LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

**Draft** **LIGO-T960162-02 -** **D** Oct. 18, 96

# Specifications of the 40m Test Mass Suspension Prototype

Seiji Kawamura, Janeen Hazel, and Jay Heefner

This is an internal working note
of the LIGO Project.

**California Institute of Technology**
**LIGO Project - MS 51-33**
**Pasadena CA 91125**
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

**Massachusetts Institute of Technology**
**LIGO Project - MS 20B-145**
**Cambridge, MA 01239**
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

1. Introduction 1
2. Mechanical system 1
    - 2.1. Suspension Support Structure ....2
    - 2.2. Test Mass ....2
    - 2.3. Wire ....2
    - 2.4. Suspension Block ....3
    - 2.5. Wire Standoff and Guide Rod ....3
    - 2.6. Magnet/Standoff Assembly ....4
    - 2.7. Sensor/Actuator Head ....5
    - 2.8. Head Holder ....6
    - 2.9. Safety Cage, Safety Bar, and Safety Stop ....6
    - 2.10. Cable Harness ....6
    - 2.11. Suspension Configuration ....7
    - 2.12. Resonance Frequency and Q ....8
3. Control System 9
    - 3.1. Electronic System ....10
    - 3.2. Output Driver and LSC Signal Injection ....11
    - 3.3. Configuration of Control System ....12
    - 3.4. Block Diagram of Control System ....13
    - 3.5. Sensor and Actuator ....14
    - 3.6. Gain of Control System ....15
    - 3.7. Sensor Noise ....15
    - 3.8. Driver Noise ....16
    - 3.9. Range of Actuator ....16
    - 3.10. Relative Position of Magnet to Coil ....17
4. Installation 18
    - 4.1. Fixture ....18
        - 4.1.1. Magnet-to-Standoff Fixture ....18
        - 4.1.2. Magnet/Standoff Assembly Fixture ....18
        - 4.1.3. Guide Rod Fixture ....18
        - 4.1.4. PZT Buzzer ....18
        - 4.1.5. Precision Bubble Leveler ....18
        - 4.1.6. Optical Lever Leveler ....18
        - 4.1.7. LED Fixture ....18
    - 4.2. Procedure of Installation ....19
5. Drawings 22
6. Improvement to be done 24
    - 6.1. Mechanical System ....24
    - 6.2. Control System ....24

# 1. INTRODUCTION

This document describes the specifications of the prototype suspension system for the 40m test mass (TM). It was installed to be used as the East-Vertex TM suspension in the 40m interferometer and characterized in summer of 1996.

# 2. MECHANICAL SYSTEM

The schematic view of the mechanical system of the 40m TM suspension is shown in Fig. 1. The test mass is suspended by a single loop **suspension wire** from the **suspension block** on the top plate of the **suspension support structure**. The **wire standoffs** and the **guide rods** are used to balance the test mass. Six **magnet/standoff assemblies** are glued to the test mass and five **sensor/actuator heads** are mounted on the **head holders**. The suspension support structure is strengthened by the **stiffening bars**. The test mass is protected by the **safety cage** and the **safety bar** which contain the **safety stops**. The whole assembly, including a test mass, weighs 12.6 kg.

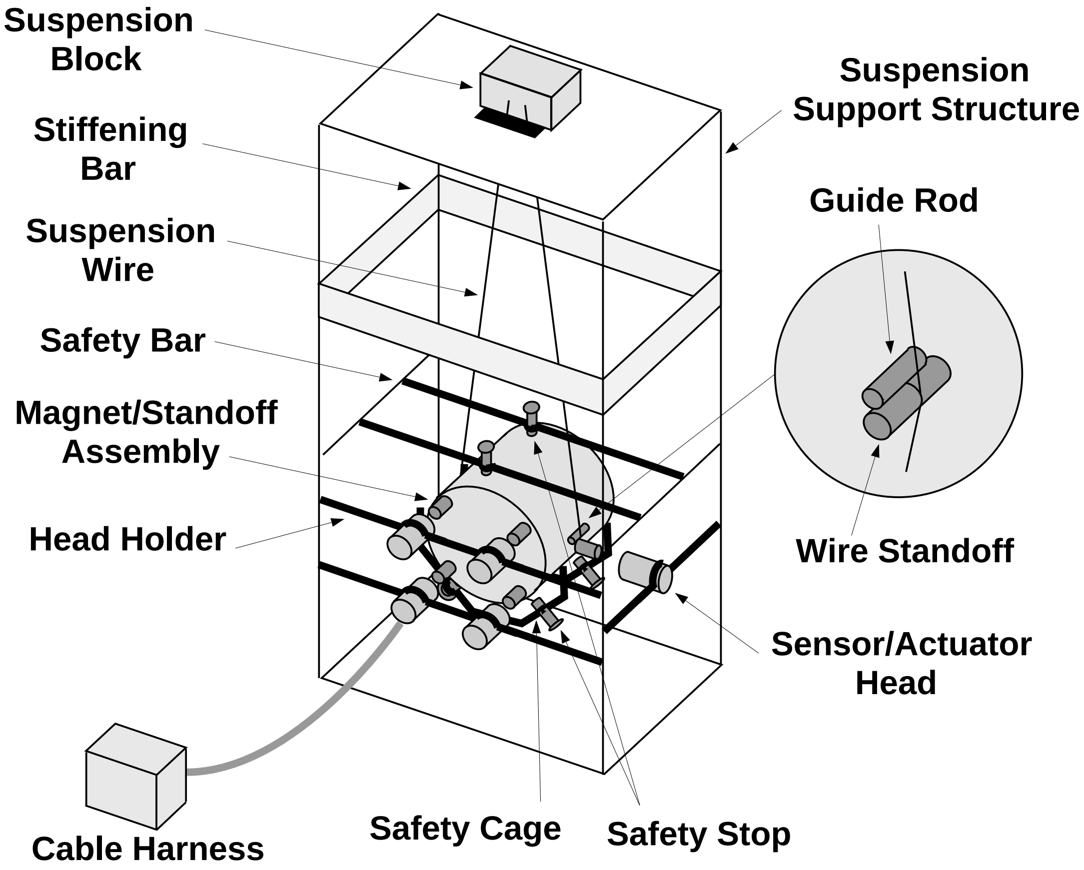

**FIG. 1. Schematic view of the mechanical system of the 40m TM suspension.**

## 2.1. Suspension Support Structure

The suspension support structure is a rectangular frame on which, the suspension block, the head holder, the safety cage, and the safety bar are mounted. This modular support structure makes it possible to assemble the system and balance the test mass on a clean bench; then it can be transferred into the chamber without changing the relative position of the test mass to the sensor/actuator head.

