LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Large and Small Optics Suspension Electronics Preliminary 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.

1.2. System Overview

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

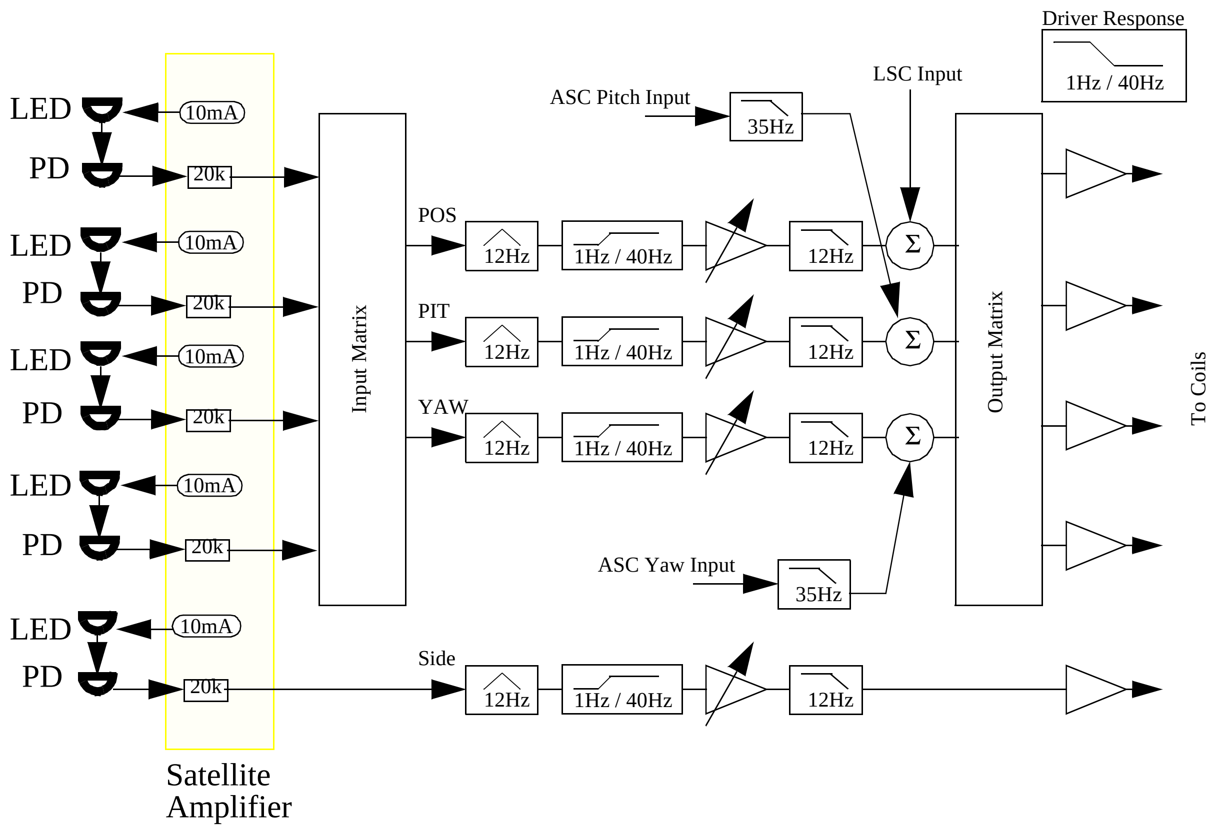


Figure 1: Suspension Control System Block Diagram

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 many respects the design of the LIGO suspension system electronics will be simpler than those used and tested on the 40 meter interferometer. The differences are as follows:

1. The output coil driver has been redesigned to meet the LIGO requirements. This redesign incorporated a 1 Hz pole and 40 Hz zero into the driver response. This required that a 1 Hz zero and 40 Hz pole be added to the suspension controller response.
2. The new coil driver design with a pole at 1 Hz allowed the LSC input to be moved from a direct injection into each coil, to injection directly into the POS path of the controller. This removed the need for a separate adjustable output matrix for the LSC input.
3. The new coil driver design with a pole at 1 Hz allowed the last 8 poles of the chebychev filter required by the servo design to be moved from after the output matrix to before the output matrix. This reduces the required number of filters from 5 to 4.
4. The ASC input with its 35 Hz elliptic filter has been incorporated into the design. This replaces the global pitch and yaw inputs used on the 40 meter electronics. In addition, the sep-

arate AC and DC gain paths required by the 40 meter are not required by LIGO and have been removed from the design.

5. Testing on the 40 meter has shown that the input matrix does not need to be adjustable by the operator.

1.3. 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:

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

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

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.

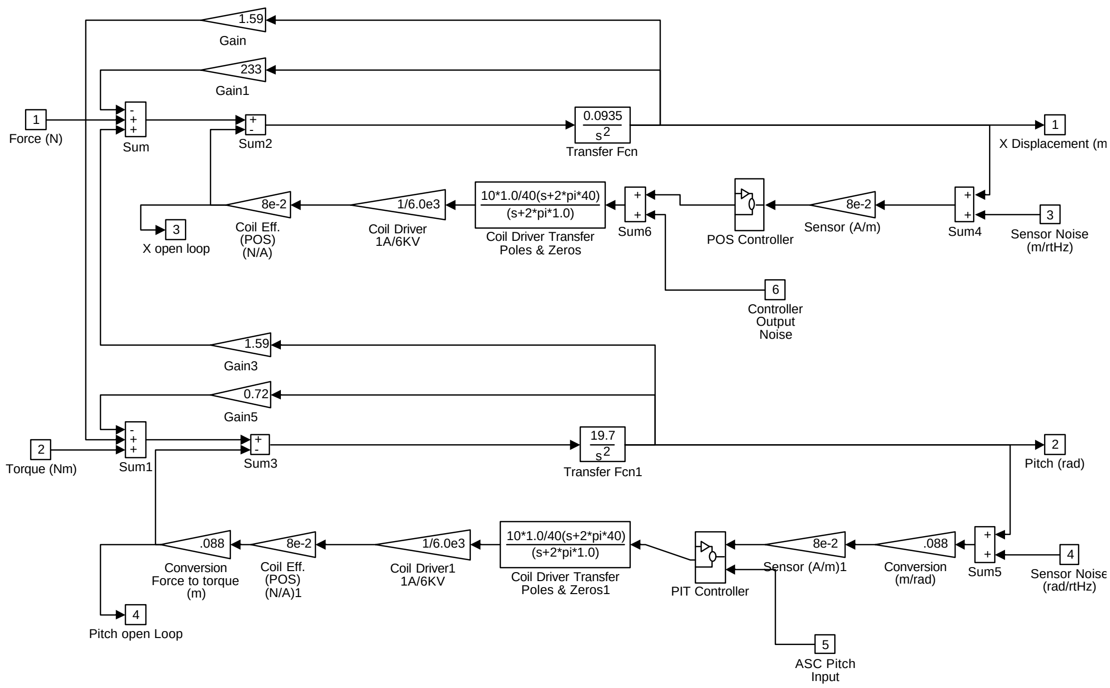


Figure 2: LOS Simulink Model for Position and Pitch Degrees of Freedom

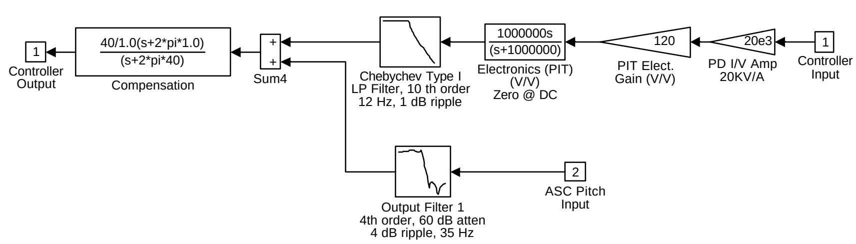


Figure 3: LOS Pitch Controller

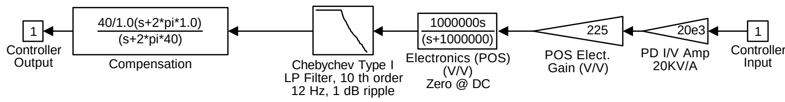


Figure 4: LOS Position Controller

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).

