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Specifications of the 40m Beamsplitter/ Recycling Mirror Suspension

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TABLE OF CONTENTS

1. INTRODUCTION

This document describes the specifications of the suspension systems for the 40m beamsplitter (BS) and recycling mirror (RM). The BS suspension was installed in the 40m interferometer and characterized in the first quarter of 1997. The RM suspension will be installed and characterized in the second quarter of 1997. The 40m BS&RM suspension serves also as the LIGO small optics suspension (SOS) prototype. This document will be revised after the RM suspension is installed and characterized.

2. MECHANICAL SYSTEM

2.1. General Description

The schematic view of the mechanical system of the 40m BS/RM suspension is shown in Fig. 1. The BS/RM is suspended by a single loop **suspension wire** from the **suspension block** which is a part of the **suspension support structure**. The **wire standoffs** and the **guide rods** are used to balance the BS/RM. Six **magnet/standoff assemblies** are glued to the BS/RM and five **sensor/actuator heads** are mounted on the **head holders**. The suspension support structure is strengthened by the **stiffener plate**. The BS/RM is protected by the **safety stops**.

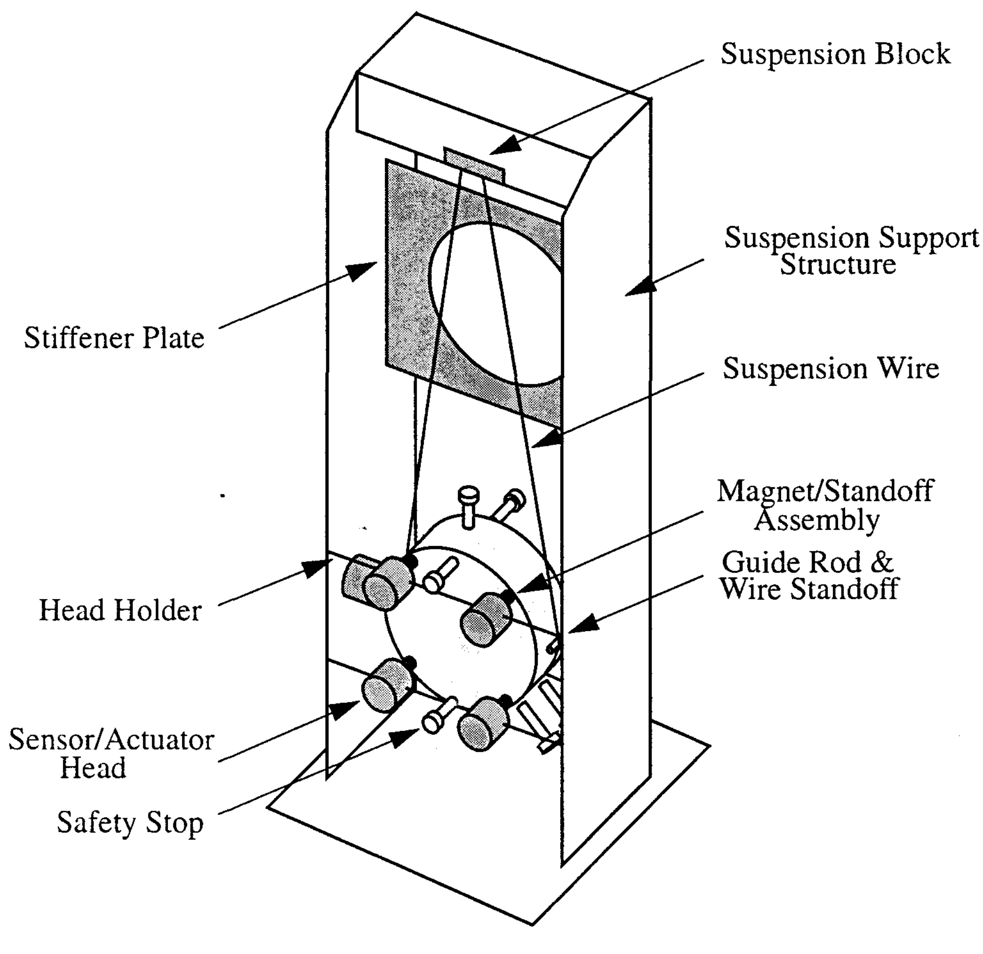


Fig. 1. Schematic view of the mechanical system of the 40m BS&RM suspension.

2.2. Suspension Components

2.2.1. Beamsplitter and Recycling Mirror

The 40m BS/RM suspension is designed to accommodate a beamsplitter or a recycling mirror with the following specifications:

- Size: 76.2 mmD × 25.4 mmL (3"D × 1"L)
- Weight: 250 g
- Moment of inertia ($M\left(\frac{D^2}{16}+\frac{L^2}{12}\right)$): $1.04 \times 10^{-4} \mathrm{kg} \cdot \mathrm{m}^2$
- Wedge: 30 minutes, horizontally configured
- Height of the center of the test mass relative to the upper surface of the stack top plate: 140 mm (5.5")
- Optical Clear Aperture: 32 mmD (1.25"D)

2.2.2. Suspension Support Structure

The suspension support structure is a rectangular frame on which, the head holders, the side sensor/actuator head, and the safety stops are mounted. This modular support structure makes it possible to assemble the system on a clean bench and then transfer it into the chamber without changing the relative position of the BS/RM to the sensor/actuator head. The side legs have two rectangular holes for better access to the safety stops and for better viewing of the BS/RM. Resonant frequencies of the suspension support structure with the bottom plate of the structure clamped rigidly on a optical bench were found to be above 156 Hz.