All the resonant frequencies of the suspension support structure are calculated to be above 127 Hz with four stiffening bars in the middle of the suspension support structure legs.

Transverse separation of the vertical frames is wide enough so that it is easy to get access to the safety stops, and is still narrow enough so that the frames do not obstruct the optical lever beam and the folding mirrors.

Longitudinal separation of the vertical frames is wide enough to allow one to see the mirror surface directly from each side.

- Height: 476.8 mm (18.77”)
- Transverse Width: 241.3 mm (9.5”)
- Longitudinal Width: 162.6 mm (6.4”)
- Material: Aluminum
- Calculated lowest resonance frequency: 127 Hz

## 2.2. Test Mass

The 40m TM suspension is designed to accommodate a test mass with the following specifications:

- Size: 101.6 mmD × 88.9 mm (4”D × 3.5”L)
- Weight: 1.6 kg
- Moment of inertia: $2.1 \times 10^{-3} \mathrm{m}^2 \mathrm{kg}$
- Wedge: 2 degrees ±30” (end mass), 25-30” (vertex mass), horizontally oriented.
- Height of the center of the test mass relative to the upper surface of the stack top plate: 139.7 mm (5.5”)
- Optical Clear Aperture: 50 mmD (1.97”D)

## 2.3. Wire

A single loop wire is used to suspend the test mass.

- Type: Steel music wire
- Density: 7.8 g/cm$^3$
- Young's modulus: $2.1 \times 10^{11} \mathrm{N/m}^2$
- Diameter: 91 $\mu$m (0.0036”)
- Ultimate Tensile Strength: 2.0 kg
- Measured breaking strength: 3.6-3.8 kg with one loop
- Yield Strength: 75% of Ultimate Tensile Strength

## 2.4. Suspension Block

The suspension wire is hung down from the suspension block which is mounted on the top plate of the suspension support structure. The suspension block has two guide pins and a clamp so that the distance of the wire at the suspension block ($d_{yaw}$ defined in 2.11.) may be maintained properly (Fig. 2). The winding screws are used to adjust the length of the wire.

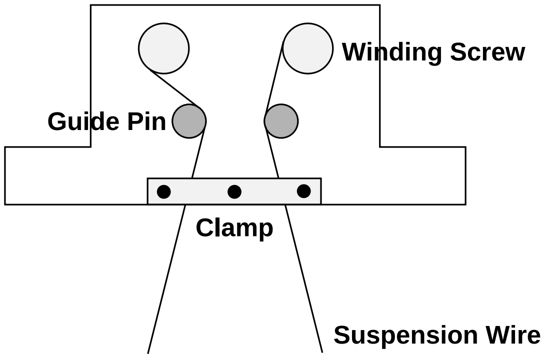

**FIG. 2. Suspension Block**

## 2.5. Wire Standoff and Guide Rod

A small aluminum guide rod is glued to the mass, to guide and position the wire standoff. It aids in balancing the test mass in pitch orientation. A larger aluminum rod is placed below the guide rod between the test mass and the wire (Fig. 3). The wire standoff has a groove on it so that the wire doesn't slip on the rod. This allows for stable balancing of the test mass.

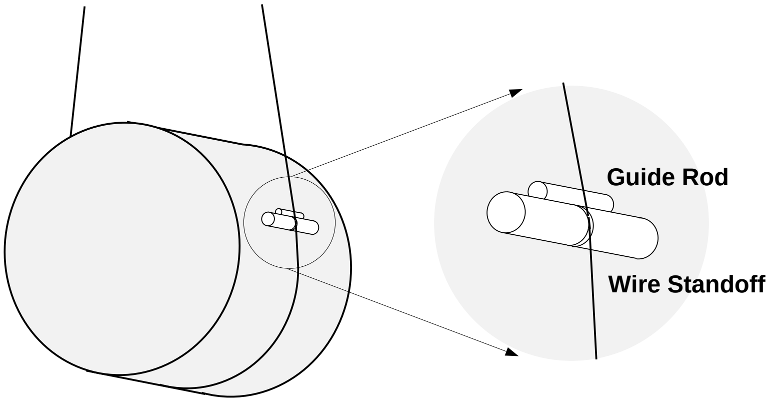

**FIG. 3. Guide rod and wire standoff.**

- Wire standoff
  - Material: Aluminum
  - Size: 1.0 mmD × 4.8 mmL (0.039”D × 0.19”L)
  - Groove: 0.004"W, 90 degree 0.001"Rmax
- Guide rod
  - Material: Aluminum
  - Size: 0.6 mmD × 3.3 mmL (0.025”D × 0.13”L)

## 2.6. Magnet/Standoff Assembly

Six magnet/standoff assemblies are attached to the test mass (Fig. 4): four on the back surface and two on the side surface of the test mass. The back surface of the test mass is considered to be the one with the anti-reflective coating. The magnets are placed so that polarities of the magnets alternated; this is to prevent the mass from being shaken in position and orientation, by time-varying ambient magnetic field.

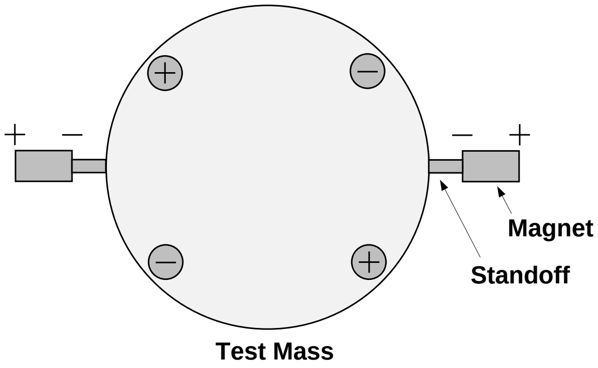

**FIG. 4. Magnet/standoff Assembly.**

- Magnet
  - Material: Nd:Fe:B (NEO-35, Curie temperature 337 ˚C)
  - Size: 1.9 mmD × 3.2 mmL (0.075”D × 0.125”L)
- Standoff
  - Material: aluminum
  - Size: 1.0 mmD × 2.0 mmL (0.04”D × 0.08”L)

## 2.7. Sensor/Actuator Head

The sensor/actuator head consists of a pair of an LED and a photodiode, a coil, and a housing. Five sensor/actuator heads are supported by the head holders which are mounted on the suspension support structure, so that each sensor/actuator head is located properly, along the corresponding magnet/standoff assembly: four sensor/actuator heads on back and one sensor/actuator head on one side.