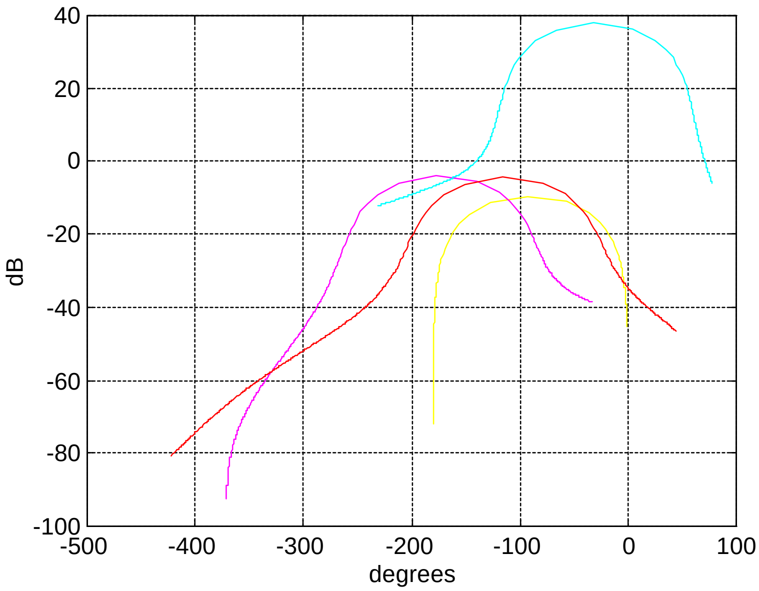


Figure 5: Nichols Plot for LOS Position Degree of Freedom

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).

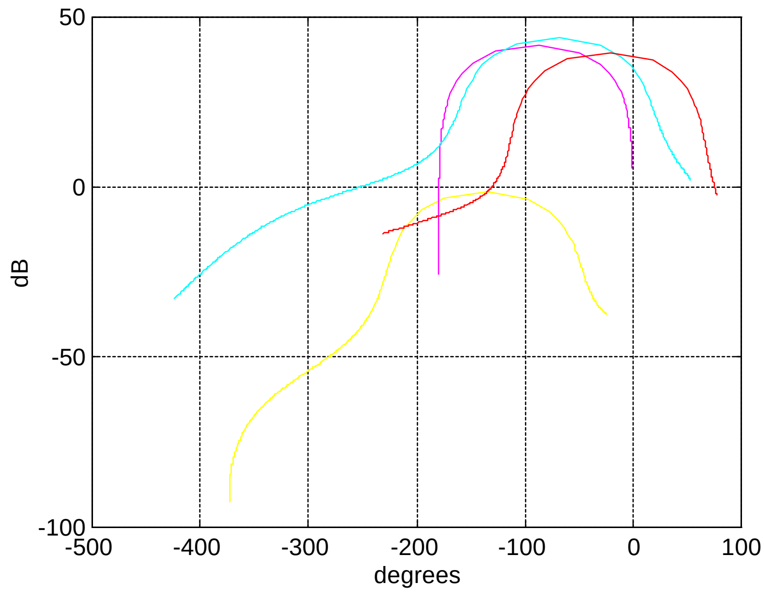


Figure 6: Nichols Plot for LOS Pitch Degree of Freedom

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 position and pitch degrees of freedom.

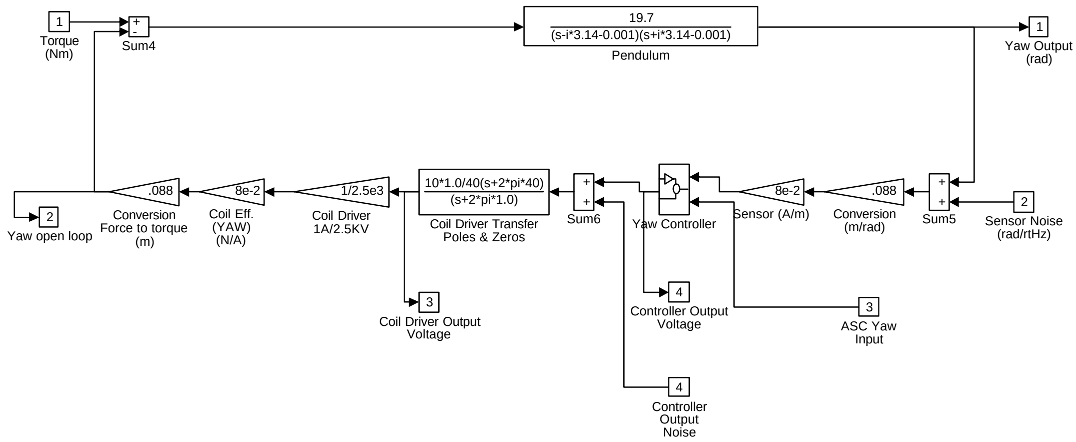


Figure 7: LOS Simulink Model for Yaw Degree of Freedom

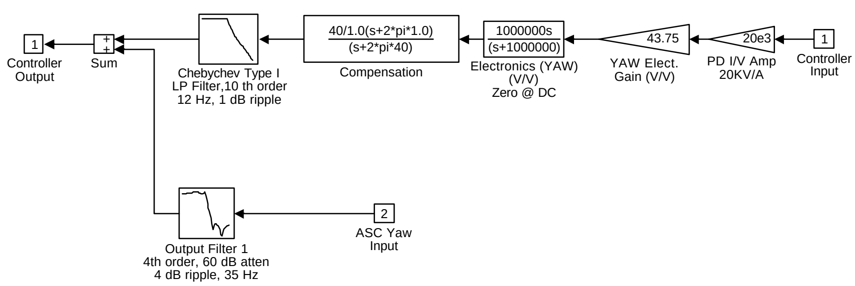


Figure 8: LOS Yaw Controller

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).

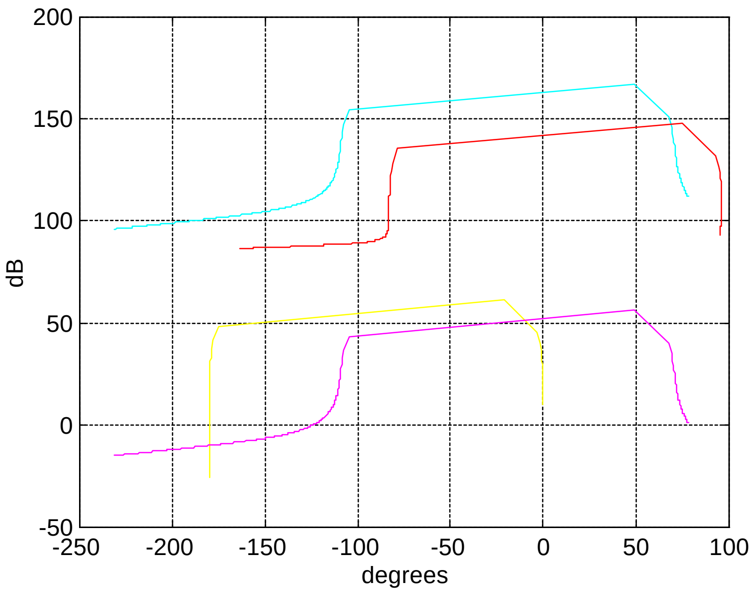


Figure 9: Nichols Plot for LOS Yaw Degree of Freedom

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 amplifier are attached in Appendix 1 Satellite Amplifier Schematics.

2.3. Controller

2.3.1. Input and Output Matrices

Testing on the 40 meter interferometer has determined that the input matrix used by the local damping servo loop do not need to be adjustable by the operator. The input matrix for the LOS controllers will be fixed and adjusted during module calibration.

The 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 D961292).

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.