- Height: 417 mm (16.4")
- Transverse Width: 155 mm (6.1")
- Longitudinal Width: 127 mm (5.0")
- Material: Stainless and aluminum
- Measured lowest resonance frequency: 156 Hz

2.2.3. 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: $2.1 \times 10^{11} N/m^2$
- Diameter: 41 μm (0.0016")
- Breaking strength: 430 g with one loop
- Yield strength: 75% of breaking strength

2.2.4. Suspension Block

The suspension wire is hung down from the suspension block which is a part of the suspension support structure. The suspension block has two guide pins and a clamp so that the distance of the wire at the bottom of the suspension block (d_{yaw} defined in 2.3.) may be maintained properly (Fig. 2). The two screws above the guide pins may be used to adjust the height of the BS/RM.[1]

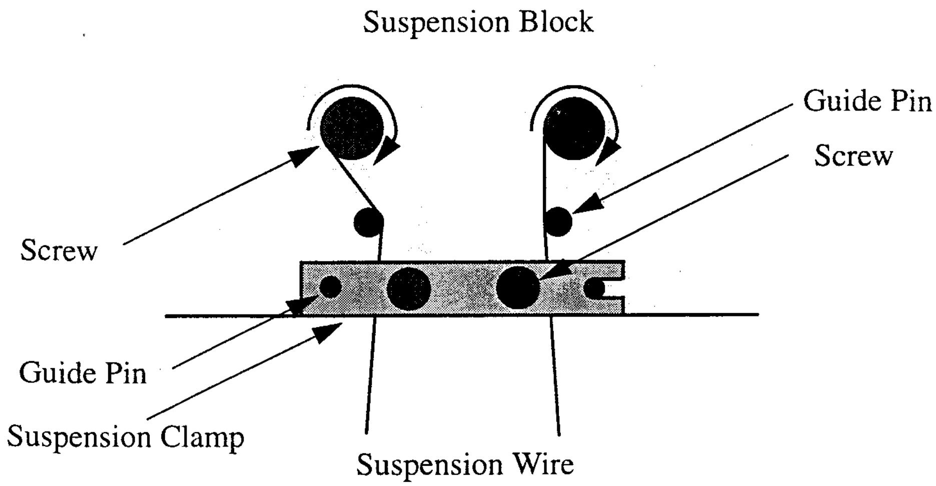


Fig. 2. Suspension block.

1. Since this height adjusting mechanism does not work very well, a new design will be tried for the LIGO SOS suspension.

2.2.5. 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 BS/RM 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 BS/RM.

- 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)
- Glue
  - Vacseal
  - Care should be taken so that the glue is not put on the wire.

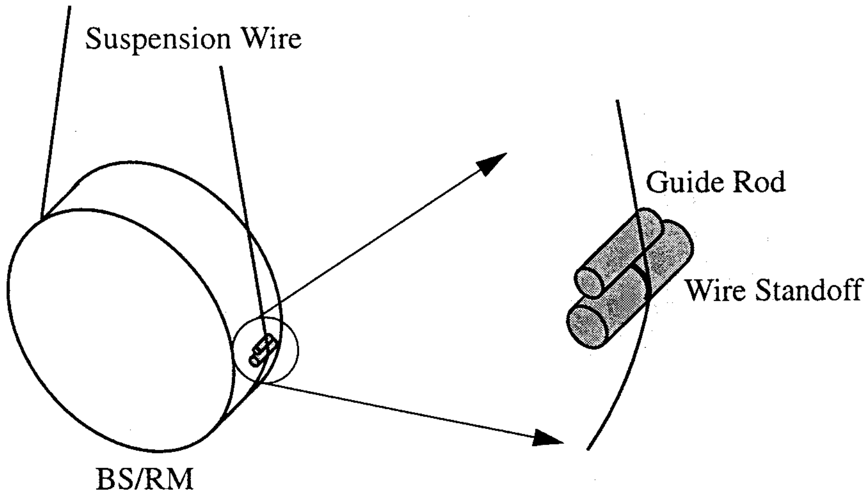
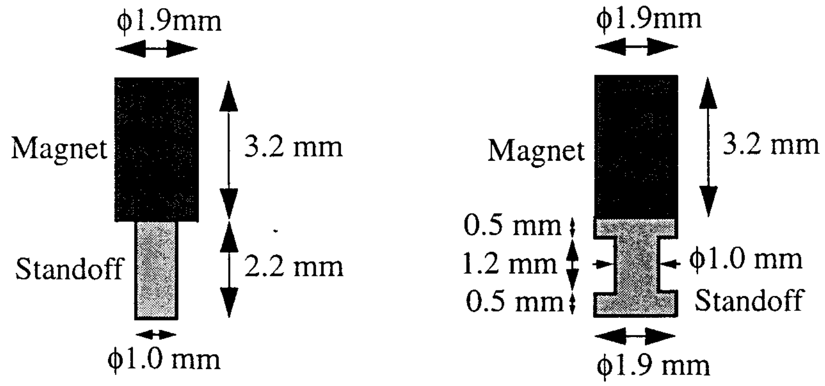


Fig. 3. Guide rod and wire standoff.

2.2.6. Magnet/Standoff Assembly

Aluminum standoffs are used as buffers between the magnets and the BS/RM to protect the internal mode *Q*s of the BS/RM from the lossy magnets. Cylindrical standoffs are used for the BS, and dumbbell-type ones will be used for the RM (Fig. 4).[1]



a) Cylindrical standoff b) Dumbbell-type standoff

Fig. 4. A cylindrical standoff and a dumbbell-type standoff.

Six magnet/standoff assemblies are attached to the BS/RM (Fig. 5): four on the front (for the BS) or back (for the RM) surface and two on the side surface of the test mass. 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.

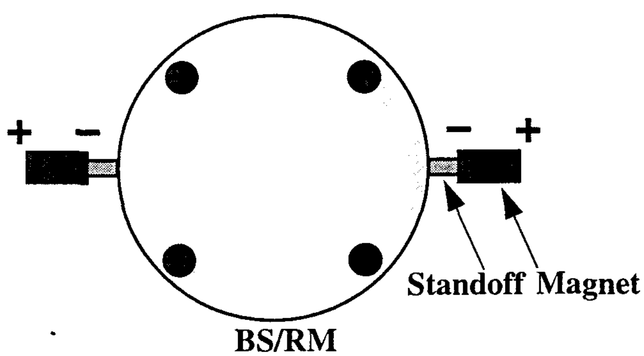


Fig. 5. Configuration of the magnet/standoff Assembly.

