modeled version of the system. The following graphs are of the transfer functions of the first stage to the first stage using BOSEM readout and the first stage to the final stage using optical lever readouts, as well as phase and coherence diagrams of the system.

The state space model resonances are close to the experimentally found resonances. Any discrepancy could have been caused by imprecise weight measurements because the scale had one gram resolution, the weight distribution could be uneven.

For every degree of freedom there are three stages of isolation because the suspension is a triple pendulum system, except in the vertical degree of freedom because the wires are not stretchy the isolation is from the cantilever blades.

3" Sus BOSEM Undamped Resonances

Resonances	Model (Hz)	Exp. (Hz)
Long 1	0.928	0.925
Long 2	1.637	1.647
Long 3	3.199	3.275
Yaw 1	0.720	0.735
Yaw 2	2.058	2.075
Yaw 3	2.936	2.915
Pitch 1	2.016	1.94
Pitch 2	3.024	3.019
Pitch 3	4.0231	4.418
Roll 1	1.752	1.74
Roll 2	6.796	6.671
Vert 1	2.598	2.71
Vert 2	7.792	8.09
Side 1	0.963	0.961
Side 2	1.677	1.695
Side 3	3.258	3.3045

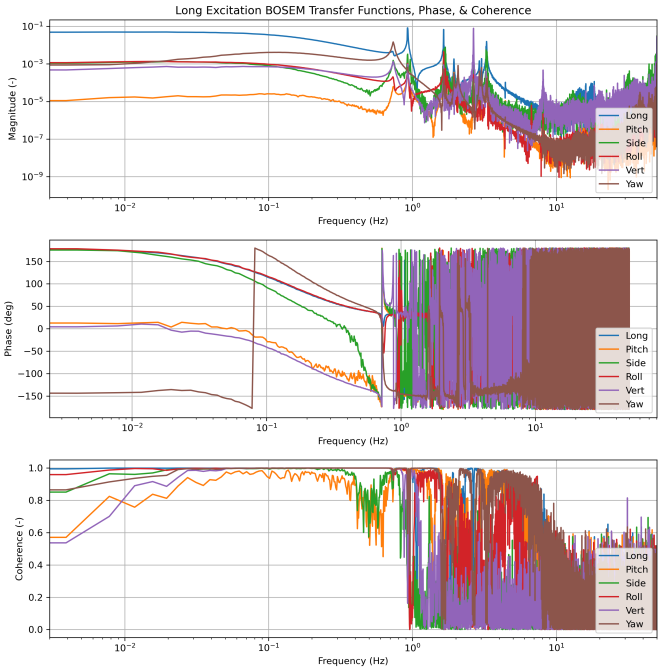


Figure 10: BOSEM readout with long excitation from BOSEMs.

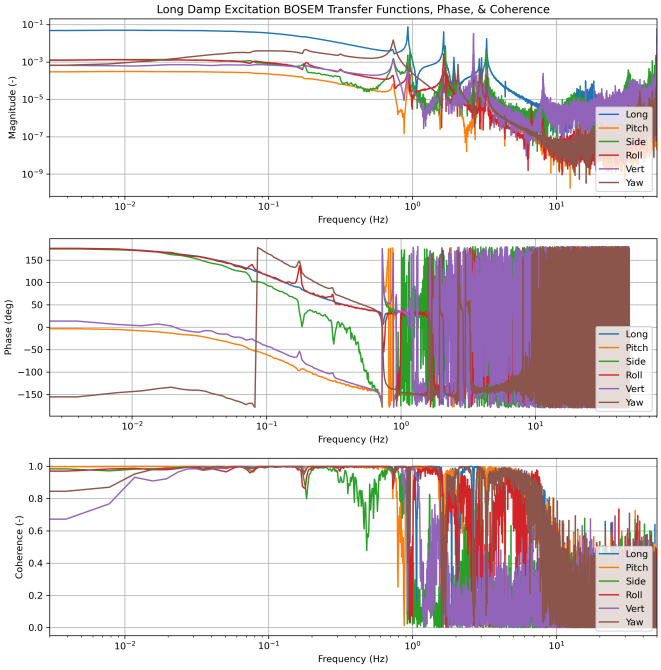


Figure 11: BOSEM readout with damping and long excitation from BOSEMs.

