LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Summary of the Controls Prototype Data

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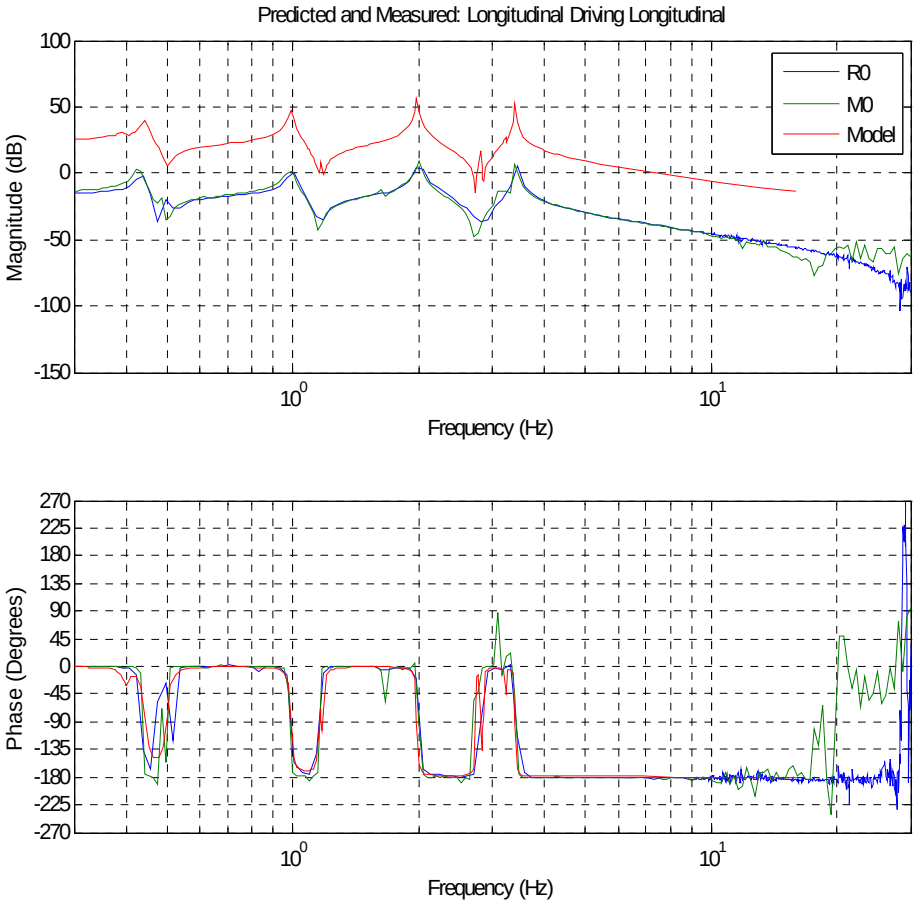
1 Introduction

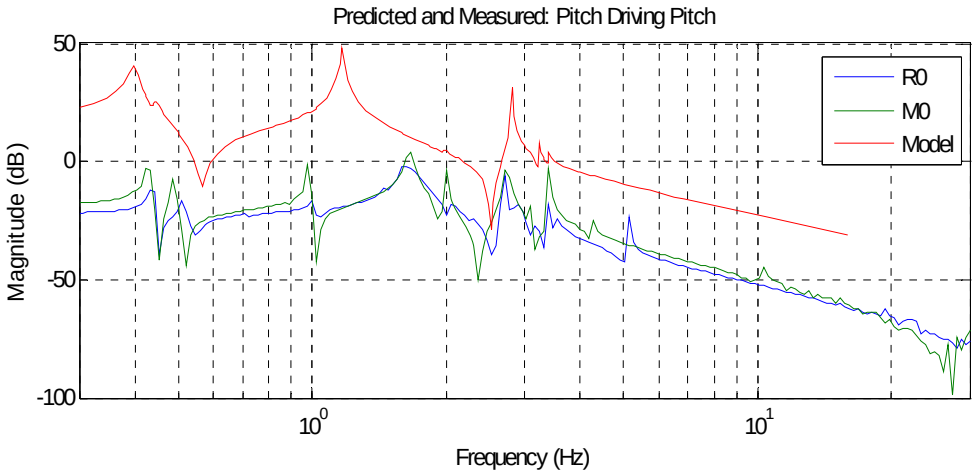
This document summarizes the data collected from the quadruple pendulum controls prototype at LASTI as of June 13, 2006. It includes the transfer functions of the undamped pendulum and their resonance frequencies as well as damping control data such as the control filters, transfer functions, and impulse responses.

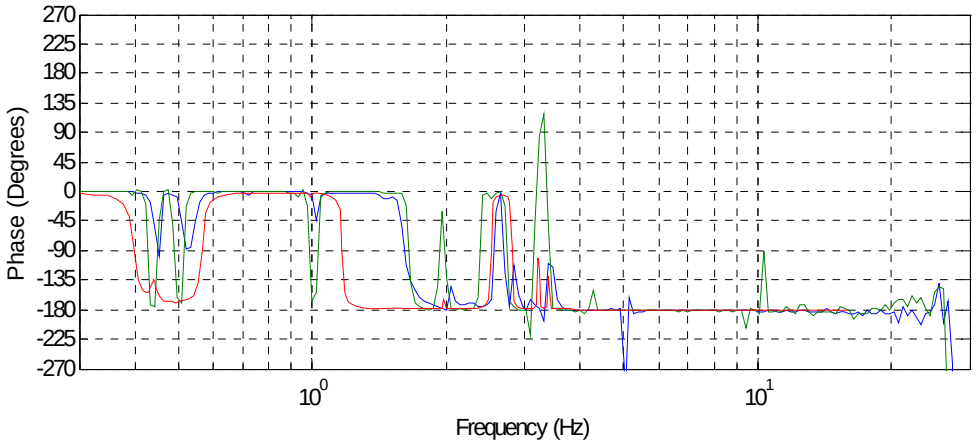
2 Undamped Local Transfer Functions and Resonance Frequencies

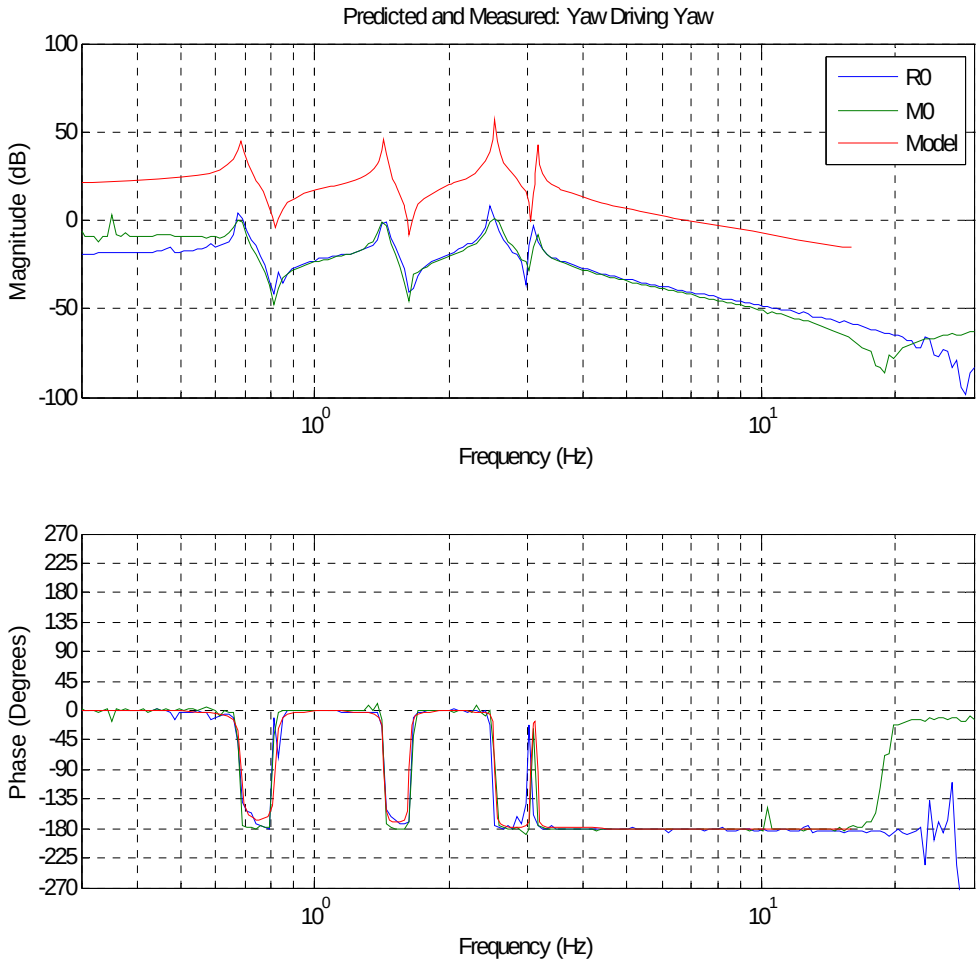
2.1 Local Transfer Functions

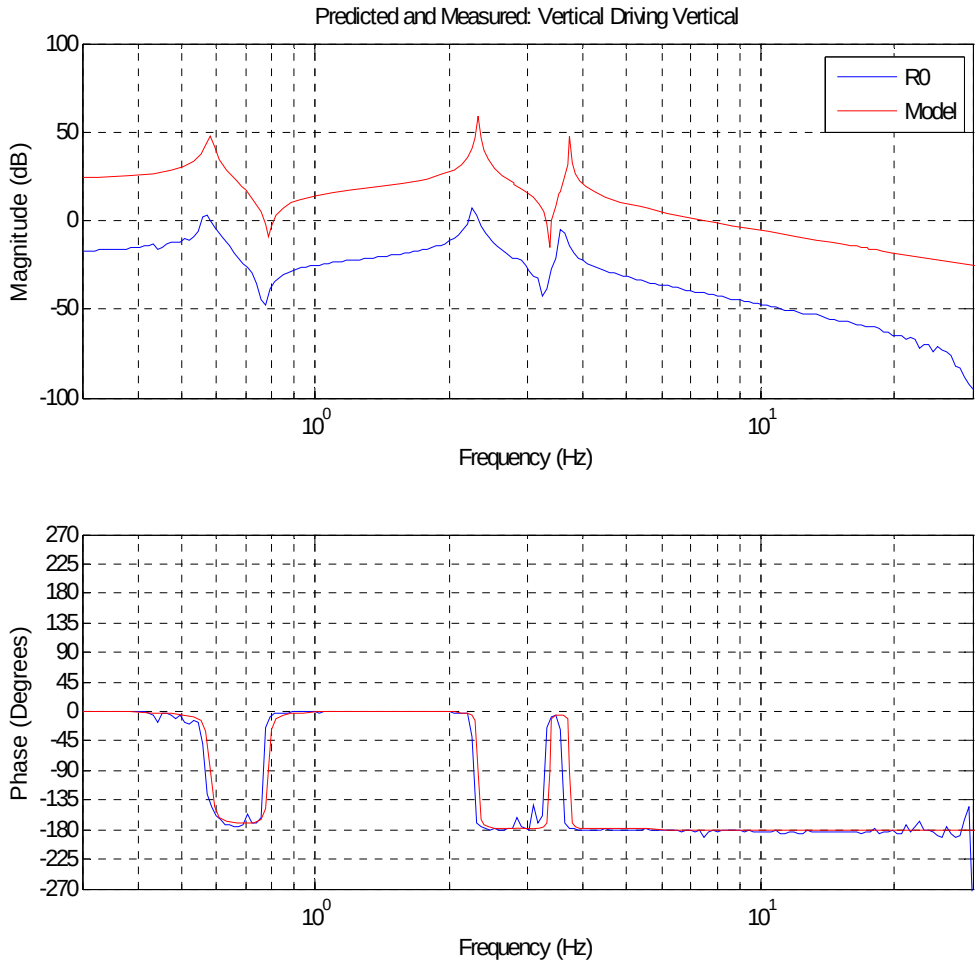
These six figures are plots of transfer functions at the top mass of each pendulum. Each transfer function is measured from a swept sine excitation at one of the degrees of freedom (DOFs) and measured from the same DOF, i.e. longitudinal to longitudinal. The red curve represents the prediction from the model, the blue the measured response from the reaction chain (R0), and the green the main chain (M0). The red curves include some velocity damping in the state space model to add some realism and increase their proximity to the measured data. Specifically I added 0.1 velocity damping to each mode in the state space. There is no other damping in these plots. Due to a misaligned OSEM there currently is no plot of the main chain for the vertical and roll DOFs. The model curves are shifted above the others simply for clarity.

