Conceptual Design of a Double Pendulum for the Output Mode Cleaner

Chris Cueva, Calum Torrie, Norna A Robertson and Janeen Romie
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1. Introduction

The Suspensions group (SUS) has been asked to consider a design of suspension for the output mode cleaner which will hang in a HAM chamber. This mode cleaner is likely to be installed during the enhanced LIGO upgrade after the S5 run, and it should also satisfy requirements for use in Advanced LIGO. The requirements received to date are that the mass will be no more than 40 kg, including a 500 x 500 mm^2 optics table supporting all associated optics, and that vertical as well as longitudinal isolation is needed. In addition the overall footprint is limited to 750 mm *x* * 750 mm *y* * 800 mm *z* (where *x* is beam direction and *z* is vertical). Although a single pendulum with blades included for vertical isolation might satisfy the requirements, we decided to investigate a double pendulum to start with for the following functional reasons.

1) The design of the upper mass, including positioning of OSEMs (and/or eddy current damping) for local control can proceed without detailed knowledge of the layout of the mode cleaner and associated optics.
2) Static adjustments for pitch can be incorporated at that stage.
3) Addition/subtraction of mass to flatten blades can be done at that stage

In addition a double pendulum gives more isolation.

Starting from an initial conceptual layout (see figure 1, LIGO-D060104) we have put together a set of parameters and investigated the isolation and local control in six degrees of freedom. Some adjustments were made to this original layout to achieve a reasonable set of mode frequencies in pitch and to simplify the suspension, avoiding highly angled wires. The revised layout is shown in figure 2 and the LIGO document has been updated to LIGO-D060104-02 (saved in the PDM works vault). A detailed list of the parameters is given in appendix A, and a possible blade design is shown in appendix B. In Appendix C we show a possible layout of actuator unit positions.

2. Design Details and Results

A MATLAB/Simulink model of a double pendulum was put together. This was built up from a single pendulum and its results checked with that of the standard MATLAB triple pendulum model with parameters set to simulate a double pendulum. Using this model we investigated the parameters as given in figure 1, and modified them as described below.

2.1 Modifications to initial layout

Firstly it was observed that assuming effective break-offs of the wires with respect to the center of mass (the "d" values) of 1mm the pitch modes did not fall in the desired range (~ 0.35 to ~ 4 Hz). One was less than 0.2 Hz and the other greater than 10 Hz. To raise the lower pitch mode, the distance of the upper wire break-off above the center of mass of the top mass, d0, was increased from 1mm to 6mm, increasing the lowest mode to ~ 0.3 Hz. To lower the upper pitch mode, the half separation of the lower wires in the x-direction, si, was decreased from 0.103/2 m to 0.03/2 m resulting in an upper pitch mode of ~4 Hz.

The half separation of the upper wires at the suspension point, n0, was changed from 0.118/2 m to 0.442/2 m. This allows the upper wires to hang vertically from the cantilever blades, simplifying the layout and relaxing the need to model the effect of the geometric anti-spring softening of the lower vertical mode frequency due to the angled wires.

In order to keep the cantilevers within the allowed footprint the length was decreased, details as given in Appendix B.

The radius of the upper wire was increased so the stress would not exceed 6.7×10^{8} N/m^2, giving a safety factor of ~ 3 below the breaking stress.

2.1 Normal mode frequencies

With these changes we achieved the following results.

Normal Mode Frequencies (Hz)

Long and pitch =
    4.0740
    2.2587
    0.6514
    0.3167
  Rotational =
    3.3765
    0.7447
Transverse and roll =
   41.4784
    2.4268
    2.2471
    0.6508
Vertical =
   24.4678
    1.4294

2.3 Damping

Damping was modeled initially assuming a simple eddy current damping law to check that low frequency modes were suitably coupled and that damping of similar magnitude in different directions could be applied. Active damping is a viable alternative/complement. In particular it should be used for pitch and yaw control so that pitch and yaw bias forces can be applied at the top mass. Active damping has not yet been fully studied. Filtering to avoid instability at the highest vertical and roll modes will be required. Transfer functions and impulse responses are shown in figures 3 to 14. The actuator positions and relative gains used are given in Appendix C

2.4 Transfer functions and decay times.

Figures 3 to 14 show the transfer functions and impulse responses for all the degrees of freedom. All low frequency modes can be damped. Some relative adjustment of gains is required to produce ~ 10 second or better damping in all cases. With active damping, MIMO digital filtering (or modal damping) can be applied to achieve similar damping in each direction.