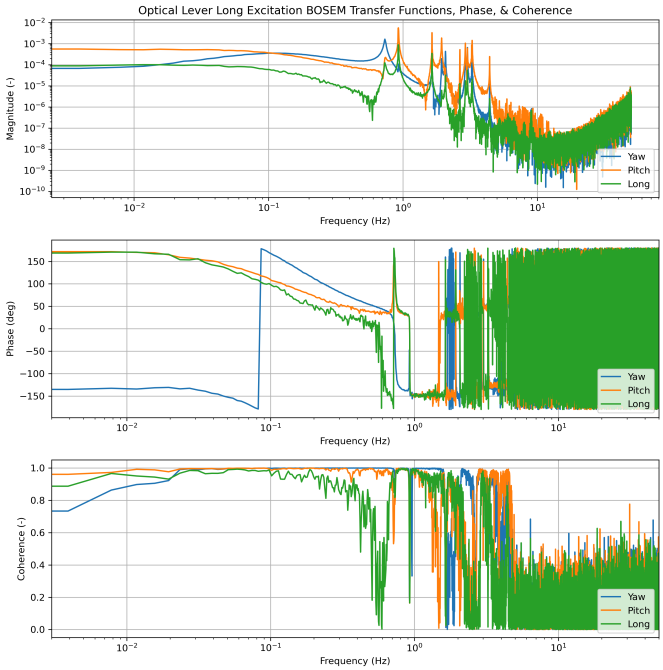


Figure 12: Optical lever readout with longitudinal excitation from BOSEMs.

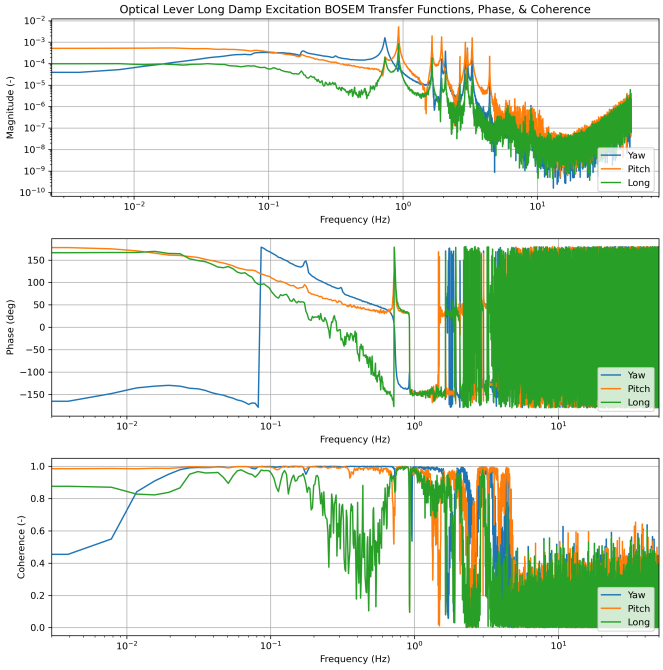


Figure 13: Optical lever readout with damping and longitudinal excitation from BOSEMs.

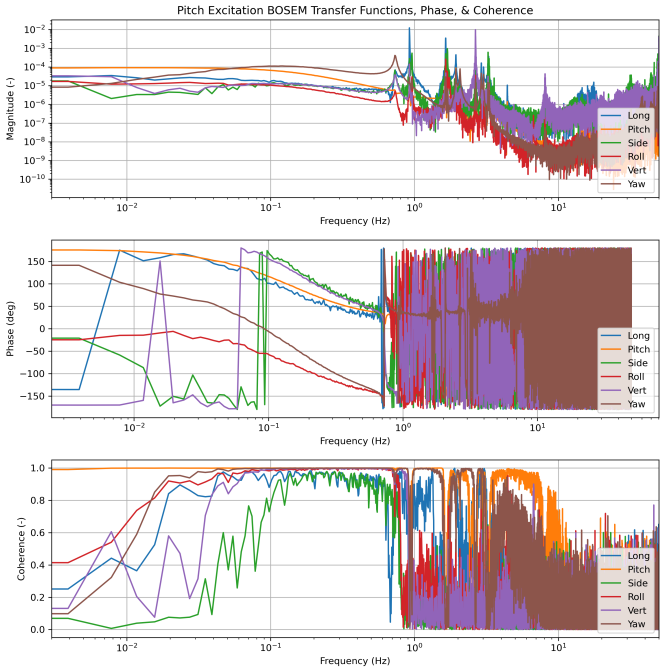


Figure 14: BOSEM readout with pitch excitation from BOSEMs.