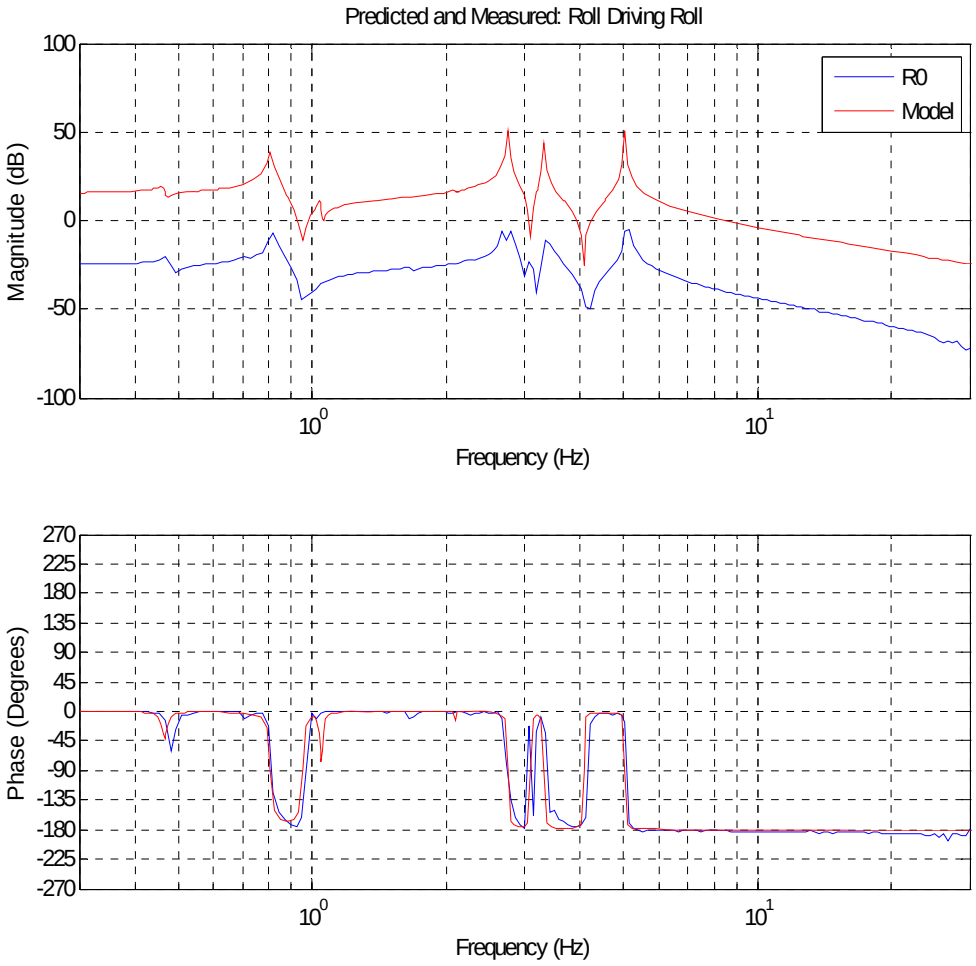

Predicted and Measured: Longitudinal Driving Longitudinal
R0
M0
Model
Magnitude (dB)
100
50
0
-50
-100
-150
10^0
10^1
Frequency (Hz)
Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)

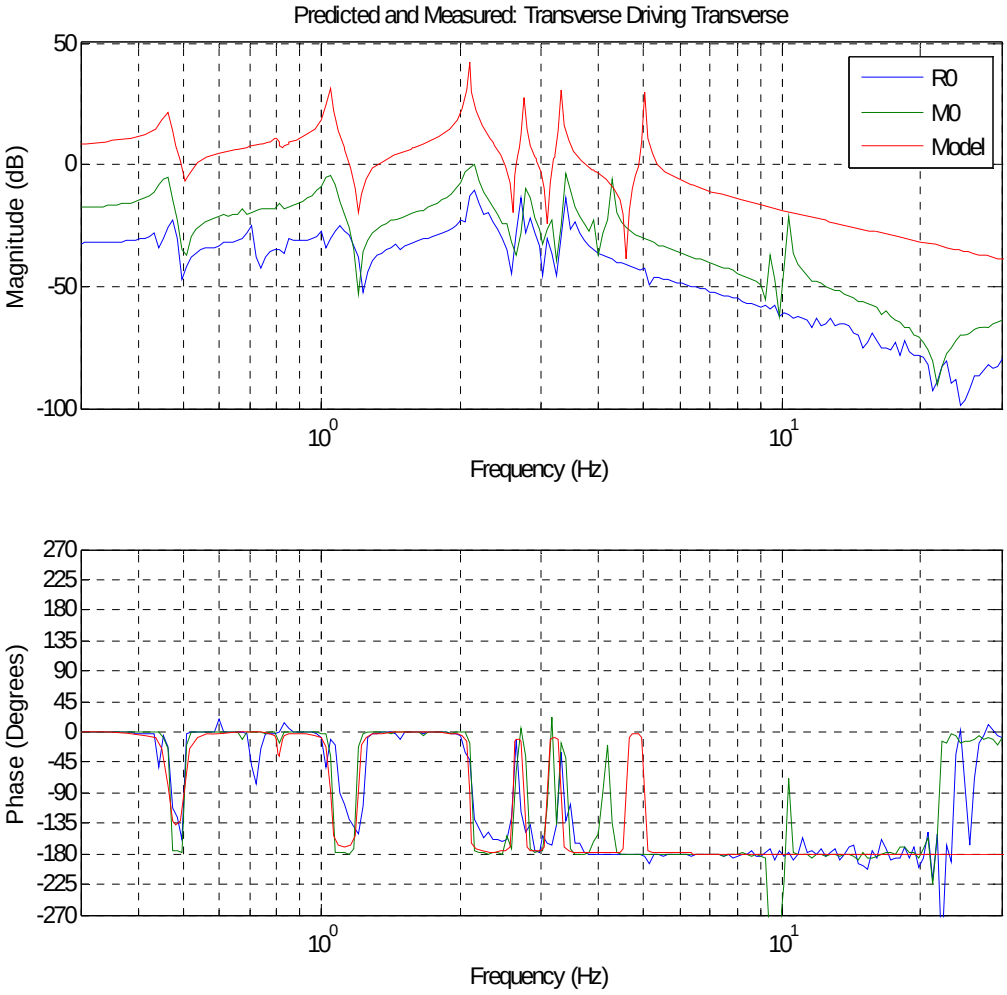

Predicted and Measured: Pitch Driving Pitch
Magnitude (dB)
50
0
-50
-100
10^0
10^1
Frequency (Hz)
R0
M0
Model


Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)


Predicted and Measured: Yaw Driving Yaw
Magnitude (dB)
100
50
0
-50
-100
R0
M0
Model
10^0
10^1
Frequency (Hz)
Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)


Predicted and Measured: Vertical Driving Vertical
Magnitude (dB)
100
50
0
-50
-100
R0
Model
10^0
10^1
Frequency (Hz)
Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)


Predicted and Measured: Roll Driving Roll
R0
Model
Magnitude (dB)
100
50
0
-50
-100
10^0
10^1
Frequency (Hz)
Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)



Both the main chain and reaction chain match each other very well in most instances and generally to the predictions as well. The greatest exception is pitch. The first two pitch modes are greater than the predictions. The first mode is greater by roughly 10% and the second by about 40%. There is a 5.1 Hz mode on the reaction chain, which is most likely coupling to roll due to asymmetrical trim mass. The main chain plot also shows some additional false coupling to the longitudinal DOF because of an arithmetic error during the test. However, some of its modes seem to be coupled to transverse-roll as well. Both the 10 Hz and 4.3 Hz from transverse, which are not supposed to be there, are visible in pitch. It will be interesting to see how strong they are in roll. Some other predicted transverse-roll modes overlap with pitch so it is difficult to tell exactly how many are coupled.

The transverse mode shows the next greatest amount of discrepancy. First there appear to be extra measured modes that are not consistent between the chains. Further testing will need to be done to confirm whether or not these modes actually exist. The 5 Hz peak is also noteworthy. Here it is not visible on the main chain at all and only slightly on the reaction chain. Two additional tests were run on this chain on different dates. Both showed a rather large 5 Hz mode, except that in one case the predicted 4.6 Hz zero came after the pole. For some unexplained reason the zero seems to be wandering around the 5 Hz mode. At one (seemingly random) point while testing the damping,

the damping filter on this DOF went unstable right at that mode on the reaction chain. The instability was removed with a 5 Hz notch. The only external event that occurred, in addition to our normal temperature fluctuations, was a HEPI run between the first and second sets of data.

2.2 Local Resonance Frequencies

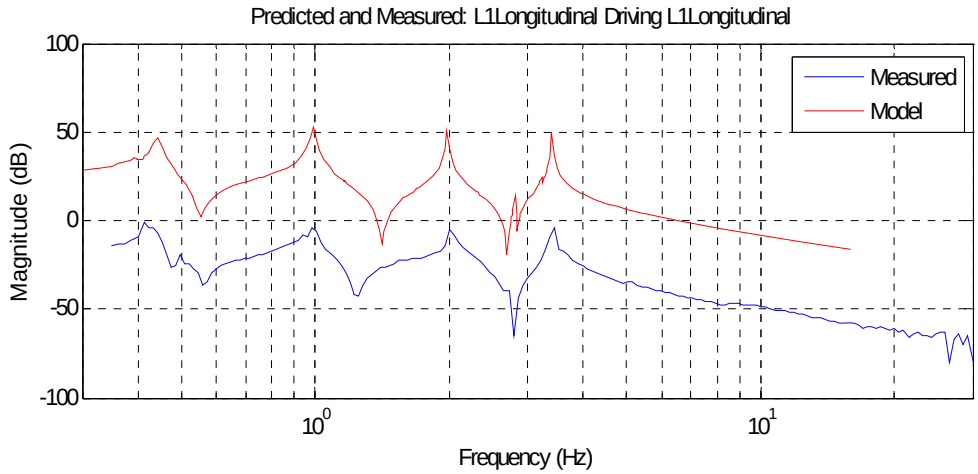
This table lists all the predicted modes next to all the reaction chain modes consistent with the main chain, where applicable.