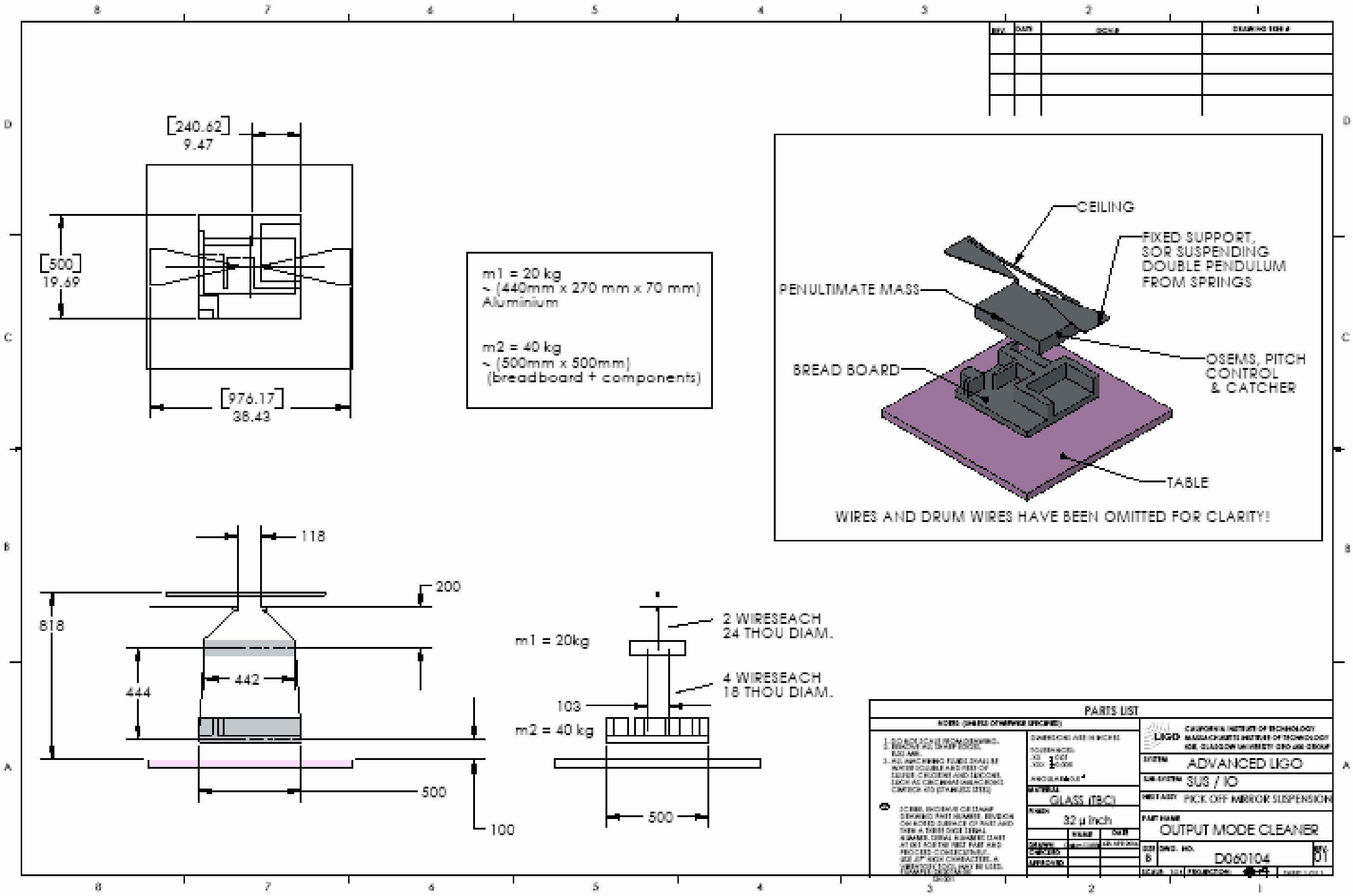

Figure 1. Initial conceptual layout of output mode cleaner suspension, LIGO-D060104-01, (from C. Torrie)