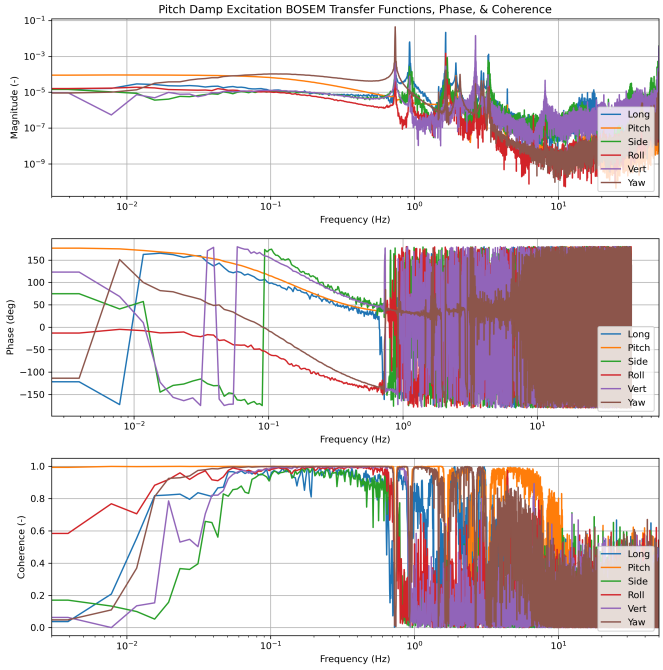


Figure 15: BOSEM readout with damping and pitch excitation from BOSEMs.

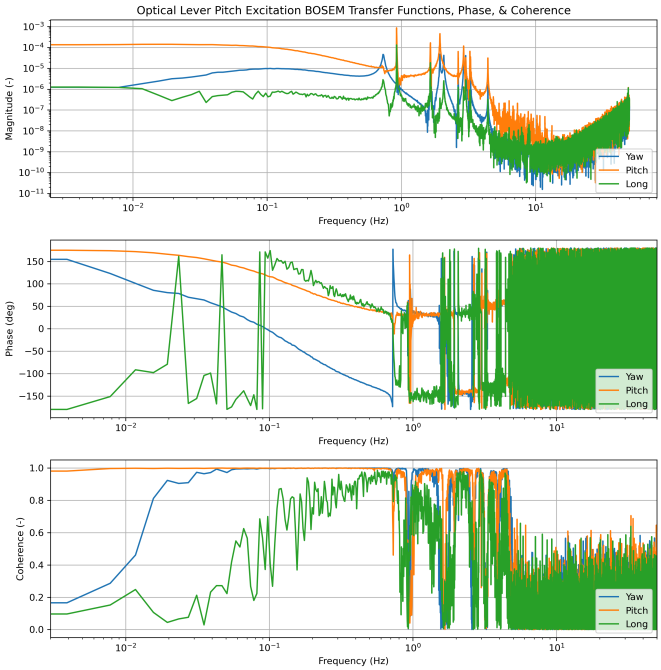


Figure 16: Optical lever readout with pitch excitation from BOSEMs.

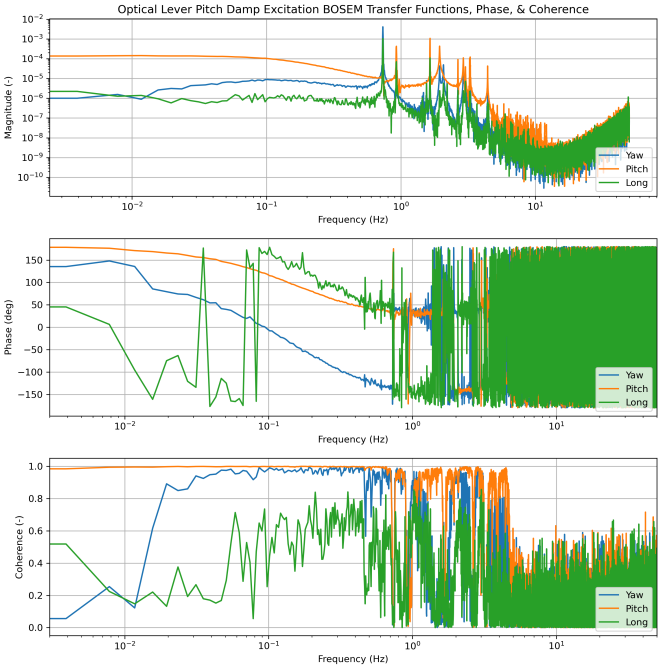


Figure 17: Optical lever readout with damping and pitch excitation from BOSEMs.