The LED-photodiode system senses the shadow of the magnet, thus position of the test mass is detected. The current in the coil actuates the magnet attached to the test mass. The system is illustrated in Fig. 5.

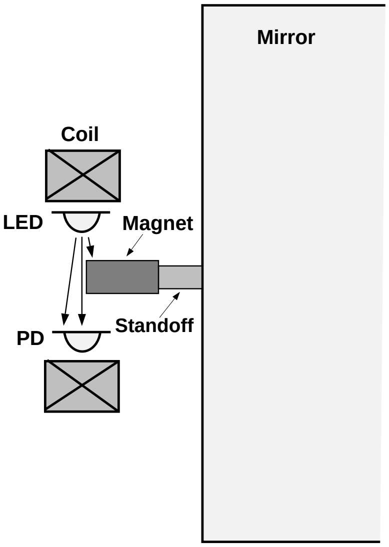

**FIG. 5. Sensor/actuator head.**

- LED: TLN107A, Toshiba, no outgas was observed after being baked at 70c
- PD: TPS703A, Toshiba, no outgas was observed after being baked at 70c
  - Distance between PD and LED: 6 mm
- Coil
  - Wire size: 0.22 mmD
  - Coil size: 7.66 mmID, 12.66 mmOD, 5 mmL
- Housing
  - Material: Macor[1]
  - Size: 25.3 mmOD × 45.9 mmL

---

[1] Machinable glass ceramic: manufactured by Corning.

## 2.8. Head Holder

The head holders are mounted 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.

- Material: Stainless steel
- Minimum distance between the head holder and the magnet: 33.7 mm (1.33”)

## 2.9. Safety Cage, Safety Bar, and Safety Stop

The safety cage and the safety bar, which have safety stops, are used to restrain the test mass motion and to protect it from damage. They are also used to hold the test mass firmly during assembly and installation.

- Safety Cage and Safety Bar
  - Material: Aluminum
- Safety stop
  - 1/4 - 20 × 1.00 long Teflon hex head screw

## 2.10. Cable Harness

The cables from the sensor/actuator heads are connected to the cable harness which is placed on the stack top plate.

## 2.11. Suspension Configuration

The parameters of the suspension configuration, the pendulum, pitch, and yaw resonance frequencies, and the wire resonance frequencies are shown in Table 1. Definitions of the parameters of the suspension configuration are shown in Fig. 6.

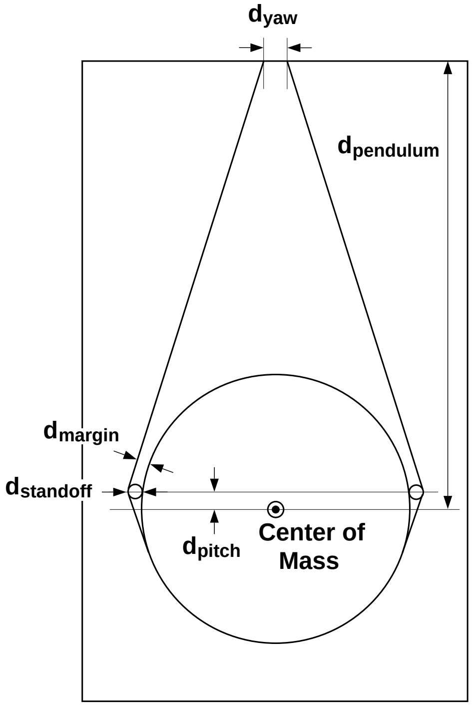

**FIG. 6. Definitions of parameters for the suspension configuration.**

**Table 1: Parameters of suspension configuration.**

| *Parameters* | | *Designed Values (Measured)* |
|---|---|---|
| Pendulum Resonance Frequency | | 0.84 Hz (0.85 Hz) |
| Pitch Resonance Frequency | | 0.50 Hz (0.49 Hz) |
| Yaw Resonance Frequency | | 0.60 Hz (0.62 Hz) |
| $d_{pendulum}$ | | 35 cm |
| $d_{pitch}$ | | 1.3 mm |
| $d_{yaw}$ | | 26 mm |
| $d_{standoff}$ | | 1.0 mmD |
| $d_{margin}$ | | 0.8 mm |
| Wire | Violin Mode Frequency | 557 Hz |
| | Vertical Resonance Frequency | 11.1 Hz |

## 2.12. Resonance Frequency and *Q*

Resonance frequencies and *Q*s of the test mass internal modes, violin mode, and the magnet/standoff assembly are measured and shown in Table 2.[1] The internal mode *Q*s are comparable with those of the end masses.[2] The violin mode Q is better than that with two loops of wire.[3]

**Table 2: Resonance frequency and Q of the test mass internal mode.**

| *Mode* | *Resonance Frequency* | *Q* |
|---|---|---|
| Internal Mode | 30.1943 kHz | $6.0 \times 10^5$ |
| | 30.7457 kHz | $3.1 \times 10^4$ |
| | ~34.8 kHz | Immeasurable |
| | 38.9653 kHz | $8.7 \times 10^4$ |
| | 44.0229 kHz | $1.0 \times 10^4$ |
| Violin Mode | 548.303 Hz | $6.0 \times 10^5$ |
| Magnet/Standoff Assembly | 7.7 kHz | 10 |

---

[1] For detail, see #45, p. 67W - 71W.

[2] See p. 93 of Aaron Gillespie's Ph. D thesis.

[3] See p. 96 of Aaron Gillespie's Ph. D thesis.

# 3. CONTROL SYSTEM

The schematic diagram of the control system of the 40m TM suspension is shown in Fig. 7. The position and angle of the test mass are detected by the edge sensor which consist of a pair of LED and photodiode. Either this signal or a signal from the 40m optical lever sensor is filter/amplified and fed back to the coil to damp the test mass. A bias signal and an interferometer LSC signal are injected in the control loop.

