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- LIGO -
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Suspension Preliminary Design

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1 INTRODUCTION

1.1. Purpose and Scope

This document:

- provides a preliminary design of the suspension mechanical system,
- describes a framework, a sample conceptual design, and critical requirements of the SUS control system, and
- demonstrates by analysis and experience that the preliminary design and the sample conceptual design meet the SUS design requirements.

1.2. Acronyms

- LOS1: Large Optics Suspension 1
- LOS2: Large Optics Suspension 2
- SOS: Small Optics Suspension

Acronyms for names of subsystems should be referred to [1] LIGO-1401051 Rev. B: LIGO DETECTOR Construction Phase Implementation Plan (p. 13).

1.3. Applicable Documents

1.3.1. LIGO Documents

[1] LIGO-1401051 Rev. B: LIGO DETECTOR Construction Phase Implementation Plan
[2] LIGO-T950011-08-D: Suspension Design Requirements
[3] LIGO-E950099-01-D: Core Optics Components Requirements (1064 nm)
[4] LIGO-T960040-00-D: Response of Pendulum to Motion of Suspension Point
[5] LIGO-P950006-00-I: Thermal Noise in the Initial LIGO Interferometer
[6] LIGO-T960081-00-D: Pendulum Thermal Noise: Pendulum and Pitch Mode
[7] LIGO-P940011-00-R: Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detector
[8] LIGO-P930001-00-R: Thermal Noise in the Test Mass Suspensions of a Laser Interferometer Gravitational-Wave Detector Prototype
[9] LIGO-T960076-00-D: Estimate of the Effect of Scattered Light on the Suspension Sensor

1.3.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Design Requirements

The preliminary design of the suspension system (SUS) must meet the SUS requirements described in[2] LIGO-T950011-08-D: Suspension Design Requirements.

2.2. Design Philosophy

The following design philosophy are considered for the preliminary design:

- Reliability
- Simplicity
- Tractability
- Safety
- As little excess noise as possible

2.3. Design Type

There are three types of the suspension design depending on the size of the suspended optical component: LOS 1, LOS 2, and SOS. However preliminary designs for only LOS1 and SOS are provided in this document because the size of the beam splitter (accommodated in LOS2) is still **TBD** (See [3] LIGO-E950099-01-D: Core Optics Components Requirements (1064 nm)). Besides the final design of LOS2 will be very similar to that of LOS1 except for the size of the suspension assembly.

2.4. Assumptions

The assumed size for the suspended components is listed in Table 1. Although wedge angles for test masses and mode cleaner mirrors are still **TBD**, they are assumed plausibly to make the design possible and consistent.

Table 1: Size and optical clear aperture of suspended components.

Physical Quantity	*LOS1*	*SOS*
Diameter	25 cm	7.62 cm
Thickness	10 cm	2.54cm
Weight	10.7kg	0.25 kg
Optical Clear Aperture	24 cm (Fore) 19 cm (Back)	2 cm
Wedge Angle	3° vertical thick side up	0° horizontal

3 PRELIMINARY DESIGN OF SUS MECHANICAL SYSTEM

3.1. Design Overview

A preliminary design of the suspension assembly is schematically illustrated in Fig. 1. General features of the design are:

- The suspension assembly is held together by a suspension support structure.
- The optical component is suspended by a single loop of wire from a suspension block (and a wire guide crescent for LOS1) with wire standoffs and guide rods between the suspension wire and the component.
- The optical component is damped and actuated by sensor/actuator heads and magnet/standoff assemblies.
- The optical component is protected during operation or held during transfer by a safety cage and safety stops.
- The suspension support structure is strengthened by stiffening bars to increase its resonance frequencies.

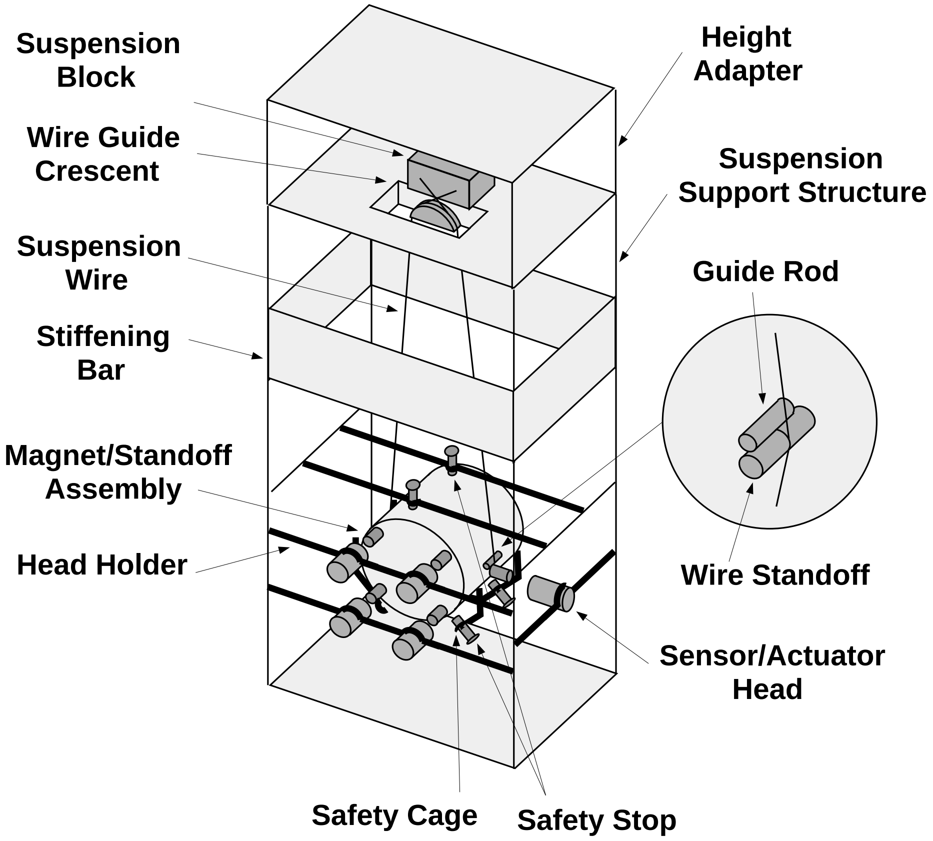

Figure 1: Schematic illustration of the preliminary design of the suspension system.

3.2. Suspension Configuration

A single loop of wire suspends the optical component. A sketch of the configuration of a suspended component is given in Fig. 2. The important design parameters of this single loop suspension are:

- Length of the pendulum ($d_{pendulum}$ in Fig. 2)
- Vertical deviation of the center of mass from the center of cylinder due to wedge of the optical component (d_{CM})
- Distance between the two suspension points at the upper release points (d_{yaw})
- Height from a horizontal level through the center of cylinder to the wire release points (d_{pitch})
- Diameter of the wire standoff ($d_{standoff}$)
- Minimum distance between the wire and the optical component above the wire release points (d_{margin})

These parameters are chosen to satisfy the desired pendulum, pitch, and yaw frequency for non-vanishing d_{margin} as shown in Table 2. (See Appendix A for detail.)

