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Specifications of the 40m Beamsplitter/ Recycling Mirror Suspension

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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**.

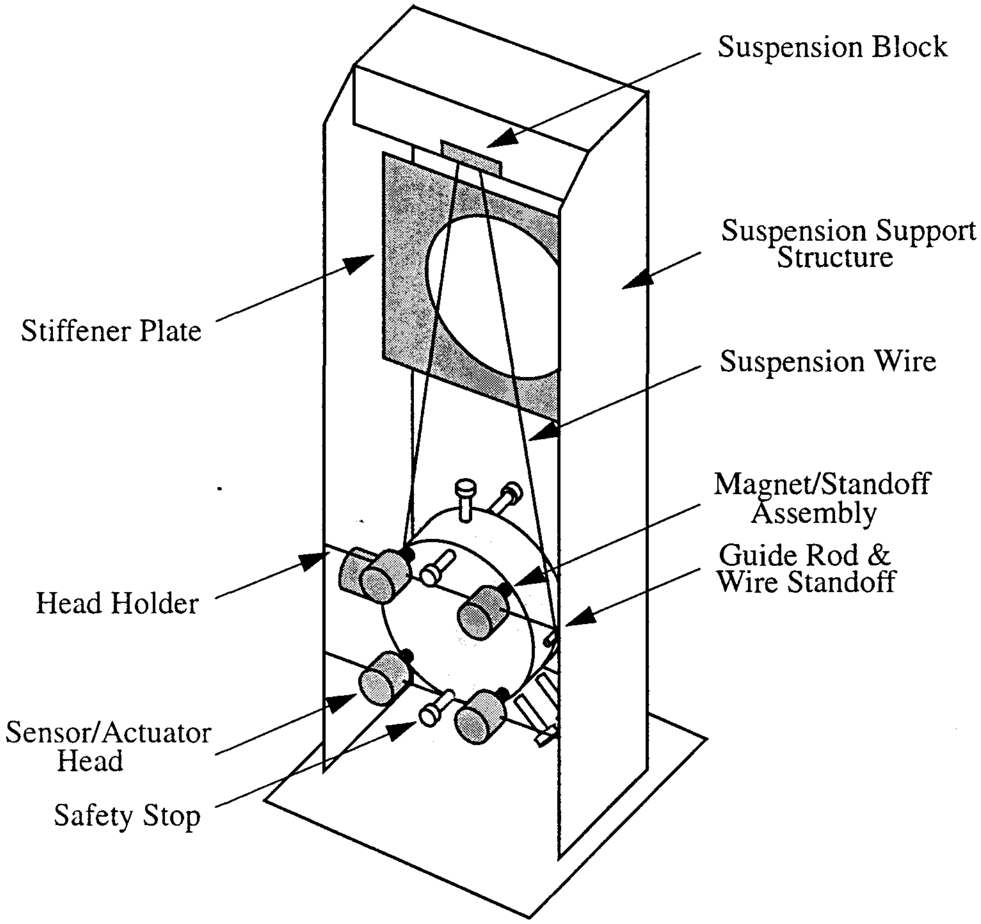

Fig. 1. Schematic view of the mechanical system of the 40m BS&RM suspension.

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]

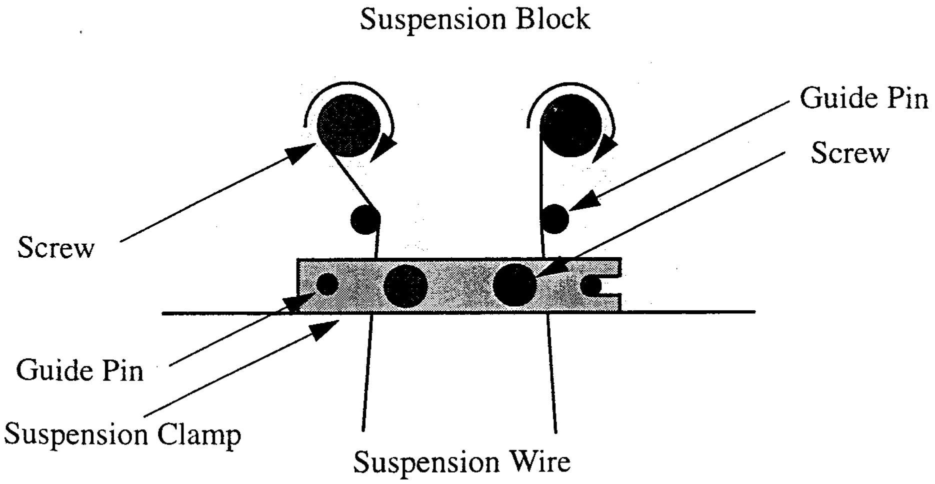

Fig. 2. Suspension block.