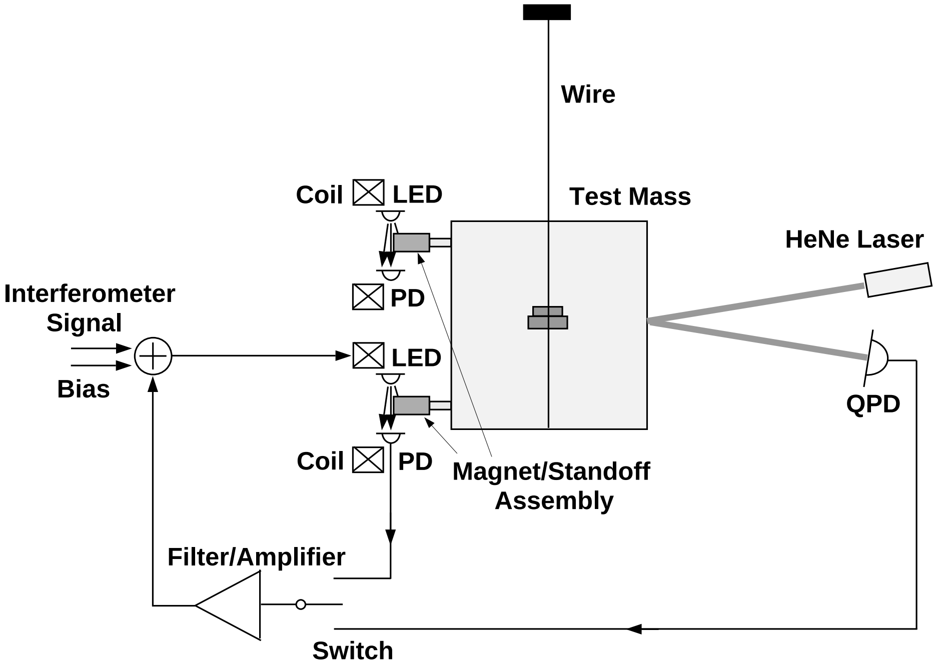

**FIG. 7. Schematic diagram of the control system for the 40m TM suspension.**

## 3.1. Electronic System

The schematic diagram of the electronic system of the suspension control is shown in Fig. 8. The suspension satellite detector/amplifier provides current to the LEDs and converts photocurrent in the photodiode into voltage. The output of the suspension satellite detector/amplifier is then sent to the suspension controller. The signals that represent the position of each magnet are, by the input matrix, converted into position, pitch, yaw and side signal of the test mass. The derivative of the signals is produced for damping and amplified. Coarse bias (inside the suspension controller) and fine bias (from the fine bias controller) are added to the pitch and yaw signals. Test signals can be also added to each signal. The signals are then, by output matrix, converted into signals that are to be used for each coil. The signals are low-pass-filtered and the LSC signal may be added. Drivers inject the signals into each coil. The switch between the input matrix and the filter gain makes it possible to choose either the suspension's sensor signal or the 40m optical lever signal.

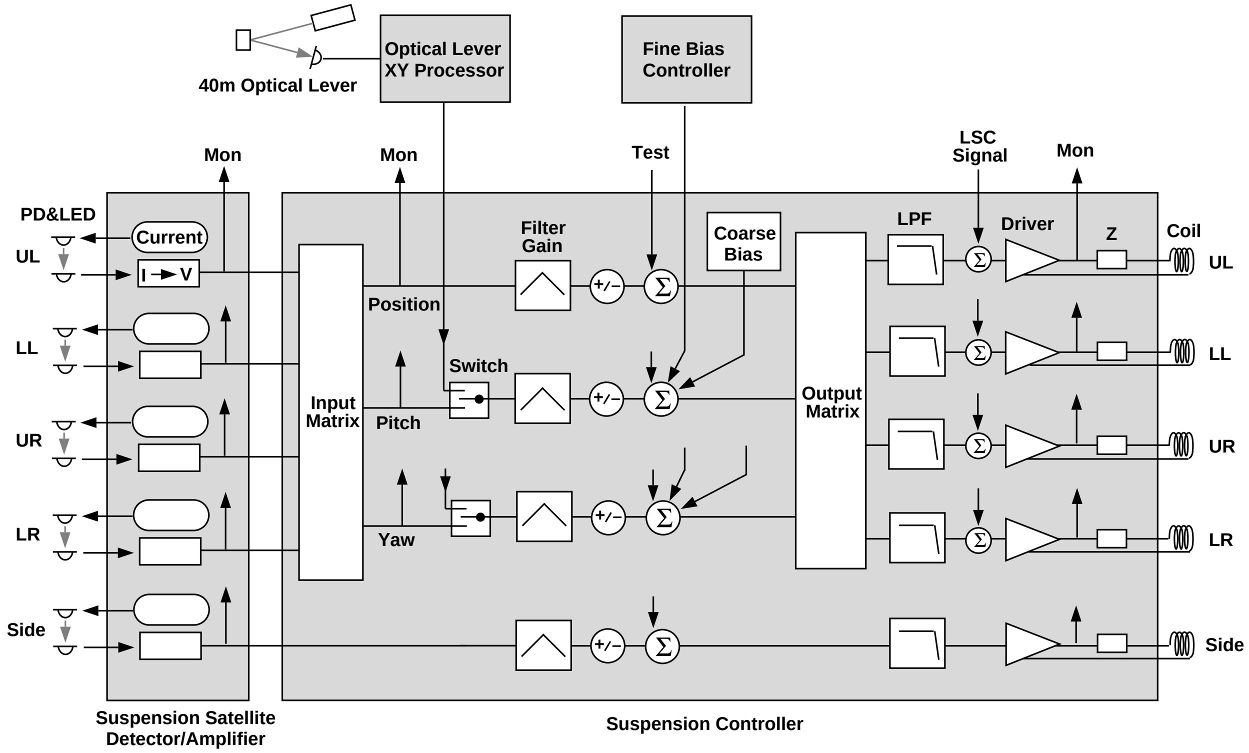

FIG. 8. Schematic diagram of the electronic system of the suspension control.

## 3.2. Output Driver and LSC Signal Injection

A current-source type driver is used; as shown in Fig. 9, the coil is placed inside the feedback loop of the driver OP-amplifier. The LSC signal is injected into the inverting input of the OP-amplifier. The voltage at the right end of the series resistor ($R_3$) can be monitored as the LSC feedback signal. $R_1$ is 1 kΩ, $R_2$ is 100 Ω, and $R_3$ can be 100 Ω during lock acquisition and switched to 1 kΩ for signal monitor. The LSC input can be disabled by the switch. This configuration has several advantages[1] as follows:

- Because of 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 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.
- The maximum current for the LSC signal can be big enough with $R_3$=100 Ω for the acquisition mode.
- The signal to noise ratio at the monitor point can be good enough with $R_3$=1 kΩ for the operation mode.
- Switching between the acquisition mode and the operation mode doesn't change the gain of both the LSC system and the damping control system.
- Effect of any noise produced before the summing junction including the Johnson noise of $R_1$ and $R_2$ is suppressed by the loop gain of the LSC servo system.