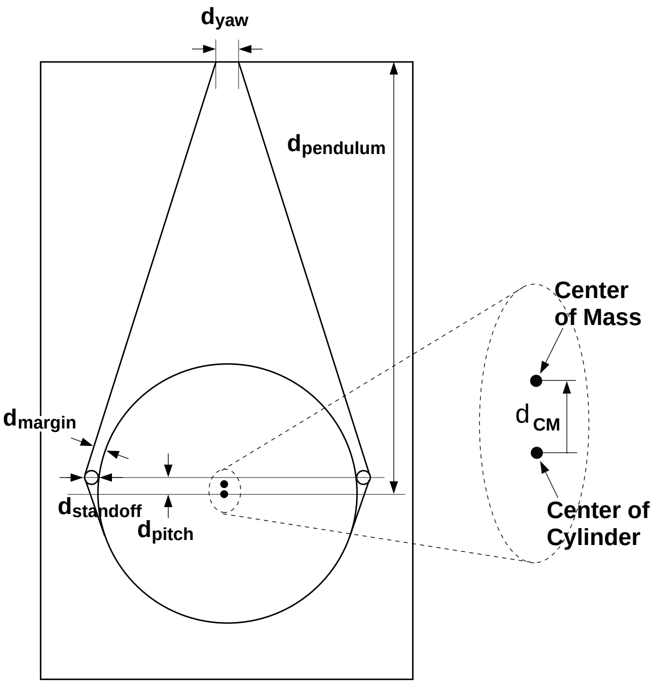

Figure 2: Sketch of the suspension configuration with the definition of parameters.

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Table 2: Suspension configuration parameters

Physical Quantity	*Specification*	
	LOS 1 (TM)	*SOS (MC mirror)*
Pendulum Frequency	0.74 Hz	1.0 Hz
Pitch Frequency	0.6 Hz	0.75 Hz
Yaw Frequency	0.5 Hz	0.85 Hz
$d_{pendulum}$	45 cm	24.8 cm
d_{CM}	2.0 mm	0 mm
d_{pitch}	8.9 mm	0.9 mm
d_{yaw}	33.5 mm	15.7 mm
$d_{standoff}$	2.8 mm	1.0 mmD
d_{margin}	1.1 mm	0.8 mm

3.3. Design Detail

The SUS components are listed in Table 3. for SOS and for LOS1.

Table 3: SUS components for SOS.

Name	*Description*	*Drawing Number*
Suspension Block [Top Plate]	Guide and support suspension wire	D960003
Magnet	Neo-35, 2mm dia x 3mm long	D960501, Ref
Sensor/Actuator Head Assembly	Registers position of magnet on optic and damps optic’s movement when required.	D960011
Standoff	alum, 1mm dia x 2.2mm long	D960010
Head Holder	Position and hold sensor/actuator head assemblies.	D960002
Suspension Fiber	Holds the optic. 0.044 mm dia steel music wire.	

Table 3: SUS components for SOS.

Name	*Description*	*Drawing Number*
Wire Standoff	Provides line contacts between optic and suspension wire.	1205184-1
Guide Rod	Positions wire standoff.	1205184-2
Safety Cage	Assorted brackets that position the safety stops.	D960007 D960008-1 D960008-2 D960002
Safety Stop	Assorted teflon screws that act as bumpers or supports for the optic	commercial items 1205311-1

Table 4: SUS components for LOS1.

Name	*Description*	*Drawing Number*
Suspension Support Structure	A welded structure that holds and protects the optic.	D960133
Suspension Block	Guides and supports suspension wire	D960144
Wire Guide Crescent	Welded in wire guide that provides line contacts for the wire to the top plate.	D960135
Sensor/Actuator Head Assembly	Registers position of magnet on optic and damps optic’s movement when required.	D960011
Magnet	Neo-35, 2mm dia x 3mm long	D960501
Head Holder	Various brackets that position and hold the sensor/actuator head assemblies.	D960136 D960137 D960141
Suspension Fiber	0.31 mm dia steel music wire	
Wire Standoff	Provides line contacts between optic and suspension wire.	D960755

Table 4: SUS components for LOS1.

Name	*Description*	*Drawing Number*
Guide Rod	Positions wire standoff.	D960146
Safety Cage	Assorted brackets that position the safety stops.	D960138 D960139 D960140 D960142 D960143
Safety Stop	Assorted teflon screws that act as bumpers or supports for the optic	commercial items D960499

3.3.1. Suspension Support Structure

The suspension assembly has a modular support structure. The optical component is suspended from the suspension block (and the wire guide crescent for LOS1), which is fixed to the top plate of the support structure. The sensor/actuator heads and the safety cage are also attached to the support structure. The advantage of this modular support structure is that the system can be assembled and adjusted (including balancing the test mass/mirror in pitch) on a clean bench and then can be transferred into the tank without changing the relative position between the optical component and the sensor/actuator head.

For LOS1 the suspension support structure, the stiffening bars, the safety cage, and the wire guide crescent are all welded together to eliminate excess noise. SOS uses bolts to assemble them.

The legs of the suspension support structure for LOS1 is hollow to satisfy the requirement for the resonance frequency of the structure.

Dimensions:

- LOS1: length 44.5 cm x depth 26.7 cm x height 61.6 cm
- SOS: length 15.6 cm x depth 12.7 cm x height 41.7 cm

3.3.2. Suspension Block and Wire Guide Crescent

A suspension block for SOS is used to position the wire such that it complies with the d_{yaw} (defined in 3.2.3.) requirement. It is mounted to the top of the suspension support structure. Two dowel pins, press fit into the block, guide the wire into its proper position.The wire is then held in place with a clamp.

The LOS1 suspension support structure has a crescent shaped wire guide welded into a hole in the top plate, below the area where the suspension block mounts. As an alternative to the suspension block/clamp means of holding the wire, the crescent may be used, along with a suitable solder, to position and support the wire. The crescent has the same groove, or wire guide, machined into it as the wire standoff, discussed later. This groove assures line contacts between the wire and the crescent.

3.3.3. Sensor/Actuator Head

The position sensor for a suspended component is a simple edge sensor, which consists of an LED paired with a photodiode, which senses the shadow of a magnet/standoff assembly attached to the component. The force/torque actuator is a fixed coil which drives the magnet attached to the suspended component. The system is illustrated in Fig. 3. The sensor/actuator head is placed so that approximately half the light from the LED is blocked by the magnet. The sensor detects the position of the magnet as the change in the photocurrent. The preamplifier for the sensor is external to the vacuum system.

In order to sense the longitudinal position and the orientation (pitch and yaw) of the optical component and to apply forces and torques to it, four sensor/actuator heads are placed in a plane at the back face of the suspended component. An elevation view of the sensor/actuator configuration is shown in Fig. 1. One additional head is placed on the side of the suspended optic to damp its transverse motion.

- LED: TLN107A, Toshiba, no outgas was observed after being baked at $70°C$.
- PD: TPS703A, Toshiba, no outgas was observed after being baked at $70°C$.
    - Distance between PD and LED: 6 mm
- Coil
    - Wire size: **TBD**
    - Coil size: 7.66 mmID, 12.66 mmOD, 5 mmL
- Housing
    - Material: Macor[1]
    - Size: 25.3 mmOD x 25.4 mmL
    - Wire clamp: Wires wrapped around a screw which is threaded into back of the head housing.

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[1] Machinable glass ceramic: manufactured by Corning.