- Magnet
  - Material: Nd:Fe:B (NEO-35, Curie temperature 337 °C)
  - Size: See Fig. 4
- Standoff
  - Material: aluminum
  - Size: See Fig. 4
- Glue
  - Vacseal

1. "Dumbbell-type Standoff for Magnet/Standoff Assembly" LIGO-T970096-00-D

2.2.7. 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 or located on the suspension support structure: 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 BS/RM is detected. The current in the coil actuates the magnet attached to the BS/RM. The system is illustrated in Fig. 6.

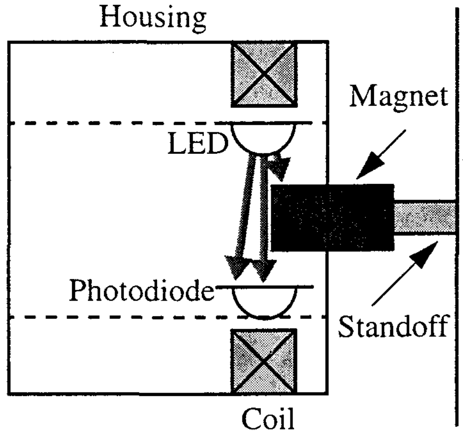


Fig. 6. Sensor/actuator head and the magnet/standoff assembly.

- LED: TLN107A, Toshiba, passed the RGA scanning test after being baked at 80°C
- PD: TPS703A, Toshiba, passed the RGA scanning test after being baked at 80°C[1]
  - 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[2] (Machinable glass ceramic: manufactured by Corning)
  - Size: 25.3 mmOD × 45.9 mmL

1. "RGA Scanning Test of Sensor/Actuator Head and Kapton Cable" LIGO-T970094-02-R
2. The electrostatic interaction between the BS/RM and the Macor heads could be a problem. Gold coating of the Macor head will be tried.

2.2.8. Head Holder

The front head holders are mounted on the suspension support structure and the side head holder is a part of the side leg of 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 is made of stainless steel because of its relatively high resistivity and is located far enough from the magnets on the BS/RM to reduce the eddy current thermal noise.[1]

- Material: Stainless steel
- Minimum distance between the head holder and the magnet: 15.7 mm (0.62")

2.2.9. Safety Stop

The safety stops are used to restrain the test mass motion and to protect it from damage. They are also used to hold the BS/RM firmly during assembly and installation.

- 1/4 - 20 × 1.00 long Teflon[2] hex head screw

2.2.10. Cable and Cable Harness

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

1. "Loss due to Eddy Current Damping between Magnets and Sensor/Actuator Head Holders in the Small Optics Suspension" LIGO-T970073-01-D
2. The electrostatic interaction between the BS/RM and the teflon safety stop is a problem. A technique of brushing the teflon as well as a conductive material will be tried out soon.

2.3. 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. 7.

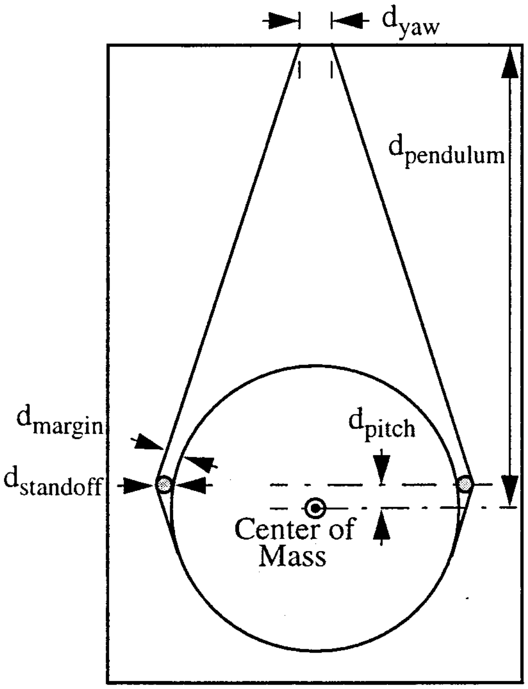


Fig. 7. Definitions of parameters for the suspension configuration.

Table 1: Parameters of the suspension configuration.

Parameters		*Designed Values (Measured)*
Pendulum Resonance Frequency		1.00 Hz (1.04 Hz)
Pitch Resonance Frequency		0.75 Hz (0.79 Hz)
Yaw Resonance Frequency		0.85 Hz (0.85 Hz)
$d_{pendulum}$		24.8 cm
d_{pitch}		0.9 mm
d_{yaw}		15.7 mm
$d_{standoff}$		1.0 mmD
d_{margin}		0.8 mm
Wire	Violin Mode Frequency	703 Hz (708 Hz)
	Vertical Resonance Frequency	14.8 Hz

2.4. Resonance Frequency and *Q*

Resonance frequencies and *Q*s of the BS internal modes, violin mode, and the magnet/stand-off assembly are measured and shown in Table 2.

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

Mode	*Resonance Frequency*	*Q*
Internal Mode	20.15194 kHz	4.9×10^5
	20.18583 kHz	2.7×10^5
	28.40520 kHz	3.1×10^5
	37.97721 kHz	2.4×10^5
	37.99493 kHz	2.4×10^5
Violin Mode	708.3040 Hz	2.2×10^5
	1,416.5378 Hz	6.7×10^5
Magnet/Standoff Assembly	7.484 kHz	540

3. CONTROL SYSTEM

3.1. General Description

The schematic diagram of the control system of the 40m BS/RM suspension is shown in Fig. 8. The motion of the BS/RM is detected by the **shadow sensor** which consists of a pair of LED and photodiode. Either this signal or a signal from the 40m **optical lever** sensor is filtered/amplified by the **suspension control electronics** and fed back to the **magnet-coil actuator** to damp the test mass. An interferometer **LSC signal** can be injected in the control loop.

