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Large and Small Optics Suspension Electronics Final Design

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1 INTRODUCTION

1.1. Document Organization

The document is organized as follows:

- Section 2 Large Optics Suspension Electronics Design describes the design of the LOS local damping servo, the controller, the coil driver and the ASC and LSC inputs.
- Section 3 Small Optics Suspension Electronics Design describes the design of the SOS local damping servo, the controller, the coil driver and the ASC and LSC inputs. Many of the designs of the SOS system are similar to the LOS and where applicable the appropriate sections of the LOS design are referenced.
- Section 4 Suspension System Layout/Design describes the operator screens, alarms, back up and restore function, data acquisition channels and vacuum cabling to be used for the LOS and SOS systems.
- Section 5 Test Plans, Testing and Operations describes the test plans and operations manuals that are being developed for the electronics modules and the systems.

1.2. System Overview

A block diagram of a typical suspension control system is shown in the figure below.

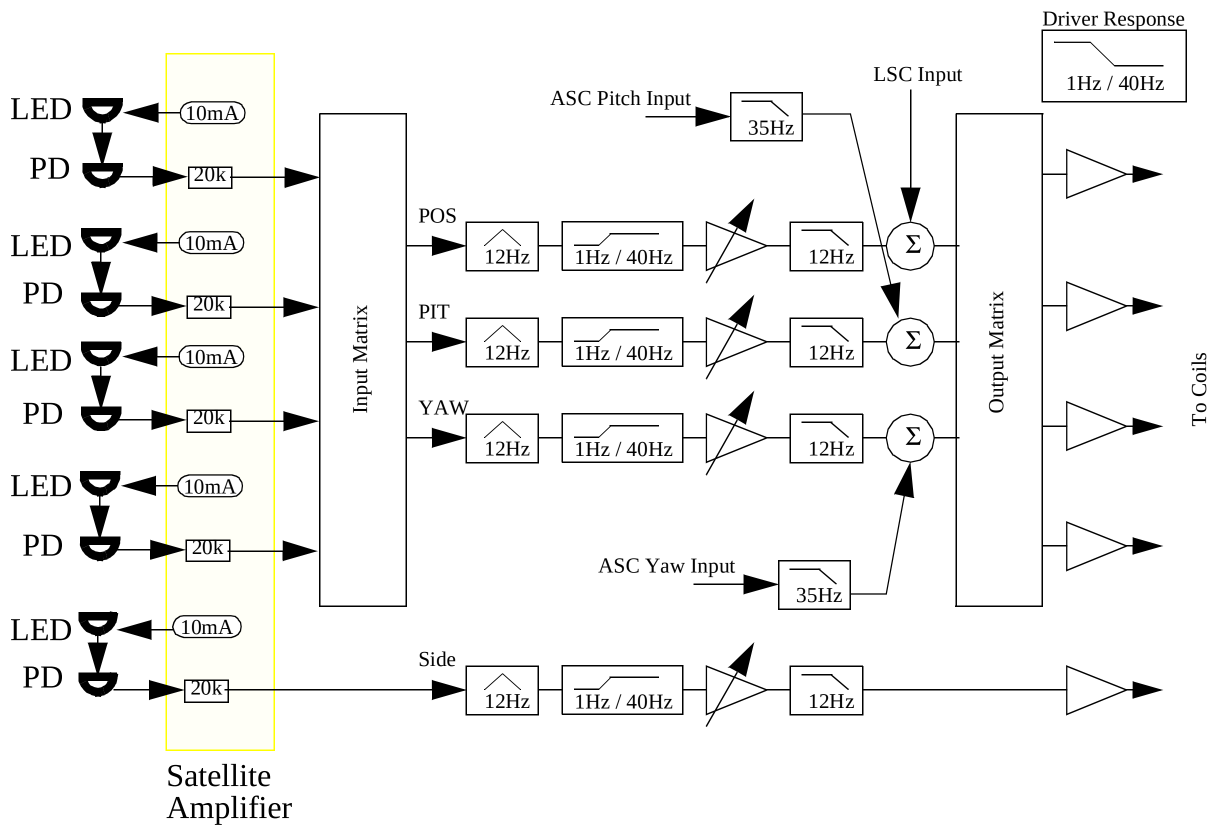

Figure 1: Suspension Control System Block Diagram

It should be noted that the suspension system electronics to be used for the LIGO LOS and SOS are very similar in design to those used for the 40 meter beam splitter and recycling mirror suspensions. In addition, several prototypes of each type of controller has been built since the PDR and performance has been verified.

1.3. Changes Since the PDR

- The input matrix that was proposed to be removed at the time of the PDR has been retained at the request of the PDR committee.
- Due to the change in the requirements for the SOS controllers needed for the IOO it was determined that a flat response versus frequency could be used. In addition, it was determined that different versions of the SOS controller could be used to more effectively match the capabilities of the coil driver to the requirements.
- The noise requirement for the LOS controller has been relaxed in an effort to keep the range of the controller at the 20 ump-p level and maintain a large dynamic range in the acquire

mode. If in the course of the LSC commissioning it is determined that the range requirement can be relaxed, components in the coil driver circuit can be changed to meet the noise requirement. (See LIGO T960151-02 for details of the requirements change).

- The simulink models for each suspension system have not been updated since they are still valid. The only difference between the model results and the actual controller responses that are required are in the areas of controller voltage gain and acquisition/detection mode compensation. These differences and how to adjust the model results to determine the required controller responses are discussed in the appropriate sections of this document.
- A coil current sum channel has been added to the design.
- The interface to the DAQ system will be via a daughter card mounted in the controller chassis. This daughter card will meet all interface requirements for DAQ/GDS.

1.4. Summary of Design and Fabrication Status

- LOS and SOS controller designs have been fabricated and tested and meet all the requirements outlined in LIGO T960151-02.
- Satellite amplifier designs have been fabricated and tested and meet all the requirements outlined in LIGO T960151-02.
- Chassis designs for LOS controllers, SOS controllers and Satellite amplifiers have been completed and prototype units built. These chassis designs are ready for final fabrication.
- System designs for WA 2K IOO, WA test stand and LA test stand systems have been completed. Rack cross connect wiring for each has been completed and sent to the respective sites for installation. Rack cross connect wiring for the WA 2K LVEA core optics suspensions has been started.
- The software used for the Caltech test stands can be copied and modified (i.e. tag names changed) and used for the software for each suspension system at the sites.

1.5. Acronyms

ASC: Alignment Sensing and Control

CDS: Control and Data System

LSC: Length Sensing and Control

POS: Position degree of freedom

PIT: Pitch degree of freedom

SIDE: Side degree of freedom

YAW: Yaw degree of freedom

2 LARGE OPTICS SUSPENSION ELECTRONICS DESIGN

2.1. Servo Design

2.1.1. LOS Position and Pitch Degrees of Freedom

The equations of motion for force and torque are:

$$F - \frac{Mg}{l}x + \frac{Mgd}{l}\Theta_2 - K_1 x \;=\; Ms^2 x$$

$$T + \frac{Mgd}{l}x - \frac{Mgd(\quad)}{l}\Theta - K_2\Theta_2 \;=\; Is^2\Theta_2$$

where,

M=10.7 Kg, g=9.8 m/s^2

l=0.45 m, d=0.0068 m, I=5.07x10^{-2} m^{2}Kg.

The figures below detail the simulink system model and controller designs that were used to obtain psuedo-critical damping and meet the noise requirements listed in the DRD for the position and pitch degrees of freedom.