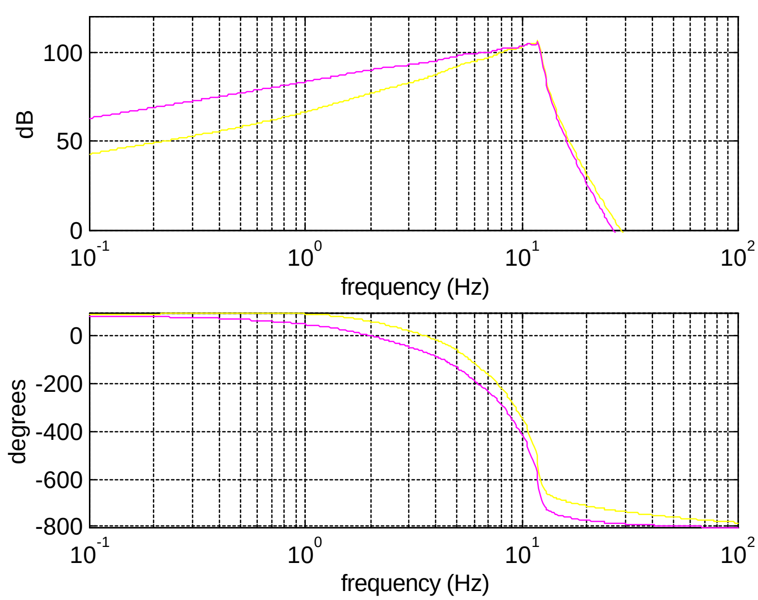


Figure 10: LOS Position Controller Response versus Frequency

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.

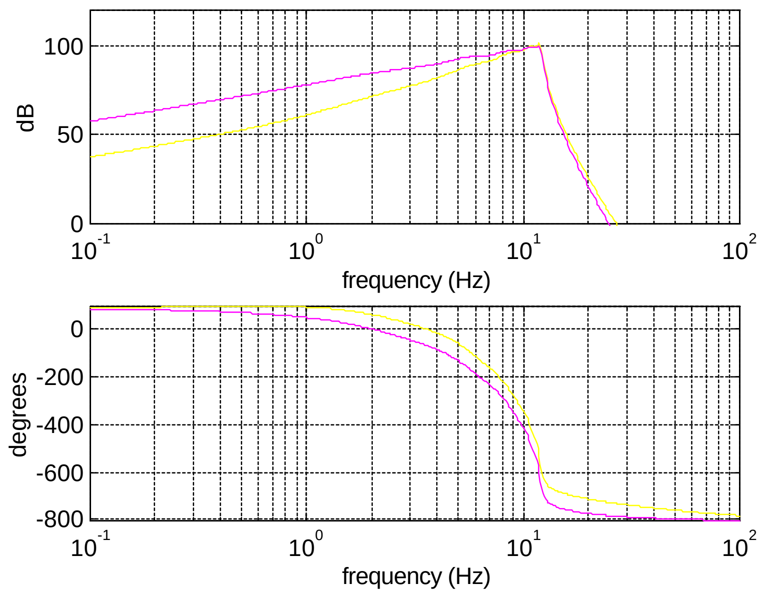


Figure 11: LOS Pitch Controller Response versus Frequency

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.

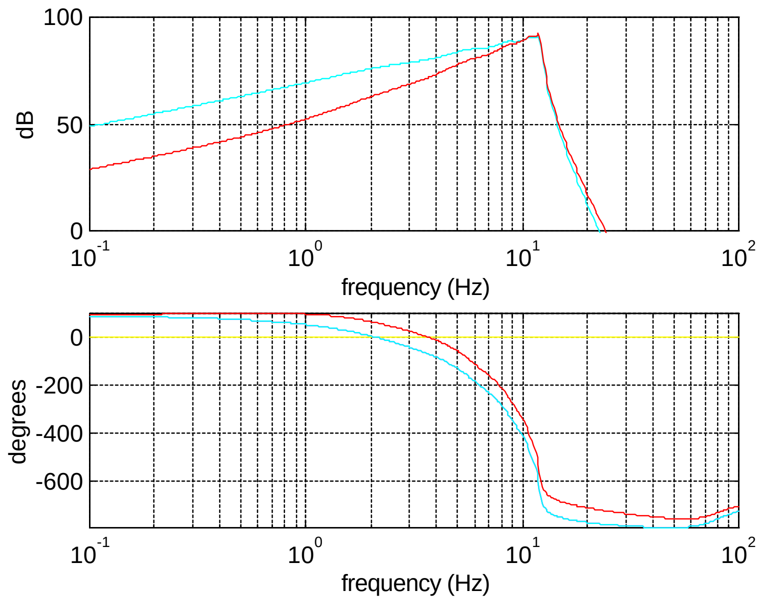


Figure 12: LOS Yaw Controller Response versus Frequency

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. This controller transfer function is the same as that used for the 40 meter interferometer East Vertex Test Mass and only differs from the beam splitter and recycling mirror controllers in terms of frequency (12 Hz instead of 35 Hz).

2.3.3. Coil Driver

The coil driver to used for the LOS will be a new design that has been developed during the preliminary design phase. The design uses a PA-85 high voltage op-amp as the output stage and a low noise AD797 to suppress output current noise above 40 Hz. The allows the LOS electronics to meet both the dynamic range and noise requirements called out in the DRD (LIGO T960151).

A schematic of the Cadence Analog Workbench model that was used to simulate the performance of the coil driver is shown in the figure below.

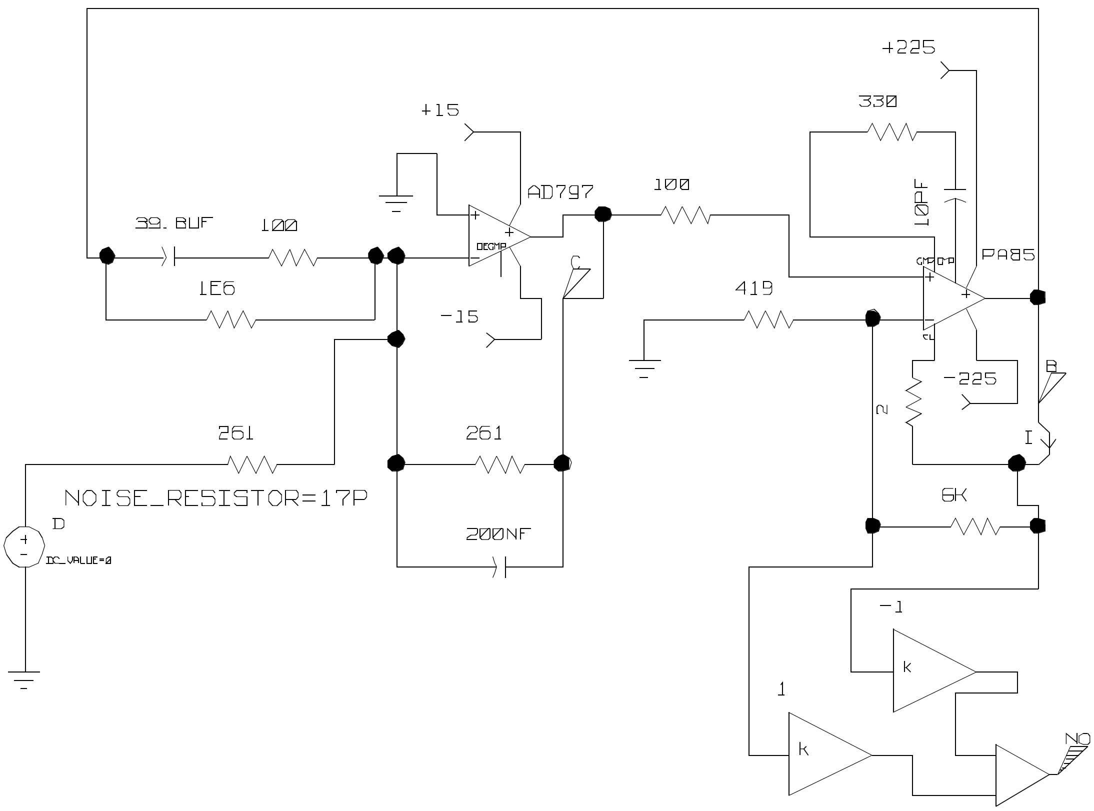


Figure 13: Analog Workbench Model of LOS Coil Driver

The coil is represented by the current probe "I" in the figure. The predicted frequency response and noise current in the coil versus frequency are shown in figure below. Note that the noise current measurement at 40 Hz is labelled 852 fV, but is really 0.852 pA. This is an artifact of how the modeling software calculates noise current.