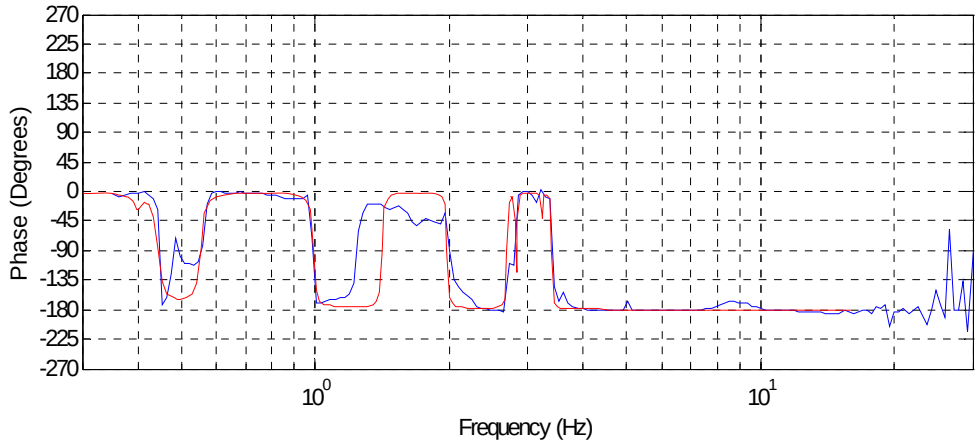
Long-Pitch			Transverse-Roll			Yaw			Vertical	
Pred.	Meas.		Pred.	Meas.		Pred.	Meas.		Pred.	Meas.
0.396	0.44		0.464	0.467		0.685	0.67		0.595	0.57
0.443	0.49		0.810	0.82		1.428	1.43		2.36	2.25
0.987	1.0		1.04	1.096		2.538	2.46		3.79	3.57
1.167	1.63		2.10	2.14		3.167	3.11		17.30	-
1.981	2.0		2.76	2.73						
2.818	2.7		3.33	3.35						
3.228	3.18		5.12	5.1						
3.401	3.4		25.08	-						

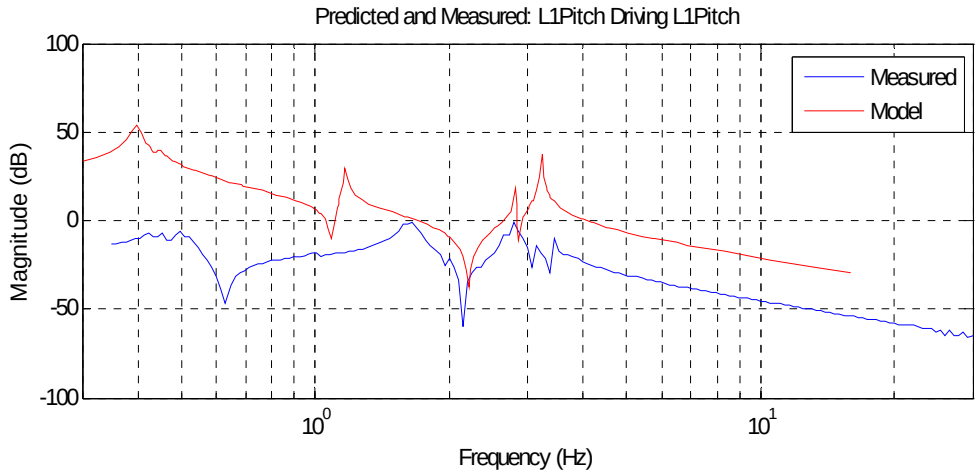
It is predicted that 22 of the 24 modes will be visible in the measurements. Generally this is true, however some of the smaller modes are rather difficult to distinguish. More testing will need to be done to confirm the locations in these cases. The 0.49 Hz measured pitch mode likely corresponds to the 0.396 predicted mode.

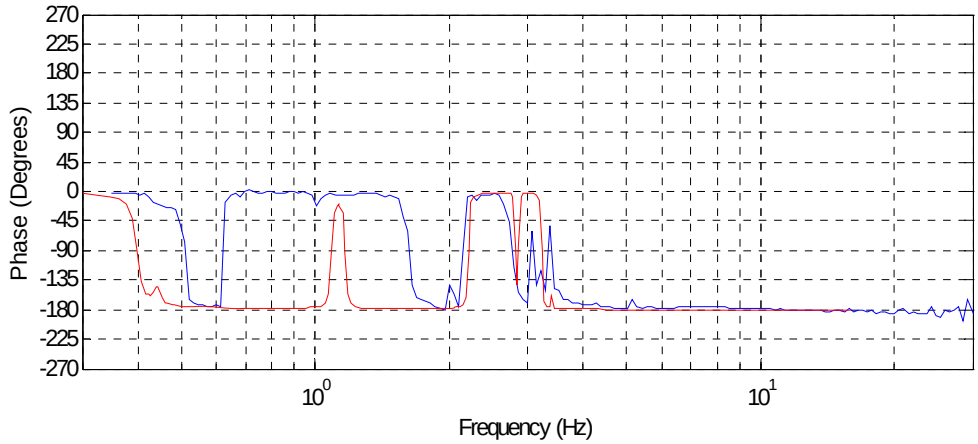
3 Undamped Global Transfer Functions

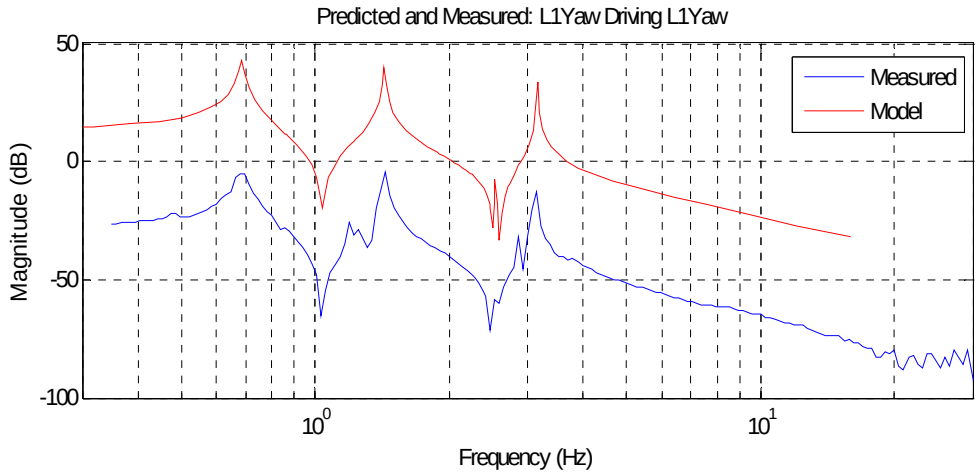
This section includes plots of the six global to global DOF transfer functions i.e. UI Yaw to UI Yaw. L1 is the UI mass and L2 the penultimate mass. The predicted response from the model is plotted in red along with the measured response in blue.

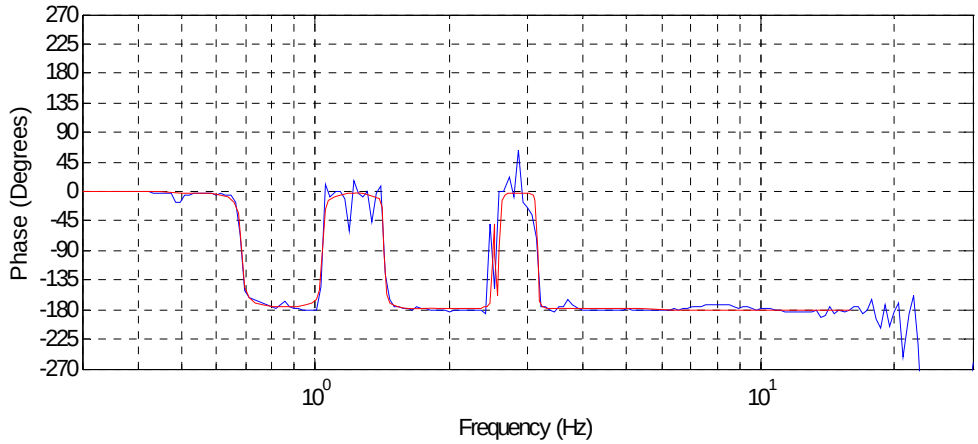

Predicted and Measured: L1Longitudinal Driving L1Longitudinal
Measured
Model
Magnitude (dB)
100
50
0
-50
-100
10^0
10^1
Frequency (Hz)

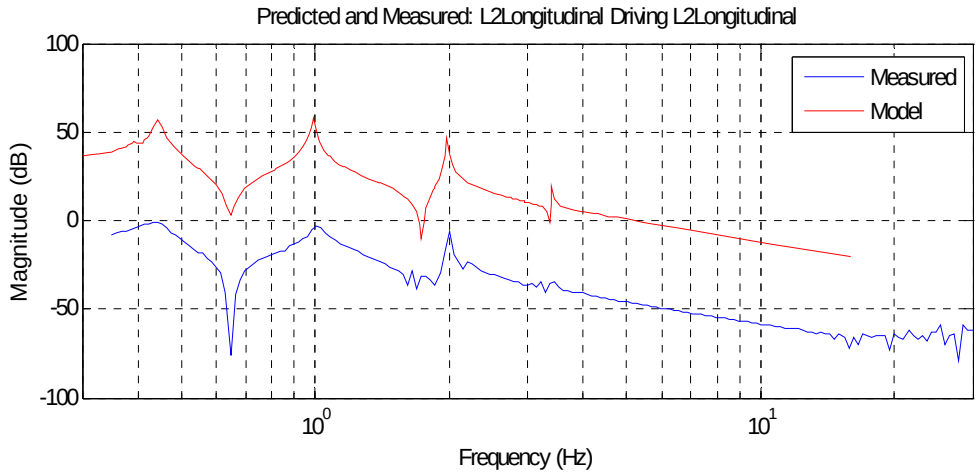

Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)