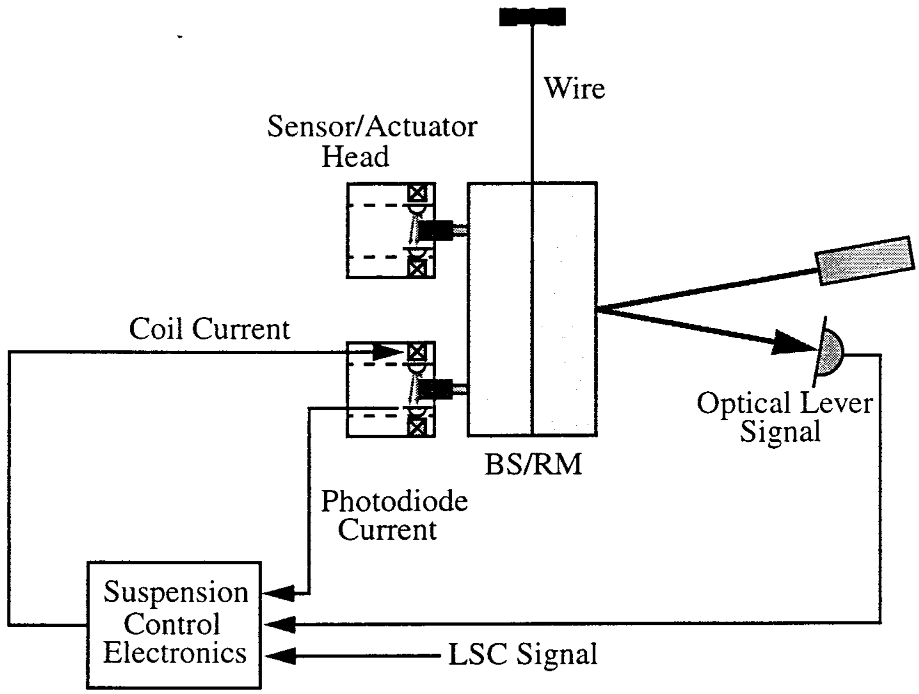


Fig. 8. Schematic diagram of the control system for the 40m BS/RM suspension.

3.2. Control Electronics

3.2.1. Overview

The schematic diagram of the suspension control electronics is shown in Fig. 9. 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. Bias are added to the pitch and yaw signals. Test signals can be also added to each signal. The signals are then converted by the **output matrix** into signals that are to be used for each coil. The signals are low-pass-filtered and the **LSC signal** may be added. The **Drivers** inject the signals into each coil. The switch makes it possible to choose either the suspension's sensor signal or the 40m optical lever signal (AC and DC modes) for pitch and yaw.

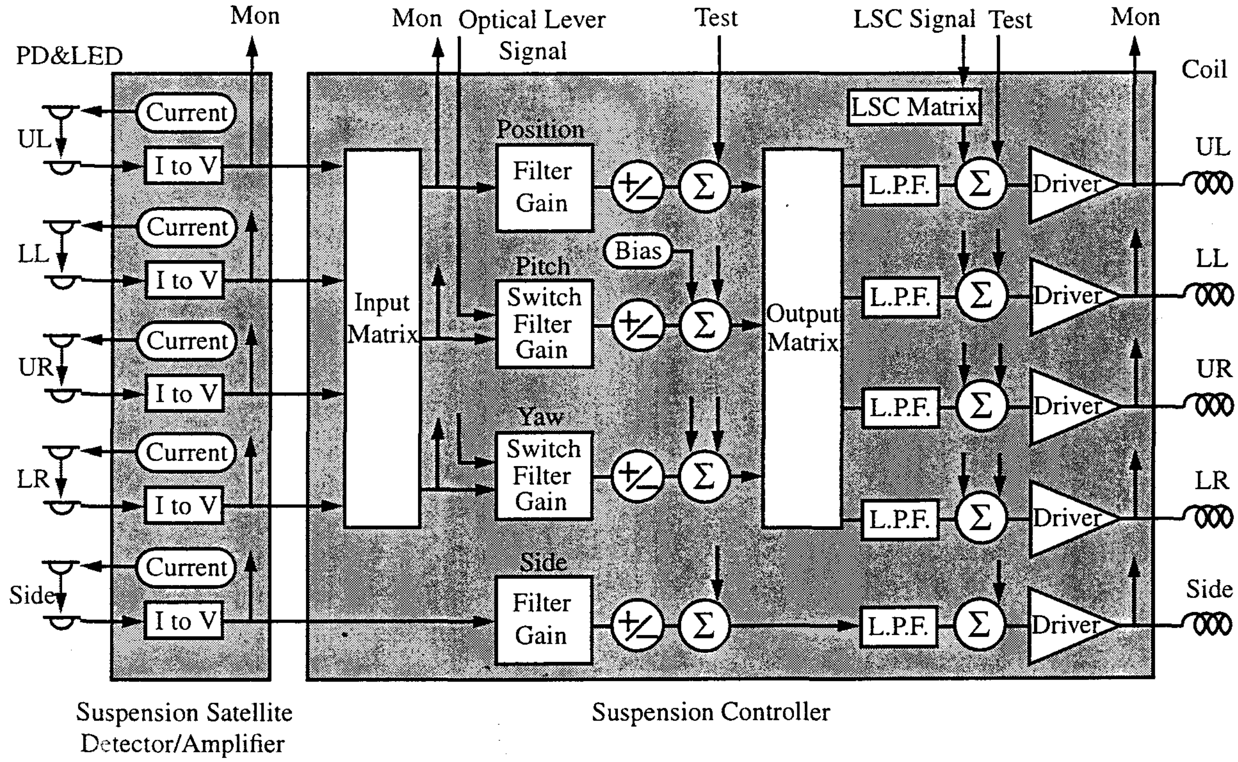


Fig. 9. Schematic diagram of the suspension control electronics.

3.2.2. Suspension Satellite Detector/Amplifier

The Suspension Satellite Detector/Amplifier is located by the vacuum chamber which accommodates the BS/RM suspension. This is to reduce the pick-up noise in the sensor signal.