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[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.

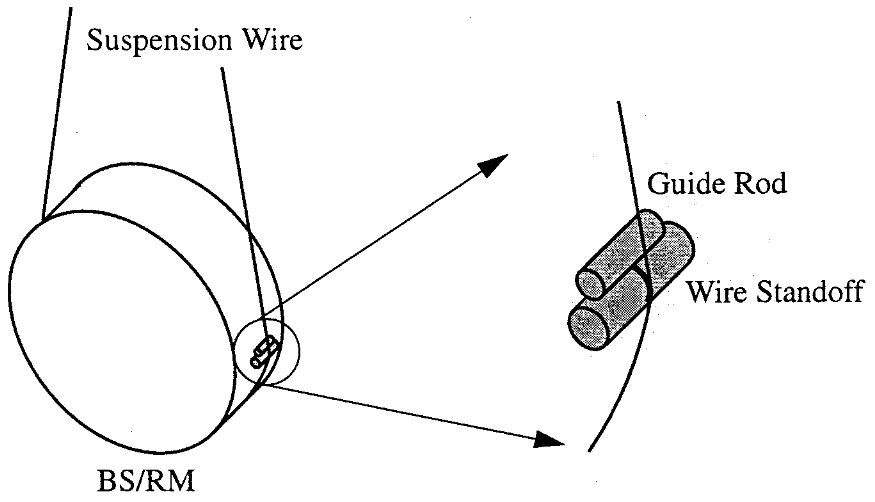
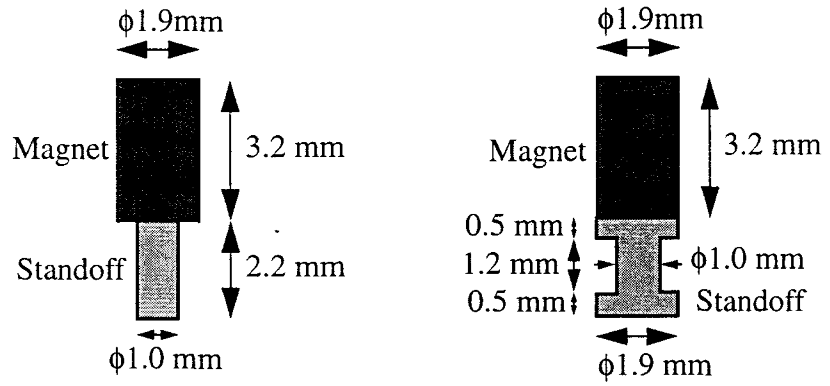


Fig. 3. Guide rod and wire standoff.

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.

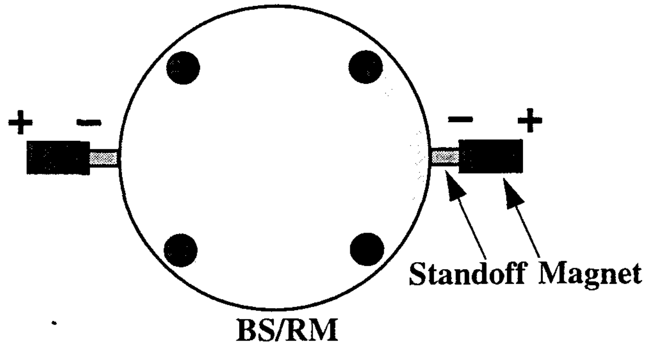


Fig. 5. Configuration of the magnet/standoff Assembly.

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

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[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.

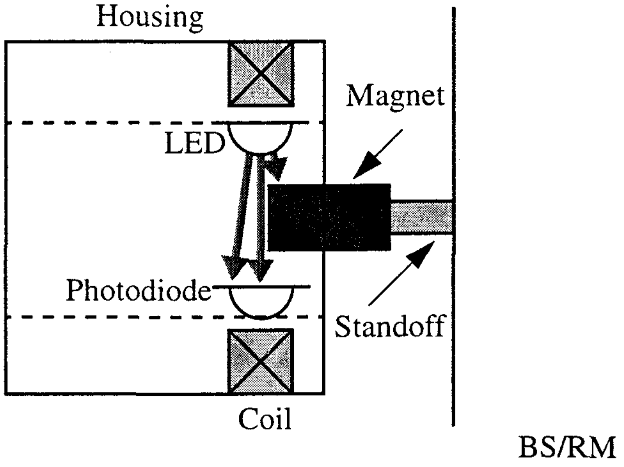

Fig. 6. Sensor/actuator head and the magnet/standoff assembly.