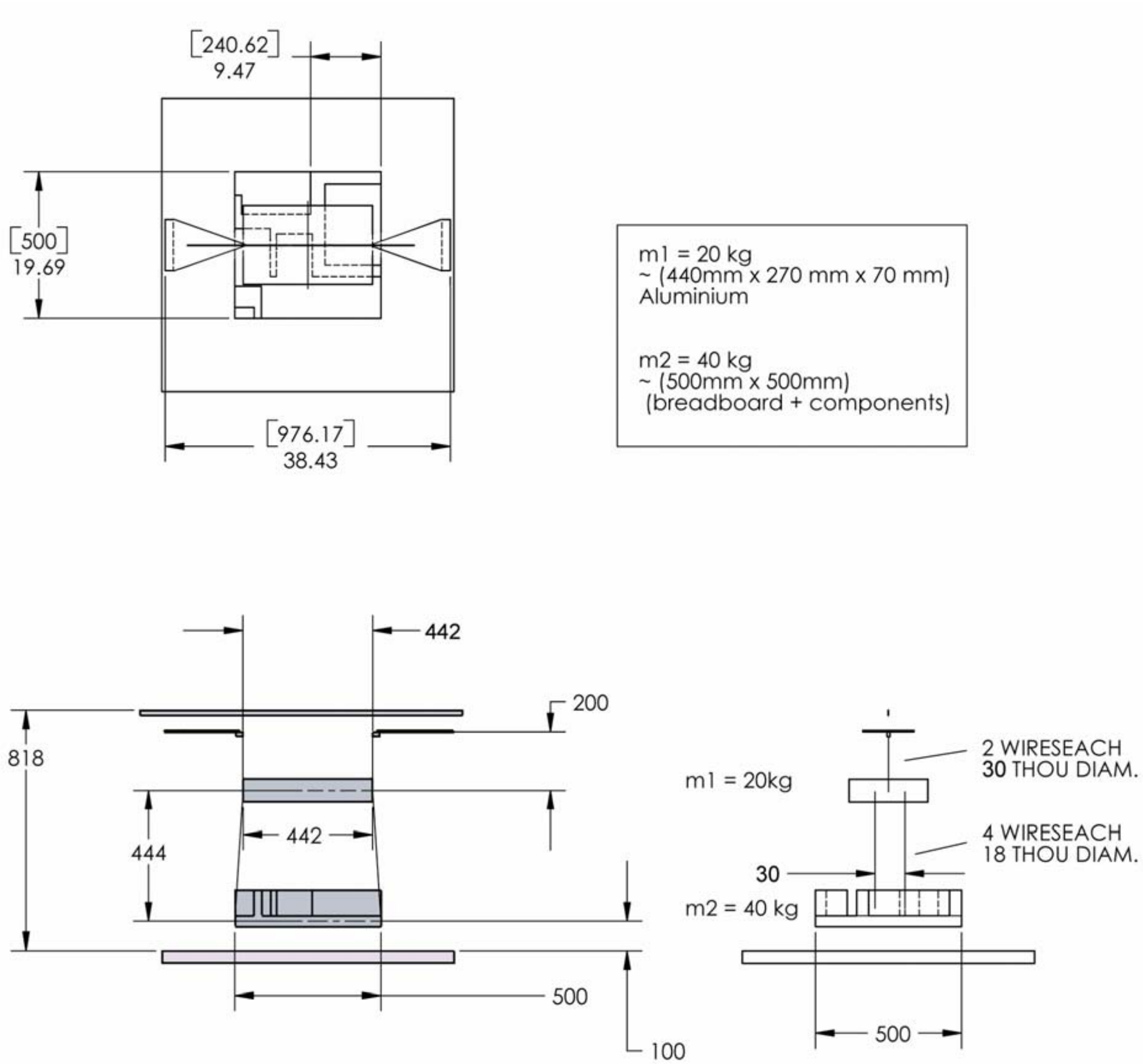

Figure 2. Revised layout of output mode cleaner suspension, LIGO-D060104-02

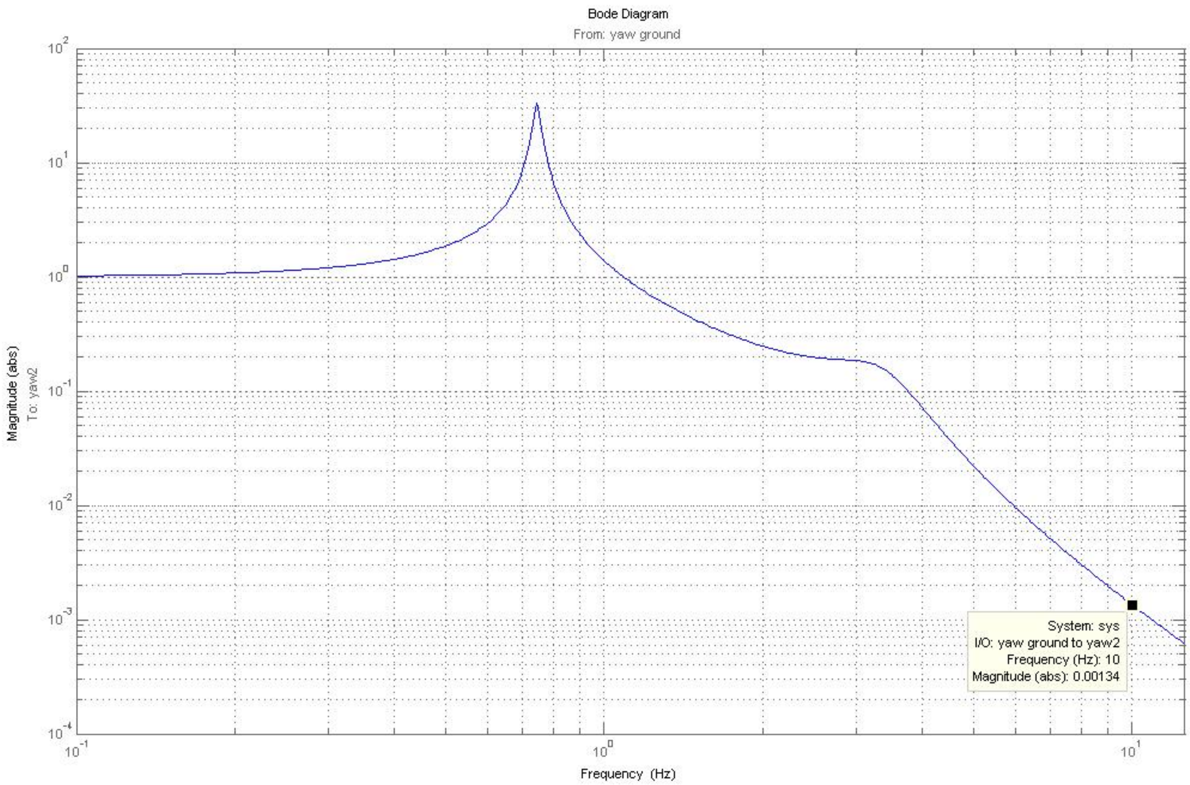