- Current to each LED: 10 mA
- Reverse bias voltage for the photodiode: 10 V
- Transimpedence resistance: 20 kΩ

3.2.3. Input/Output/LSC Matrix

The sensor voltage from each sensor, $V_{S;UL,LL,UR,LR}$, is related to the sensor voltage for each degree of freedom, $V_{S;position,pitch,yaw}$, by the input matrix $M_{S;i,j}$, which is nominally unity and adjustable around unity.

$$\begin{bmatrix} V_{S;position} \\ V_{S;pitch} \\ V_{S;yaw} \end{bmatrix} = \begin{bmatrix} M_{S;position,\,UL} & M_{S;position,\,LL} & M_{S;position,\,UR} & M_{S;position,\,LR} \\ M_{S;pitch,\,UL} & -M_{S;pitch,\,LL} & M_{S;pitch,\,UR} & -M_{S;pitch,\,LR} \\ M_{S;yaw,\,UL} & M_{S;yaw,\,LL} & -M_{S;yaw,\,UR} & -M_{S;yaw,\,LR} \end{bmatrix} \begin{bmatrix} V_{S;UL} \\ V_{S;LL} \\ V_{S;UR} \\ V_{S;LR} \end{bmatrix}$$

The feedback voltage for each degree of freedom, $V_{F;position,pitch,yaw}$, is related to the feedback voltage to each actuator, $V_{F;UL,LL,UR,LR}$, by the output matrix $M_{F;i,j}$, which is nominally unity and adjustable around unity.

$$\begin{bmatrix} V_{F;UL} \\ V_{F;LL} \\ V_{F;UR} \\ V_{F;LR} \end{bmatrix} = \begin{bmatrix} M_{F;UL,\,position} & M_{F;UL,\,pitch} & M_{F;UL,\,yaw} \\ M_{F;LL,\,position} & -M_{F;LL,\,pitch} & M_{F;LL,\,yaw} \\ M_{F;UR,\,position} & M_{F;UR,\,pitch} & -M_{F;UR,\,yaw} \\ M_{F;LR,\,position} & -M_{F;LR,\,pitch} & -M_{F;LR,\,yaw} \end{bmatrix} \begin{bmatrix} V_{F;position} \\ V_{F;pitch} \\ V_{F;yaw} \end{bmatrix}$$

The LSC signal voltage, V_{LSC}, is related to the LSC voltage to each actuator, $V_{LSC;UL,LL,UR,LR}$, by the LSC matrix $M_{LSC;i}$, which is nominally unity and adjustable around unity.

$$\begin{bmatrix} V_{LSC;UL} \\ V_{LSC;LL} \\ V_{LSC;UR} \\ V_{LSC;LR} \end{bmatrix} = \begin{bmatrix} M_{LSC;UL} \\ M_{LSC;LL} \\ M_{LSC;UR} \\ M_{LSC;LR} \end{bmatrix} V_{LSC}$$

3.2.4. Output Driver and LSC Signal Injection

A current-source type driver is used; as shown in Fig. 10, the coil is placed inside the feedback loop of the driver operational amplifier. The LSC signal is injected into the inverting input of the operational amplifier. The voltage at the right end of the series resistor (R_3) can be monitored as the LSC feedback signal.[1] R_1 is 5 kΩ, R_2 is 500 Ω, and R_3 can be 500 Ω during lock acquisition and switched to 5 kΩ for signal monitor. The LSC input can be disabled by the switch. This configuration has several advantages[2] 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=500 Ω for the acquisition mode.
- The signal to noise ratio at the monitor point can be good enough with R_3=5 kΩ for the operation mode.
- Switching between the acquisition mode and the operation mode does not 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.

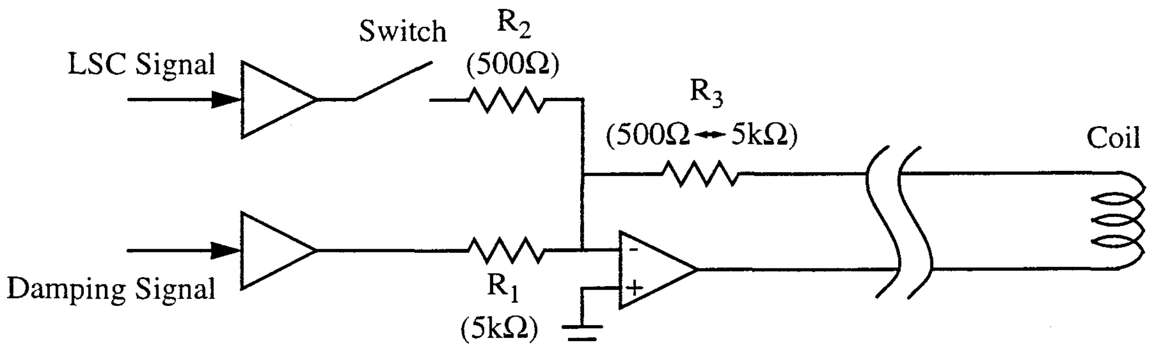


Fig. 10. Schematic diagram of the output driver and the LSC signal injection.

The specification of the LSC input is as follows:

- Input impedance: 1 k Ω
- Actuating efficiency: 1.7×10^{-4}N/V (See 3.3.2.)

1. The monitor point has been set at the output of the operational amplifier in the actual circuit mistakenly.
2. 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.

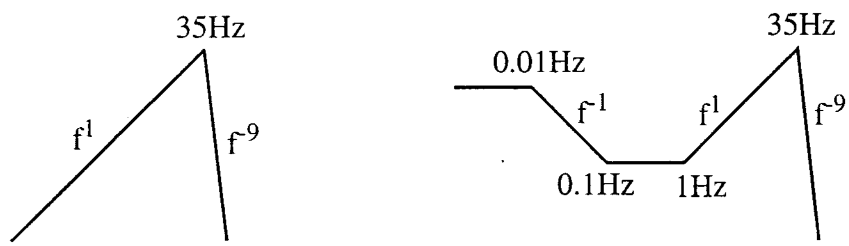
3.2.5. Control Mode

There are three control modes in the suspension control system, depending on which sensor signal is used and whether there is a DC gain or not:

- AC control mode using the suspension sensors
- AC control mode using the optical lever
- DC control mode using the optical lever

The DC control mode using the optical lever has been incorporated for a better DC stability of the BS/RM orientation, assuming that the angular reference given by the optical lever is more stable at DC than the local reference of the stack top plate.

The transfer function of the control electronics for the AC and DC modes are shown in Fig. 11. Both modes use 10 pole Chebyshev (1 dB) 35 Hz low pass filters.



(a) AC control mode (b) DC control mode

Fig. 11. Transfer function of the control electronics.