- 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

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[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.

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[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.

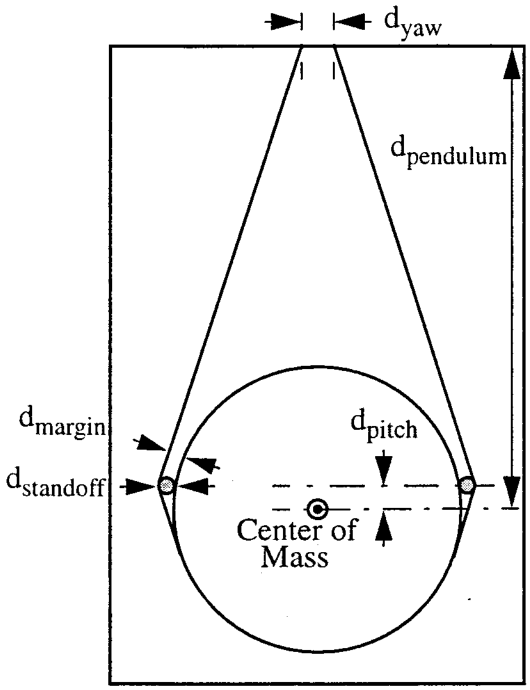

Fig. 7. Definitions of parameters for the suspension configuration.

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 Qs of the BS internal modes, violin mode, and the magnet/standoff 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.

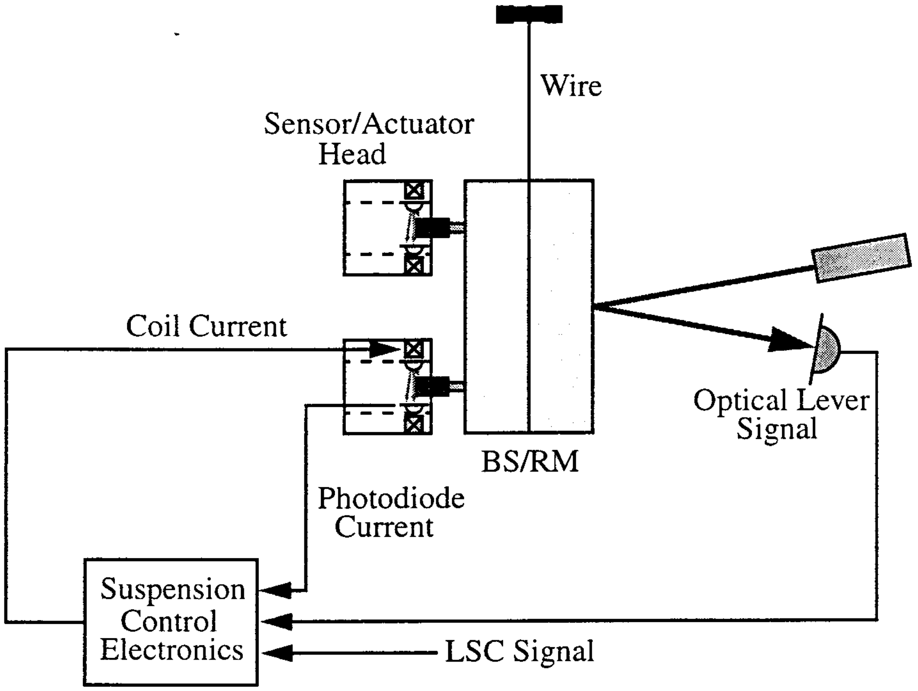

Fig. 8. Schematic diagram of the control system for the 40m BS/RM suspension.

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.