Figure 3. Bode Magnitude – Yaw

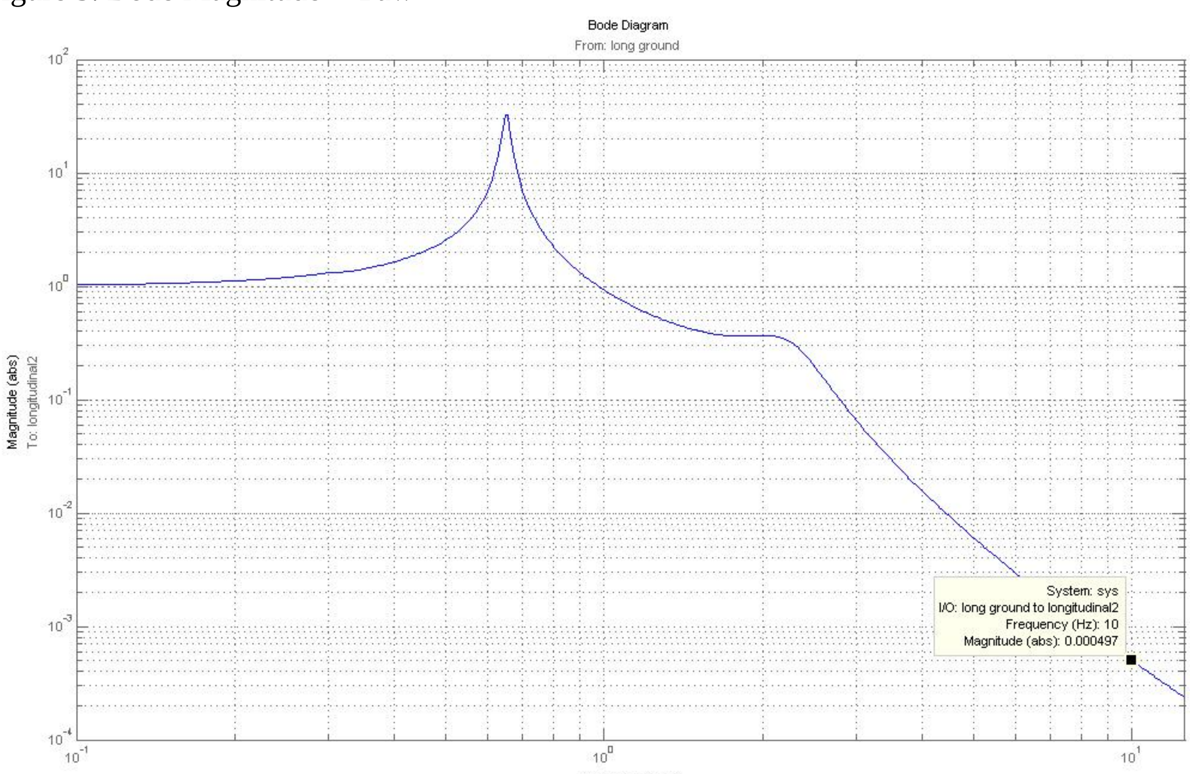

Figure 4. Bode Magnitude – Longitudinal

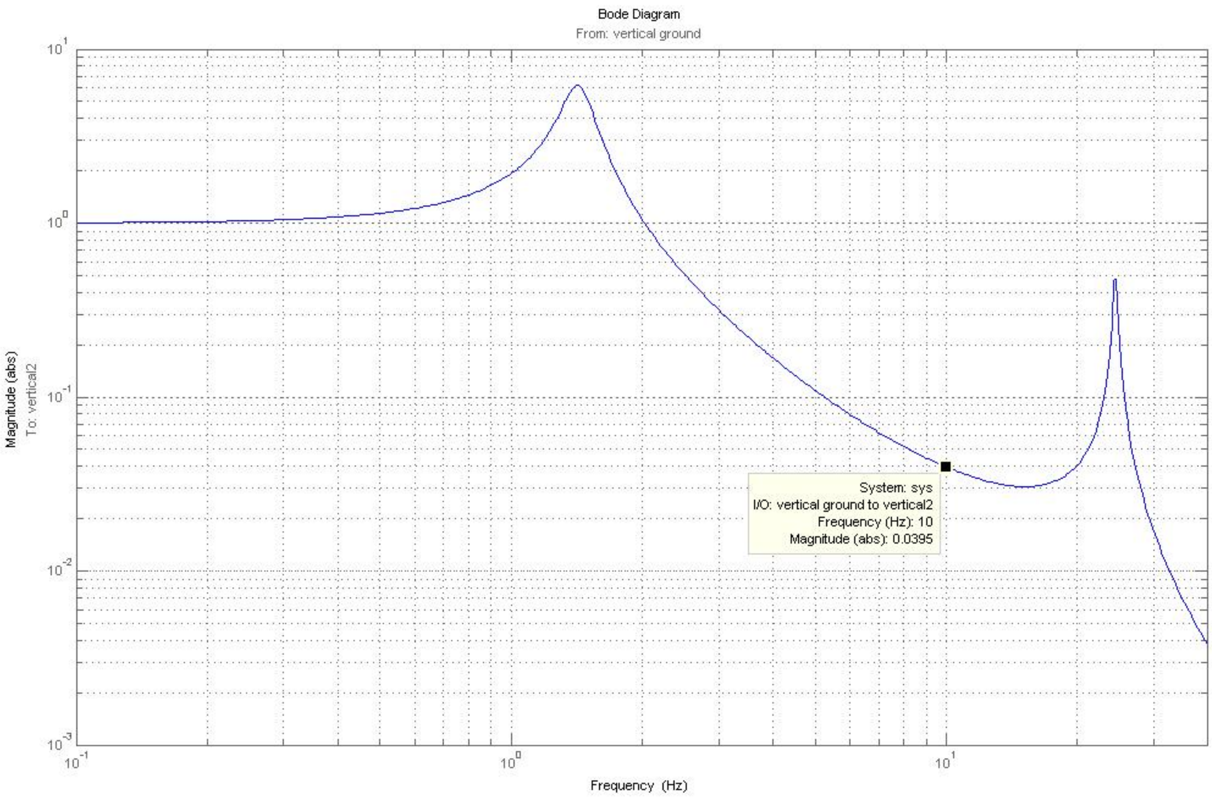