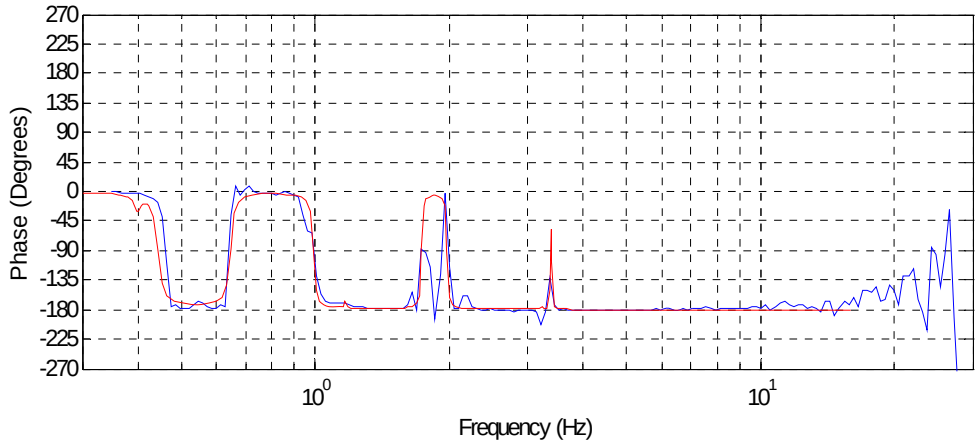

Predicted and Measured: L1Pitch Driving L1Pitch
Measured
Model
Magnitude (dB)
100
50
0
-50
-100
10^0
10^1
Frequency (Hz)

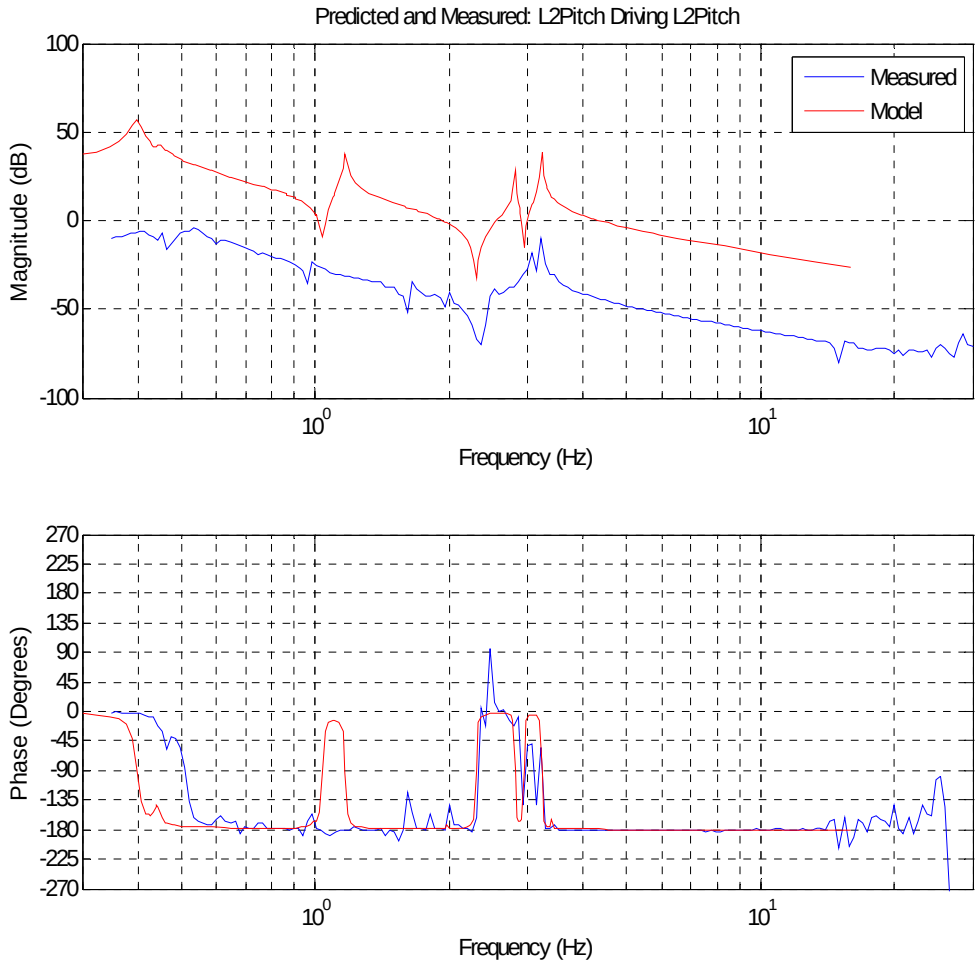

Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)

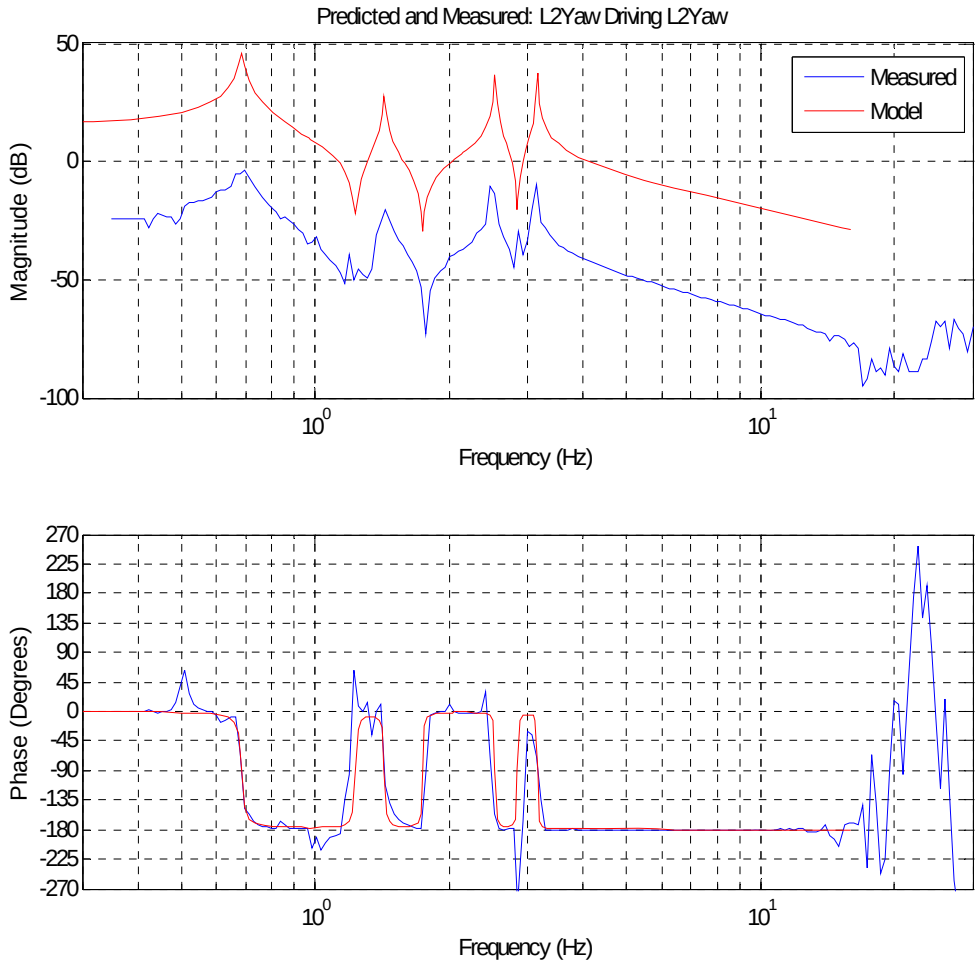

Predicted and Measured: L1Yaw Driving L1Yaw
Measured
Model
Magnitude (dB)
50
0
-50
-100
10^0
10^1
Frequency (Hz)


Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)


Predicted and Measured: L2Longitudinal Driving L2Longitudinal
Measured
Model
Magnitude (dB)
100
50
0
-50
-100
10^0
10^1
Frequency (Hz)


Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)


Predicted and Measured: L2Pitch Driving L2Pitch
Measured
Model
Magnitude (dB)
100
50
0
-50
-100
10^0
10^1
Frequency (Hz)
Phase (Degrees)
270
225
180
135
90
45
0
-45
-90
-135
-180
-225
-270
10^0
10^1
Frequency (Hz)



Again, the greatest discrepancies are in pitch. L1 pitch has a zero at 6.3 Hz, which coincides with the first zero at L2 longitudinal. The 1.6 Hz peak coincides with the 1.6 Hz peak from the local pitch DOF. The first L2 Pitch mode occurs at a greater frequency as well.