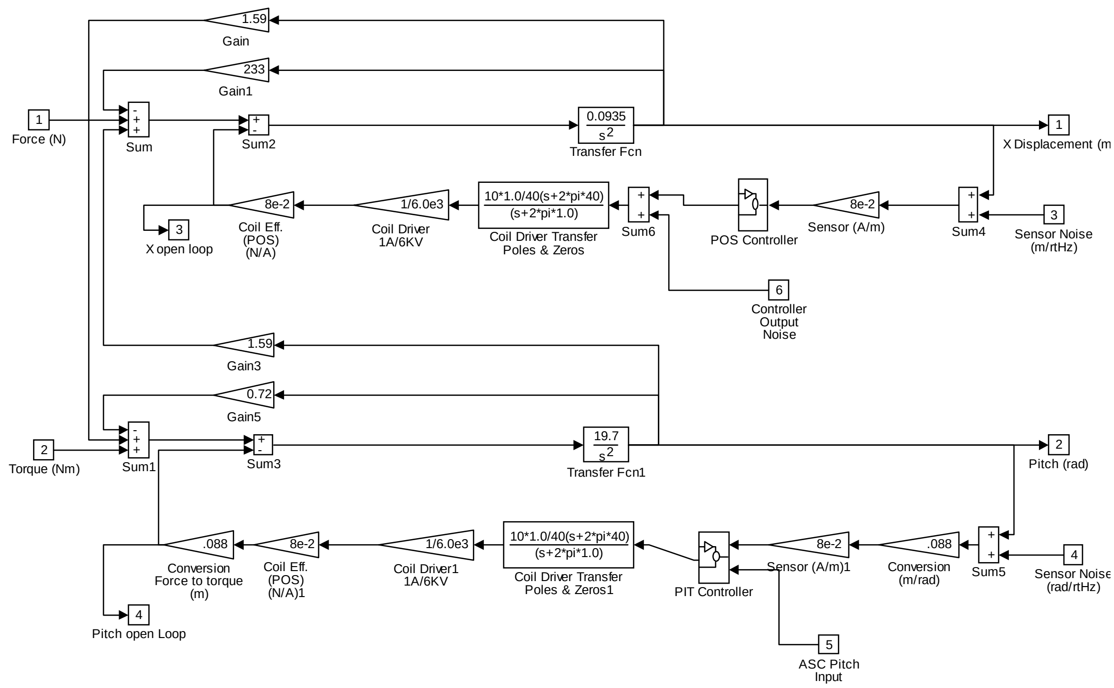

Figure 2: LOS Simulink Model for Position and Pitch Degrees of Freedom

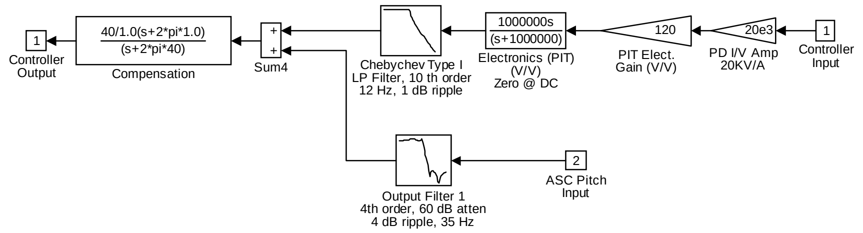

Figure 3: LOS Pitch Controller

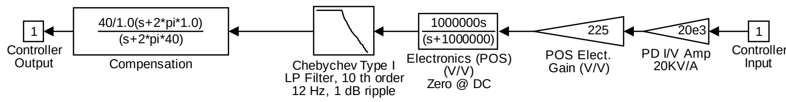

Figure 4: LOS Position Controller

The figure below is a nichols plot showing the phase margin for the position degree of freedom. The plot shows that for the given gain setting, the phase margin is approximately 45 degrees (cyan curve).

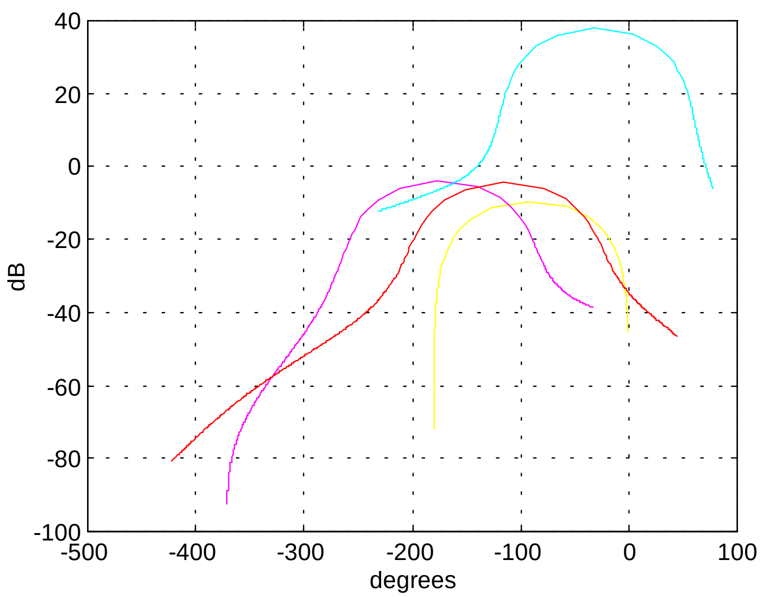

Figure 5: Nichols Plot for LOS Position Degree of Freedom

The figure below is a nichols plot showing the phase margin for the pitch degree of freedom. The plot shows that for the given gain setting, the phase margin is approximately 45 degrees (red curve).

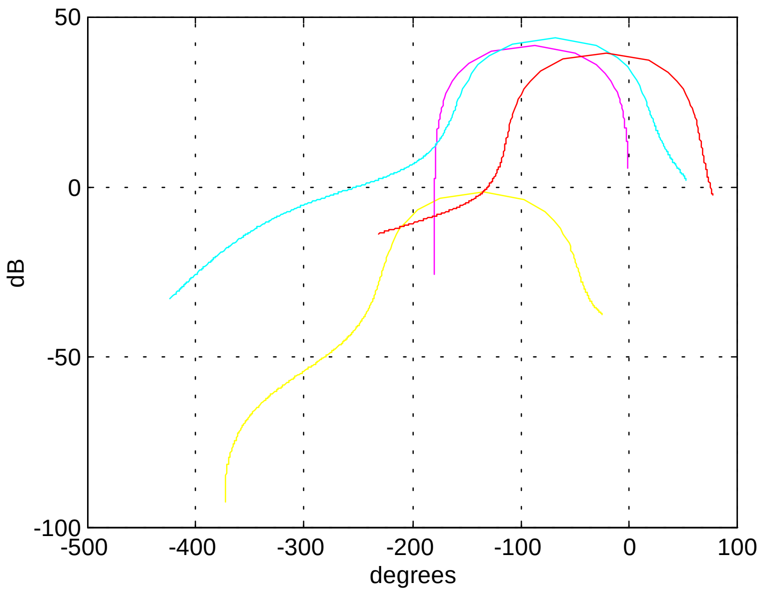

Figure 6: Nichols Plot for LOS Pitch Degree of Freedom

The controllers for pitch and position, shown in Figure 3: LOS Pitch Controller and Figure 4: LOS Position Controller, achieve the required pseudo-critical damping. Sensor noise attenuation above 40 Hz is greater than 190 dB for both degrees of freedom.

2.1.2. LOS Yaw Degree of Freedom

The figures below detail the simulink system model and controller designs that were used to obtain psuedo-critical damping and meet the noise requirements listed in the DRD for the yaw degree of freedom.