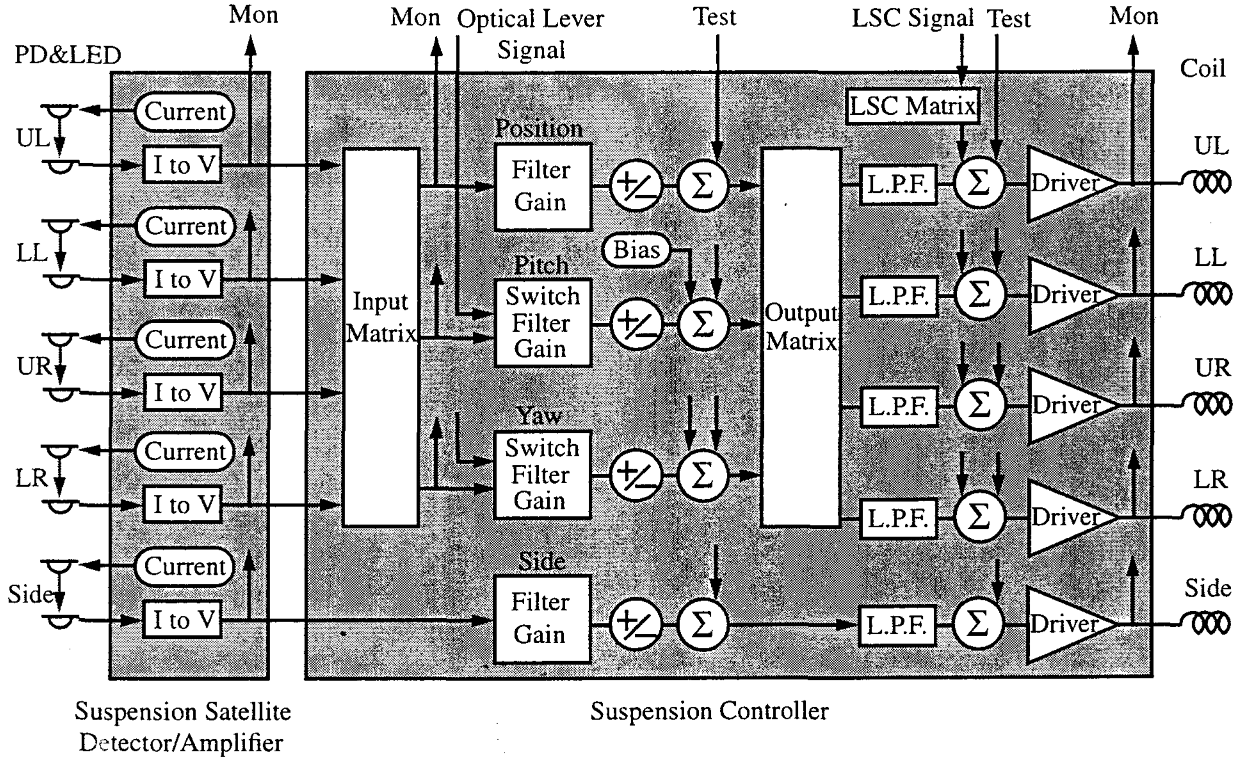

Fig. 9. Schematic diagram of the suspension control electronics.

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.

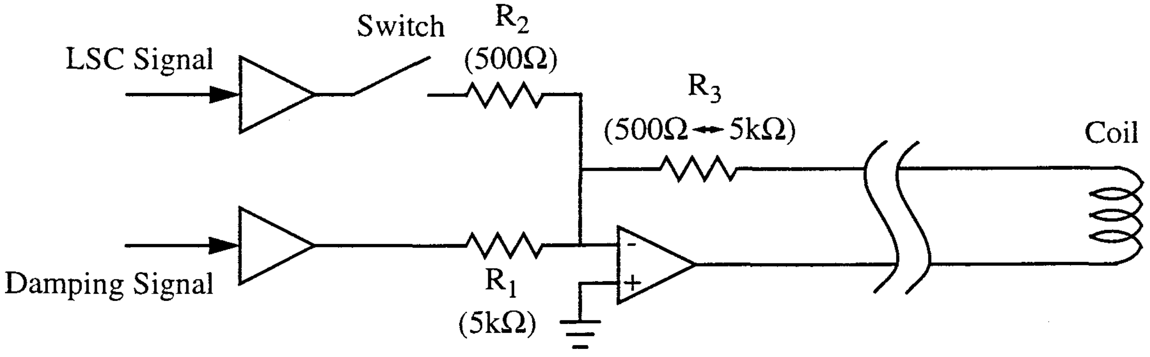

Fig. 10. Schematic diagram of the output driver and the LSC signal injection.

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.)

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[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.