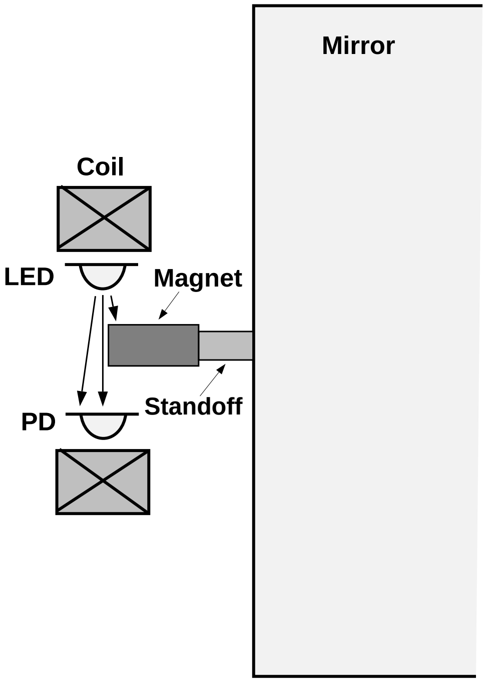

Figure 3: Sensor and actuator

3.3.4. Magnet/Standoff Assembly

The magnet and standoff are bonded into a single assembly which is then epoxied to the suspended component (See Fig. 3).

Six magnet/standoff assemblies are attached on the test mass: four on the back surface and two on the side surface of the test mass. The magnets are placed so that polarity of the magnets is located alternately to prevent the mass from being shaken in position and orientation by time-varying magnetic field.

- Magnet
  - Material: Nd:Fe:B (NEO, Curie temperature $337°C$)
  - Dimensions: 1.9 mmD x 3.2 mmL (0.075”D x 0.125”L) for SOS and LOS1
- Standoff
  - Material: aluminum
  - Dimensions: 1.0 mmD x 2.0 mmL (0.04”D x 0.08”L) for SOS and LOS1 except for side standoffs on the LOS1 which are 1.0 mmD x 3.2 mmL (0.04”D x 0.13”L).

3.3.5. Head Holder

The head holders are mounted (for SOS) or welded (for LOS1) on the suspension support structure. The head holder has a hole with machined line contacts and a set screw for the sensor/actuator head so that the sensor/actuator head can be placed and fixed properly without changing its position. The head holder, which is made of stainless, is located far enough from the magnets on the test mass so that the thermal noise caused by the eddy current damping is negligible. The loop of the holder is cut for LOS1 for the same reason.

Minimum distance between the head holder and the magnet[1]:

- 13.9 mm for LOS1
- 15.6 mm for SOS

3.3.6. Suspension Fiber

Steel music wire is used as the suspension fiber material. The diameter of the wire is chosen so that the wire will be loaded to one-half its breakage stress, to obtain the lowest possible wire losses and the smallest number of violin modes in the gravitational-wave signal band, without incurring undue risks due to wire failure or the production of excess non-gaussian noise (through acoustic emission from the loaded wire).[2]

A single loop wire is used.

- Type: Steel music wire
- Density: 7.8 g/cm^3
- Diameter: 0.044 mm for SOS
  0.31 mm for LOS1
- Ultimate Tensile Strength: 0.5 kg for SOS
  21.4 kg for LOS1
- Yield Strength: 75% of Ultimate Tensile Strength
- Violin Mode Frequency: 660 Hz for SOS
  340 Hz for LOS1
- Vertical Frequency: 16 Hz for SOS
  13 Hz for LOS1

3.3.7. Wire Standoff and Guide Rod

Small quartz rods will be used as standoffs where the wire contacts to the suspended component, as shown in Fig. 4. Each rod has a groove in it so that the wire may be repeatedly placed in the same position, which assures the stable balancing of the suspended component. Smaller alumi-

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[1] 13.7 mm for the PNI suspension

[2] It should be noted that tests of other fiber materials are intended as part of ongoing R&D and will likely result in a material that has better thermal noise properties and a more stable surface finish. Because of the importance of non-gaussian noise to the overall detector performance, any contemplated replacement for steel music wire should be thoroughly characterized for evidence of acoustic emission prior to its use in LIGO.

num guide rods are used for aligning the grooved rod to balance the pitch orientation of the component.

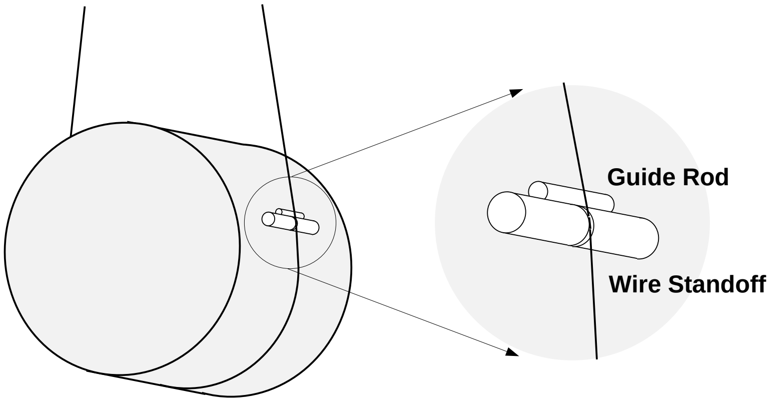


Figure 4: Details of wire standoff attachment

3.3.8. Safety Cage and Safety Stop

The motion of the optical component is restrained within +/- 1 mm by a safety stop mounted on a safety cage to protect the component from large motion. The safety cage is also used to hold the suspended component during installation after it is assembled and balanced on a clean table.

3.3.9. Stray Light Shield

TBD

3.3.10. Glue

Vacseal **TBD** is used for gluing.

3.4. Fixtures

There are a number of fixtures or tools required to mount and align components. The list of them is shown in Table 5.

Table 5: Fixtures and tools required for the SUS system.

Name of Fixture	*Description*	*Drawing Number*
Magnet-to-Standoff Fixture	Bonding standoff to magnet	P/N D960500
Magnet/Standoff Assembly Fixture	Bonding magnet/standoff assemblies to face of optic.	P/N D960050 for LOS1 P/N D960020 for SOS
Kapton Template	Protecting optical coatings when using Magnet/Standoff Assembly Fixture	P/N D960762 for LOS1 P/N D960021 for SOS

Table 5: Fixtures and tools required for the SUS system.

Name of Fixture	*Description*	*Drawing Number*
Guide Rod Fixture	Positioning and bonding guide rods and side magnet/standoff assemblies	P/N D960147 for LOS1 P/N D960022 for SOS
LED Fixture	Positioning and mounting LED relative to photodiode in the sensor/actuator head	P/N D950126
Dummy Mass	Used for the prototype test.	P/N D960763 for LOS1, 3 deg wedge P/N D960159 for SOS, no wedge
PZT Buzzer	Used for sliding the wire standoff for the pitch balance of the optic.	Existing
Wire & Optics Fixture	Positioning the wire, protecting and moving the optic into position in the LOS1 suspension support structure.	P/N D960753
Lifting Fixture	Transferring and mounting the LOS1 suspension assembly into the tank.	P/N D960761
Electronic Leveler	Leveling optical benches where the optic is balanced.	Commercial Product
Optical Lever Leveler	Balancing the optic on the optical bench.	P/N D960752

3.4.1. Magnet-to-Standoff Fixture

A magnet-to-standoff fixture is used to bond the standoffs to the magnets. This fixture has an epoxy reservoir to control the bond fillet and assure repeatability and alignment.

3.4.2. Magnet/Standoff Assembly Fixture

A magnet/standoff assembly fixture is used to bond the magnet/standoff assemblies to the face of the test mass/mirror. This fixture tightly controls the positioning of the magnet/standoff array. A Kapton template is used to protect the coating of the test mass/mirror.