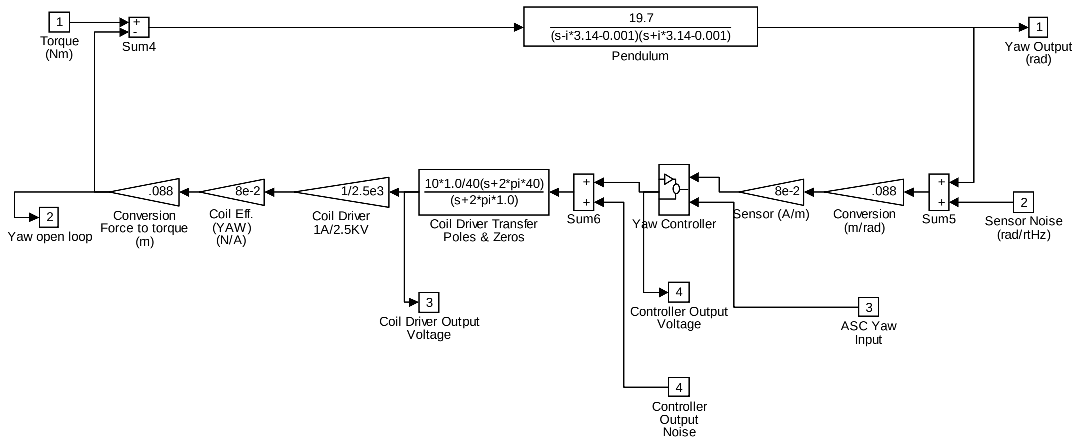

Figure 7: LOS Simulink Model for Yaw Degree of Freedom

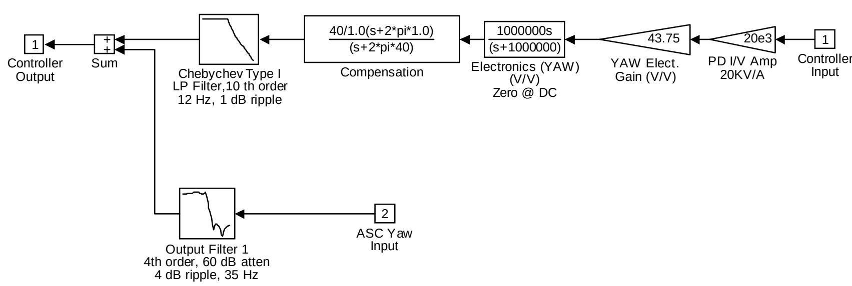

Figure 8: LOS Yaw Controller

The figure below is a nichols plot showing the phase margin for the yaw degree of freedom. The plot shows that for the given gain setting, the phase margin is approximately 55 degrees (magenta curve).

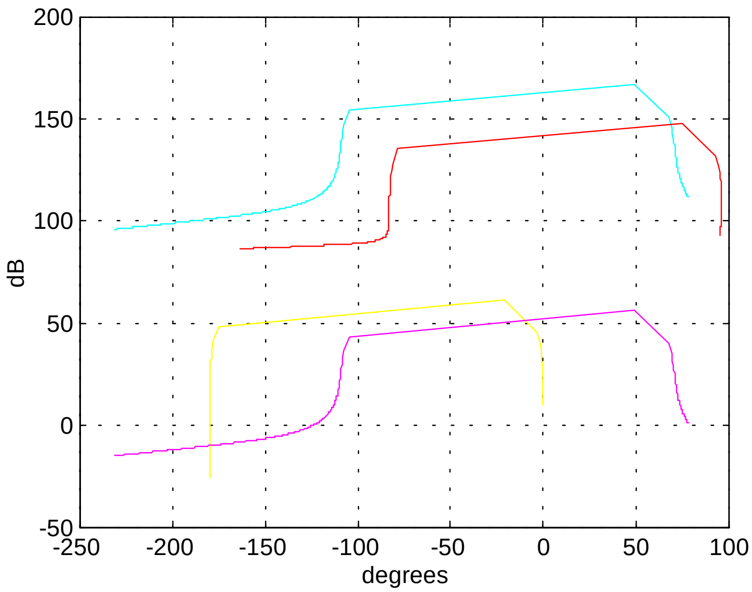

Figure 9: Nichols Plot for LOS Yaw Degree of Freedom

The controller for yaw, shown in Figure 8: LOS Yaw Controller, achieves the required pseudo-critical damping. Sensor noise attenuation above 40 Hz is greater than 190 dB for the yaw degree of freedom.

2.1.3. LOS Side Degree of Freedom

The side degree of freedom is identical to the POS degree of freedom, with the exception that the gain of the SIDE amplifier must be increased by 24 dB to account for the reduced sensitivity of the sensor and the reduced actuator force (one coil and sensor instead of four each).

2.2. Satellite Amplifier

The satellite amplifier that will be used for the LIGO LOS will be identical to the design that has been used for the 40 meter beam splitter and recycling mirror suspension controls. The amplifier meets or exceeds the requirements for LED drive current and photodiode current to voltage conversion.

The schematics for the module are LIGO D961289.

2.3. Controller

2.3.1. Input and Output Matrices

The input and output matrix for the LOS controllers will be similar in design to the 40 meter beam splitter and recycling mirror systems. Operator adjustment of the matrix coefficients will be achieved using DACs in a programmable gain configuration (ref. schematic D980013).

2.3.2. Servo Amplifier/Function

The figure below shows the response of the servo amplifier for the position degree of freedom. The yellow curve is a plot of the controller response alone and the magenta curve is a plot of the controller and coil driver combined response.

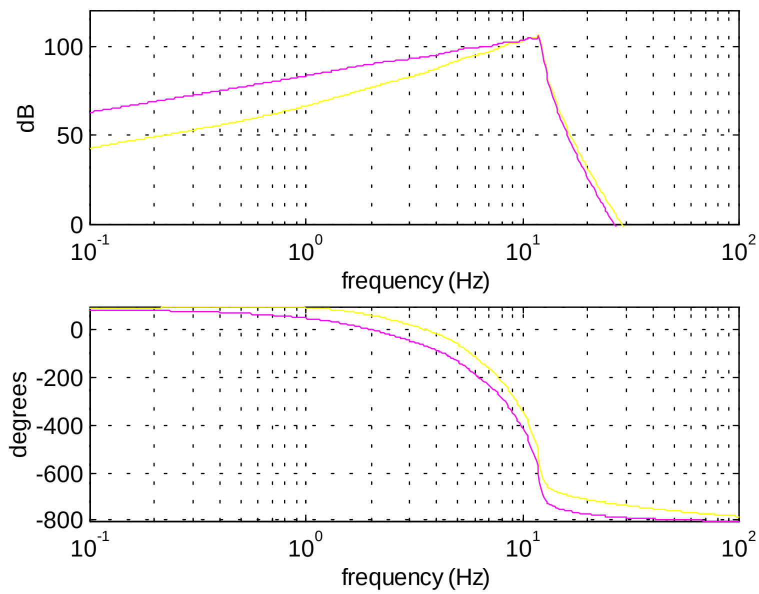

Figure 10: LOS Position Controller Response versus Frequency

The figure below shows the response of the servo amplifier for the pitch degree of freedom. The yellow curve is a plot of the controller response alone and the magenta curve is a plot of the controller and coil driver combined response.

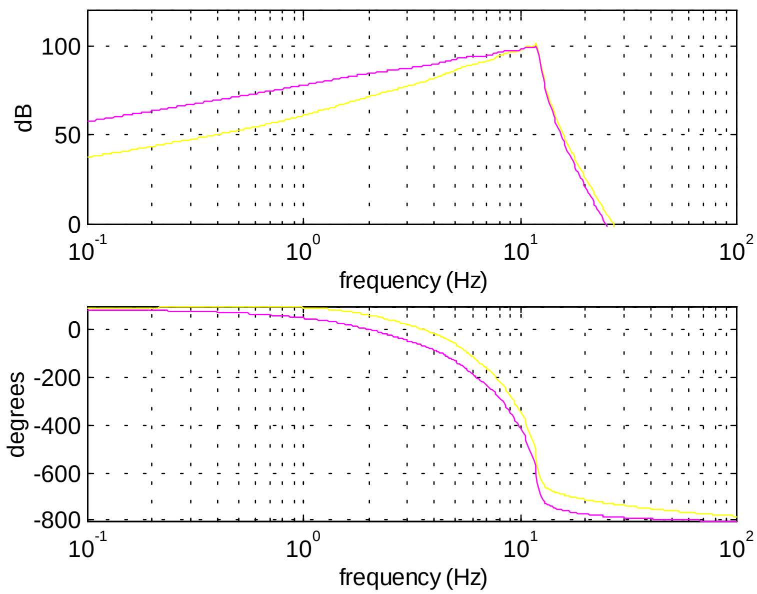

Figure 11: LOS Pitch Controller Response versus Frequency

The figure below shows the response of the servo amplifier for the yaw degree of freedom. The red curve is a plot of the controller response alone and the cyan curve is a plot of the controller and coil driver combined response.