Figure 5. Bode Magnitude – Vertical

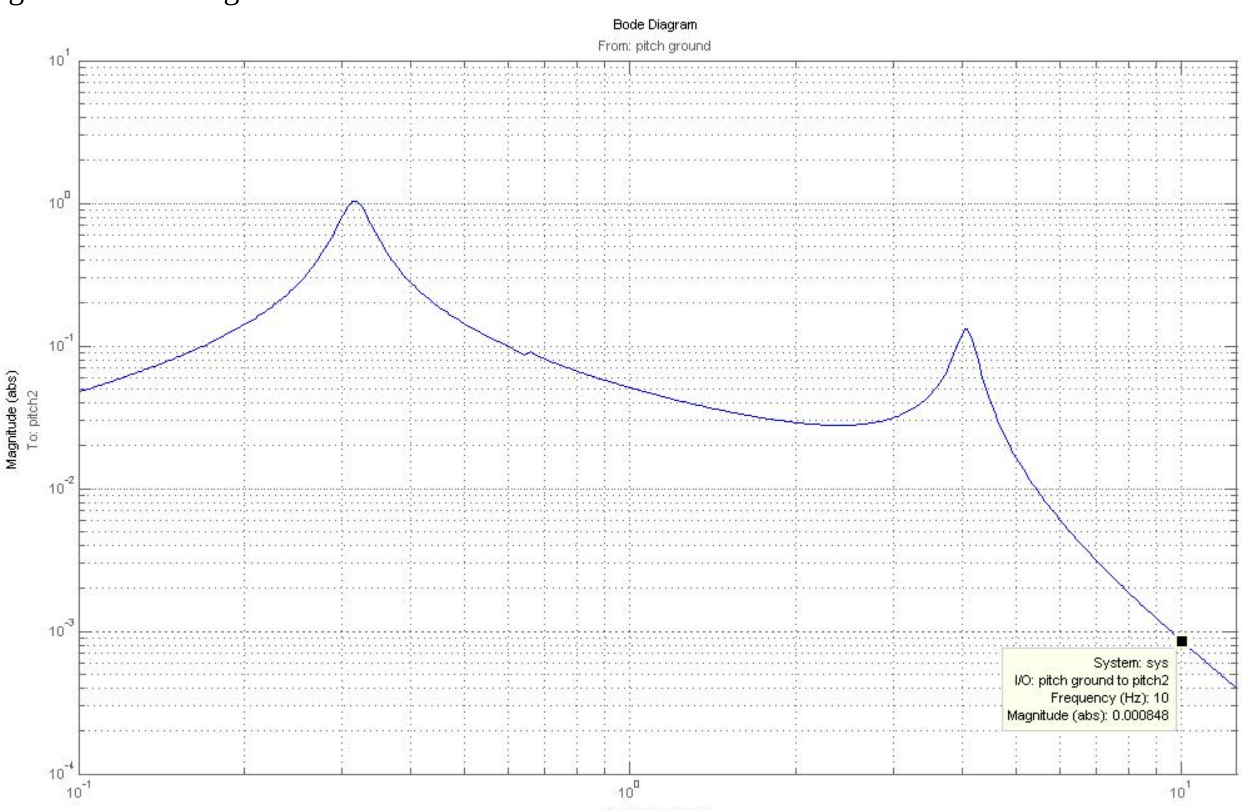

Figure 6. Bode Magnitude – Pitch

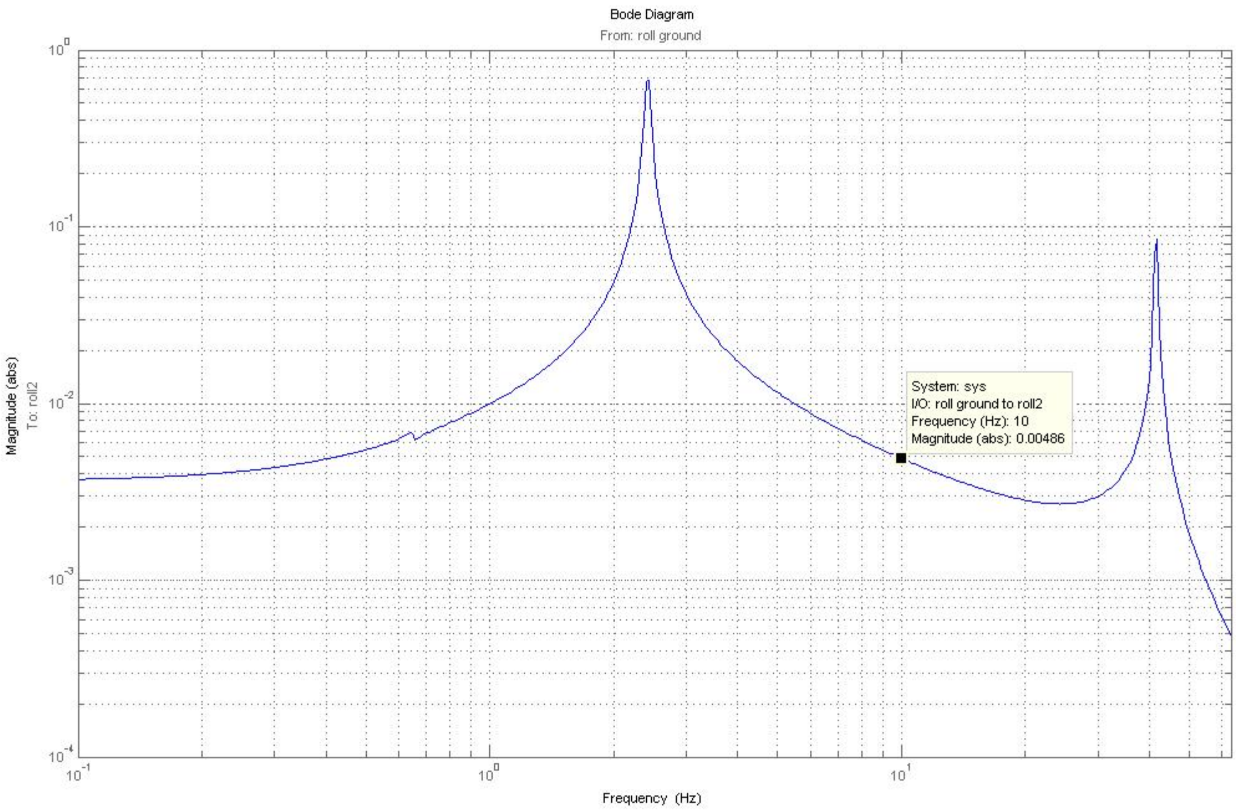

Figure 7. Bode Magnitude – Roll