3.4.3. Guide Rod Fixture

A guide rod fixture allows for positioning and epoxying the guide rods and the side magnet/standoff assemblies to the side of the test mass/mirror. A separate fixture assembly is required for each different wedge. The position of the guide rod is tightly controlled because of it’s relationship to the d_{pitch} parameter.

3.4.4. LED Fixture

The relative position of the LED to the photodiode in the sensor/actuator head is controlled by a LED fixture. The LED is mounted into the fixture, the fixture is positioned into the hole in the sensor/actuator head then the LED is bonded to the sensor/actuator head.

3.4.5. Dummy Mass

Each of the different optics has an aluminum dummy mass associated with it that has the same mass and the same center of mass. As they are much less fragile and expensive, these dummy masses are used in the prototype test for assembling the suspensions and using the fixtures.

3.4.6. PZT Buzzer

A PZT buzzer is used to slide the wire standoff by an extremely small amount for the pitch balance of the optic.

3.4.7. Wire & Optics Fixture

Because of its size and weight, the LOS1 requires a fixture assembly to move the optic into position inside of the safety cage. Many of the parts of this assembly are Teflon to protect the optical surfaces. The optic is moved from its container to a Teflon cradle in an upright position. There is a V-groove in the cradle to place the suspension wire in before moving the optic onto the cradle. The V-groove will help maintain the proper position for the wire during the suspending process. Two metal upright brackets are mounted onto the cradle fixture in front and behind the optic, but not touching it. Above the optic, and mounted to the metal brackets, is a Teflon strap that does not come in contact with the optic but will not allow it to tip. The fixture assembly also includes a metal plate that is the same thickness as the base plate of the suspension structure assembly. The metal plate, cradle fixture, optic, wire, brackets and strap are all assembled next to the suspension structure so that the cradle fixture and all that is mounted to it can be slid along the top of the base plate of the suspension structure and correctly positioned.

3.4.8. Lifting Fixture

Again, because of its weight, the LOS1 has a lifting fixture to move it from one location to another, especially from a clean bench to inside the vacuum tank. The fixture bolts to the underside of the suspension support structure or the underside of the height adapter, whichever is needed. This fixture is aluminum and may be baked for cleanliness. The fixture bolts to an adapter plate on a forklift or hoist.

3.4.9. Electronic Leveler

An electronic leveler is used to level the optical table where the optic is to be balanced.

3.4.10. Optical Lever Leveler

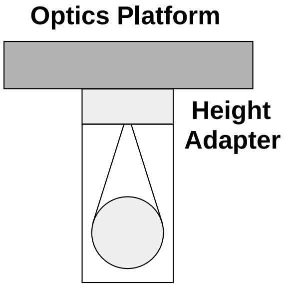
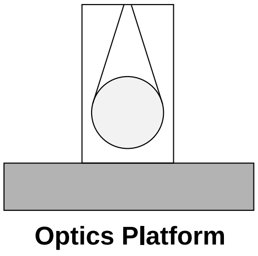
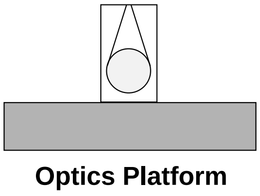
An optical lever leveler consists of a HeNe laser beam and a quadrant photodetector. The optic is balanced in pitch with the help of this system on the leveled optical bench.

3.5. installation

3.5.1. Installation Type

The suspension assembly is mounted to the optics platform with a height adapter (for the BSC chamber) or directly (for the HAM chamber) as shown in Table 6.

Table 6: Suspension assembly installation type.

Suspension Type	LOS 1/LOS 2	LOS 1	SOS
Chamber Type	BSC	HAM	HAM
Installation			

3.5.2. Installation Scenario

1. Clean all the suspension components including the optical component and the fixtures.
2. Bake all the suspension components to be installed inside the vacuum.

3. Glue the magnets to the magnet standoffs using the magnet-to-standoff fixture, considering the polarity of the magnets.
4. Glue the magnet/standoff assemblies to the optical component using the magnet/standoff assembly fixture, considering the polarity of the magnets.
5. Glue the guide rods and the side magnet/standoff assemblies to the optical component using the guide rod fixture.
6. Level a clean bench using the electronic leveler.
7. Assemble the suspension support structure (for SOS) or place the suspension support structure (for LOS1) on the clean bench.
8. Place the wire and the optical component on the wire & optics fixture (only for LOS1).
9. Slide the optical component with the wire & optics fixture to the proper position (only for LOS1).
10. Place the optical component on the safety stops.
11. Insert the wire standoff between the wire and the component.
12. Hang the optical component by the wire.
13. Clamp the wire.
14. Install the sensor/actuator heads in place.
15. Connect the control system to damp the component.
16. Adjust the pitch orientation by sliding the wire standoff tangent to the guide rod and optic by the PZT buzzer. Utilize the optical lever leveler to orient the optic.
17. Glue the wire standoff in place.
18. Remove the optical component with the attachments and bake it.
19. Clean the baked optical component and measure the ringdown.
20. Install the optical component into the suspension support structure and hung it by the method described above.
21. Install the sensor/actuator heads properly so that the sensor output is 50% +/- 10% of the maximum voltage.
22. Clamp the optical component using the safety stops for transfer.
23. Put the height adapter on the top of the suspension support structure (only for the BSC chamber).
24. Carry the suspension assembly to inside the tank by a fork lift using the lifting fixture.
25. Place the suspension assembly properly against the optics platform with the instruction given by ASC and clamp it into place.
26. Loosen the safety stops by 1 mm.
27. Level the optics platform so that the magnet is within 200 μm from the center of the sensor actuator head.

4 SUS CONTROL SYSTEM

A framework, critical requirements, and a sample conceptual design of the SUS control system are provided in this section.

4.1. Framework

The framework of the SUS control system is shown in Fig. 5. The sensor signal from each photodiode of a sensor actuator head goes into the control electronics, and the output signal from it is sent to each coil. The LSC/ASC/IOO signal is fed into the control electronics.

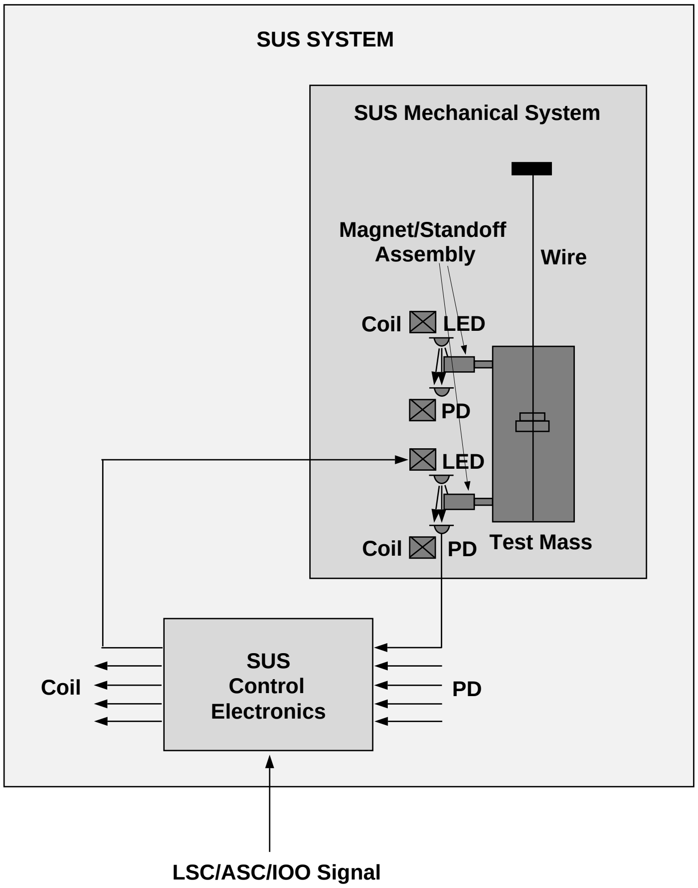


Figure 5: Framework of the SUS control system.