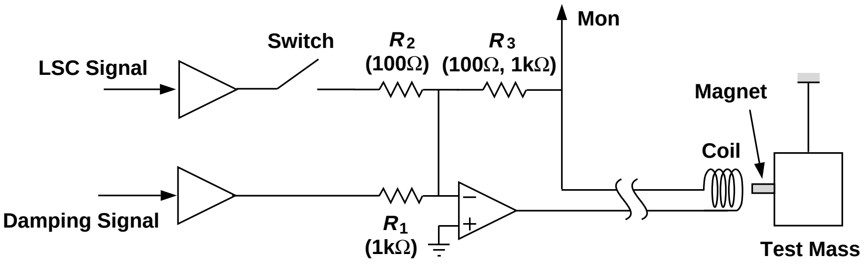

**FIG. 9. Schematic diagram of the output driver and the LSC signal injection.**

The specification of the LSC input is as follows:

- Input impedance: 125 Ω
- Actuating efficiency: $8.4 \times 10^{-4}\mathrm{N/V}$ (See 3.5.)

---

[1] One might think that using this current-source type driver, eddy current damping due to finite impedance of the coil loop could be avoided. It is true that impedance looking from the coil is very high when the coil is placed in the feedback loop, but the Johnson noise of $R_1$ injects the current noise into the coil, which results in the displacement noise of the test mass identical to that by the eddy current damping when the voltage-source type driver is used.

The LSC input was used to acquire and hold locking of the interferometer successfully.[1] The interferometer sensitivity spectrum using this LSC input was identical to that using the conventional East-End mass actuator.

## 3.3. Configuration of Control System

Fig. 10 shows the configuration of the control system of the 40m TM suspension. The cable from each edge sensor is gathered at the cable harness on the stack top plate, and led to the cable connector of the chamber via each stage of the stack. The suspension satellite detector/amplifier is located by the EV chamber and the suspension controller is in the rack near the chamber. A fine bias controller is placed in the center rack. The XY processor of the 40m optical lever for the EV test mass is located in the EE rack.

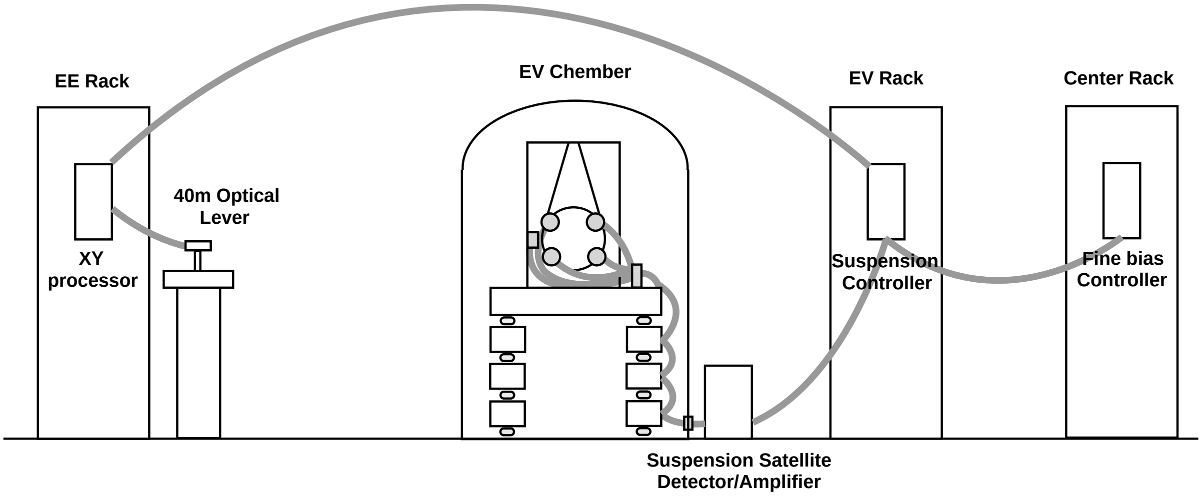

**FIG. 10. Configuration of the control system of the 40m TM suspension system.**

---

[1] See #45, p.71W - 72Y.

## 3.4. Block Diagram of Control System

Fig. 11 shows a block diagram of the 40m suspension 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. The displacement (or angle) is then detected by the sensor, producing current with a frequency-independent coefficient. The voltage signal is then filter/amplified by a transfer function of the electronics, which consists of a zero at DC and 10 pole Chebyshev (1 dB) 12 Hz low pass filter. This feedback current produces force (or torque) with a frequency-independent coefficient of the actuator. The phase margin is zero at 2.0 Hz.

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

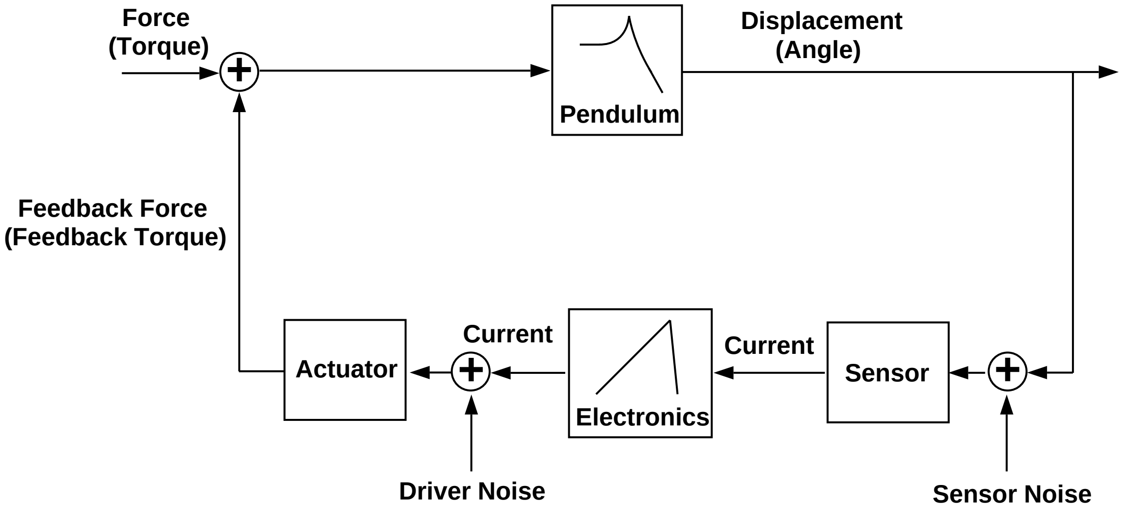

**FIG. 11. Block diagram of the 40m suspension damping control system together with typical noise sources.**

## 3.5. Sensor and Actuator

The LED-photodiode system senses the position of the magnet. The current in the coil applies force to the magnet.