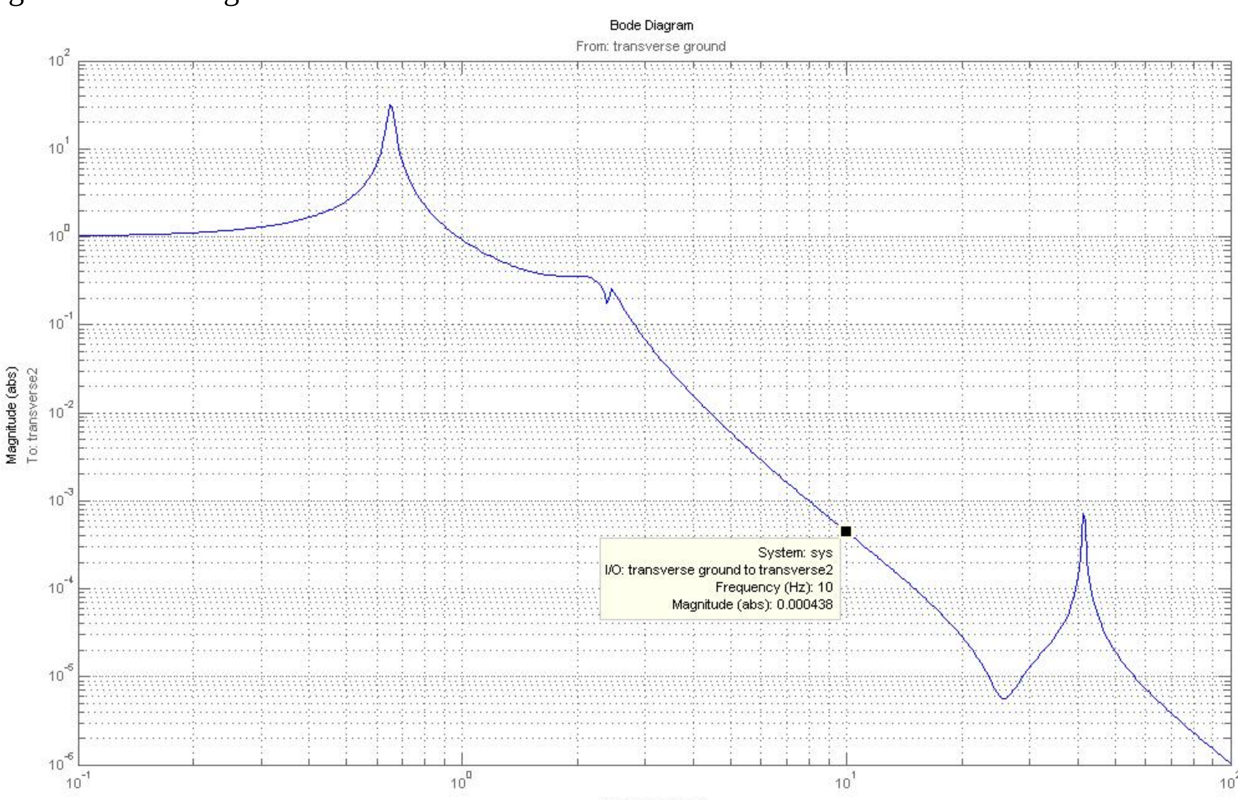

Figure 8. Bode Magnitude – Transverse

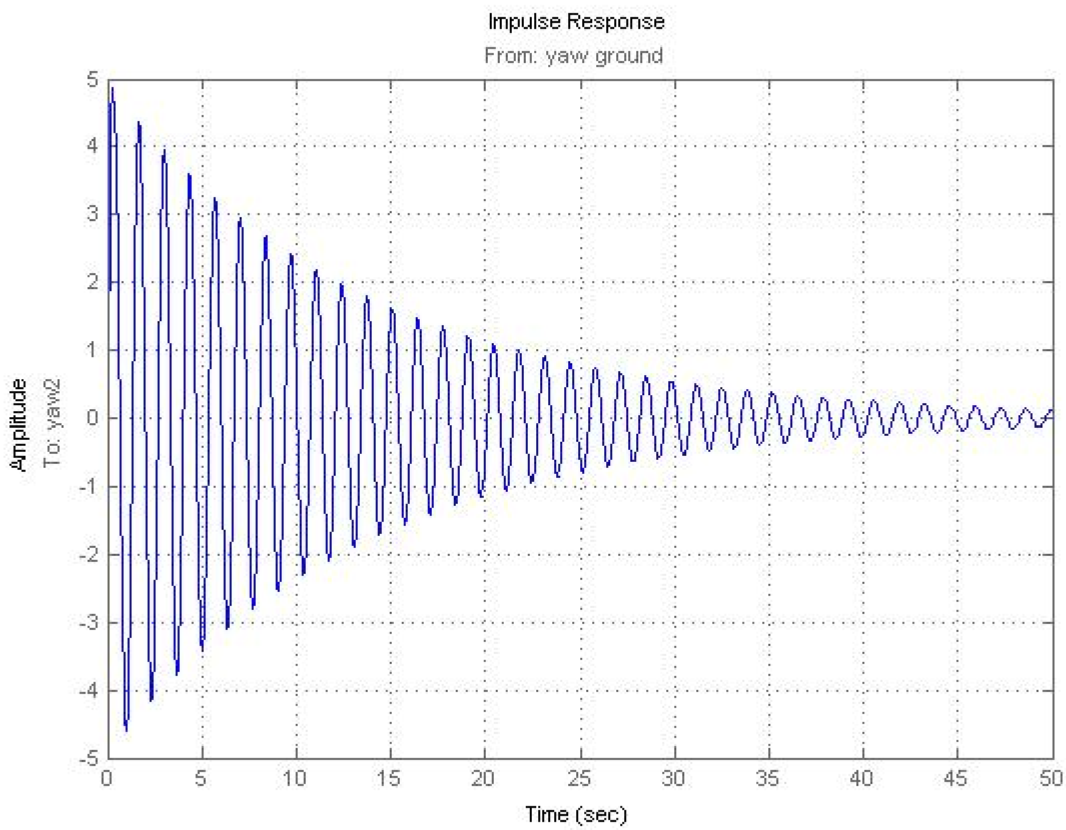

Figure 9. Impulse Response – Yaw