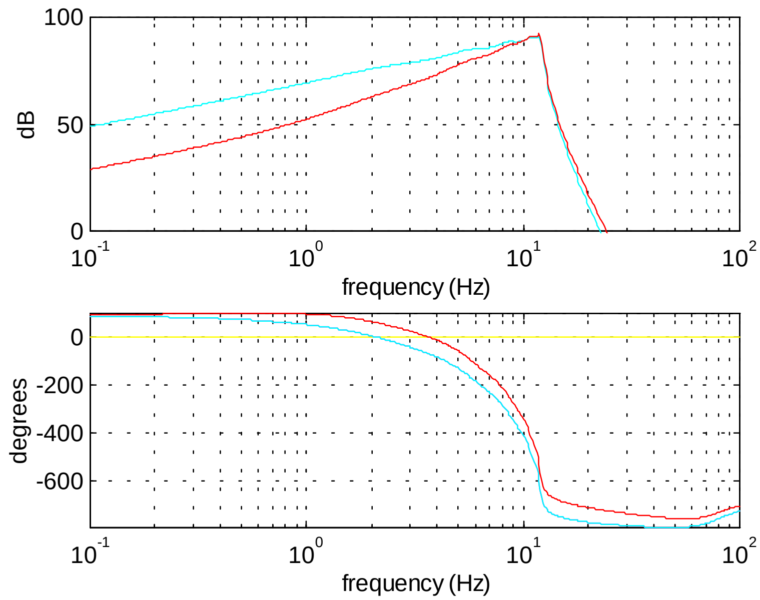

Figure 12: LOS Yaw Controller Response versus Frequency

Note that all of the controllers (POS, PIT, YAW) use a 10 pole, 12 Hz, 1 dB passband ripple chebychev and a zero at DC as the base filter function. The zero at 1 Hz and the pole at 40 Hz compensate the pole and zero of the coil driver. It should be noted that the controller gain curves shown above are the voltage gain of the controller assuming a 6Kohm resistor in series with the coil. If this resistor is changed in an effort to change the range and noise the voltage gain of the controller needs to be scaled accordingly, i.e.

$$ScaleFactor = \frac{R_{series}}{6Kohm}$$

In addition, the values of the other resistors and capacitors in the coil driver circuit would have to scaled accordingly to maintain the circuit gain and the 1Hz pole and 40 Hz zero.

2.3.3. LOS Coil Driver and Number of the Turns on the Coils

It was decided that the number of turns on the LOS sensor/actuator head coils should be kept at the present number (~400) at least until some operational experience with the suspension systems and LSC systems can be acquired. This decision implies that the dynamic range requirement and the noise requirements can not be simultaneously met by the present coil driver design (ref T950151-02, section 3.1.1.2.4) and that the noise requirement should be compromised in order to meet the dynamic range requirement. If, at some point in the future, it is desired that the noise requirement be met, there are two options that can be exercised individually or in combination:

- Increase the resistance in series with the coil
- Reduce the number of turns on the coil.

Each of these options is discussed in the paragraphs below.

2.3.3.1 Increasing the Series Resistance

The design of the LOS coil driver is such that the current noise seen by the coil at frequencies greater than 40 Hz is totally dominated by the current noise of the series resistance. If the number of turns on the coil remained at the current level and the noise requirement had to be met it would imply that the current noise in the coil would need to be less than 0.8pA/rtHz. This current noise requirement leads to a 25Kohm resistance in series with the coil. The corresponding reduction in range would be given by:

$$Range = 20um_{p-p} \times \frac{7.3Kohm}{25Kohm} = 5.8um_{p-p}$$

Note that the reduction in the range is a linear function of the increase in series resistance, while the reduction in the noise current only goes as the square root of the increase.

2.3.3.2 Decreasing the Number of Turns on the Coil

If the number of turns on the coil is decreased, the noise current requirement for the coil driver is increased linearly, i.e. half the number of turns doubles the acceptable noise current. The maximum force applied to the coil is also reduced linearly and therefore the maximum range is also reduced. At first glance it may appear that reducing the number of turns on the coil is at best a break even scenario until it is recognized that the noise current scales as the square root of the series resistor and the range (given a constant drive voltage) scales linearly. The table below summarizes a few design examples given the present coil driver design maximum output voltage and current (400Vp-p and 300mAp-p). Each design example meets the noise requirement called out in LIGO T960151-02.

Table 1: LOS Coil Driver Design Examples

Turns Reduction Ratio	*Series Resistance*	*Detection Mode Range*	*Acquisition Mode Range*[a]
1.0	25 Kohm	5.8 ump-p	110 ump-p
1.85	7.3 Kohm[b]	11 ump-p	59 ump-p
3.54	2.0 Kohm	20.5 ump-p	31 ump-p
4.33	1.333 Kohm	25 ump-p	25 ump-p

a. Note that in these examples the acquisition mode range is being traded for detection mode range and noise.
b. Present series resistance

It goes without saying, changing the number of turns on the coil would require major rework of the previously installed suspension system components.

2.3.4. LOS ASC Input Elliptic Filter

The ASC inputs to the PIT and YAW degrees of freedom require 35 Hz, 4th order, 4 dB passband ripple, 60 dB stopband attenuation filters with input referred noise less than $(\quad)/(\sqrt{\quad})$ for frequencies less than 40 Hz and less than $(80nV)/(\sqrt{Hz})$ for frequencies greater than 40 Hz. The circuit to be used has been designed and modeled using Cadence Analog Workbench. The figures below show the circuit and the predicted response. A prototype of the circuit was built and the performance was as predicted by the model.

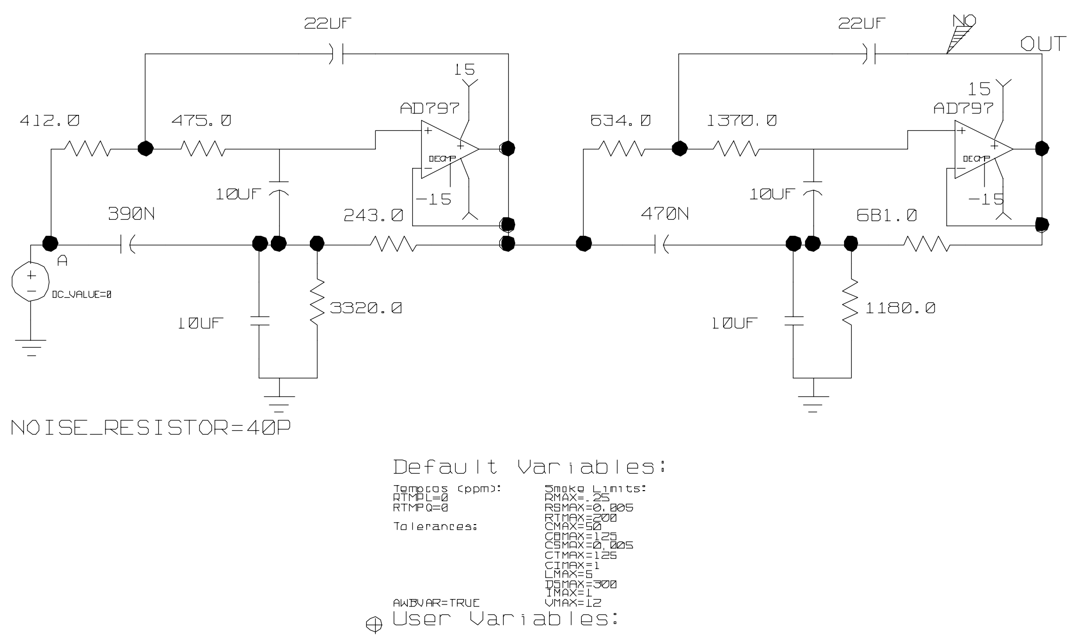

Figure 13: ASC Input Elliptic Filter

The circuit was then incorporated into the controller prototype and performance verified.