- Sensor
    - LED current: 10 mA
    - Reverse PD voltage: 10 V
    - Maximum PD current: 60 - 100 μA (Half PD current: 30 - 50 μA)[1]
    - PD current-voltage converting resistance: 20 kΩ
    - Sensitivity: 35 μA/mm per head[2]
    - Range: 0.6 $\mathrm{mm}_{pp}$ (for 90% of maximum)
    - Sensor noise: $9.4 \times 10^{-11} \mathrm{m} / \sqrt{\mathrm{Hz}}$ (f > 40 Hz) per sensor (Shot noise dominant)
    - Low-frequency position output noise: $9.0 \times 10^{-9} \mathrm{m} / \sqrt{\mathrm{Hz}}$ (f = 100 mHz)

      $2.8 \times 10^{-7} \mathrm{m} / \sqrt{\mathrm{Hz}}$ (f = 10 mHz)

      $1.3 \times 10^{-5} \mathrm{m} / \sqrt{\mathrm{Hz}}$ (f = 1 mHz)[3]
- Actuator
    - Current-force coefficient: approximately 21 mN/A per head[4]
    - Full pitch range: 2.9 $\mathrm{mrad}_{pp}$[5]
    - Driver noise: $2.0 \times 10^{-11} \mathrm{A} / \sqrt{\mathrm{Hz}}$ per actuator[6]

---

[1] See #45, p.20W.
[2] See #45, p.37Y - 38W.
[3] See #45, p.73W - 73Y, 83W.
[4] See #45, p.39Y.
[5] See #45, p.40W.
[6] See #45, p.44W - 44Y.

## 3.6. Gain of Control System

The loop gain is set to give pseudo-critical damping[1]; the loop gain around (but not) the resonance frequency is approximately unity:

$$[\text{Pendulum (@ DC)}] \times [\text{Sensor}] \times [\text{Electronics (@ } f_0)] \times [\text{Actuator}] = 1 \qquad (7)$$

Table 3 summarizes the gain of each block (Pendulum, Sensor, Electronics, and Actuator in Fig. 11) for pseudo-critical damping for each degree of freedom.

**Table 3: Gains of control system for each degree of freedom.**

| *Degree of Freedom* | *Pendulum @DC* | *Sensor* | *Electronics @ 1Hz* | *Actuator* |
|---|---|---|---|---|
| Position | $2.2 \times 10^{-2} \mathrm{m/N}$ | 0.14 A/m | $3.9 \times 10^{3}$ | $8.4 \times 10^{-2} \mathrm{N/A}$ |
| Side | $2.2 \times 10^{-2} \mathrm{m/N}$ | $3.5 \times 10^{-2} \mathrm{A/m}$ | $6.2 \times 10^{4}$ | $2.1 \times 10^{-2} \mathrm{N/A}$ |
| Pitch | 48 rad/N·m | $4.5 \times 10^{-3} \mathrm{A/rad}$ | $1.7 \times 10^{3}$ | $2.7 \times 10^{-3} \mathrm{N \cdot m/A}$ |
| Yaw | 34 rad/N·m | $4.5 \times 10^{-3} \mathrm{A/rad}$ | $2.4 \times 10^{3}$ | $2.7 \times 10^{-3} \mathrm{N \cdot m/A}$ |

## 3.7. Sensor Noise

The sensor noise is dominated by the shot noise at the photodiode. It is attenuated by the steep low pass filter. Table 4 shows resultant displacement noise at 40 Hz caused by the sensor noise, together with sensor noise, loop gain, and coupling coefficient.

$$[\text{Displacement Noise}] = [\text{Effective Sensor Noise}] \times [\text{Loop Gain}] \times [\text{Coupling}] \qquad (8)$$

**Table 4: Sensor noise and the resultant displacement noise for each degree of freedom.**

| *Degree of Freedom* | *Effective Sensor Noise @40Hz* | *Loop Gain @ 40 Hz* | *Coupling* | *Displacement Noise @ 40 Hz* |
|---|---|---|---|---|
| Position | $4.7 \times 10^{-11} \mathrm{m/\sqrt{Hz}}$ | $7 \times 10^{-10}$ | 1 | $4 \times 10^{-20} \mathrm{m/\sqrt{Hz}}$ |
| Side | $9.4 \times 10^{-11} \mathrm{m/\sqrt{Hz}}$ | $7 \times 10^{-10}$ | < 0.1 | $< 7 \times 10^{-21} \mathrm{m/\sqrt{Hz}}$ |
| Pitch | $1.5 \times 10^{-9} \mathrm{rad/\sqrt{Hz}}$ | $4 \times 10^{-10}$ | < 3 mm | $< 2 \times 10^{-21} \mathrm{m/\sqrt{Hz}}$ |
| Yaw | $1.5 \times 10^{-9} \mathrm{rad/\sqrt{Hz}}$ | $4 \times 10^{-10}$ | < 3 mm | $< 2 \times 10^{-21} \mathrm{m/\sqrt{Hz}}$ |

---

[1] 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.

## 3.8. Driver Noise

The driver noise is produced after the steep low pass filter. This includes the Johnson noise of the series impedance. Table 5 summarizes displacement noise caused by the driver noise for each degree of freedom.