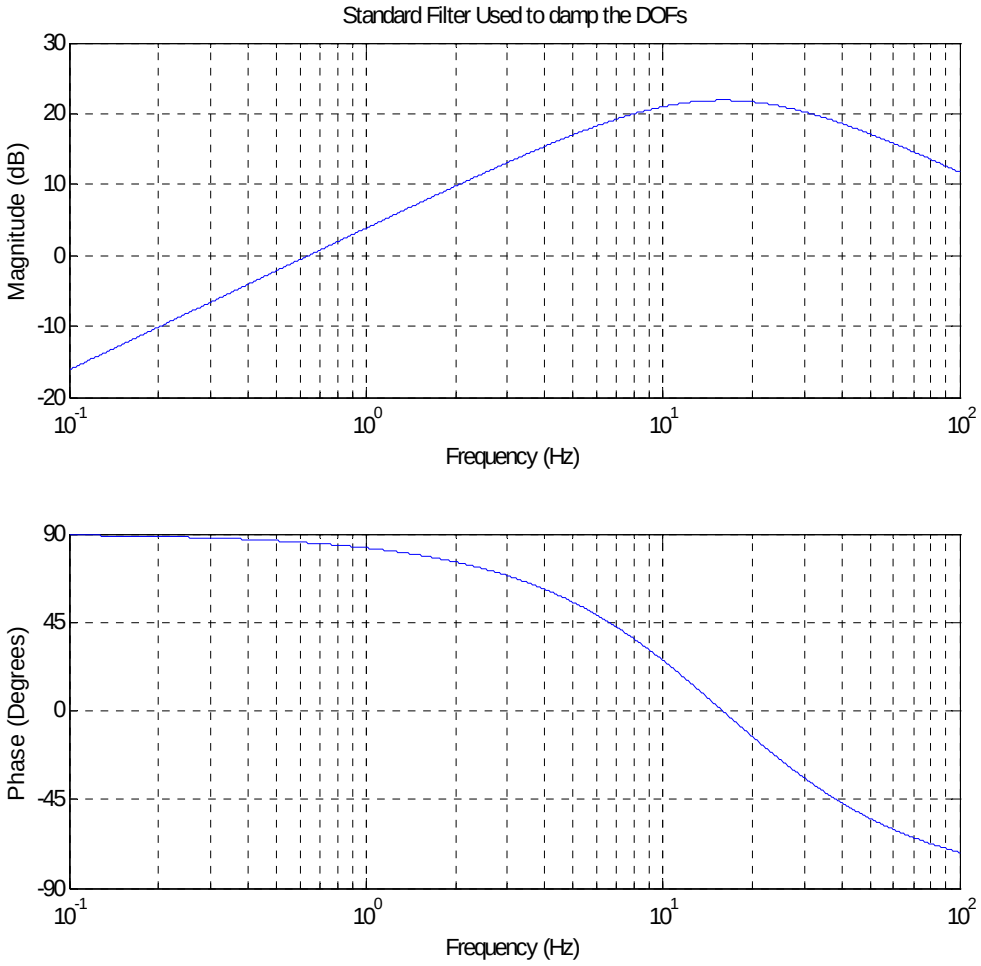
4 Local Damping

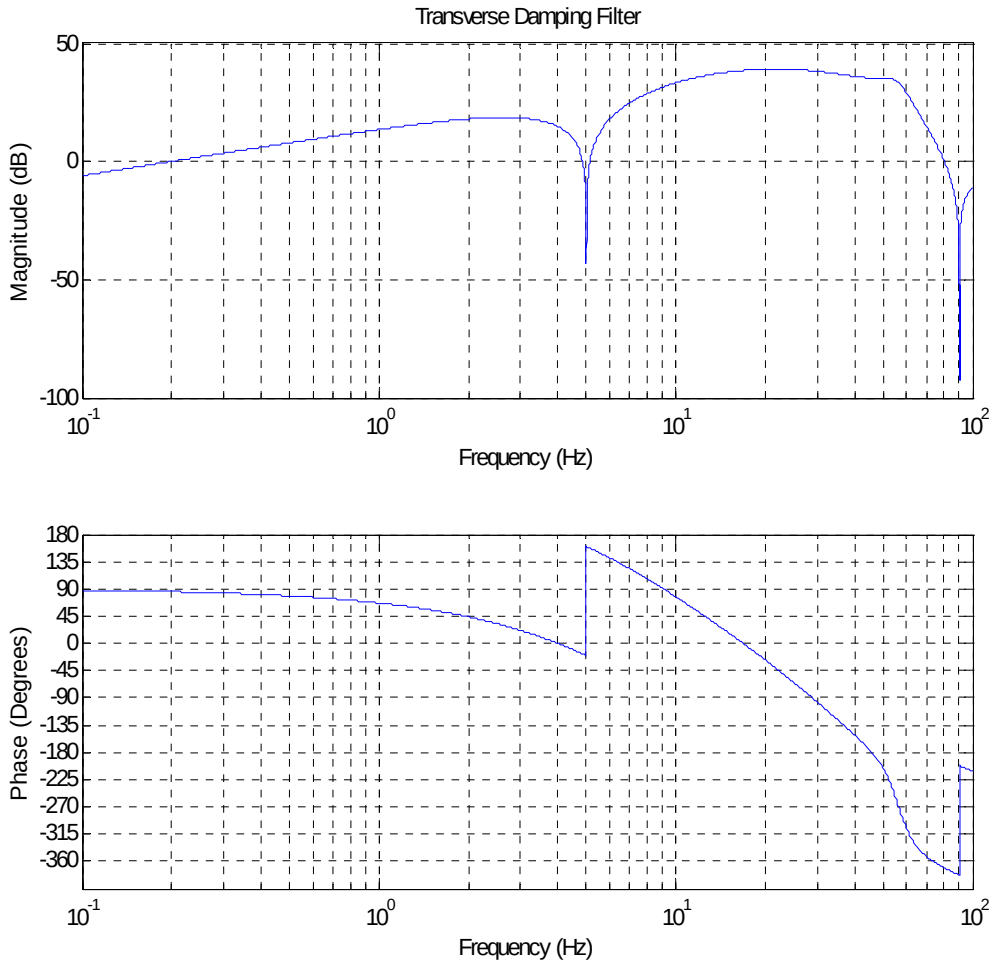
All the damping data reported here are from the reaction chain since it has experienced greater luck with its sensors and has more complete data. The main chain, with one exception, uses the same damping filters and behaves very similarly, due to the symmetry between the two.

4.1 Local Damping Filters

There are currently two types of damping filters on the quadruple pendulum. The first is a simple velocity damper, titled as 'Standard Damping' in the figure, which damps all the degrees of freedom except transverse. Due to an intermittent instability of the coupled 5.1 Hz roll mode a notch was added to add a more robust phase margin. It was then necessary to add an elliptical filter

to roll the high frequency gain off at a sufficient rate. If the gain is too large at high frequencies instability develops around 90 Hz. The interesting thing is that this instability is coupled between the chains and only exists while both are simultaneously damped.