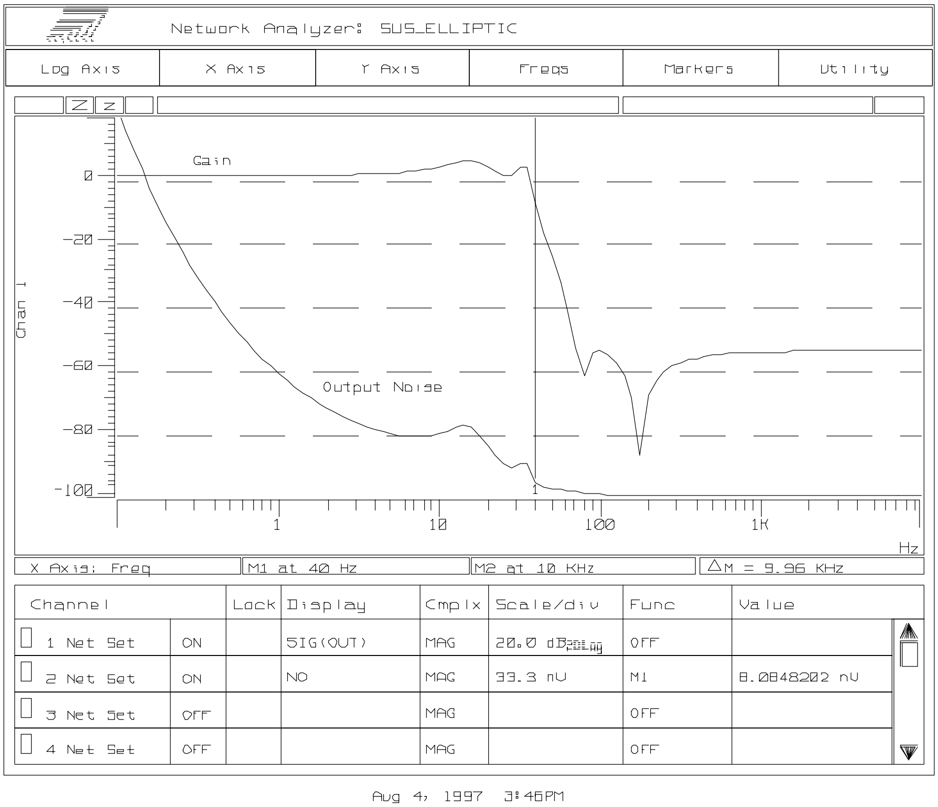

Figure 14: Analog Workbench Predictions for Frequency Response and Output (Input) Noise

3 SMALL OPTICS SUSPENSION ELECTRONICS DESIGN

3.1. Servo Design

3.1.1. SOS Position and Pitch Degrees of Freedom

The equations of motion for force and torque are:

$$F - \frac{Mg}{l}x + \frac{Mgd}{l}\Theta_2 - K_1 x = Ms^2 x$$

$$T + \frac{Mgd}{l}x - \frac{Mgd(\quad)}{l}\Theta - K_2\Theta_2 = Is^2\Theta_2$$

where,

M=0.25 Kg, g=9.8 m/s^2

l=0.248 m, d=0.0009 m, I=1.04x10^{-4} m^{2}Kg.

The figures below detail the simulink system model and controller designs that were used to obtain psuedo-critical damping and meet the noise requirements listed in the DRD for the position and pitch degrees of freedom.

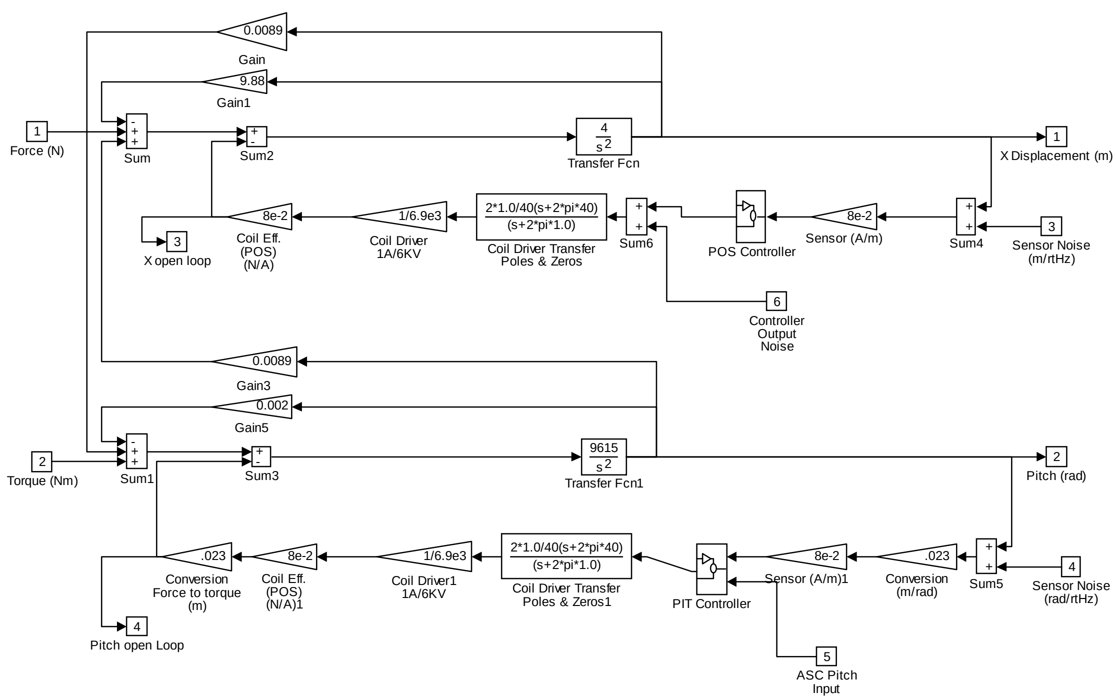

Figure 15: SOS Simulink Model for Position and Pitch Degrees of Freedom

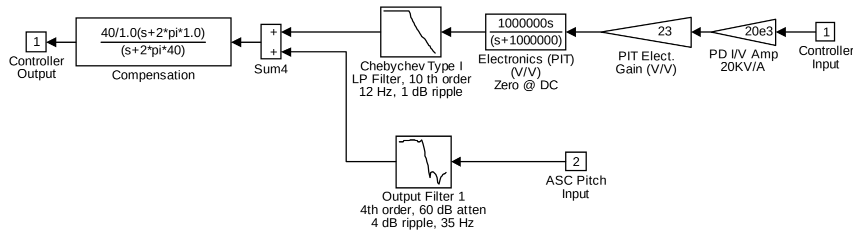

Figure 16: SOS Pitch Controller

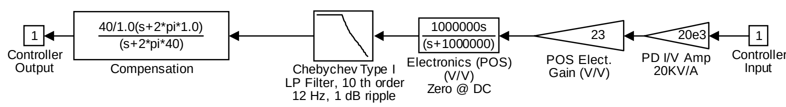

Figure 17: SOS Position Controller

The figure below is a nichols plot showing the phase margin for the position degree of freedom. The plot shows that for the given gain setting, the phase margin is approximately 45 degrees (cyan curve).