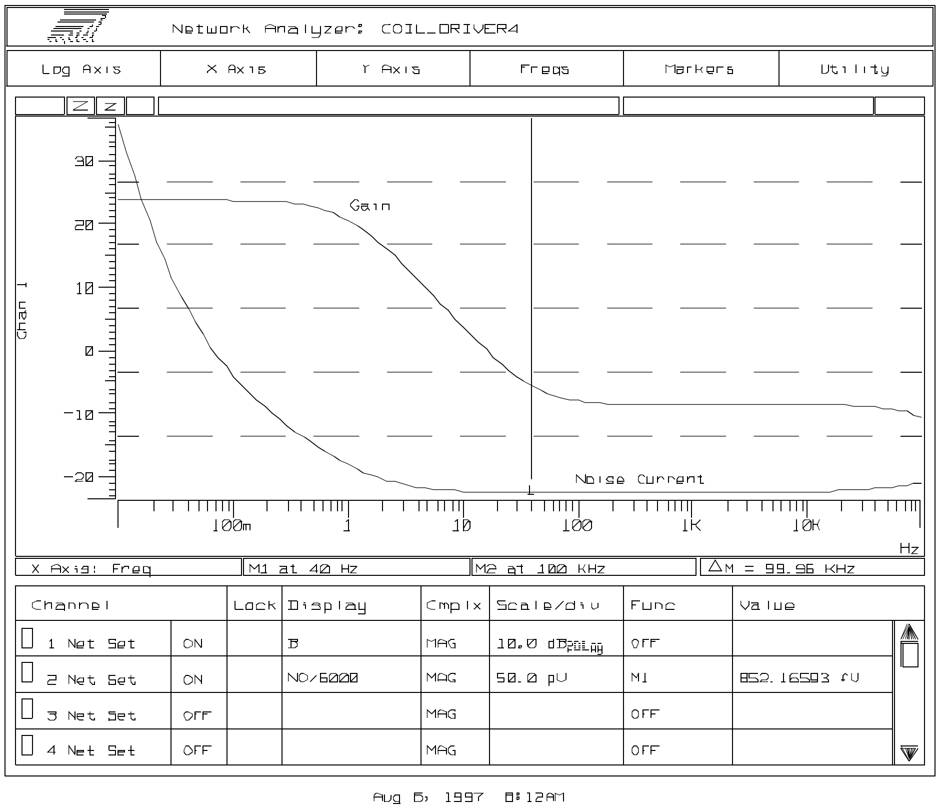


Figure 14: Analog Workbench Predictions for LOS Coil Driver

The theory of operation of the circuit is as follows (ref. Figure 15: Coil Driver Response versus Frequency):

1. The 40 Hz zero required by LSC is set by the 39.8 uF and 100 ohm resistor tied to the inverting input of the AD797. These components also set the corner frequency for the noise suppression in the feedback loop.
2. The 1 Hz pole is set using the following equation:

$$F_{pole} = \frac{40Hz}{GK}$$

where, G is the gain of the PA-85 stage, in this case 15.3 and K is the gain of the AD797 stage in the loop above 40 Hz, in this case 2.61.

3. The gain of the circuit for frequencies below 1 Hz is G. The gain at frequencies above 40 Hz

is 1/K.

4. The output noise voltage of the PA-85 stage is suppressed by a factor GK at frequencies greater than 40 Hz. This suppresses the current noise in the coil since the current noise is the root sum of the squares of the PA-85 output current noise (~Vnoise/6000) and the current noise at the inverting input of the PA-85.

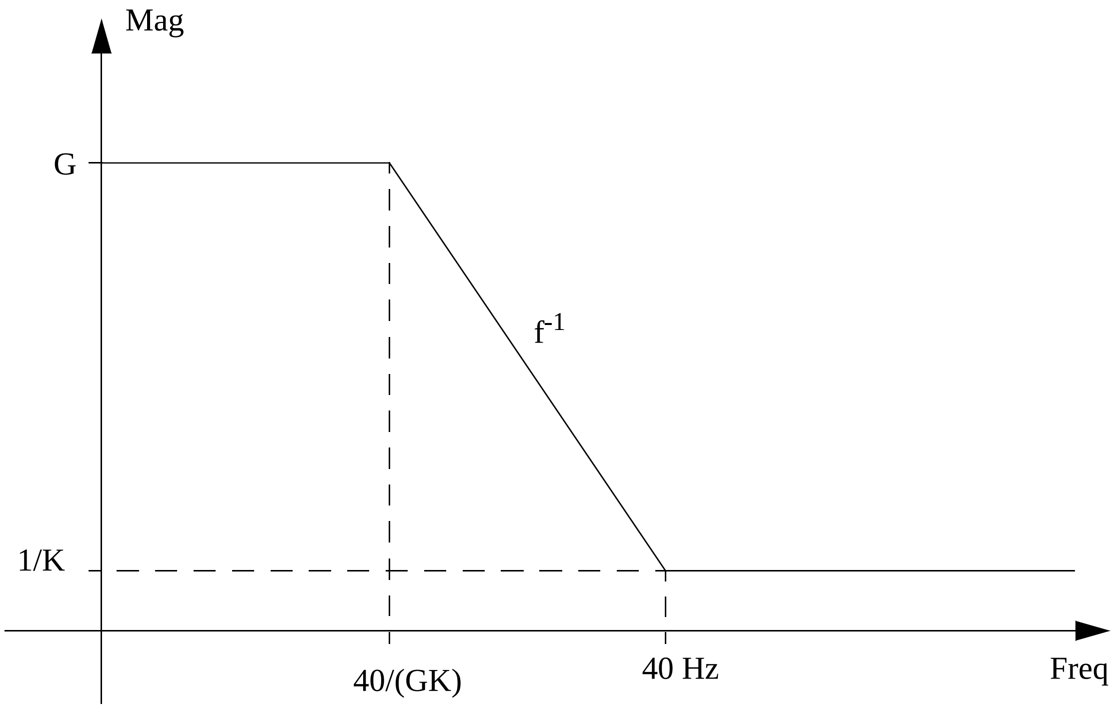


Figure 15: Coil Driver Response versus Frequency

The circuit was prototyped and performance was verified to match the model predictions. The current noise in the coil could not be measured to the level required, but the output noise voltage of the PA-85 stage matched the predictions. From this measurement it can be inferred that the circuit performs as the model predicts.

The Run/Acquire mode option required for the controller will be implemented by providing a switch to open the feedback loop within the coil driver when acquire mode is selected. The response of the coil driver circuit will then be flat from DC to frequencies greater than 10 KHz and have a gain of 23.7 dB (the nominal gain of the circuit from DC to 1 Hz when the feedback is engaged). In addition, a switch will be provided that will remove the compensating 1 Hz zero and 40 Hz pole in the controller when the acquire mode is selected. This is necessary to maintain stability of the local damping loop.

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 $(1uV)/(\sqrt{Hz})$ for frequencies less 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.