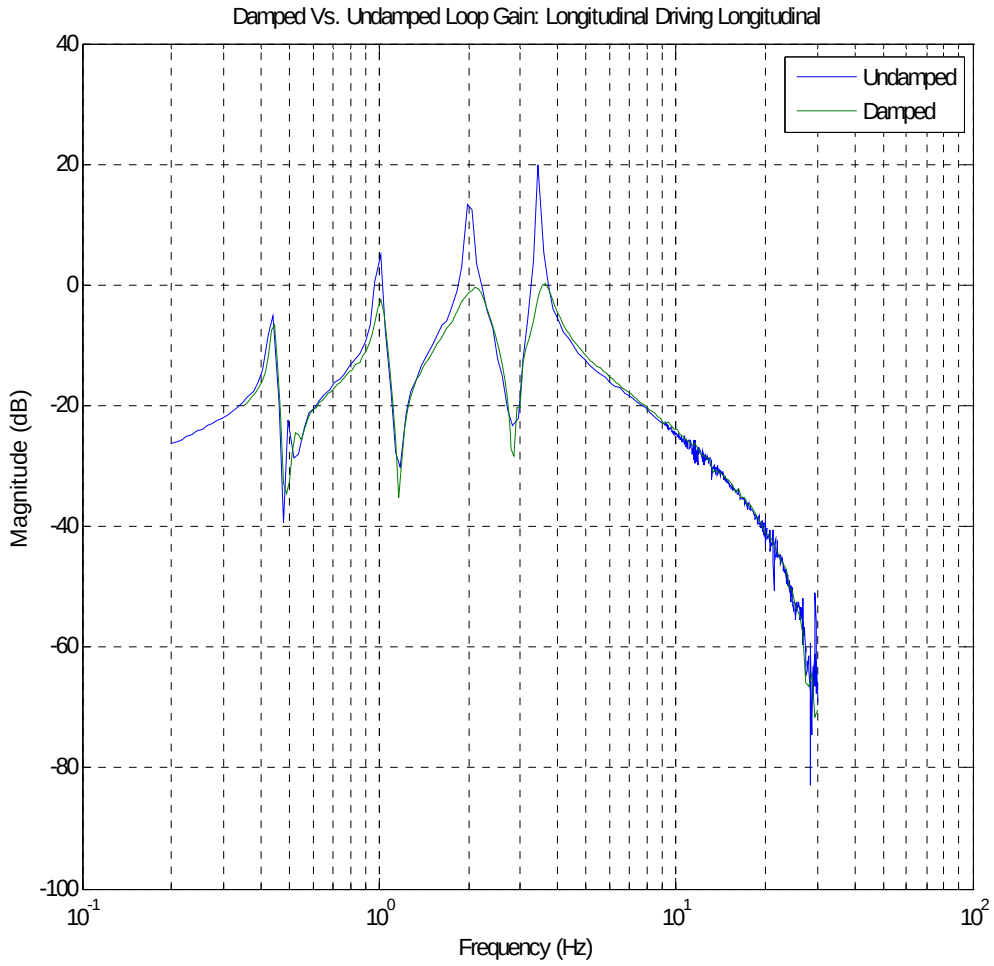


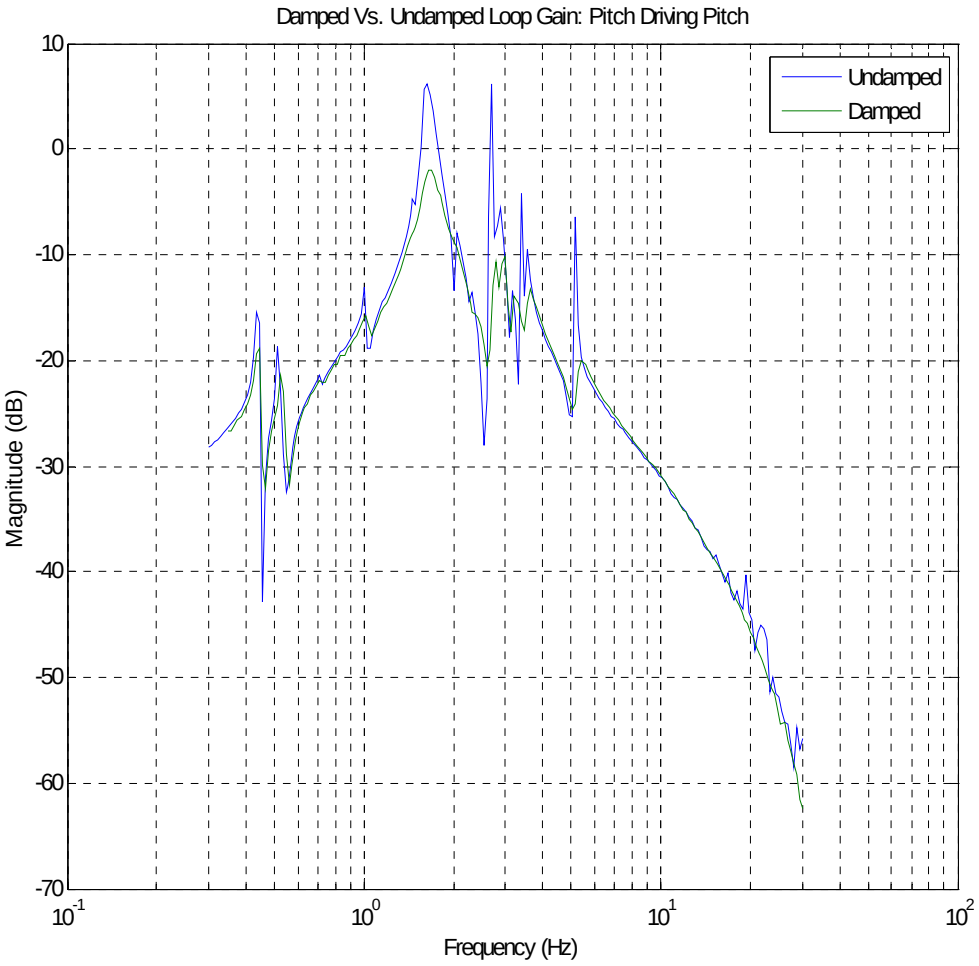


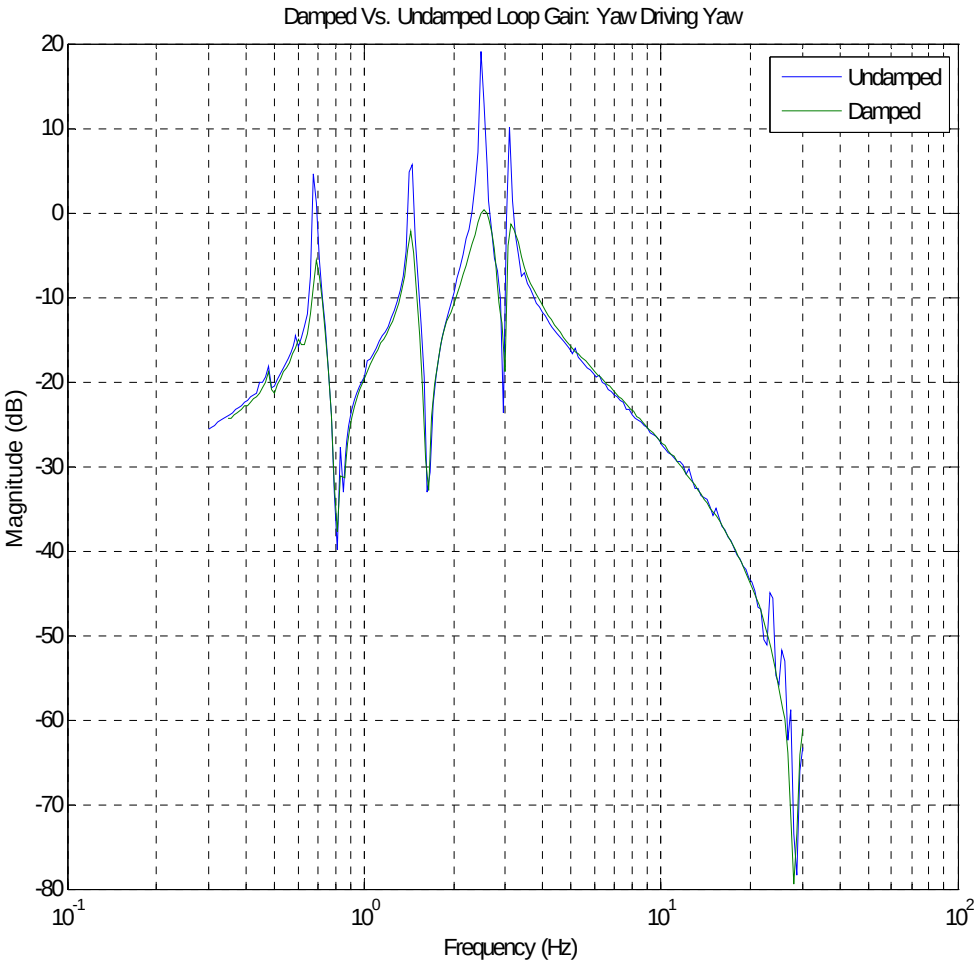
The standard filter uses a zero at 0 Hz and two poles at 16 Hz. Some of the DOFs have an additional gain between 0.5 and 5 in order to improve damping or stability. The transverse filter uses a zero at 0 Hz, a notch at 5 Hz, 3 poles at 10 Hz, 1 pole at 15 Hz, and an elliptical filter that begins rolling off the gain at 56 Hz. The latter filter is not used on the main chain.

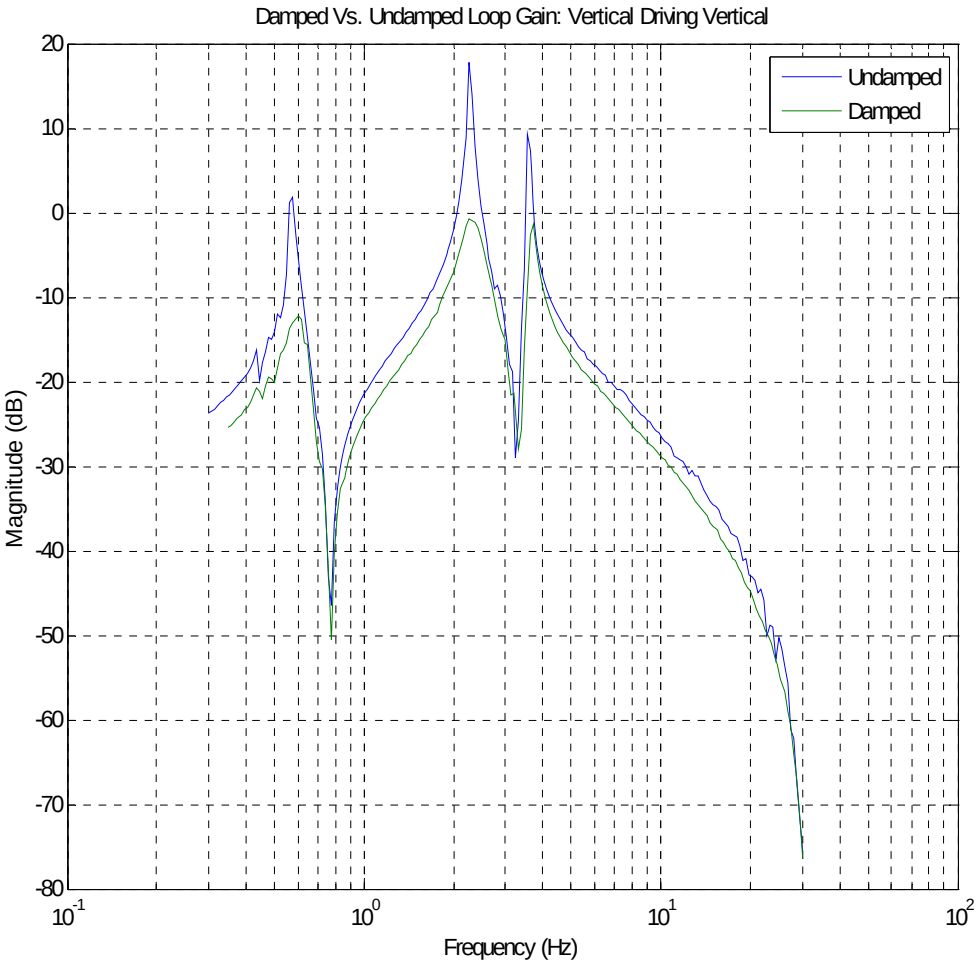
4.2 Local Damping Transfer Functions

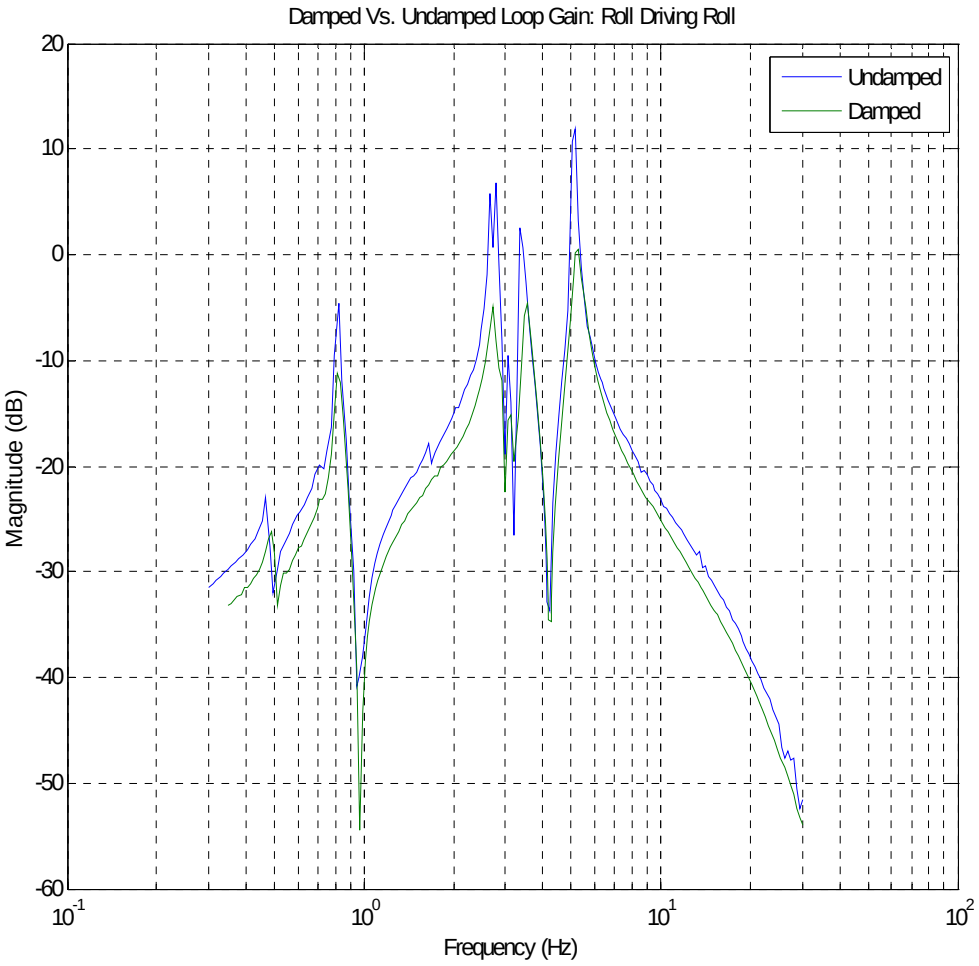
These plots show the reaction chain undamped local transfer functions (same locations as section 1.1) together with the damped transfer functions. The damped transfer functions are measured from the excitation to the response and thus have the form of PC/(1+PC) where P is the plant and C the controller.

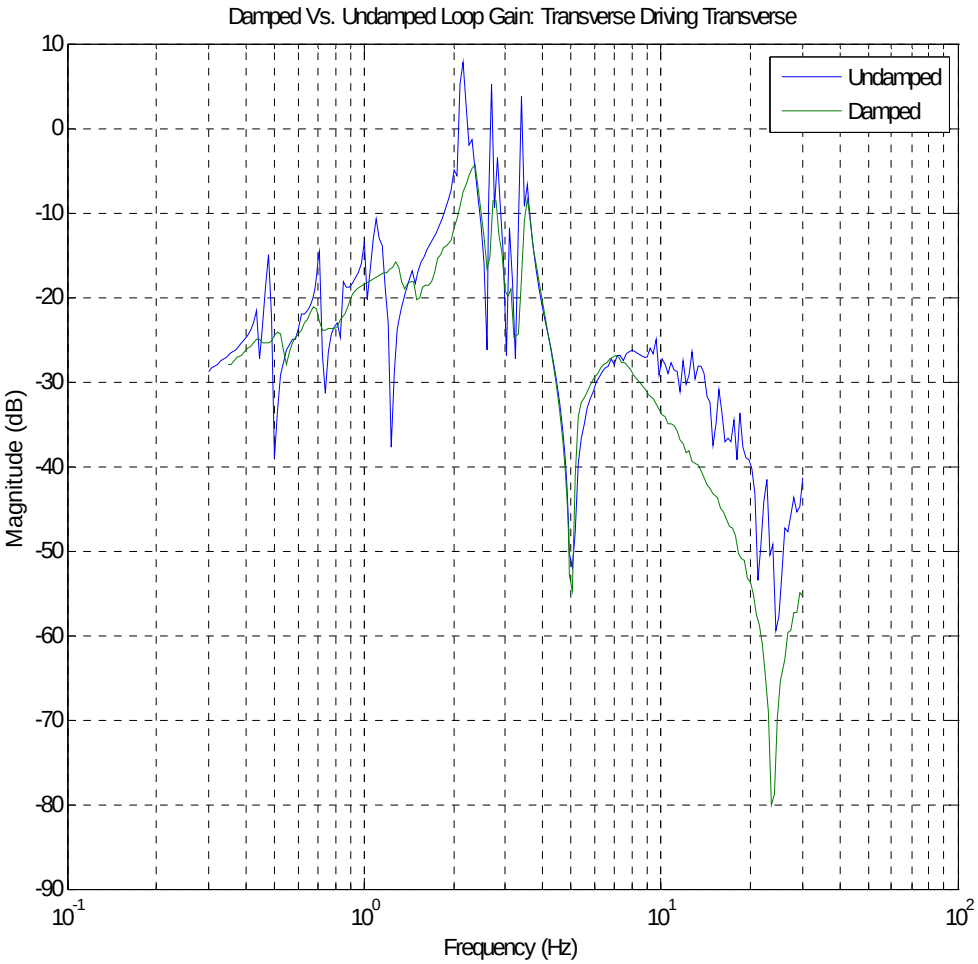

Damped Vs. Undamped Loop Gain: Longitudinal Driving Longitudinal
Undamped
Damped
Magnitude (dB)
Frequency (Hz)
40
20
0
-20
-40
-60
-80
-100
10^-1
10^0
10^1
10^2