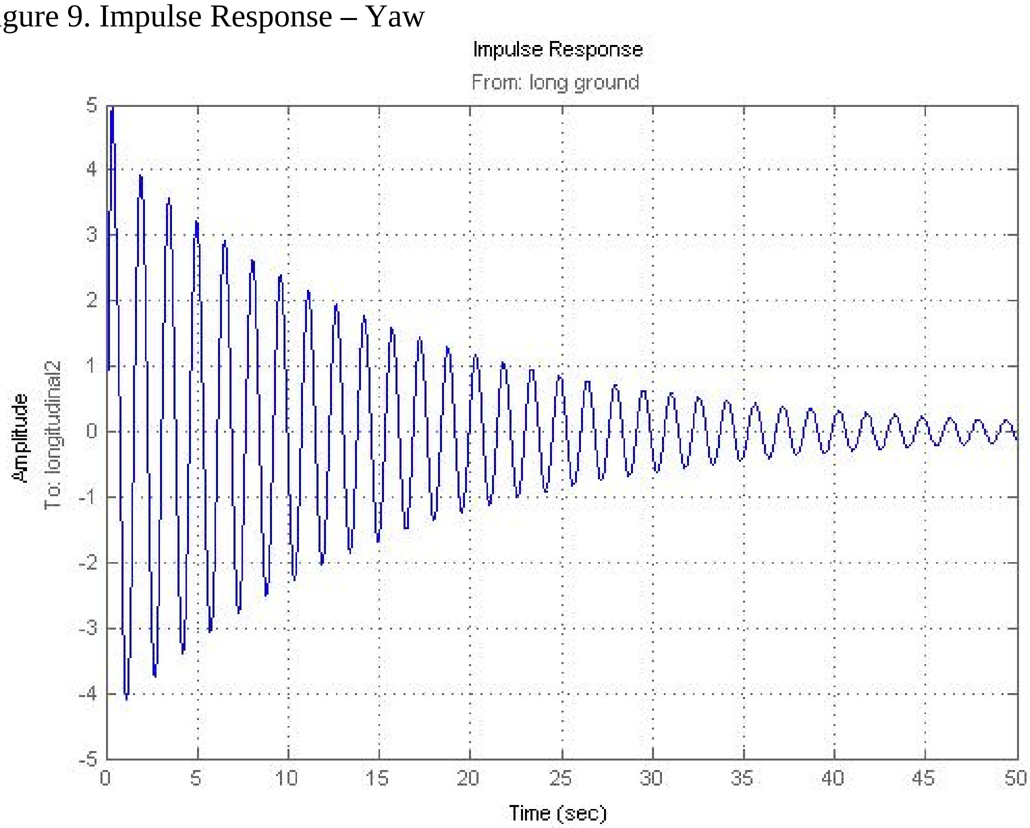

Figure 10. Impulse Response – Longitudinal

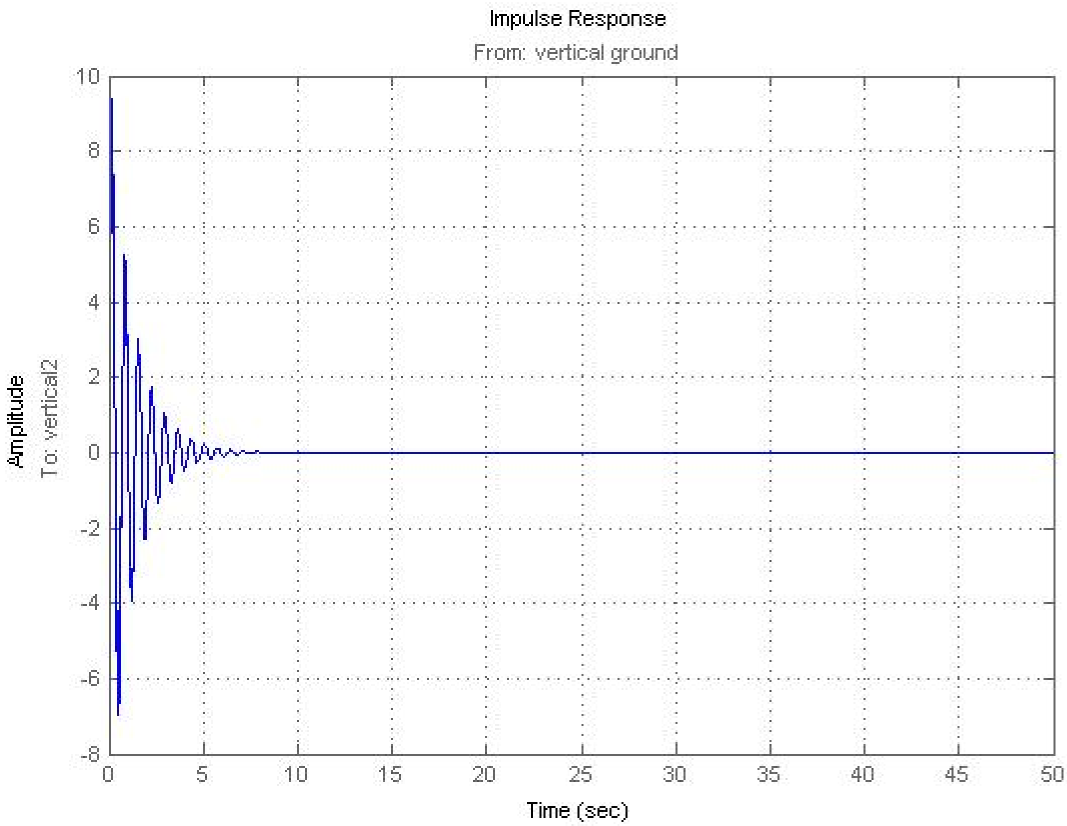

Figure 11. Impulse Response – Vertical