[Displacement Noise] = [Effective Driver Noise] × [Actuator] × [Pendulum] × [Coupling] (9)

**Table 5: Driver noise and the resultant displacement noise for each degree of freedom.**

| ***Degree of Freedom*** | ***Effective Driver Noise @100 Hz*** | ***Actuator*** | ***Pendulum @ 100 Hz*** | ***Cou-pling*** | ***Displacement Noise @ 100 Hz*** |
|---|---|---|---|---|---|
| Position | $1.0 \times 10^{-11} \mathrm{A}/\sqrt{\mathrm{Hz}}$ | $8.4 \times 10^{-2} \mathrm{N}/\mathrm{A}$ | $1.6 \times 10^{-6} \mathrm{m}/\mathrm{N}$ | 1 | $1.3 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ |
| Side | $2.0 \times 10^{-11} \mathrm{A}/\sqrt{\mathrm{Hz}}$ | $2.1 \times 10^{-2} \mathrm{N}/\mathrm{A}$ | $1.6 \times 10^{-6} \mathrm{m}/\mathrm{N}$ | < 0.1 | $< 6.7 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ |
| Pitch | $1.0 \times 10^{-11} \mathrm{A}/\sqrt{\mathrm{Hz}}$ | $2.7 \times 10^{-3} \mathrm{N} \cdot \mathrm{m}/\mathrm{A}$ | $1.2 \times 10^{-3} \mathrm{rad}/\mathrm{N} \cdot \mathrm{m}$ | < 3 mm | $< 9.7 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ |
| Yaw | $1.0 \times 10^{-11} \mathrm{A}/\sqrt{\mathrm{Hz}}$ | $2.7 \times 10^{-3} \mathrm{N} \cdot \mathrm{m}/\mathrm{A}$ | $1.2 \times 10^{-3} \mathrm{rad}/\mathrm{N} \cdot \mathrm{m}$ | < 3 mm | $< 9.7 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ |

## 3.9. Range of Actuator

The range of the actuator for each degree of freedom is summarized in Table 6.

[Range] = [Maximum Driver Current] × [Actuator] × [Pendulum] (10)

**Table 6: Range of actuator for each degree of freedom.**

| ***Degree of Freedom*** | ***Maximum Driver Current*** | ***Actuator*** | ***Pendulum @ DC*** | ***Range @ DC*** |
|---|---|---|---|---|
| Position | $2.4 \times 10^{-2} \mathrm{A}_{\mathrm{pp}}$ | $8.4 \times 10^{-2} \mathrm{N}/\mathrm{A}$ | $2.2 \times 10^{-2} \mathrm{m}/\mathrm{N}$ | $4.4 \times 10^{-5} \mathrm{m}_{\mathrm{pp}}$ |
| Side | $2.4 \times 10^{-2} \mathrm{A}_{\mathrm{pp}}$ | $2.1 \times 10^{-2} \mathrm{N}/\mathrm{A}$ | $2.2 \times 10^{-2} \mathrm{m}/\mathrm{N}$ | $1.1 \times 10^{-5} \mathrm{m}_{\mathrm{pp}}$ |
| Pitch | $2.4 \times 10^{-2} \mathrm{A}_{\mathrm{pp}}$ | $2.7 \times 10^{-3} \mathrm{N} \cdot \mathrm{m}/\mathrm{A}$ | 48 rad/N·m | $3.1 \times 10^{-3} \mathrm{rad}_{\mathrm{pp}}$ |
| Yaw | $2.4 \times 10^{-2} \mathrm{A}_{\mathrm{pp}}$ | $2.7 \times 10^{-3} \mathrm{N} \cdot \mathrm{m}/\mathrm{A}$ | 34 rad/N·m | $2.2 \times 10^{-3} \mathrm{rad}_{\mathrm{pp}}$ |

## 3.10. Relative Position of Magnet to Coil

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

$$\tilde{x}(f) = \frac{\tilde{x}_s(f)}{\omega^2 M} \cdot F_{DC} \cdot \frac{(dF_{DC}/F_{DC})}{dx}, \qquad (11)$$

where $x_s(f)$, M, $F_{DC}$, and $\frac{(dF_{DC}/F_{DC})}{dx}$ are motion of the coil, mass, maximum DC force, and fraction change of DC force per unit displacement. Taking and assuming the following values:

- $\tilde{x}_s(100\mathrm{Hz}) = 1 \times 10^{-13} \mathrm{m}/\sqrt{\mathrm{Hz}}$
- M = 1.6 kg
- $\omega = 100 \times 2\pi$
- $F_{DC} = 1 \times 10^{-3} \mathrm{N}$
- $\frac{(dF_{DC}/F_{DC})}{dx} = \frac{0.1}{1\mathrm{mm}} = 1 \times 10^2 \cdot 1/\mathrm{m}$ (10% change for 1 mm).

The estimated displacement noise is $\tilde{x}_{coil}(100\mathrm{Hz}) = 1.6 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$.

# 4. INSTALLATION

## 4.1. Fixture

### 4.1.1. 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.

### 4.1.2. 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.

### 4.1.3. 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. The position of the guide rod is tightly controlled because of it's relationship to the $d_{pitch}$ parameter.

### 4.1.4. PZT Buzzer

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

### 4.1.5. Precision Bubble Leveler

A precision bubble leveler is used to level the optical table where the test mass is to be balanced.

### 4.1.6. Optical Lever Leveler

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

### 4.1.7. LED Fixture

An LED fixture is used to position the LFD in the sensor/actuator head.

## 4.2. Procedure of Installation

### Preparation

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.
   - Baking temperature: 70 ˚C for the magnets and the sensor/actuator heads
     120 ˚C for the other components
   - Baking period: 48 hours

### Assembly

3. Assemble the suspension support structure, the stiffening bars, and the head holders.
   - Torque for bolting: 70 inch-pound. (Torque the head holders’ fasteners to finger tightness.)
4. Glue the magnets to the magnet standoffs using the magnet-to-standoff fixture.
   - Glue: Vacseal
   - Polarity: 5 “plus”s and 3 “minus”s
5. Glue the magnet/standoff assemblies to the optical component using the magnet/standoff assembly fixture.
   - Glue: Vacseal
   - Polarity: See Fig. 4
   - This can be done at the same time as the procedure 6.
6. Glue the guide rods and the side magnet/standoff assemblies to the optical component using the guide rod fixture.
   - Glue: Vacseal
   - Polarity of the side magnets: See Fig. 4
   - Apply glue to the side of the guide rod/test mass interface that is closest to the top of the test mass.
   - Wait for one day for the glue to cure.
7. Remove the magnet/standoff assembly fixture and the guide rod fixture.
   - Extra care should be taken when removing the fixtures.
8. Put more glue on the guide rod in the area that was covered by the fixture
   - Apply glue to the side of the guide rod/test mass interface that is closest to the top of the test mass.
   - Wait for two days for the glue to cure.