Damped Vs. Undamped Loop Gain: Pitch Driving Pitch
Undamped
Damped
Magnitude (dB)
Frequency (Hz)
10
0
-10
-20
-30
-40
-50
-60
-70
10^-1
10^0
10^1
10^2


Damped Vs. Undamped Loop Gain: Yaw Driving Yaw
Undamped
Damped
Magnitude (dB)
Frequency (Hz)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
10^-1
10^0
10^1
10^2


Damped Vs. Undamped Loop Gain: Vertical Driving Vertical
Undamped
Damped
Magnitude (dB)
Frequency (Hz)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
10^-1
10^0
10^1
10^2

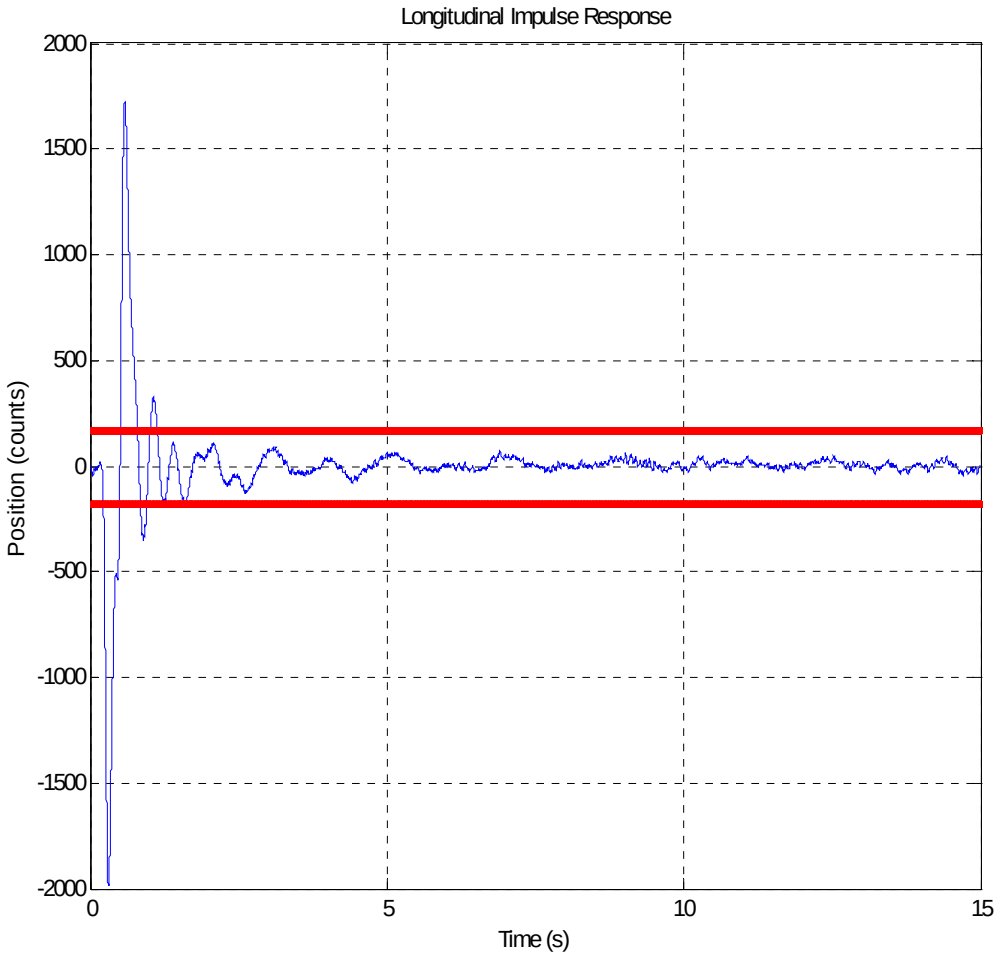

Damped Vs. Undamped Loop Gain: Roll Driving Roll
Undamped
Damped
Magnitude (dB)
Frequency (Hz)
20
10
0
-10
-20
-30
-40
-50
-60
10^-1
10^0
10^1
10^2

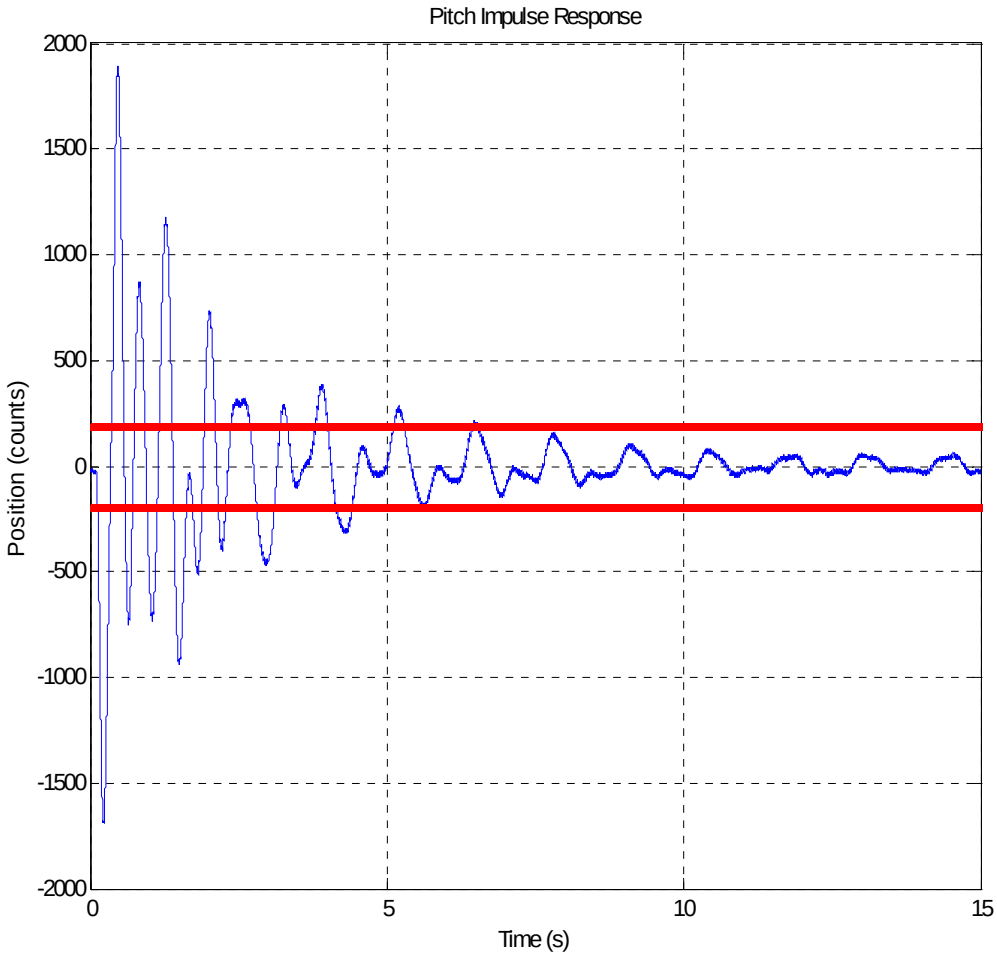


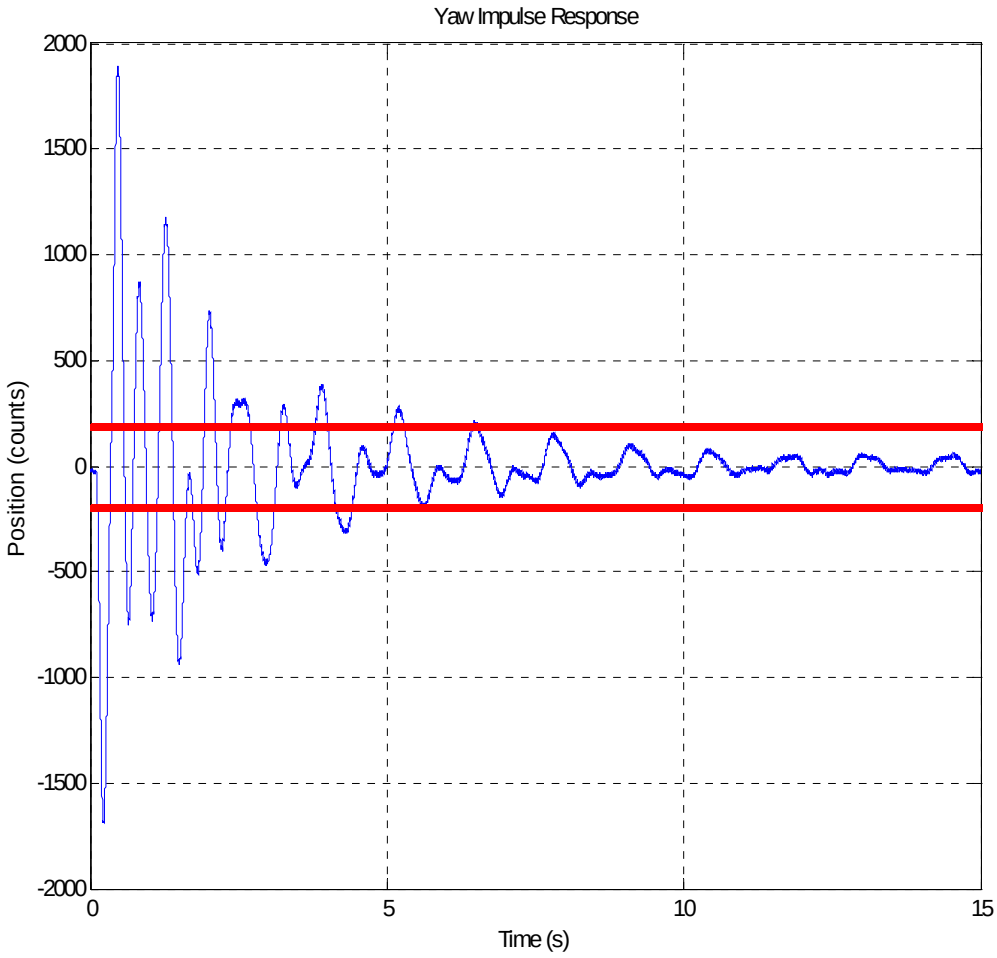
The lowest longitudinal mode does not show much damping here but the controller gain has been adjusted since this data was taken. There was not enough time to include the new data but damping is now much more significant. The roll damping has been adjusted as well and also has more damping then shown.