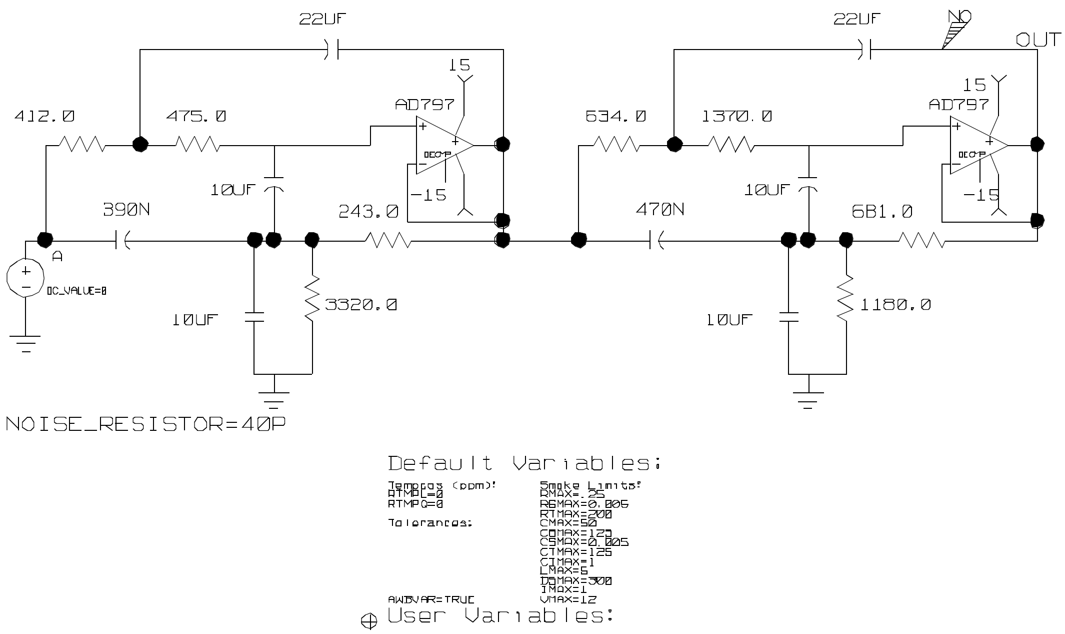


Figure 16: ASC Input Elliptic Filter

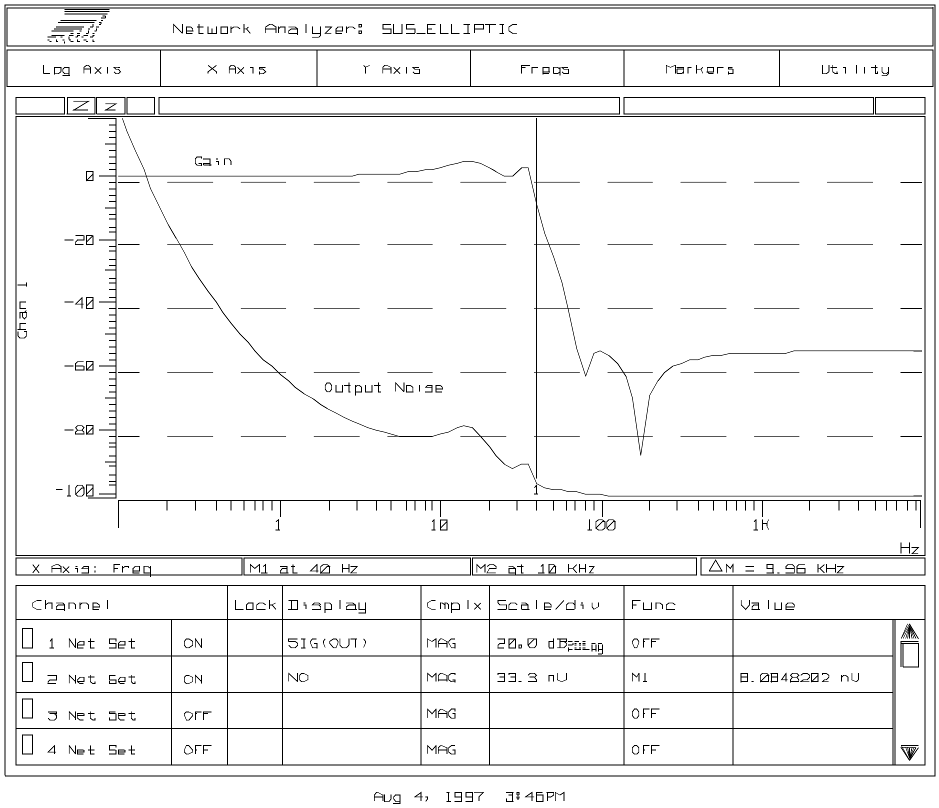


Figure 17: Analog Workbench Predictions for Frequency Response and Output (Input) Noise

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:

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

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

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.

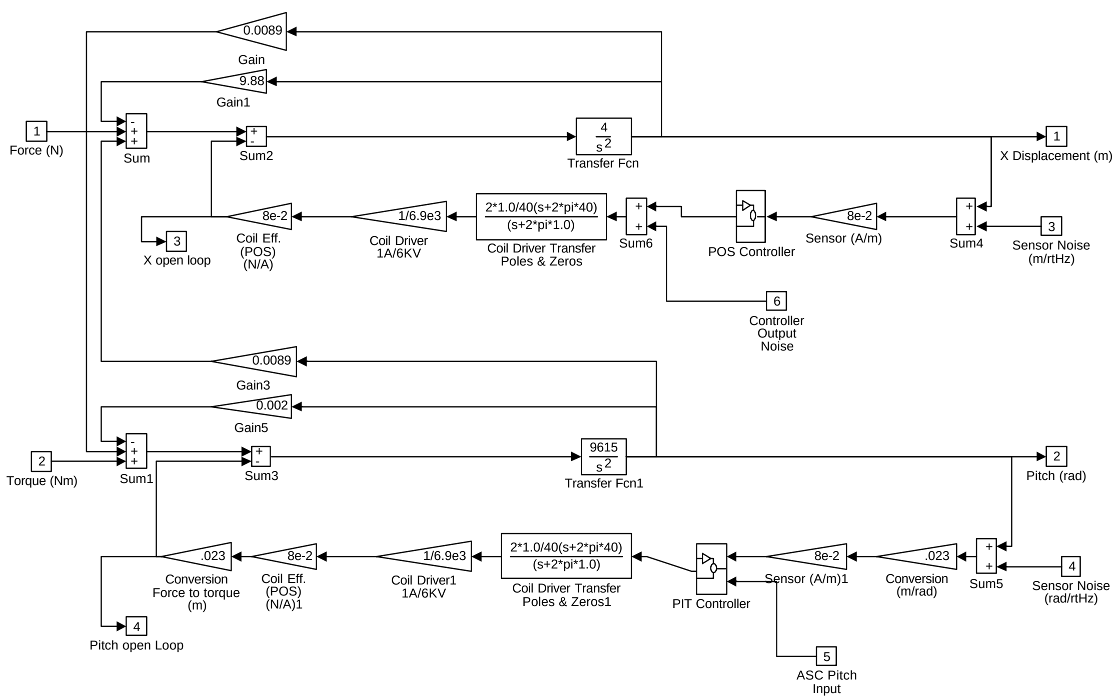


Figure 18: SOS Simulink Model for Position and Pitch Degrees of Freedom

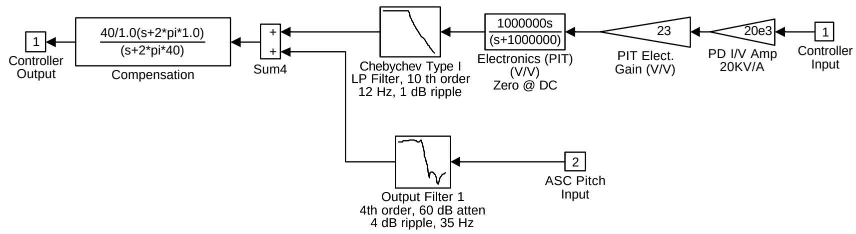


Figure 19: SOS Pitch Controller

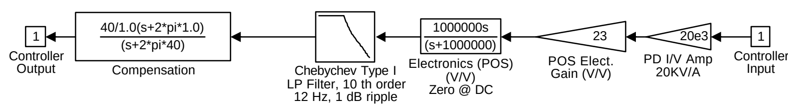


Figure 20: SOS Position Controller

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).

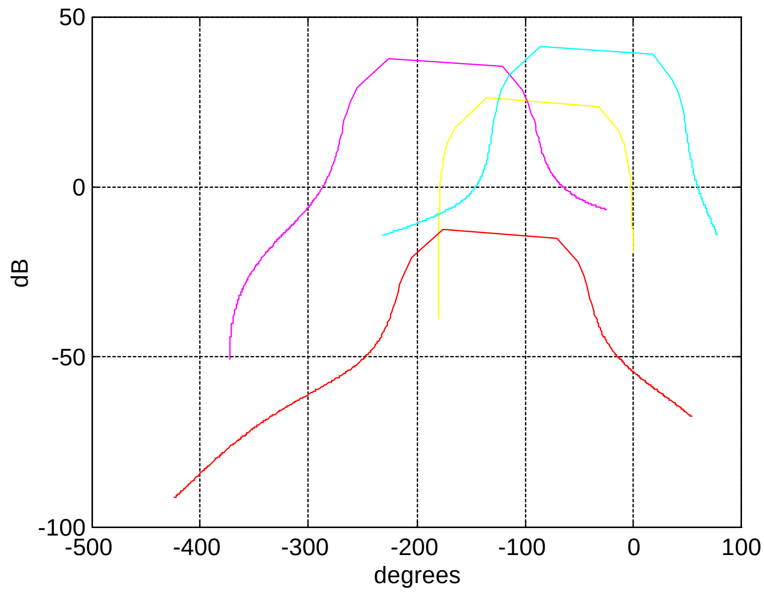


Figure 21: Nichols Plot for SOS Position Degree of Freedom

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).