3.3. Control Parameters

3.3.1. Topology of Control System

Fig. 12 shows a block diagram of the suspension control system for each degree of freedom. Force (or torque, depending on the degree of freedom) applied to the BS/RM produces displacement (or angle) of the BS/RM by the transfer function which has two almost imaginary poles at the resonant frequency. The displacement (or angle) is then detected by the sensor (the suspension's sensor or the optical lever), producing current/voltage (photocurrent for the suspension's sensor, and XY-processor output voltage for the optical lever) with a frequency-independent coefficient. The current/voltage signal is then filter/amplified by a transfer function of the electronics. The resulting feedback current produces force (or torque) with a frequency-independent coefficient of the actuator.

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 electronics; they act on the BS/RM directly without being suppressed by the filter.

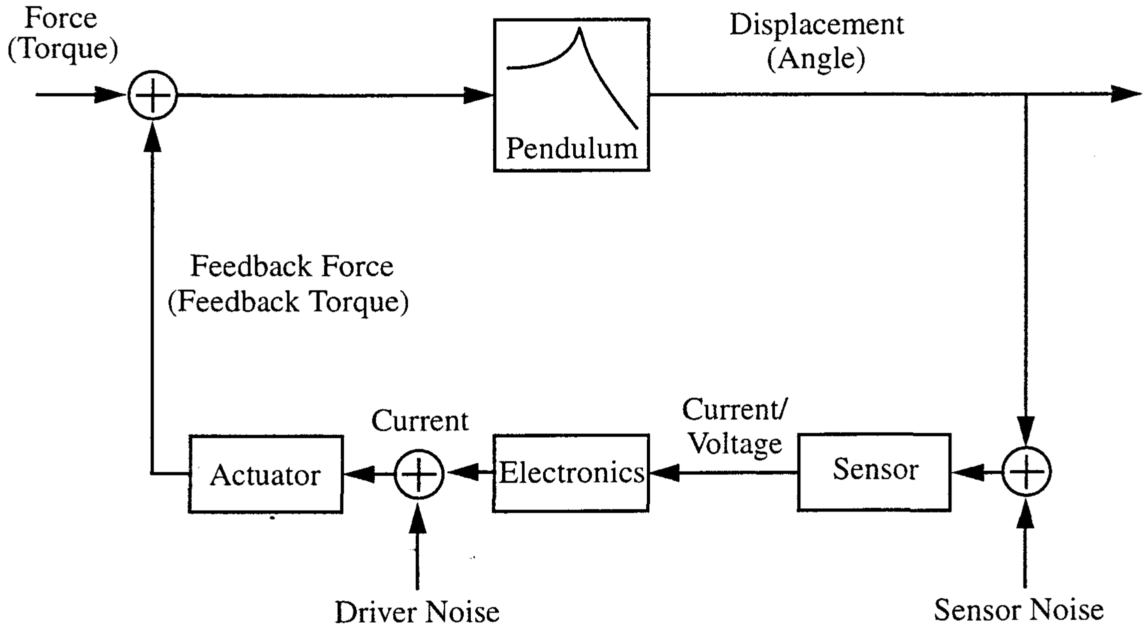


Fig. 12. Block diagram of the suspension control system together with typical noise sources. The sensor output is current for the suspension's sensor and voltage for the optical lever for convenience.

3.3.2. Sensor and Actuator

The LED-photodiode system senses the position of the magnet. The current in the coil applies force to the magnet. The following specifications are the measured values.[1]

- Sensor
  - LED current: 10 mA
  - Reverse PD voltage: 10 V
  - Maximum PD current: 60 - 100 μA (Half PD current: 30 - 50 μA)
  - PD current-voltage converting resistance: 20 kΩ
  - Sensitivity: 35 μA/mm per head
  - Range: 0.6 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)
- Actuator
  - Current-force coefficient: approximately 21 mN/A per head
  - Full pitch range: 5.1 $mrad_{pp}$ (pitch), 5.8 $mrad_{pp}$ (yaw)
  - Driver noise: $4.0 \times 10^{-12} \mathrm{A}/\sqrt{\mathrm{Hz}}$ per actuator

1. "Specifications of the 40m Test Mass Suspension Prototype" LIGO-T960162-02-D

3.3.3. Gain of Control System

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

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

Table 3 summarizes the gain of each block (Pendulum, Sensor, Electronics, and Actuator in Fig. 12) 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 @ f_0*	*Actuator*
Position	1.0×10^{-1} m/N	1.4×10^{-1} A/m	8.5×10^{2}	8.4×10^{-2} N/A
Side	1.0×10^{-1} m/N	3.5×10^{-2} A/m	1.4×10^{4}	2.1×10^{-2} N/A
Pitch	4.3×10^{2} rad/N · m	Suspension's sensor: 4.5×10^{-3} A/rad	2.3×10^{2}	2.2×10^{-3} N · m/A
		Optical Lever: 3.9×10^{5} V/rad	2.7×10^{-6} A/V	
Yaw	3.4×10^{2} rad/N · m	Suspension's sensor: 4.5×10^{-3} A/rad	3.0×10^{2}	2.2×10^{-3} N · m/A
		Optical Lever: 2.6×10^{5} V/rad	5.1×10^{-6} A/V	

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.

3.3.4. Sensor Noise

The sensor noise is dominated by the shot noise at the photodiode. It is attenuated by the steep low pass filter. Table 4 shows resultant displacement noise at 100 Hz caused by the sensor noise, together with sensor noise, loop gain, and coupling coefficient.