### Rough Balancing

9. Install the test mass into the suspension support structure
   - Place the test mass in the safety cage, making sure it rests evenly on the safety stops, and slide the cage into the suspension support structure.
10. Adjust the safety stops roughly for height and angle.
11. Put the wire around the test mass and clamp it at the suspension block.
12. Insert the wire standoffs under the guide rods.
13. Balance the test mass roughly by adjusting the position of the wire standoffs and then backing off on the safety stops to check the position of the test mass.
    - Before readjusting the position of the wire standoffs, clamp the optic with the safety stops.
    - Accuracy: within 10 mrad

14. Glue one wire standoff to the test mass.
    - The wire standoff on the side with the sensor/actuator head is the best one to glue first as the fine balancing will be done with the other wire standoff where there is more room to maneuver without a sensor/actuator head.
    - Glue: Vacseal
    - Wait for one day for the glue to cure.

## Fine Balancing

15. Level a clean bench using the precision bubble leveler.
    - Accuracy of the leveler: 0.25 mrad/div
    - Required accuracy: within 0.25 mrad
16. Level the laser beam using the quadrant photodiode.
    - Required accuracy: within 0.1 mrad
17. Balance the test mass finely by adjusting the position of the free wire standoff, using the laser beam and the quadrant photodiode.
    - Accuracy: within 0.5 mrad
    - Make the wire on the lower rim straight by rotating the mass back and forth around the beam axis.
18. Glue the free wire standoff to the test mass.
    - Glue: Vacseal
    - Wait for two days for the glue to cure.

## Baking

19. Remove the test mass from the suspension support structure.
20. Clean the test mass.
    - Make sure to keep solvents away from glue joints.
    - Solvent: Acetone and Methanol
21. Bake the test mass.
    - Baking Temperature: 70 ˚C
    - Baking period: 48 hours
22. RGA scan the outgas.

## Optics Test

23. Clean the test mass.
    - Make sure to keep solvents away from glue joints.
    - Solvent: Acetone and Methanol
24. Inspect the mirror surface.
25. Measure the transmission and the ringdown.

## Re-hanging and Damping

26. Install the test mass into the suspension support structure following steps 9-11.
27. Install the sensor/actuator heads half way into the head holders.
    - LED and PD lined up vertically
28. Adjust the length of the wire and reclamp it at the suspension block.
    - Torque the head holders’ bolts to 70 in lb.

- The magnets should be within 500 μm vertically from the center of the sensor/actuator heads.

29. Adjust the orientation of the suspension support structure by using shims.
    - The magnets should be within 300 μm horizontally from the center of the sensor/actuator heads.
30. Incrementally move the sensor/actuator heads closer to the optic.{SEIJI - should you mention the fact that you have turned on the sensor/actuator controller, have hooked up an oscilliscope...etc. at this point?}
    - Turn on the controller and hook up an oscilloscope.
    - LED and PD lined up vertically
    - The sensor output should be 50% ± 10% of the maximum.
31. Check the sign of the sensor output signal by lightly shaking the test mass.
32. Adjust the polarity and gain, and check damping.

## Installation

33. Clamp the test mass using the safety stops for transfer.
34. Transfer the suspension assembly to inside the tank.
35. Place the suspension assembly properly on the stack top plate.
36. Unscrew the safety stops leaving a 1 mm gap between the tip of the safety stop and the test mass.
37. Level the stack top plate and shim the suspension support structure, if necessary.
    - The magnets should be within 300 μm horizontally from the center of the sensor/actuator heads.
    - The sensor output should be 50% ± 10% of the maximum.
38. Check the sign of the sensor output signal by lightly shaking the test mass.
39. Adjust the polarity and gain, and check damping.

## Cabling

40. Connect the cable as shown in Fig. 10.

# 5. DRAWINGS

Table 7 shows a list of drawings for the 40m TM suspension system.

**Table 7: Drawings for the 40m TM suspension system.**

| *System* | *Item* | *Drawing Number* | *Detail* |
|---|---|---|---|
| Mechanical Parts | System | D950104 | |
| | Suspension Support Structure | D950120 | top plate |
| | | D950108 | front leg |
| | | D950109 | back leg |
| | | D950106 | base plate |
| | Stiffening Bar | D950124 | front |
| | | D950125 | side |
| | Suspension Block | D950121 | |
| | Wire Standoff | 1205184-1 | Aluminum |
| | Guide Rod | 1205184-2 | Aluminum |
| | Magnet/Standoff Assembly | D960501 | magnet |
| | | D960010 | smaller standoff |
| | Sensor/Actuator Head Assembly | D960138 | |
| | Head Holder | D950114 | bottom |
| | | D950115 | side |
| | | D950116 | top |
| | Safety Cage | D950107 | base |
| | | D950110 | face bracket |
| | | D950111 | cradle |
| | | D950112 | corner bracket, one |
| | | D950113 | corner bracket, two |
| | Safety Bar | D950118 | brace |
| | | D950119 | bar |

**Table 7: Drawings for the 40m TM suspension system.**

| *System* | *Item* | *Drawing Number* | *Detail* |
|---|---|---|---|
| Circuit Diagram | Controller | D950166 | |
| | Satellite Detector/ Amplifier | D950145 | |
| Fixture | Magnet-to-Standoff Fixture | D960500 | |
| | Magnet/Standoff Assembly Fixture | D950127 | |
| | | D950161 | Kapton template |
| | Guide Rod Fixture | D950154 | assembly |
| | | D950156 | base plate |
| | | D950157 | left block |
| | | D950158 | right block |
| | Optical Lever Leveler | D960752 | |
| | LED Fixture | D960126 | |

# 6. IMPROVEMENT TO BE DONE

## 6.1. Mechanical System

- Silver-plated bolts get stuck in aluminum threaded holes. Stainless bolts should be used.
- It is difficult to remove the magnet/standoff assembly fixture and the guide rod fixture from the optical component. The design should be improved.
- The safety bar is in the way of test mass cleaning. The design should be improved.
- A test mass container should be made.
- A test mass holder for the mirror surface inspection should be made.
- The wire clamp should be separate two pieces.
- The wire should be able to be clamped above the suspension clamps.
- The electrostatic interaction between the test mass and the safety stop was such that changing the gap between the test mass and one of the safety stop from 1 mm to 2 mm resulted in the test mass pitch angle change of 0.6 mrad. This effect should be eliminated.

## 6.2. Control System

- In addition to the LSC input, the calibration input should be incorporated.
- The position, pitch, and yaw monitor signals should be able to be brought to around zero by subtracting an adjustable DC voltage from the signals.
- The offset of the side control system is too big; the feedback output would be saturated if the gain is set to give pseudo-critical damping. The low offset OP-amplifier should be used for the first stage.
- A function of making the gain completely zero should be incorporated.
- The driver noise is too large.