4.2. Requirements

4.2.1. Critical Requirements

The control system must provide the relevant SUS design requirements such as:

- Damping Quality
- Actuator Range
- Control Noise

4.2.2. Mode of Operation

The control system must provide the following modes of operation:

- Normal mode
- Off mode: No damping control
- High gain mode: To prevent a large motion of the optics from external disturbances

4.3. Sample Conceptual Design

In the following sections, some sample conceptual design will be described.

4.3.1. Electronics Configuration

The schematic diagram of the sample configuration of the SUS control electronics is shown in Fig. 6. Current for LEDs is supplied, and the photocurrent in the photodiode is transformed into voltage. The signals are then by input matrix converted into position, pitch, yaw and side signal. The derivative of the signals is produced for damping and amplified. After bias signal is added to the pitch and yaw signals, the signals are by output matrix converted into signals for each coil. The signals are low-pass-filtered and LSC/ASC/IOO signals may be added. Drivers with frequency-dependent impedance inject the signals into each coil.

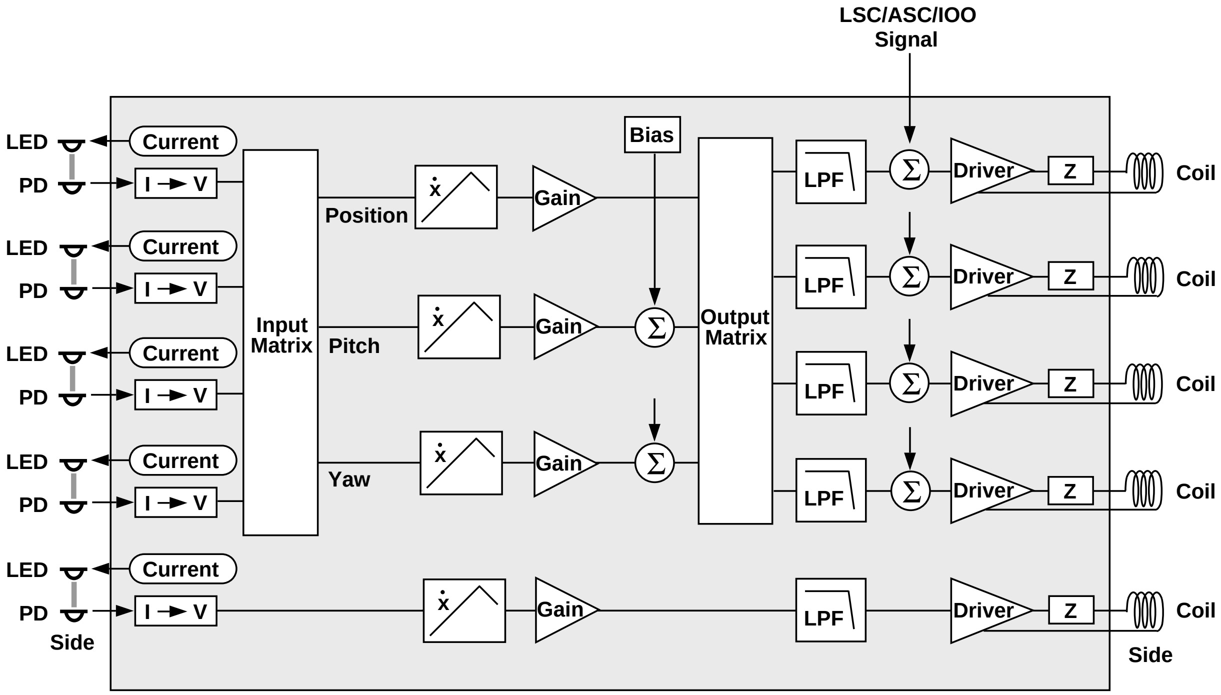


Figure 6: Sample configuration of the SUS control electronics.

4.3.2. Output Driver and LSC Signal Injection

A current-source type driver is used. The coil is placed inside the feedback loop of the last OP-amplifier. The LSC/ASC/IOO signal is injected into the inverting input of the OP-amplifier. The voltage at the right end of the series impedance (Z_3) is monitored as the LSC feedback signal. The impedance Z_1, Z_2, and Z_3 are frequency dependent and can be switched in value.

This configuration has several advantages as follows:

- Effect of any noise produced before the summing junction including the Johnson noise of Z_1 and Z_2 is suppressed by monitoring the LSC feedback signal afterward.

- Because of the high impedance looking from the coil, no pick-up current can flow in the coil.
- Monitor signal is free from any pick-up existing in the long loop containing the coil.
- Because of the high impedance looking from the coil, vibration of the coil with respect to the magnet doesn’t cause eddy current; the mass is not dragged.
- Large current at low frequencies can be obtained, while extremely low noise is maintained at higher frequencies, by incorporating appropriate frequency dependence in the impedance.
- It is possible to switch between the above-mentioned acquisition mode and monitor mode without disturbing both the LSC system and the damping control system.

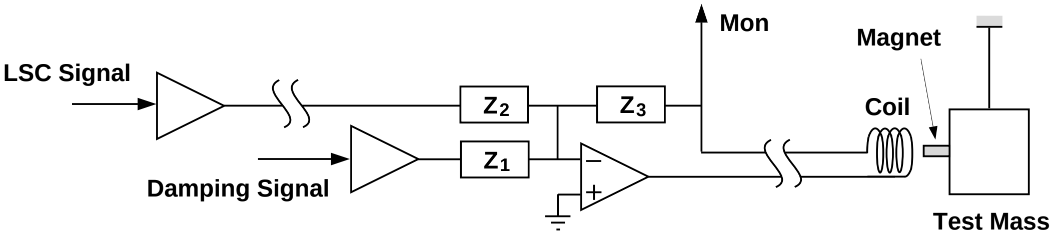


Figure 7: Sample conceptual design of the driver in the SUS control electronics.

4.3.3. Configuration of Electronic Modules, Cables, and Cable Harness

Fig. 8 shows the configuration of the electronic modules, cables, and a cable harness of the SUS control system. The cable from each edge sensor is gathered at the cable harness on the optics platform, and then the cable from the harness is led to the cable connector of the chamber via each stage of the stack. A preamplifier satellite is located by the chamber and the control module is in the rack near the chamber.