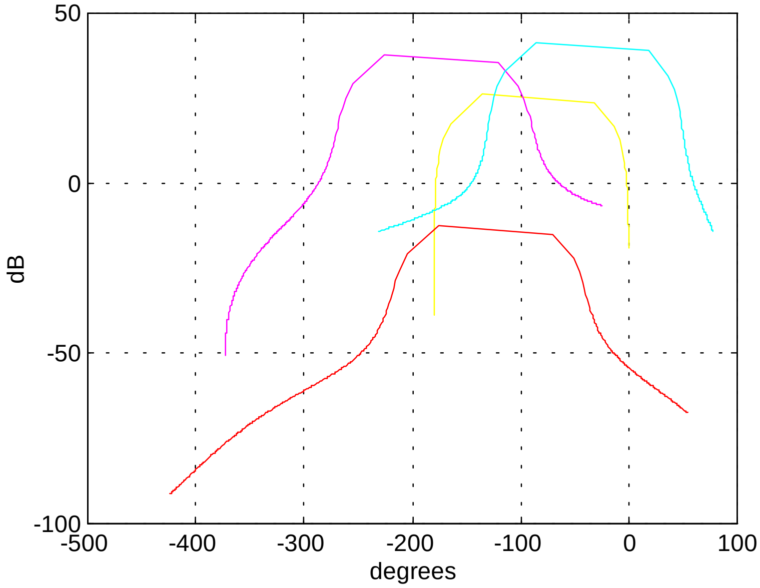

Figure 18: Nichols Plot for SOS Position Degree of Freedom

The figure below is a nichols plot showing the phase margin for the pitch degree of freedom. The plot shows that for the given gain setting, the phase margin is approximately 45 degrees (red curve).

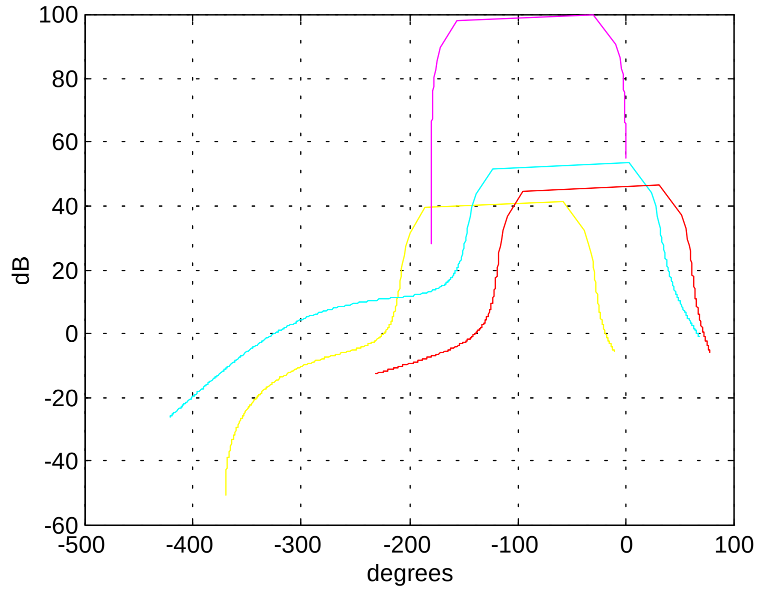

Figure 19: Nichols Plot for SOS Pitch Degree of Freedom

The controllers for pitch and position, shown in Figure 16: SOS Pitch Controller and Figure 17: SOS Position Controller, achieve the required pseudo-critical damping. Sensor noise attenuation above 40 Hz is greater than 190 dB for both degrees of freedom.

3.1.2. SOS Yaw Degree of Freedom

The figures below detail the simulink system model and controller designs that were used to obtain psuedo-critical damping and meet the noise requirements listed in the DRD for the yaw degree of freedom.

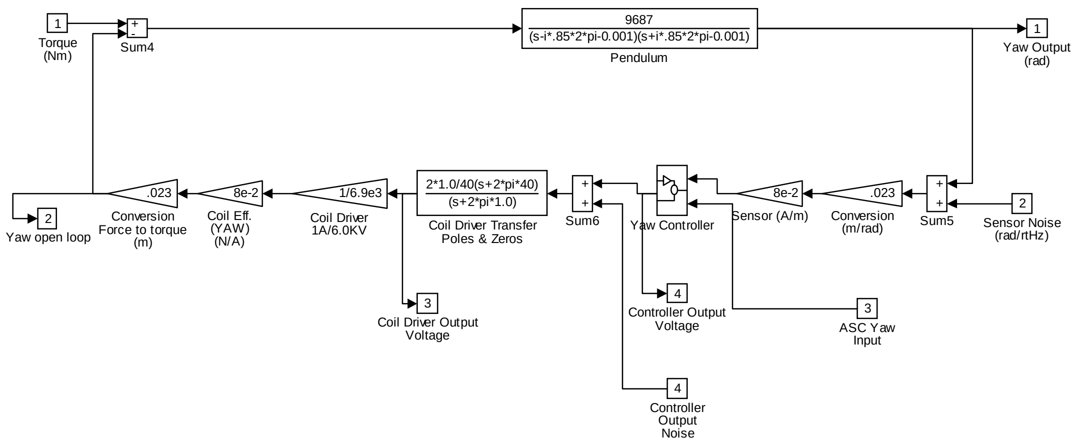

Figure 20: SOS Simulink Model for Yaw Degree

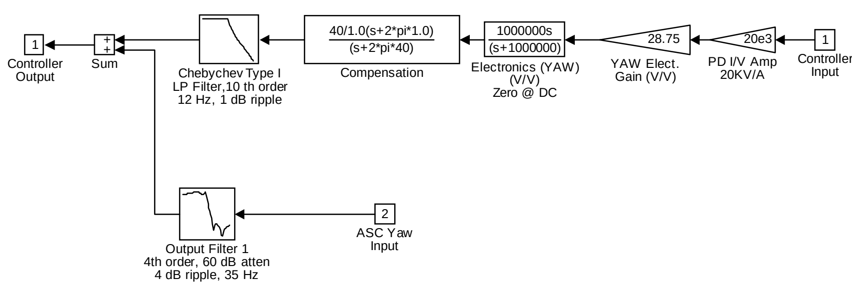

Figure 21: SOS Yaw Controller

The figure below is a nichols plot showing the phase margin for the yaw degree of freedom. The plot shows that for the given gain setting, the phase margin is approximately 55 degrees (magenta curve).

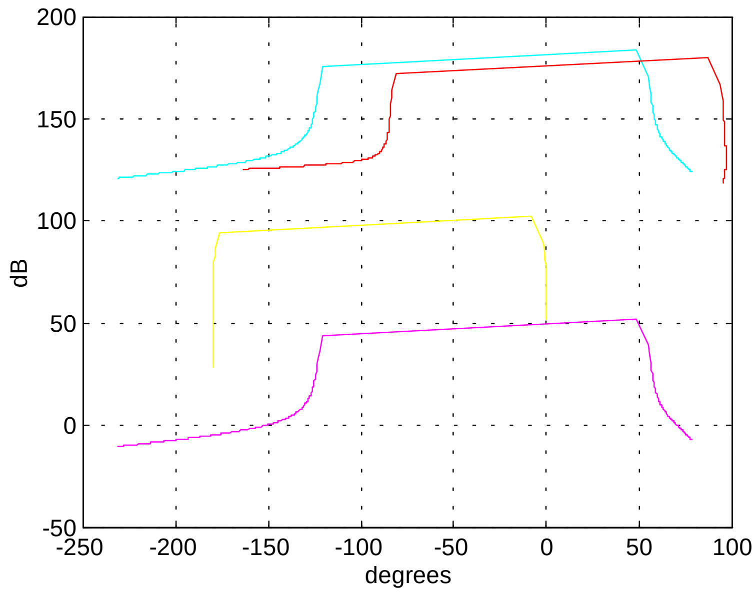

Figure 22: Nichols Plot for SOS Yaw Degree of Freedom

The controller for yaw, shown in Figure 21: SOS Yaw Controller, achieves the required pseudo-critical damping. Sensor noise attenuation above 40 Hz is greater than 190 dB for the yaw degree of freedom.