[Displacement Noise] = [Effective Sensor Noise] × [Loop Gain] × [Coupling] (2)

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

Degree of Freedom	*Effective Sensor Noise @100Hz*	*Loop Gain @ 100 Hz*	*Coupling*	*Displacement Noise @ 100 Hz*
Position	$4.7 \times 10^{-11} \mathrm{m}/\sqrt{\mathrm{Hz}}$	3.2×10^{-9}	1	$1.5 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$
Side	$9.4 \times 10^{-11} \mathrm{m}/\sqrt{\mathrm{Hz}}$	3.2×10^{-9}	< 0.1	$< 3.0 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$
Pitch	Suspension's sensor: $1.8 \times 10^{-9} \mathrm{rad}/\sqrt{\mathrm{Hz}}$	2.4×10^{-9}	< 3 mm	$< 1.3 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$
	Optical lever: Not Measured			-
Yaw	Suspension's sensor: $1.8 \times 10^{-9} \mathrm{rad}/\sqrt{\mathrm{Hz}}$	2.7×10^{-9}	< 3 mm	$< 1.5 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$
	Optical lever: Not Measured			-

3.3.5. 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.

$$[\text{Displacement Noise}] = [\text{Effective Driver Noise}] \times [\text{Actuator}] \times [\text{Pendulum}] \times [\text{Coupling}] \quad (3)$$

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	$2.0 \times 10^{-12} \mathrm{A}/\sqrt{\mathrm{Hz}}$	$8.4 \times 10^{-2} \mathrm{N/A}$	$1.0 \times 10^{-5} \mathrm{m/N}$	1	$1.7 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$
Side	$4.0 \times 10^{-12} \mathrm{A}/\sqrt{\mathrm{Hz}}$	$2.1 \times 10^{-2} \mathrm{N/A}$	$1.0 \times 10^{-5} \mathrm{m/N}$	< 0.1	$< 8.4 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$
Pitch	$2.0 \times 10^{-12} \mathrm{A}/\sqrt{\mathrm{Hz}}$	$2.2 \times 10^{-3} \mathrm{N \cdot m/A}$	$2.4 \times 10^{-2} \mathrm{rad/N \cdot m}$	< 3 mm	$< 3.2 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$
Yaw	$2.0 \times 10^{-12} \mathrm{A}/\sqrt{\mathrm{Hz}}$	$2.2 \times 10^{-3} \mathrm{N \cdot m/A}$	$2.4 \times 10^{-2} \mathrm{rad/N \cdot m}$	< 3 mm	$< 3.2 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$

3.3.6. Range of Actuator

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

$$[\text{Range}] = [\text{Maximum Driver Current}] \times [\text{Actuator}] \times [\text{Pendulum}] \quad (4)$$

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

Degree of Freedom	*Maximum Driver Current*	*Actuator*	*Pendulum @ DC*	*Range @ DC*
Position	$4.8 \times 10^{-3} \mathrm{A_{pp}}$	$8.4 \times 10^{-2} \mathrm{N/A}$	$1.0 \times 10^{-1} \mathrm{m/N}$	$4.0 \times 10^{-5} \mathrm{m_{pp}}$
Side	$4.8 \times 10^{-3} \mathrm{A_{pp}}$	$2.1 \times 10^{-2} \mathrm{N/A}$	$1.0 \times 10^{-1} \mathrm{m/N}$	$1.0 \times 10^{-5} \mathrm{m_{pp}}$
Pitch	$4.8 \times 10^{-3} \mathrm{A_{pp}}$	$2.2 \times 10^{-3} \mathrm{N \cdot m/A}$	$4.3 \times 10^{2} \mathrm{rad/N \cdot m}$	$4.5 \times 10^{-3} \mathrm{rad_{pp}}$
Yaw	$4.8 \times 10^{-3} \mathrm{A_{pp}}$	$2.2 \times 10^{-3} \mathrm{N \cdot m/A}$	$3.4 \times 10^{2} \mathrm{rad/N \cdot m}$	$3.6 \times 10^{-3} \mathrm{rad_{pp}}$

3.3.7. Electromagnetic Induction

Current flowing in the actuator coil produces the time-varying magnetic field. This is picked up by the loop consisting of the photodiode and its legs, producing voltages across the photodiode. This results in a spurious path from the actuator to the sensor. Since this effect has a f^1 dependence, the total transfer function from the actuator current to the sensor current is contaminated by this spurious path above some frequency. This effect is illustrated in Fig. 13.

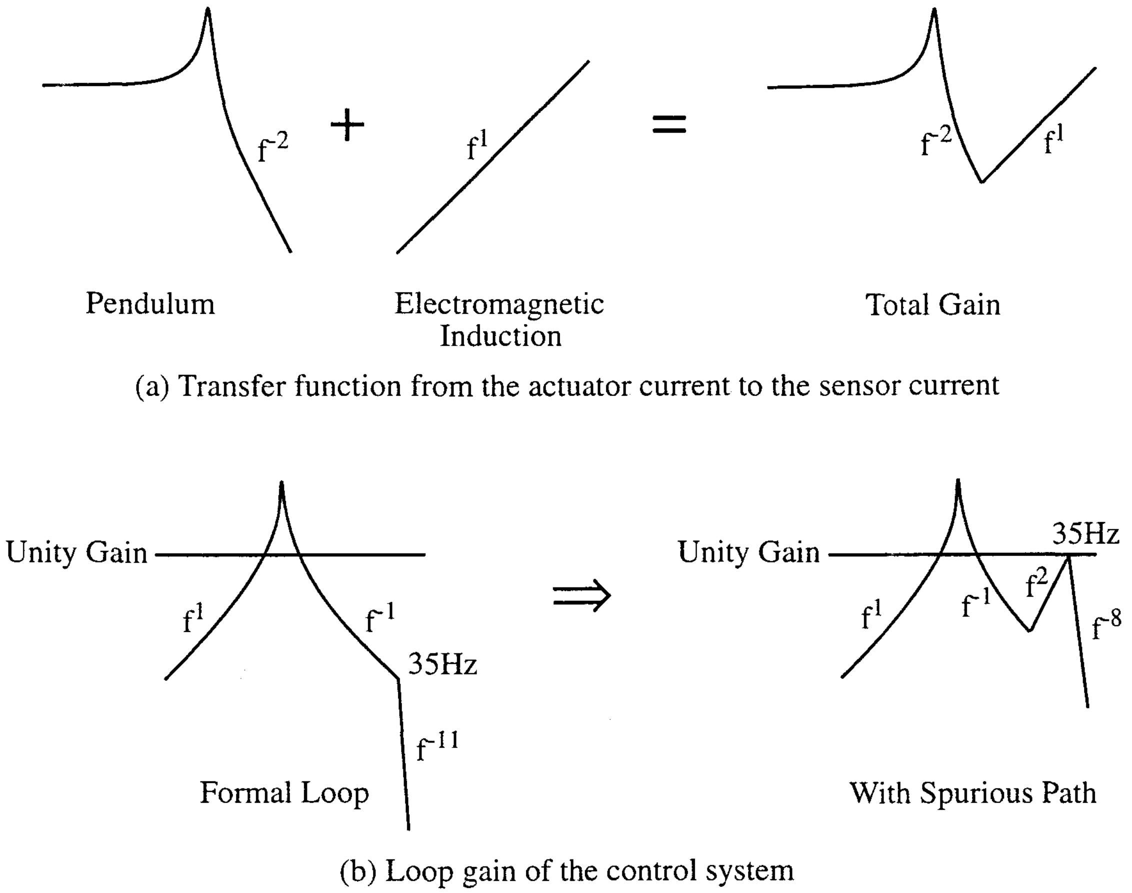


Fig. 13. Effect of the spurious path due to the electromagnetic induction effect.