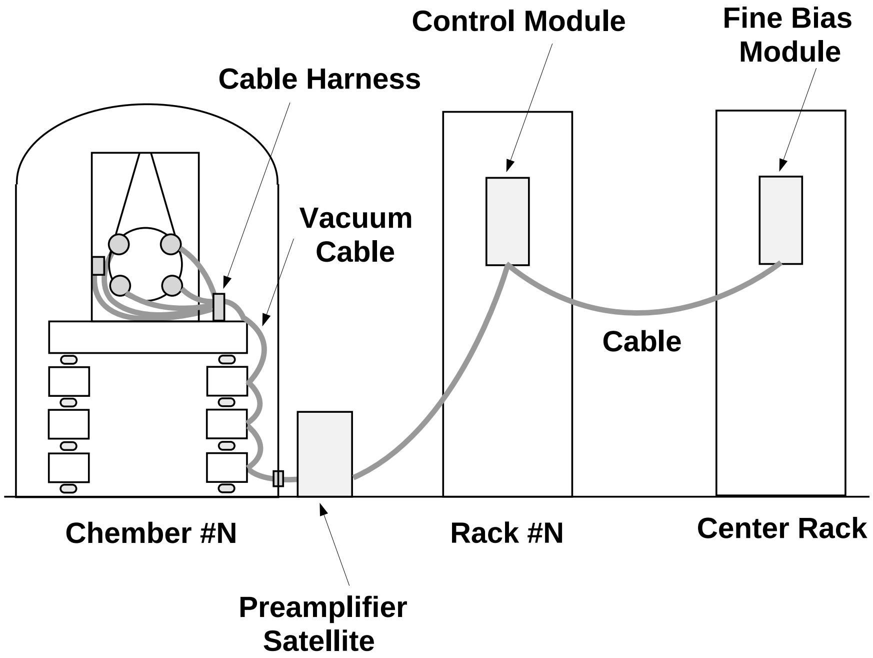


Figure 8: Sample configuration of the cable harness, vacuum cable, control module of the SUS control system.

4.3.4. Damping Control System

4.3.4.1 Servo Topology

Fig. 9 shows a sample servo topology of the SUS damping control system for each degree of freedom. Force (or torque, depending on the degree of freedom) applied to the test mass produces displacement (or angle) of the test mass by the transfer function which has two almost imaginary poles at the resonance frequency of the pendulum. The displacement (or angle) is then detected by the sensor, producing voltages with a frequency-independent coefficient. The voltage signal is then filter/amplified by a transfer function which consists of a zero at DC and 10 pole Chebyshev (1 dB) 12 Hz low pass filter. This feedback signal produces force (or torque) with a frequency-independent coefficient of the actuator.

With this configuration, when the loop gain is set appropriately, the closed loop transfer function, from force (torque) to displacement (angle) doesn’t have a bump in gain around the resonance frequency; the phase delay of the servo loop around the resonance frequency is appropriate.

The sensor noise is injected before the sensor transfer function. This noise is suppressed by the steep low pass filter. The driver noise and the Johnson noise is, on the other hand, injected after the filter/amplifier; they act on the test mass directly without being suppressed by the filter.

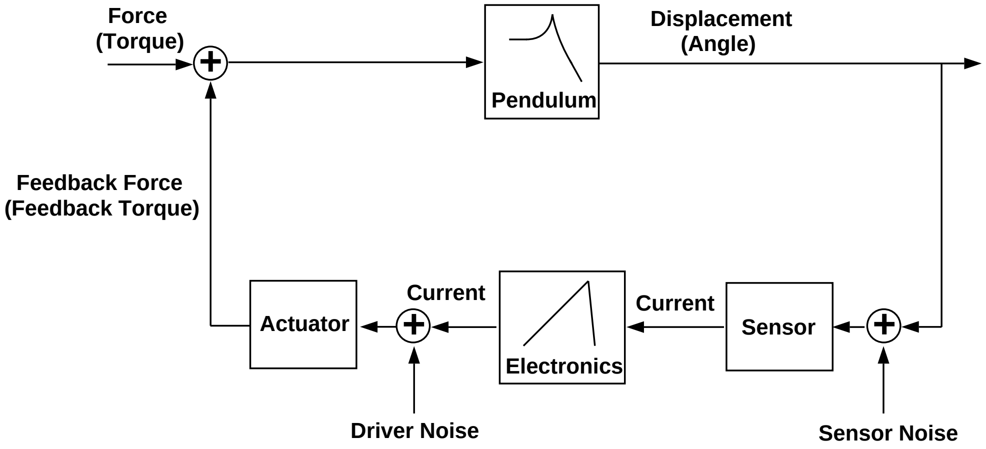


Figure 9: Sample servo topology of the SUS control system together with typical noise sources.

4.3.4.2 Sensor and Actuator

A sample efficiency of the sensor and actuator per one sensor and actuator is[1]:

- Sensor: $2.0 \times 10^{-2} \mathrm{A/m}$
- Actuator: $2.0 \times 10^{-2} \mathrm{N/A}$

4.3.4.3 Control Parameters

Each degree of freedom to be controlled has a different sensor and actuator sensitivity, and a different mechanical response coefficient, thus has a different electronic gain required for a pseudo-critical damping[2]. Table 7 provides a sample control parameters for a test mass for each degree of freedom. Each parameter (Pendulum, Sensor, Filter/Amp, and Actuator) corresponds to each transfer function shown in Fig. 9.

The filter/amp gain was obtained by the criteria:

Pendulum (@ DC) x Sensor x Electronics (@ f_0) x Actuator = 1

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[1] These numbers are based on the sensor and actuator used for the 40m test mass suspension system except the actuator efficiency for the 40m is $4.2 \times 10^{-2} \mathrm{N/A}$.

[2] The pseudo-critical damping is defined in this document to be a damping with a minimum gain which makes the closed loop transfer function in gain bumpless around the resonance frequency.

Table 7: Sample control parameters for each degree of freedom for LOS1.

Degree of Freedom	*Resonance Frequency f_0(Hz)*	*Pendulum (m/N or rad/Nm) @ DC*	*Sensor (A/m or A/rad)*	*Electronic (A/A) @ f_0 Hz*	*Actuator (N/A or Nm/A)*
Position	0.74	4.3×10^{-3}	8.0×10^{-2}	3.6×10^{4}	8.0×10^{-2}
Side	0.74	4.3×10^{-3}	2.0×10^{-2}	5.8×10^{5}	2.0×10^{-2}
Pitch	0.60	1.4	6.8×10^{-3}	1.5×10^{4}	6.8×10^{-3}
Yaw	0.50	2.0	6.8×10^{-3}	1.1×10^{4}	6.8×10^{-3}

4.3.4.4 Sensor Noise

The sensor noise is dominated by the shot noise at the photodiode. It is attenuated by the steep low pass filter. Table 8 shows resultant displacement noise at 40 Hz caused by the sensor noise, together with sensor noise, loop gain, and coupling coefficient.

The criteria to calculate the displacement noise is:

Displacement Noise = Sensor Noise x Loop Gain (at 40 Hz) x Coupling

Table 8: Sensor noise and the resultant displacement noise for each degree of freedom.

Degree of Freedom	*Sensor Noise[a] (m/rHz or rad/rHz)*	*Loop Gain @ 40 Hz*	*Coupling*	*Displacement Noise @ 40 Hz (m/rHz)*
Position	1.0×10^{-10}	7.0×10^{-10}	1	7.0×10^{-20}
Side	2.0×10^{-10}	7.0×10^{-10}	< 0.1	$< 1.4 \times 10^{-20}$
Pitch	1.2×10^{-9}	5.7×10^{-10}	1 mm	6.8×10^{-22}
Yaw	1.2×10^{-9}	4.7×10^{-10}	1 mm	5.6×10^{-22}

[a] Average sensor noise per channel.