3.1.3. SOS Side Degree of Freedom

The side degree of freedom is identical to the POS degree of freedom, with the exception that the gain of the SIDE amplifier must be increased by 24 dB to account for the reduced sensitivity of the sensor and the reduced actuator force (one coil and sensor instead of four each).

3.2. Satellite Amplifier

The satellite amplifier that will be used for the LIGO SOS will be identical to the design that has been used for the 40 meter beam splitter and recycling mirror suspension controls. The amplifier meets or exceeds the requirements for LED drive current and photodiode current to voltage conversion.

The schematics for the module are LIGO D961289.

3.3. Controller

3.3.1. Input and Output Matrices

The input and output matrix for the SOS controllers will be similar in design to the 40 meter beam splitter and recycling mirror systems. Operator adjustment of the matrix coefficients will be achieved using DACs in a programmable gain configuration (ref. schematic D980181).

3.3.2. Servo Amplifier/Function

The figure below shows the response of the servo amplifier for the position degree of freedom. The magenta curve is a plot of the controller response alone and the cyan curve is a plot of the controller and coil driver combined response.

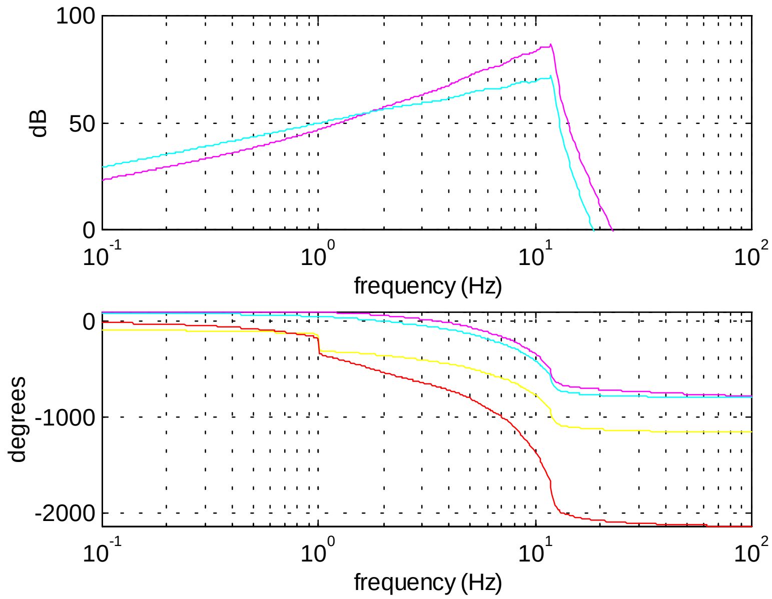

Figure 23: SOS Position Controller Response versus Frequency

The figure below shows the response of the servo amplifier for the pitch degree of freedom. The magenta curve is a plot of the controller response alone and the cyan curve is a plot of the controller and coil driver combined response.

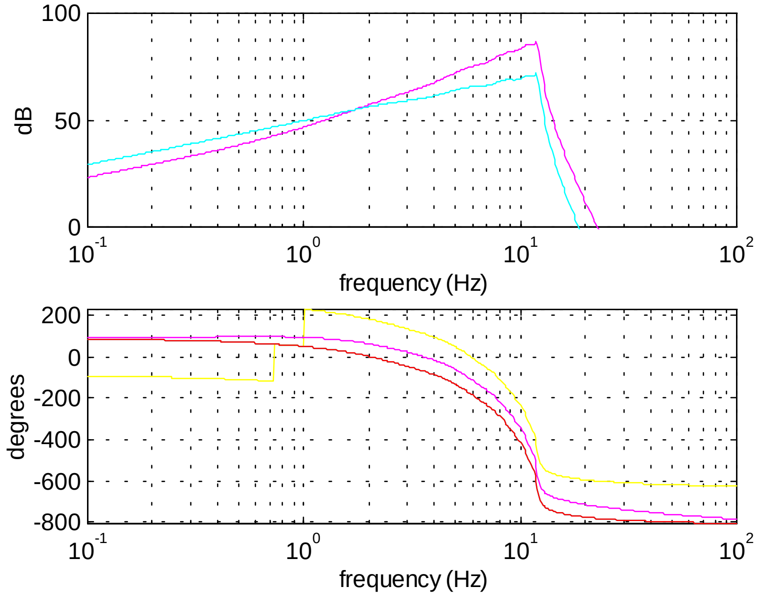

Figure 24: SOS Pitch Controller Response versus Frequency

The figure below shows the response of the servo amplifier for the yaw degree of freedom. The magenta curve is a plot of the controller response alone and the cyan curve is a plot of the controller and coil driver combined response.

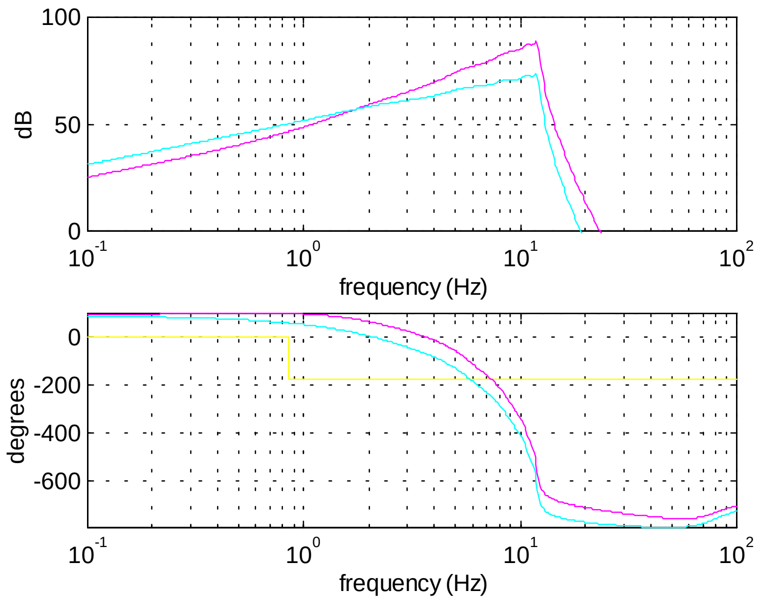

Figure 25: SOS Yaw Controller Response versus Frequency

Note that all of the controllers (POS, PIT, YAW) use a 10 pole, 12 Hz, 1 dB passband ripple chebychev and a zero at DC as the base filter function. The zero at 1 Hz and the pole at 40 Hz compensate the pole and zero of the coil driver. The design of the controller includes the ability to add these compensating poles and zeros even though the initial design for the IOO SOS controllers will not use this feature. When determining the gain required for the controller to produce pseudo-critical damping without these compensating poles and zeros, the controller voltage gain at 1 Hz should be used. It should also be noted that the controller gain curves shown above are the voltage gain of the controller assuming a 6.9Kohm resistor in series with the coil. If this resistor is changed in an effort to change the range and noise the voltage gain of the controller needs to be scaled accordingly, i.e.

$$ScaleFactor = \frac{R_{series}}{6.9Kohm}$$

3.3.3. SOS Coil Driver

In an effort to more effectively match the capabilities of the coil driver circuitry to the requirements for each type of optic used in the IOO it was decided to produce several versions of SOS controller, each with a different resistor in series with the coil. Table 2 shows the resistance, maximum drive current and predicted noise for each suspension controller. These values will meet the range requirements shown in detailed in LIGO T980039 and T960151.