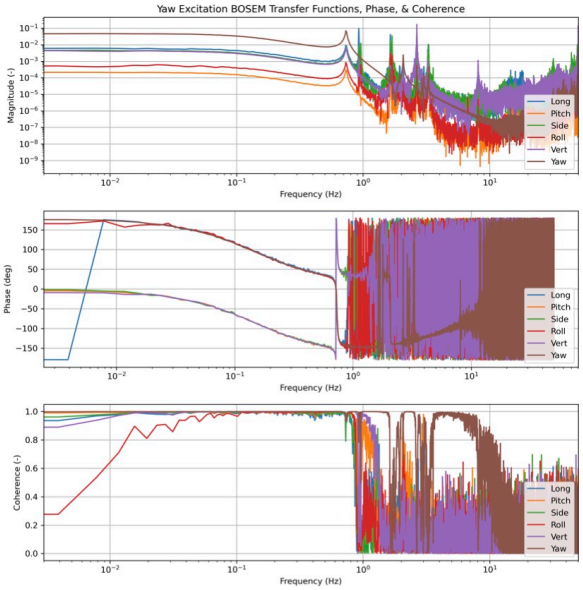


Figure 18: BOSEM readout with yaw excitation from BOSEMs.

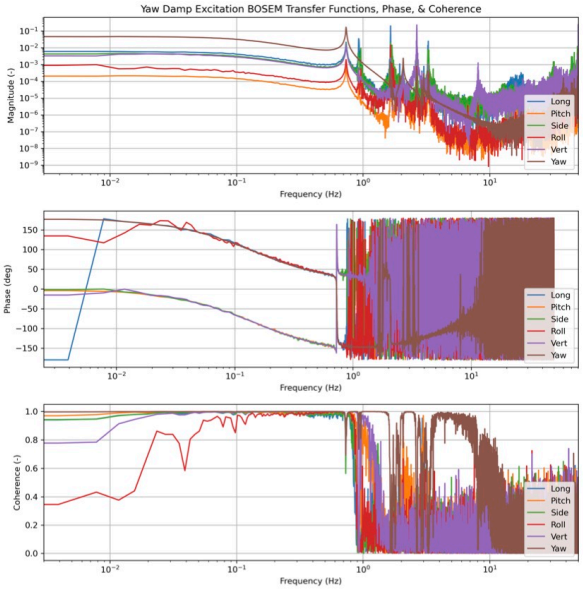


Figure 19: BOSEM readout with damping and yaw excitation from BOSEMs.

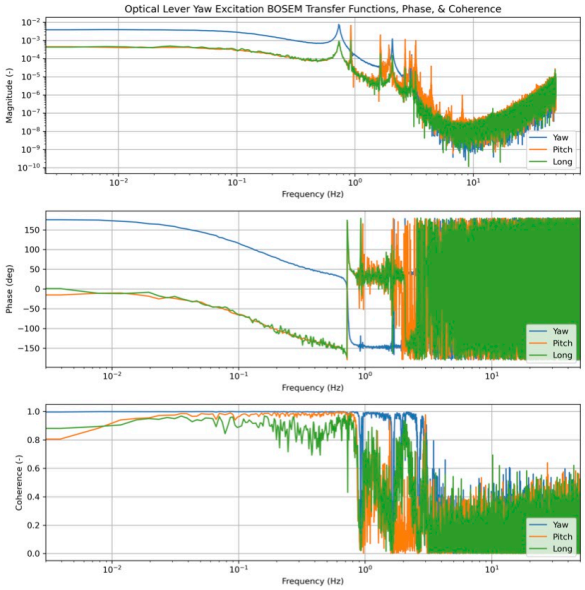


Figure 20: Optical lever readout with yaw excitation from BOSEMs.