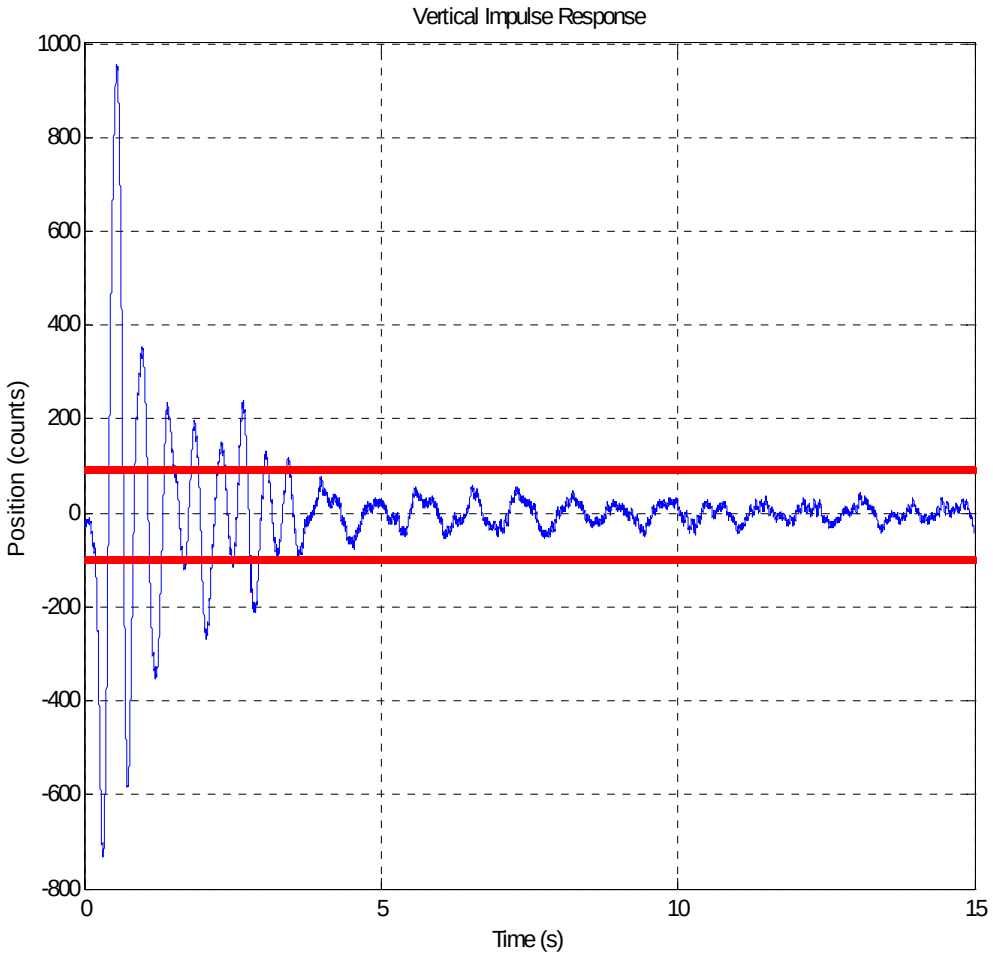
4.3 Local Damping Impulse Response

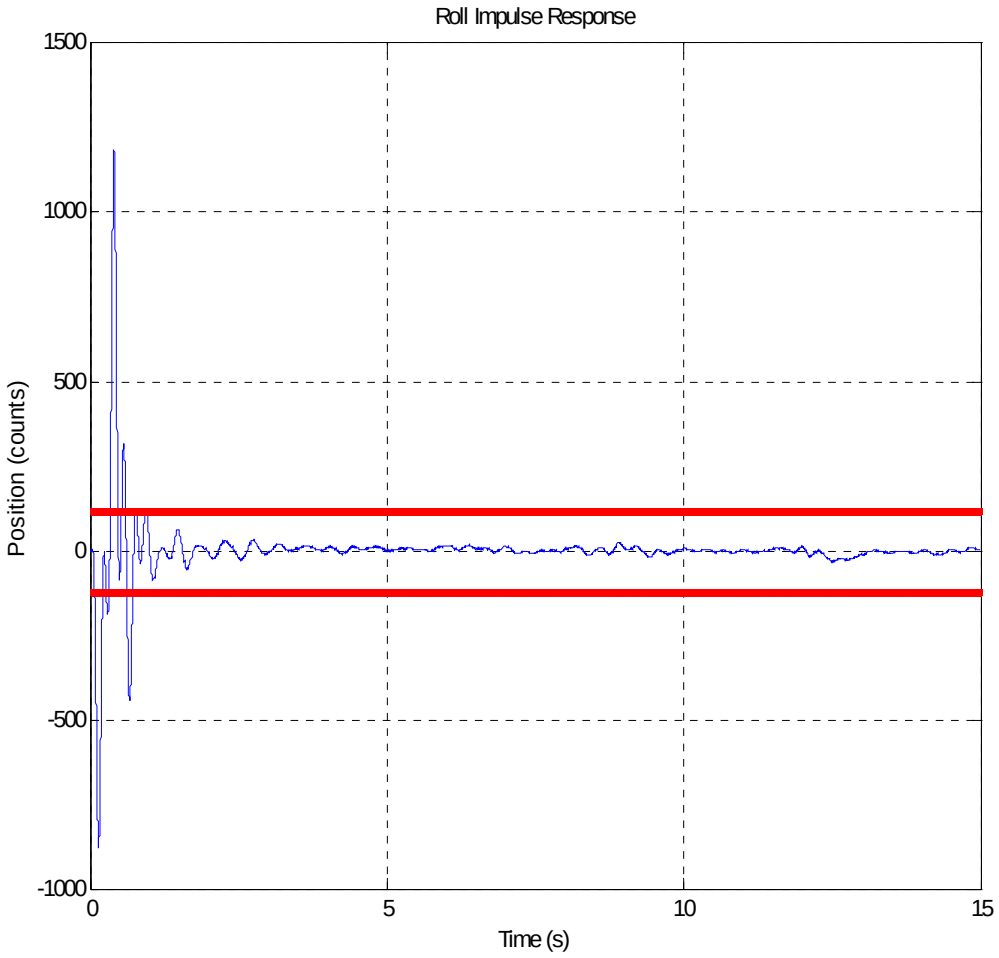
These impulse responses are measured at the same local DOFs as above. The red lines represent the 90% attenuation point, and as shown, all the DOFs damp within 10% of the initial maximum in less than ten seconds. This data was collected with the improved damping filters mentioned earlier.

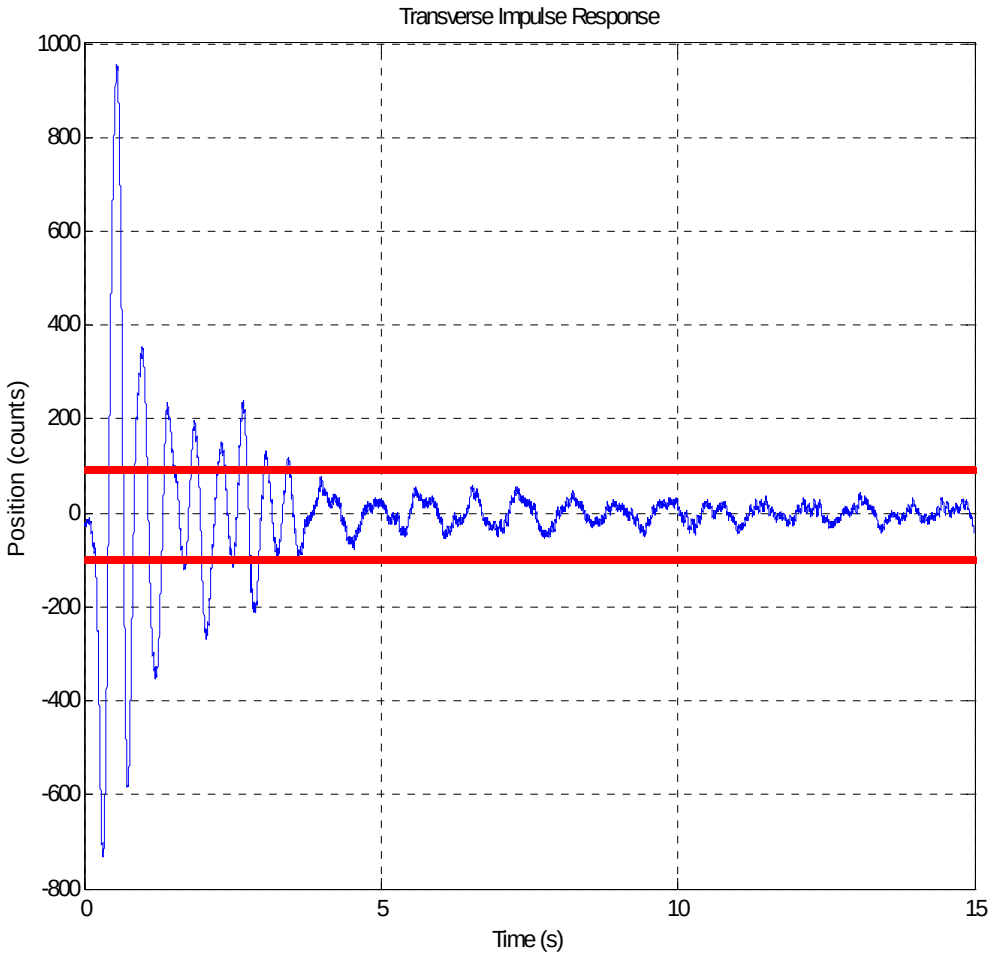

Longitudinal Impulse Response
Position (counts)
Time (s)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
5
10
15


Pitch Impulse Response
Position (counts)
Time (s)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
5
10
15


Yaw Impulse Response
Position (counts)
Time (s)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
5
10
15


Vertical Impulse Response
Position (counts)
Time (s)
1000
800
600
400
200
0
-200
-400
-600
-800
0
5
10
15


Roll Impulse Response
1500
1000
500
0
-500
-1000
Position (counts)
0
5
10
15
Time (s)



5 Continuing Work

More data needs to be collected to complete the full set of transfer functions and to identify missing/mysterious modes. Also, local to global and global to local transfer functions should be collected. This data collection will continue through the summer.

The eddy current damping will be installed during the middle to end of June and then tested. The electrostatic drive will be installed and tested in July.