4.3.4.5 Driver Noise

The driver noise here is defined as the noise produced after the steep low pass filter and it includes amplifier noise and Johnson noise. Table 9 summarizes displacement noise caused by the driver noise for each degree of freedom.

The criteria is:

Displacement Noise (@ 40 Hz) = Driver Noise (@ 40 Hz) x Actuator x Pendulum (@ 40 Hz) x Coupling

Table 9: Driver noise and the resultant displacement noise for each degree of freedom.

Degree of Freedom	*Driver Noise[a] @ 40 Hz (A/rHz)*	*Actuator (N/A or Nm/A)*	*Pendulum @ 40 Hz (m/N or rad/Nm)*	*Coupling*	*Displacement Noise @ 40 Hz (m/rHz)*
Position	1×10^{-12}	8.0×10^{-2}	1.5×10^{-6}	1	1.2×10^{-19}
Side	2×10^{-12}	2.0×10^{-2}	1.5×10^{-6}	0.1	6.0×10^{-21}
Pitch	1×10^{-12}	6.8×10^{-3}	3.2×10^{-4}	1 mm	2.2×10^{-21}
Yaw	1×10^{-12}	6.8×10^{-3}	3.2×10^{-4}	1 mm	2.2×10^{-21}

[a] Average driver current noise per channel.

4.3.4.6 Range of Actuator

The range of the actuator for each degree of freedom is summarized in Table 10.

The criteria to get the range is:

Range = Driver Maximum Current (@ DC) x Actuator x Pendulum (@DC)

Table 10: Range of actuator for each degree of freedom.

Degree of Freedom	*Driver Max. Current @ DC (A_{pp})*	*Actuator (N/A or Nm/A)*	*Pendulum @ DC (m/N or rad/Nm)*	*Range @ DC (m_{pp} or rad_{pp})*
Position	0.25	8.0×10^{-2}	4.3×10^{-3}	8.6×10^{-5}
Side	0.25	2.0×10^{-2}	4.3×10^{-3}	2.2×10^{-5}
Pitch	0.25	6.8×10^{-3}	1.4	2.4×10^{-3}
Yaw	0.25	6.8×10^{-3}	2.0	3.4×10^{-3}

4.3.4.7 Relative Position of Magnet to Coil

Displacement noise caused by the seismically vibrating coil with DC force applied to the magnet is:

$$\tilde{x}_{coil}(f) = \frac{x_s(f)}{\omega^2 M} \cdot \frac{dF_{DC}}{dx}, \tag{1}$$

where x_s, M, and F_{DC} are motion of the coil, mass, and maximum force. Using the following numbers:

$x_s(40\mathrm{Hz}) = 2.9 \times 10^{-15} \mathrm{m}/\sqrt{\mathrm{Hz}}$, M = 10.7 kg, $\omega_0 = 40 \times 2\pi$, and $dF_{DC}/dx \approx 1$[1]

the estimated motion is $\tilde{x}_{coil}(40\mathrm{Hz}) = 4.3 \times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}$.

4.3.4.8 Cross-coupling

A cross-coupling at the sensor/actuator produces a spurious path existing in parallel with the main path, and might end up causing oscillation or significant gain loss in the main servo loop, depending on the polarity and the cross-coupling factor. The most vulnerable cross-coupling in this system is the one from the side motion to the yaw motion. With α as a sensor cross-coupling, and β as an actuator cross-coupling, the criteria to avoid the mal functioning in this case is (See Fig. 10):

$$5.3 \times \alpha \times \beta \ll 1$$

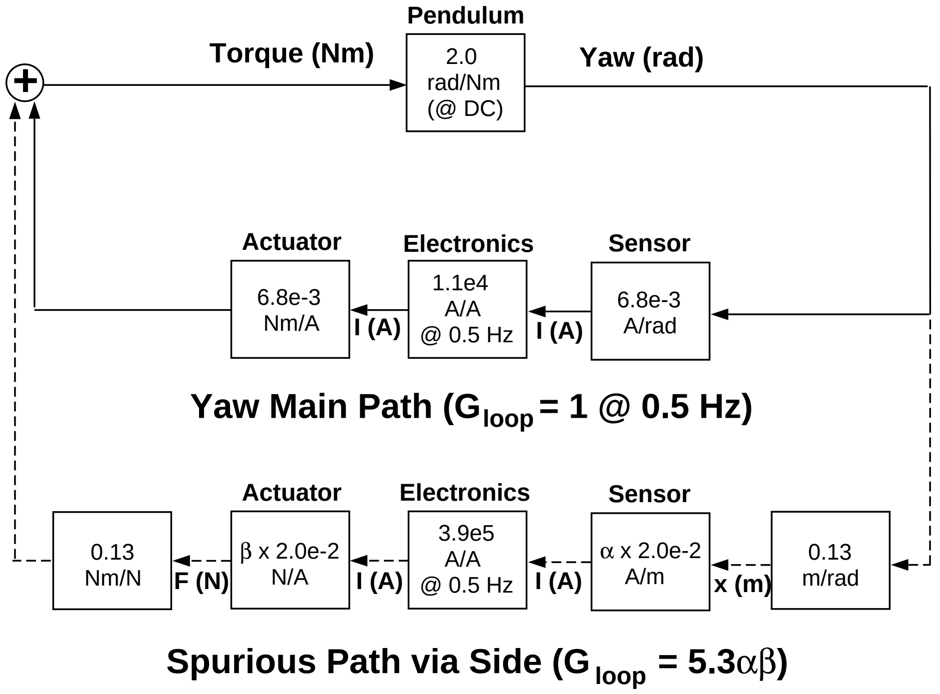

Figure 10: Spurious path via the side sensor actuator in parallel with the yaw main path.

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[1] F_{DC} = 0.01 N (See Table 10), and 10% variation for 1 mm is assumed.

5 DESIGN MATCH TO REQUIREMENTS

In this section it will be demonstrated by analysis, experiment, and common sense that the described design will meet the SUS design requirements.

5.1. Range

See 4.3.4.6 Range of Actuator. This satisfies the required DC Peak-to Peak Range. It is possible to produce the required weighting function using frequency dependent series impedance.

5.2. Damping

It was shown that with the control parameters described in 4.3.4.3 the height of the residual bump around the pendulum and pitch/yaw frequencies in the transfer function from (horizontal, vertical, and pitch/yaw) motion of the suspension point to (horizontal and pitch/yaw) motion of the suspended mass is 3.

5.3. Transfer Function of Suspension

5.3.1. Transfer Function from Horizontal to Horizontal, T_{hh}

It is self-evident that the requirement is met, considering the designed pendulum frequency. See Table 2.

5.3.2. Transfer Function from Horizontal to Pitch, T_{hp}

The requirement is met. See [4] LIGO-T960040-00-D: Response of Pendulum to Motion of Suspension Point.

5.3.3. Transfer Function from Vertical to Vertical, T_{vv}

It is self-evident that the requirement is met, considering the designed vertical frequency. See 3.3.6. Suspension Fiber.

5.3.4. Transfer Function from Vertical to Horizontal, T_{vh}

It is probably OK, but it cannot be proven until it is measured. (2)

5.3.5. Transfer Function from Vertical to Pitch, T_{vp}

The requirement is met. See [4] LIGO-T960040-00-D: Response of Pendulum to Motion of Suspension Point.