Table 2: Coil Driver Series Resistance vs. Controller

Controller	*Series Resistance*	*Max. Drive Current*	*Predicted Noise*
MMT1, MMT2, SM1, SM2	430 ohms	58 mAp-p	$1.6x10^{-17}\left(\frac{f}{40}\right)^{-2}\ (m/(\sqrt{Hz}))$ f > 40Hz
MC1, MC2, MC3	7.82K ohms	3.20 mAp-p	$3.8x10^{-18}\left(\frac{f}{40}\right)^{-2}\ (m/(\sqrt{Hz}))$ f > 40 Hz
MMT3	227 ohms	110 mAp-p	$5.2x10^{-19}\left(\frac{f}{40}\right)^{-2}\ (m/(\sqrt{Hz}))$ f > 40 Hz

3.3.4. SOS ASC Input Elliptic Filter

The SOS ASC input filter will be identical to the circuit shown in section 2.3.4. LOS ASC Input Elliptic Filter.

4 SUSPENSION SYSTEM LAYOUT/DESIGN

4.1. Sensor Actuator Head Design

The design of the sensor actuator head will be the same as the 40 meter beam splitter and recycling mirror systems. The sensor actuators are as follows:

- 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: #32 AWG teflon wire, ~400 turns per head
  - Coil size: 7.66 mm ID, 12.66 mm OD, 5 mm L
- Housing
  - Material: Macor[1]
  - Size: 25.3 mm OD x 25.4 mm L

1. Machinable glass ceramic: manufactured by Corning.

- Wire clamp: Wires wrapped around a screw which is threaded into back of the head housing.

4.2. Location and Number of Devices

The table below is a summary of the known suspension systems for the LIGO 4 Km interferometers.

Table 3: 4 Km Interferometer Suspension Systems

Type	*Quantity*	*Optic Being Controlled*
LOS	6	beam splitter recycling mirror 2 ea. ITM 2 ea. ETM
SOS	7	3 ea. IOO Mode Cleaner Mirrors 3 ea. IOO Mode Matching Mirrors 1 ea. Steering Mirror

The table below is a summary of the known suspension systems for the LIGO 2 Km interferometer.

Table 4: 2 Km Interferometer Suspension Systems

Type	*Quantity*	*Optic Being Controlled*
LOS	8	beam splitter recycling mirror 2 ea. ITM 2 ea. ETM 2 ea. Folding Mirrors
SOS	8	3 ea. IOO Mode Cleaner Mirrors 3 ea. IOO Mode Matching Mirrors 2 ea. Steering Mirrors

Rack locations for Washington suspension electronics are detailed in the table below. Louisiana rack locations are should be similar.

Table 5: Suspension Electronics Rack Locations

Suspension System	*Equipment Rack*
4 Km IOO systems	1X6
4 Km BS/RCM/ITM	1X7
4 Km ETM	1X21, 1Y22
2 Km IOO systems	2X4
2 Km BS/RCM/ITM	2X14
2 Km ETM	1X18, 1Y22

All system level schematics will be done using Protel. The use of Protel will allow cross connect lists, cable connections and system bill of materials to be generated automatically from the system schematic.

4.3. Vacuum Cabling and Connections to Sensor Actuator Heads

The vacuum cabling used for suspension systems will MDC model KAP-R25-300 cable with MDC model D25-PCC 25 pin D connectors on each end. The vacuum feedthroughs will be MDC model 633002-1000.

4.4. Operator Screens and Controls

4.4.1. Operator Screens

Operator screens will be developed similar to those used for the 40 meter beam splitter and Recycling Mirror suspension systems and LOS and SOS test stands at Caltech. A copy of the SOS Test Stand screen is shown in Appendix 2 SOS Test Stand Operator Screen.

4.4.2. Control and Monitor Points

The control and monitor points for the LOS and SOS systems will be similar to those designed into the beam splitter and recycling mirror suspension systems. They are:

- Photodiode amplifier voltage monitors
- POS, PIT, YAW, SIDE input voltage monitors
- Coil driver output current monitors
- PIT and YAW bias voltage adjust
- Run/Acquire Mode select
- POS, PIT, YAW, SIDE polarity invert select

- Input matrix gain adjust
- Output matrix gain adjust
- POS, PIT, YAW, SIDE gain adjust

Control points will be accessible via the operator screens. Monitor points will be displayed on operator screens and in addition have separate front panel monitors suitable for connecting field oscilloscopes.

4.4.3. Test Inputs

Test inputs for the LOS and SOS systems will be similar to those designed into the beam splitter and recycling mirror suspension systems. They are:

- POS, PIT, YAW, SIDE test inputs
- Coil driver test inputs
- LSC test input

All test inputs can be enabled and disabled by the operator.

4.5. Back-up and Restore Signals

The following is a list of the signals that should be periodically backed up such that the operator may restore the suspension system to a previous state.

- POS, PIT, YAW and SIDE gain settings
- Output matrix gain settings
- PIT and YAW bias settings

EPICS BURT files will be developed to allow these operations.

4.6. Operator Alarms

Operator alarms, using EPICS ALH, will be developed for the following:

- POS, PIT, YAW, SIDE input signals approaching high or low limits (MINOR)
- Coil driver output voltage approaching high limits (MINOR)

4.7. Data Acquisition Signals

The table below is a list of the signals to be acquired by the LIGO DAQ system for each LOS and SOS system.

Table 6: Suspension Data Acquisition Channels and Rates

Signal	*Quantity (per controller)*	*Sample Rate (samples/sec)*
Coil Driver Output Voltage	5	2048
Photodiode Input Voltage	5	2048
Coil Current Sum Channel	1	16384
POS, PIT, YAW, SIDE Gain	4	1
POS, PIT, YAW, SIDE enable/disable status	4	1
POS, PIT, YAW, SIDE invert status	4	1
Input Matrix Gain Settings	12	1
Output Matrix Gain Settings	12	1
POS, PIT, YAW, SIDE Invert/Non-invert Status	4	1
Run/Acquire Mode Status	1	1

5 TEST PLANS, TESTING AND OPERATIONS

A test stand for testing suspension controllers and satellite amplifiers has been constructed at Caltech. Test stands for the Washington and Louisiana sites are also been constructed. These site test stands will be located in the optics lab and will be used to aid in the initial hanging and check out of Input Optics and Core Optics.

Test plans have been developed for testing suspension controllers and satellite amplifiers. In addition, test plans will be developed to test each individual suspension system as it is installed. These documents are listed in Table 7.

Table 7: Suspension Electronics Test Plans

Document	*Number*
LOS and SOS Controller Test Plan	T980042
Satellite Module Test Plan	T980TBD
Suspension System Electronics Hardware and Software Test Plan	T980TBD

Operations manuals for the suspension systems will be developed for each type of controller or for each system (Input Optics and Core Optics). These manuals will be similar to the operators manual developed for the 40 meter suspension system (LIGO T970103). These operations manuals will include:

- block diagrams of the modules and system
- descriptions of operator interfaces
- basic troubleshooting guidelines and tips for the system
- a list of relevant schematics and documents for the system.

APPENDIX 1 SCHEMATIC LIST

Table 8: Suspension Schematics

Schematic	*Number*
LOS Controller	D980013
SOS Controller	D980181
Satellite Amplifier	D961289
Suspension Controller DAQ Daughter Board	D980234
WA 2K Suspension Rack Drawing	D980211
WA 2K Core Optics Suspension Wiring	TBD
WA 4K Suspension Rack Drawing	TBD
WA 4K Core Optics Suspension Wiring	TBD
LA 4K Suspension Rack Drawing	TBD
LA 4K Core Optics Suspension Wiring	TBD

APPENDIX 2 SOS TEST STAND OPERATOR SCREEN