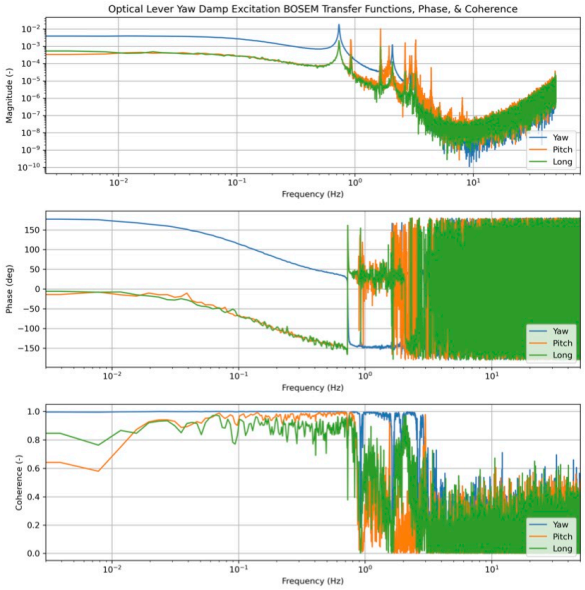


Figure 21: Optical lever readout with damping and yaw excitation from BOSEMs.

4 Conclusion

Isolating seismic motion from mirrors in gravitational wave detectors is essential to achieve good sensitivity. The HRTS system was designed to mechanically damp ground motion with three stages of isolation in yaw, roll, side, longitudinal, and pitch, and two stages of isolation in vertical degrees of freedom. With actuation on the upper stage from BOSEMs, motion was readout through BOSEMs on the upper stage and optical levers on the final stage. All resonances were found. The suspension was actively damped using BOSEM feedback loops and passively damped using eddy current dampers.

Due to unforeseen circumstances, the computer that was being used to take measurements had died, leaving the results of this paper inconclusive. The active damping from BOSEMs was not strong enough, and we were unable to see results from the ECDs.

5 Acknowledgments

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6 Apendix

The following graphs are the measured transfer functions, phase diagrams, and coherence of BOSEM actuation in the remaining three degrees of freedom, side, vertical, and roll.

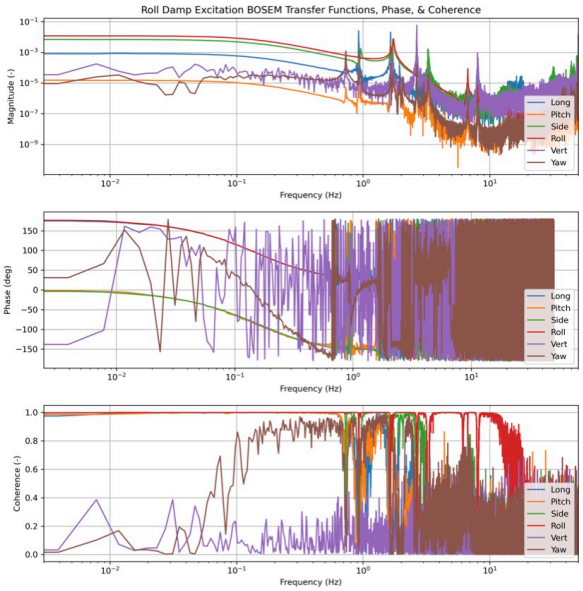


Figure 22: BOSEM readout with roll excitation from BOSEMs.

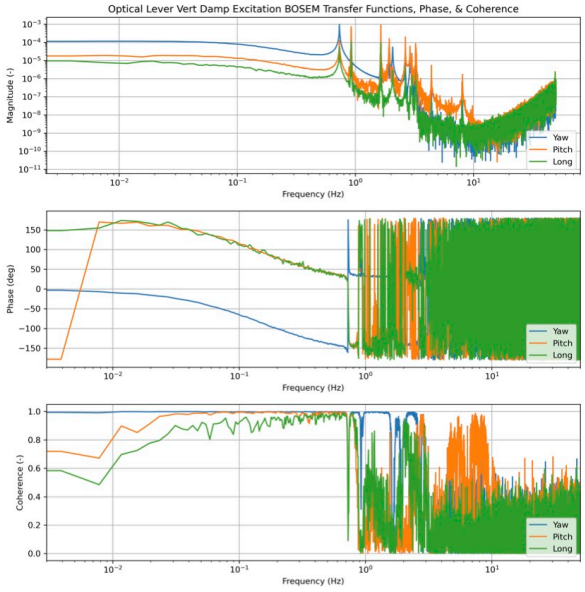


Figure 33: Optical lever readout with damping and vertical excitation from BOSEMs.

7 References

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