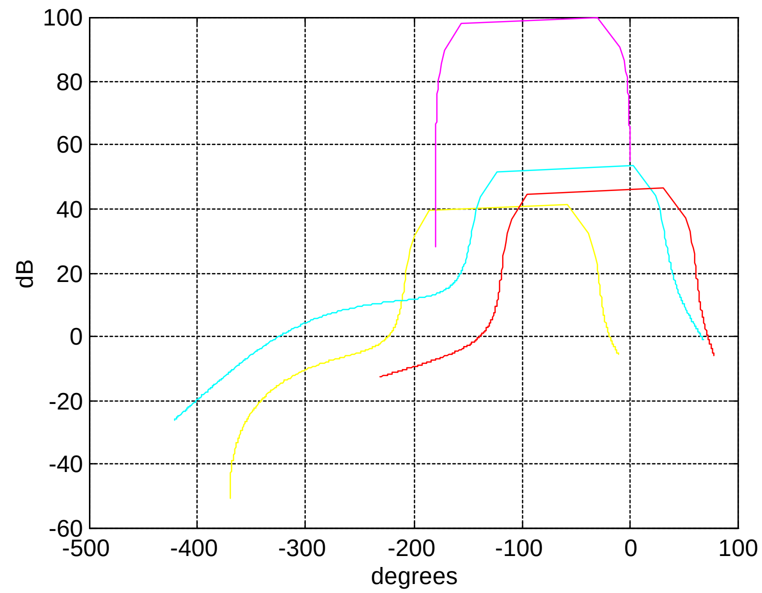


Figure 22: Nichols Plot for SOS Pitch Degree of Freedom

The controllers for pitch and position, shown in Figure 19: SOS Pitch Controller and Figure 20: 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 position and pitch degrees of freedom.

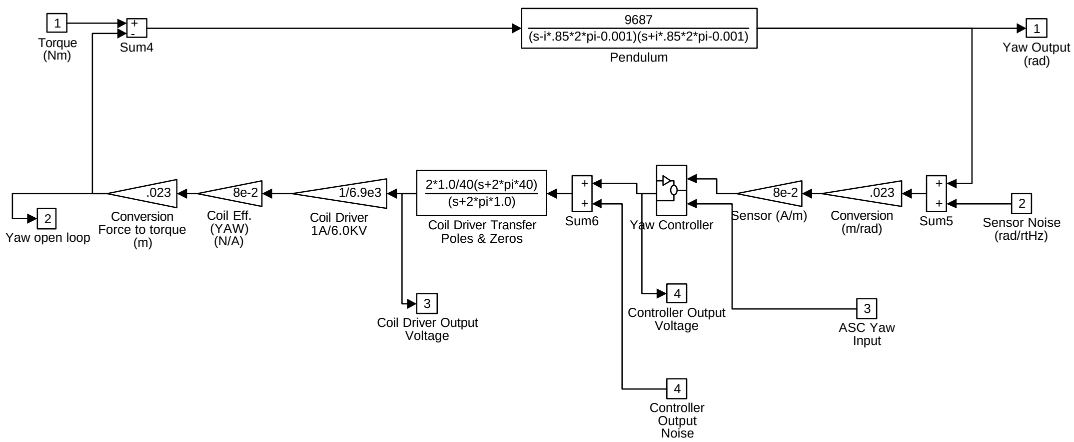


Figure 23: SOS Simulink Model for Yaw Degree

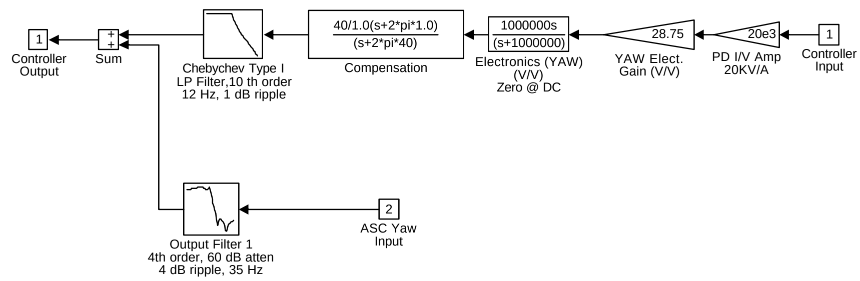


Figure 24: SOS Yaw Controller

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).

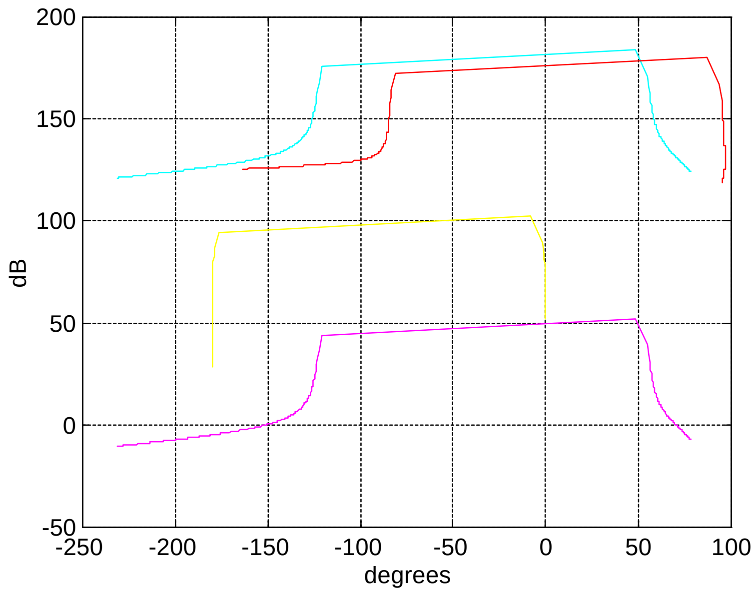


Figure 25: Nichols Plot for SOS Yaw Degree of Freedom

The controller for yaw, shown in Figure 24: 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 amplifier are attached in Appendix 1 Satellite Amplifier Schematics.

3.3. Controller

3.3.1. Input and Output Matrices

Testing on the 40 meter interferometer has determined that the input matrix used by the local damping servo loop do not need to be adjustable by the operator. The input matrix for the SOS controllers will be fixed and adjusted during module calibration.

The 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 D961292).

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.

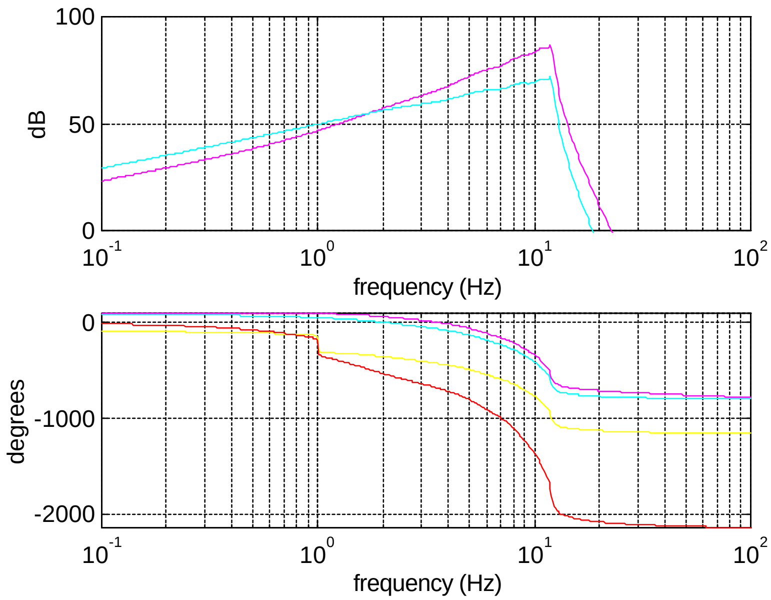


Figure 26: SOS Position Controller Response versus Frequency

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.