5.4. Resonance of Suspension Support Structure

The LOS1 suspension support structure was analyzed using finite element method to produce the lowest resonance frequency of higher than 180 Hz. The lowest resonance frequency of the PNI suspension (that is very similar to SOS) was measured to be 157 Hz. These values meet the requirements.

5.5. Thermal Loss

All the requirements are met. See below for detail.

5.5.1. LOS1

5.5.1.1 Vibrational Thermal Loss

An average effective loss $\bar{\varphi}$ was obtained from measurements on the four lowest frequency axisymmetric mechanical resonances of both of the 1.6-kg monolithic end test masses (with 2 magnet/standoff assemblies glued to each mass). The result obtained was $\bar{\varphi} = 1.2 \times 10^{-6}$ with about a 10% variation between masses. This was then assumed to be representative of the losses for other modes which were not measured. It was also assumed that the effective losses were independent of frequency over the relevant band of frequencies. Three scaling factors were then applied as follows.

- The losses for LIGO masses are assumed to be smaller by the ratio of the cross section of magnets used for LIGO (2.8 mm^2) to that for the 40-meter interferometer (8.0 mm^2).
- The losses for LIGO masses are assumed to be larger by the ratio of the number of magnet/standoff assemblies used for LIGO (6 on each mass) to that for the 40-meter interferometer (2 on each mass).
- The LIGO losses are scaled downward by the ratio of the mass of the test mass used in the 40-meter interferometer to the mass of the LIGO test mass, to account for the smaller fraction of the total vibrational energy that exists near the magnet/standoff assemblies in the LIGO masses.

This resulted in an estimated loss of 1.9×10^{-7} due to magnet/standoff assemblies.

Vibrational Loss of the pathfinder test mass with guide rods and wire standoffs was measured to be 1.8×10^{-7} for the first five modes.

Therefore an estimated total loss is 3.7×10^{-7}.

5.5.1.2 Pendulum Thermal Loss

Violin mode loss of the pathfinder mass was measured to be 1.3×10^{-5}. This leads an estimated pendulum loss of 6.3×10^{-6}.

5.5.1.3 Pitch and Yaw Thermal Loss

According to [6] LIGO-T960081-00-D: Pendulum Thermal Noise: Pendulum and Pitch Mode, the pitch mode loss would be worse than the pendulum mode loss by a factor of 33 that is the ratio of $d_{pendulum}$ to $2(d_{pitch} - d_{CM})$ (See Fig. 2 and Table 2). That leads to an estimated pitch mode loss of 2.1×10^{-4}. The yaw mode loss is considered much better than the pitch mode loss[1].

5.5.1.4 Vertical Thermal Loss

Vertical thermal loss was measured to be 2.5×10^{-4} using the 40m test mass (See [7] LIGO-P940011-00-R: Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detector). The estimated loss for LOS1 is also 2.5×10^{-4}.

5.5.1.5 Eddy Current Damping Loss

Q was measured in MIT with mass of 10 g, one magnet (3.2 mmD x 4.7 mmL) attached to the mass, the aluminum head holder, and a minimum distance of 14 mm between the magnet and the holder, to be 1800. To scale this to LOS1, we should multiply this by 1.1×10^{3} for the increase in mass, by 30 for the decrease in conductivity with SS, by 1.4 for the decreased pendulum frequency, by 4.2 for the decreased volume of the magnet, by at least 3 for the cutting the loop, and divide by 5 for the increased number of magnets. The estimated Q is 2.1×10^{8}, that is φ of 4.8×10^{-9} at 0.74 Hz.

5.5.2. SOS

5.5.2.1 Vibrational Thermal Loss

Vibrational thermal loss for the mode cleaner mirror is estimated from that of the test mass, using the mass (0.25 kg to 10.7 kg). This resulted in an estimated loss of 8.1×10^{-6} due to magnet/standoff assemblies, neglecting the loss of the bare substrate and also loss due to guide rods and wire standoffs.

5.5.2.2 Pendulum Thermal Loss

According to [7] LIGO-P940011-00-R: Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detector, the pendulum loss has a dependence of $d^2 \cdot M^{-0.5} \cdot L^{-1}$, where d is diameter of wire, M is mass of suspended components, and L is length of wire. Therefore the pendulum loss of the mode cleaner mirror estimated from that of the test mass is 1.5×10^{-6}.

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[1] Private communication with Gabriela Gonzalez.

5.5.2.3 Pitch and Yaw Thermal Loss

According to [6] LIGO-T960081-00-D: Pendulum Thermal Noise: Pendulum and Pitch Mode, the pitch mode loss would be worse than the pendulum mode loss by a factor of 140 that is the ratio of $d_{pendulum}$ to $2(d_{pitch} - d_{CM})$ (See Fig. 2 and Table 2). That leads to an estimated pitch mode loss of 2.1×10^{-4}. The yaw mode loss is considered to be much smaller than the pitch mode loss.

5.5.2.4 Vertical Thermal Loss

The estimated loss for LOS1 is 2.5×10^{-4}.

5.5.2.5 Eddy Current Damping Loss

The SOS eddy current damping loss is estimated from the MIT Q measurement, using a scale factor of 25 for mass ratio, 30 for SS, 4.2 for magnet volume, at least 1.5 for cubed distance ratio, and 0.2 for the number of magnet, to be 5.9×10^{-7}.

5.6. Control Noise

See 4.3.4.4 Sensor Noise and 4.3.4.5 Driver Noise.

APPENDIX A SUSPENSION CONFIGURATION

The suspension configuration that determines the pendulum, pitch and yaw frequencies has been optimized with the following considerations:

- The length of the pendulum principally affects the seismic isolation and the contribution of the suspension fiber to the thermal noise. The length was optimized for the estimated seismic motion at the suspension block, the estimated shot noise, the loss function for the suspension fiber, an estimate of other thermal noise sources and, finally, the waveform for the coalescence of 1.4 solar-mass, neutron-star binary, yielding a broad optimum for $d_{pendulum}$ between 30-35 cm (See [5] LIGO-P950006-00-I: Thermal Noise in the Initial LIGO Interferometer).
- In order to suppress the sensor noise in the controller to the required level, a steep low pass filter must be incorporated. The corner frequency of the low pass filter that determines the degree of isolation at higher frequencies depends on the resonance frequency of the mode because of the stability criteria. Therefore the pitch and yaw frequency should be kept lower than the pendulum frequency to avoid additional sensor noise caused by the pitch and yaw control.
- It is necessary to apply torques to balance a test mass after an initial coarse alignment is done, in order to achieve sufficiently good alignment for lock acquisition. The maximum DC angle change of the test mass caused by the DC torque must be large enough to overcome any possible residual misalignment of the test mass angle, following coarse alignment.
- The pitch and yaw frequency should not be too low; it should be well above the micro-seismic peak. Otherwise the residual angle fluctuation will be too big.
- The pitch and the yaw frequency should be different at least by 0.1 Hz to make it possible to

diagnose the performance later.

- The separation between the suspension fiber and the suspended component should be at least 0.5 mm, and the wire standoff should be small enough not to degrade the vibrational mode Q.

All these considerations have lead to the specifications of the suspension configuration in Table 2.

APPENDIX B MAGNET CHOICE

Nd:Fe:B is used. The material is good enough in the following points:

- The temperature coefficient of the residual induction is -0.12%per degree C, which is small enough.
- The individual variation of the residual induction is +/- 3%, that is small enough.
- The reduction of magnetism by vacuum baking is at maximum 5%, that is small enough.