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. The fixture design has been modified to accept the dumbbell standoffs.

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 BS/RM. This fixture tightly controls the positioning of the magnet/standoff array. A Kapton template is used to protect the coating of the VS/RM.

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 BS/RM. The position of the guide rod is tightly controlled because of its 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 BS/RM.

4.1.5. Precision Bubble Leveler

A precision bubble leveler is used to level the optical table where the BS/RM 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 BS/RM 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.

4.1.8. Cleaning Bracket

A cleaning bracket is used to replace the upper Mirror clamp for the cleaning of the BS/RM. This allows one to drag-wipe the face of the BS/RM more easily.

4.2. Procedure of Installation

Preparation

1. Clean all the suspension components including the BS/RM and the fixtures.[1]
2. Bake all the suspension components to be installed inside the vacuum.
   - Baking temperature:
     80 °C for the magnets and the sensor/actuator heads
     145 °C for the Kapton cables
     120 °C for aluminum components
     200 °C for stainless steel components
   - Baking period: 48 hours

Assembly

3. Assemble the suspension support structure, the stiffening bars, and the head holders.
   - Torque for bolting: 100 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 BS/RM using the magnet/standoff assembly fixture.
   - Glue: Vacseal
   - Polarity: See Fig. 5
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. 5
   - 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.

Coarse Balancing

9. Install the BS/RM into the suspension support structure
   - Install the BS/RM on the four lowest safety stops, making sure it rests evenly on the safety stops, and place the upper safety stop to the suspension support structure.
10. Adjust the safety stops roughly for height and angle.
11. Put the wire around the BS/RM and clamp it at the suspension block.

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12. Insert the wire standoffs under the guide rods.
13. Balance the BS/RM 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 BS/RM with the safety stops.
    - Accuracy: within 10 mrad
14. Glue one wire standoff to the BS/RM.
    - 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 BS/RM 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 gently rotating the BS/RM back and forth around the beam axis.
18. Glue the free wire standoff to the BS/RM.
    - Glue: Vacseal
    - Wait for two days for the glue to cure.

Baking

19. Remove the BS/RM from the suspension support structure.
20. Clean the BS/RM.
    - Make sure to keep solvents away from glue joints.
    - Solvent: Acetone and Methanol
21. Bake the BS/RM.
    - Baking Temperature: 80 °C
    - Baking period: 48 hours
22. RGA scan the outgas.

Optics Test

23. Clean the BS/RM.
    - Make sure to keep solvents away from glue joints.
    - Solvent: Acetone and Methanol
24. Inspect the mirror surface.

Re-hanging and Damping

25. Install the BS/RM into the suspension support structure following steps 9-11.
26. Install the sensor/actuator heads half way into the head holders.
    - LED and PD lined up vertically
27. Adjust the length of the wire and reclamp it at the suspension block.
    - Torque the head holders' bolts to 100 in lb.
    - The magnets should be within 500 μm vertically from the center of the sensor/actuator heads.
28. 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.
29. Incrementally move the sensor/actuator heads closer to the optic.
    - 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.
30. Check the sign of the sensor output signal by lightly shaking the BS/RM.
31. Adjust the polarity and gain, and check damping.

Installation

32. Clamp the BS/RM using the safety stops for transfer.
33. Transfer the suspension assembly to inside the tank.
34. Place the suspension assembly properly on the stack top plate.
35. Unscrew the safety stops leaving a 1 mm gap between the tip of the safety stop and the BS/RM.
36. 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.
37. Check the sign of the sensor output signal by lightly shaking the test mass.
38. Adjust the polarity and gain, and check damping.

Cabling

39. Connect the cable.

5. DRAWINGS

Table 7 shows a list of drawings for the 40m BS/RM suspension system.

Table 7: Drawings for the 40m BS/RM suspension system.

System	*Item*	*Drawing Number*	*Detail*
Mechanical parts	System	D960001	Small optic suspension assembly
	Suspension support structure	D960003	Suspension block
		D960005	Right side plate
		D960006	Left side plate
		D960004	Tower base
	Stiffener plate	D960009	
	Wire standoff	D970187	Aluminum
	Guide rod	D970188	Aluminum
	Magnet standoff	D960010	Cylindrical standoff
		D970075	Dumbbell standoff
	Sensor/actuator head assembly	D960011	
	Head holder	D960002	
	Safety cage	D960007	Upper mirror clamp
		D960008-1	Lower clamp
		D960008-2	Lower clamp, opposite

Table 7: Drawings for the 40m BS/RM suspension system.

System	*Item*	*Drawing Number*	*Detail*
Fixture	Magnet-to-standoff fixture	D960500	Cylindrical standoff
		D970074	Dumbbell standoff
	Magnet/standoff assembly fixture	D960020	
		D960021	Kapton template
	Guide rod fixture	D960022	assembly
		D960017	base plate
		D960018	left block, top
		D970067	left block, bottom
		D970066	right block, top
		D960019	right block, bottom
	Optical lever leveler	D960752	
	LED fixture	D950126	
	Cleaning bracket	D970181	
Circuit Diagram	Controller	D961288	
	Coil driver SIP	D961290	
	Filter SIP	D961291	
	Output matrix SIP	D961292	
	Input matrix SIP	D961293	
	Post in SIP	D961294	
	LSC input SIP	D961295	
	Electrical diagram	D961287	
	Satellite detector/ amplifier	D961289	