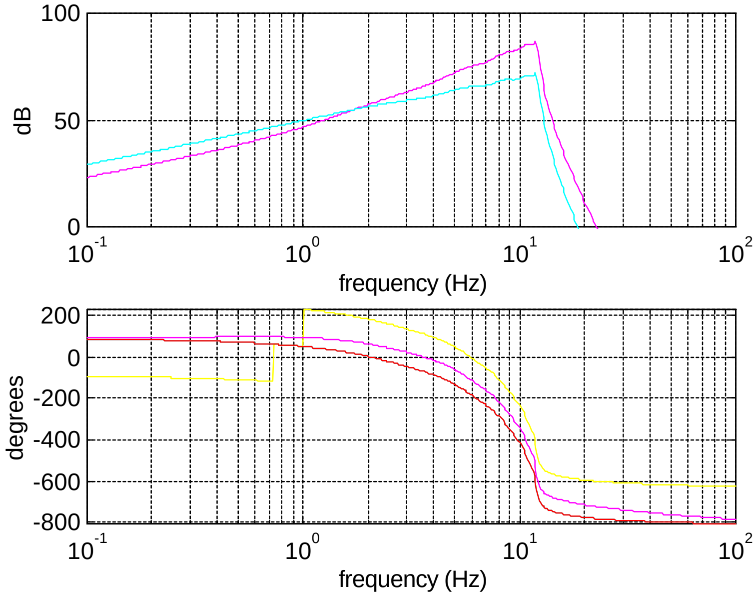


Figure 27: SOS Pitch Controller Response versus Frequency

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.

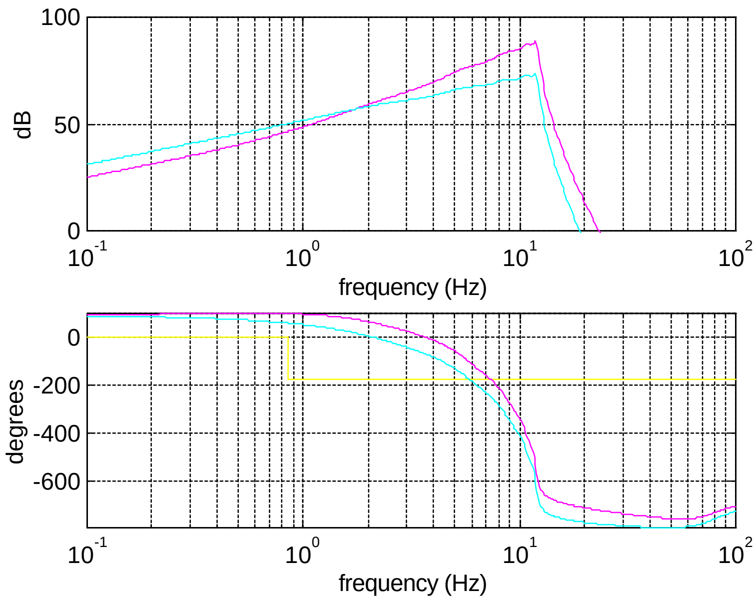


Figure 28: SOS Yaw Controller Response versus Frequency

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. This controller transfer function is the same as that used for the 40 meter interferometer East Vertex Test Mass and only differs from the beam splitter and recycling mirror controllers in terms of frequency (12 Hz instead of 35 Hz).

3.3.3. Coil Driver

The Cadence Analog Workbench schematic used to simulate the performance of the SOS coil driver is shown in the figure below.

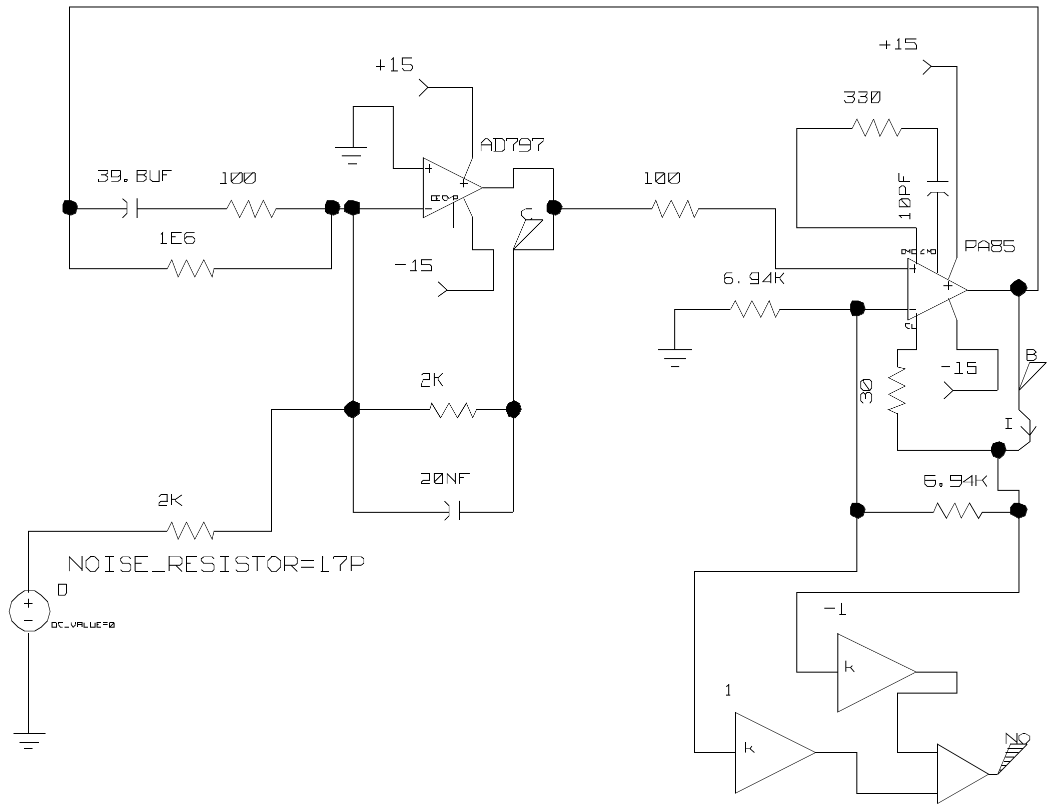


Figure 29: Analog Workbench Model of SOS Coil Driver

As can be seen from the figure, the SOS coil driver is essentially identical to the LOS coil driver described in section 2.3.3. The only changes are:

1. The resistor in series with the coil and the resistor tied to the non-inverting input of the PA-85 have been changed to 6.94K.
2. The driver input resistor and the AD797 feedback resistor have been changed to 2K.
3. The supply voltages for the PA-85 have been decreased to +/- 15 volts.

The predicted frequency response and noise current in the coil versus frequency are shown in figure below. Note that the noise current measurement at 40 Hz is labelled 1.13 pV, but is really 1.13 pA. This is an artifact of how the modeling software calculates noise current.

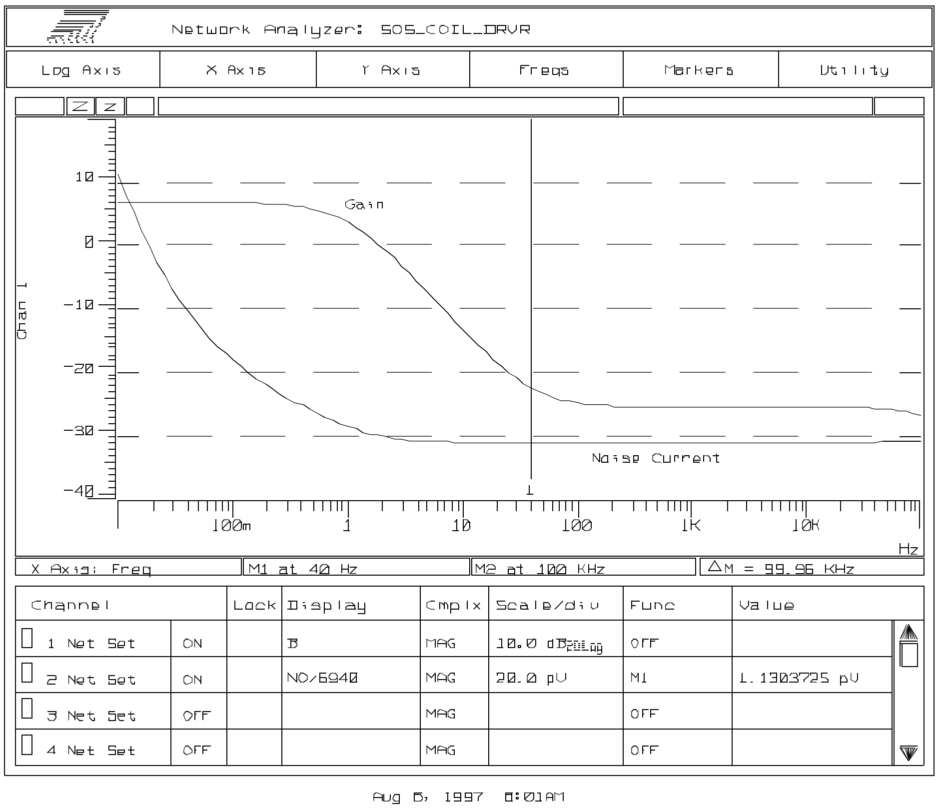


Figure 30: Analog Workbench Predictions for SOS Coil Driver

The Run/Acquire mode option required for the controller will be implemented by providing a switch to open the feedback loop within the coil driver when acquire mode is selected. The response of the coil driver circuit will then be flat from DC to frequencies greater than 10 KHz and have a gain of 6 dB (the nominal gain of the circuit from DC to 1 Hz when the feedback is engaged). In addition, a switch will be provided that will remove the compensating 1 Hz zero and 40 Hz pole in the controller when the acquire mode is selected. This is necessary to maintain stability of the local damping loop.

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 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, ~310 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
  - 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 1: 4 Km Interferometer Suspension Systems

Type	*Quantity*	*Optic Being Controlled*
LOS	7	beam splitter recycling mirror 2 ea. ITM 2 ea. ETM IOO Mode Matching Mirror
SOS	5	3 ea. IOO Mode Cleaner Mirrors 2 ea. IOO Mode Matching Mirrors

1. Machinable glass ceramic: manufactured by Corning.

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

Table 2: 2 Km Interferometer Suspension Systems

Type	*Quantity*	*Optic Being Controlled*
LOS	9	beam splitter recycling mirror 2 ea. ITM 2 ea. ETM IOO Mode Matching Mirror 2 ea. Folding Mirrors
SOS	5	3 ea. IOO Mode Cleaner Mirrors 2 ea. IOO Mode Matching Mirrors

Rack locations for Washington suspension electronics are detailed in the table below. Louisiana rack locations are TBD.

Table 3: Suspension Electronics Rack Locations

Suspension System	*Equipment Rack*
4 Km IOO systems	1X5
4 Km BS/RCM/ITM	1X9
4 Km ETM	1X21
2 Km IOO systems	2X5
2 Km BS/RCM/ITM	2X1
2 Km ETM	1X18

4.3. Vacuum Cabling and Connections to Sensor Actuator Heads

The LOS and SOS systems will use vacuum cabling and connectors similar to those that have been used for the 40 meter beam splitter and recycling mirror suspension systems. The connectors are commercially available vacuum feedthrough manufactured by Ceramaseal or ISI Corp. The cabling is a flexible Kapton ribbon cable that is clamped to the seismic isolation stack elements. The final design of the vacuum cabling and connectors is not complete at this time. When the design is complete, it will be incorporated into the design of the LOS and SOS systems.

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. A copy of the beam splitter screen is shown in Appendix 2 40 Meter Beam Splitter 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
- 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

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)
- POS, PIT, YAW, SIDE input signals beyond high or low limits (MAJOR)

The actual values of the high and low limits for the 40 meter beam splitter and recycling mirror suspension system are currently under investigation. These limits will be used as the initial limits for the LOS and SOS systems.

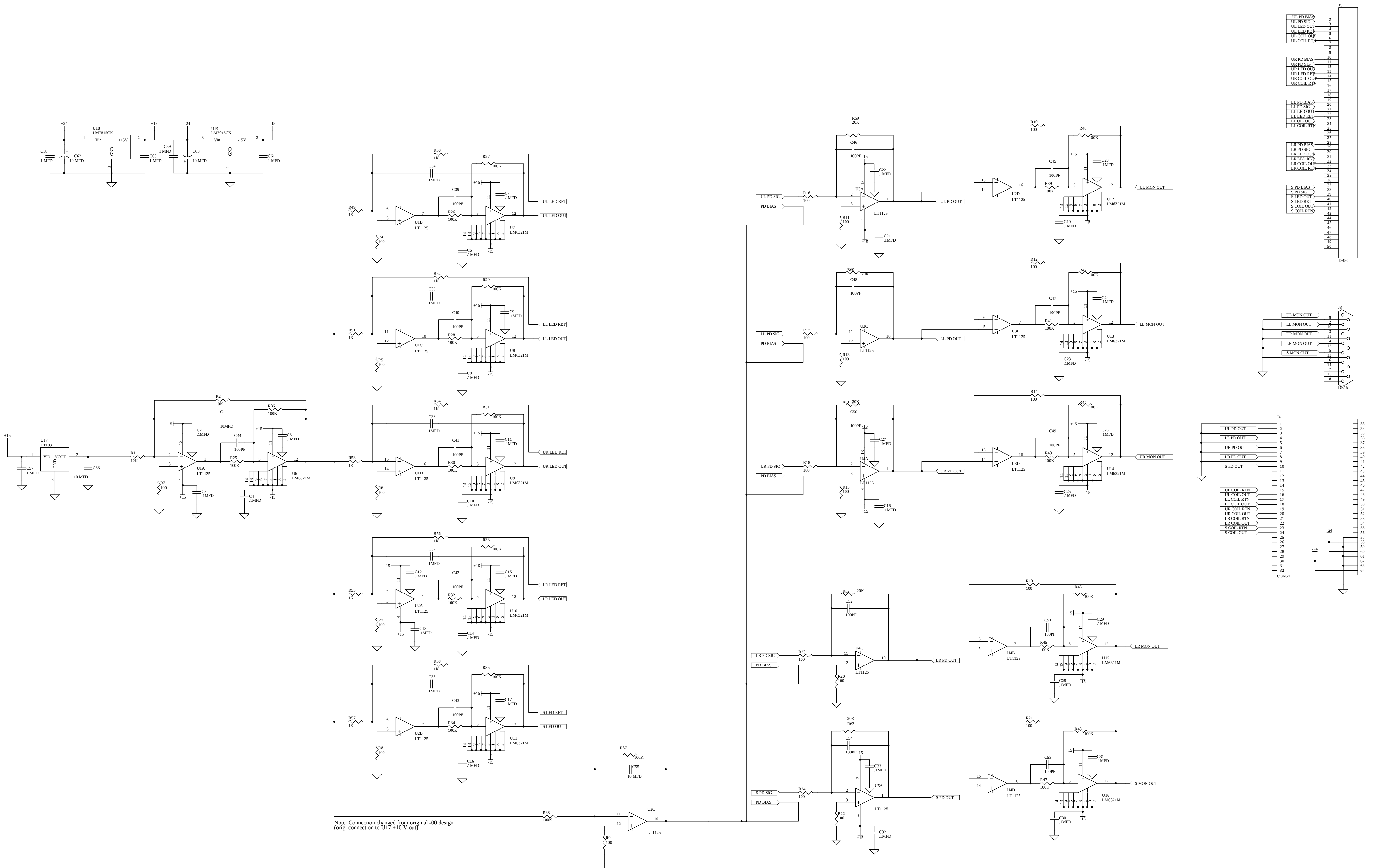
4.7. Data Acquisition Signals

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

Table 4: Suspension Data Acquisition Channels and Rates

Signal	*Quantity (per controller)*	*Sample Rate (samples/sec)*
Coil Driver Output Voltage	5	16 K
Photodiode Input Voltage	5	128
POS, PIT, YAW, SIDE Gain	4	1
Output Matrix Gain Settings	12	1
POS, PIT, YAW, SIDE Invert/Non-invert Status	4	1
Run/Acquire Mode Status	1	1

APPENDIX 1 SATELLITE AMPLIFIER SCHEMATICS



Title: **_BS & RCM Suspension Satellite Amplifier_**				_LIGO Project_ _California Institute of Technology_ _Massachusetts Institute of Technology_
Size: D	Number: D961289	Revision: 01	Engineer: R. Abbott	LIGO
File: I:\CAD\LIGO\BS_RCM_S.~IE\SATELLITE.SCH	Date: 15-Aug-1997	Time: 13:36:32	Sheet 1 of 1	

APPENDIX 2 40 METER BEAM SPLITTER OPERATOR SCREEN