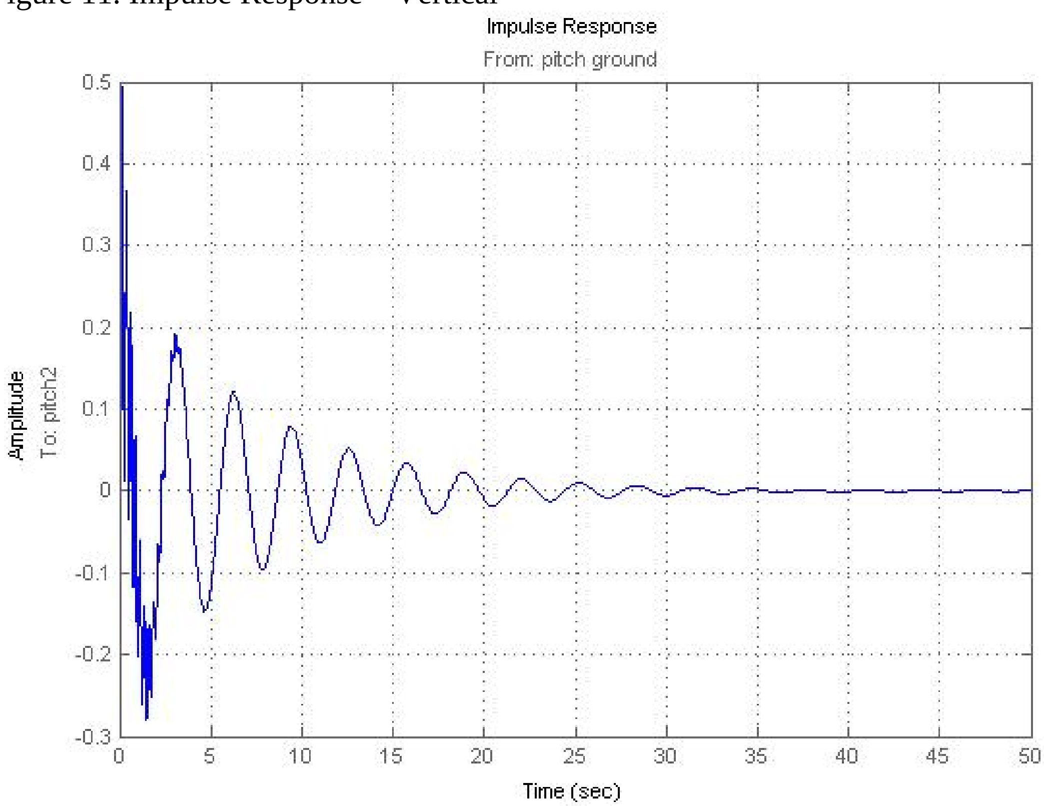

Figure 12. Impulse Response – Pitch

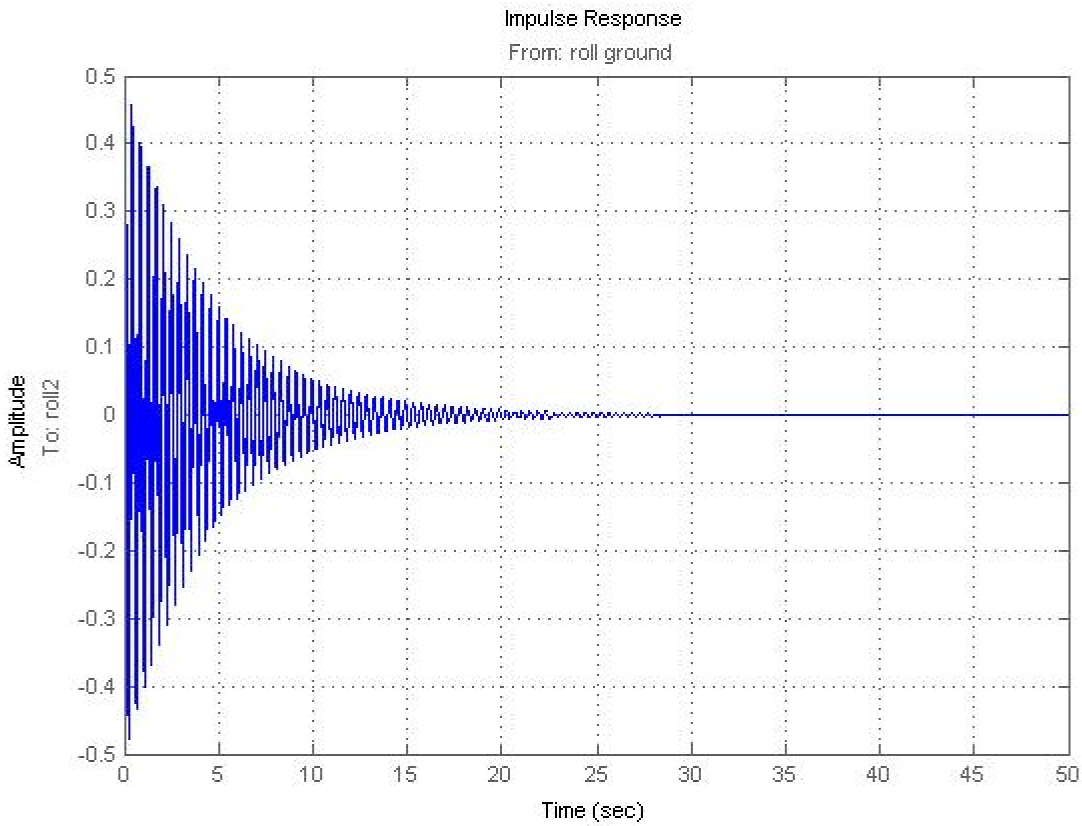

Figure 13. Impulse Response – Roll

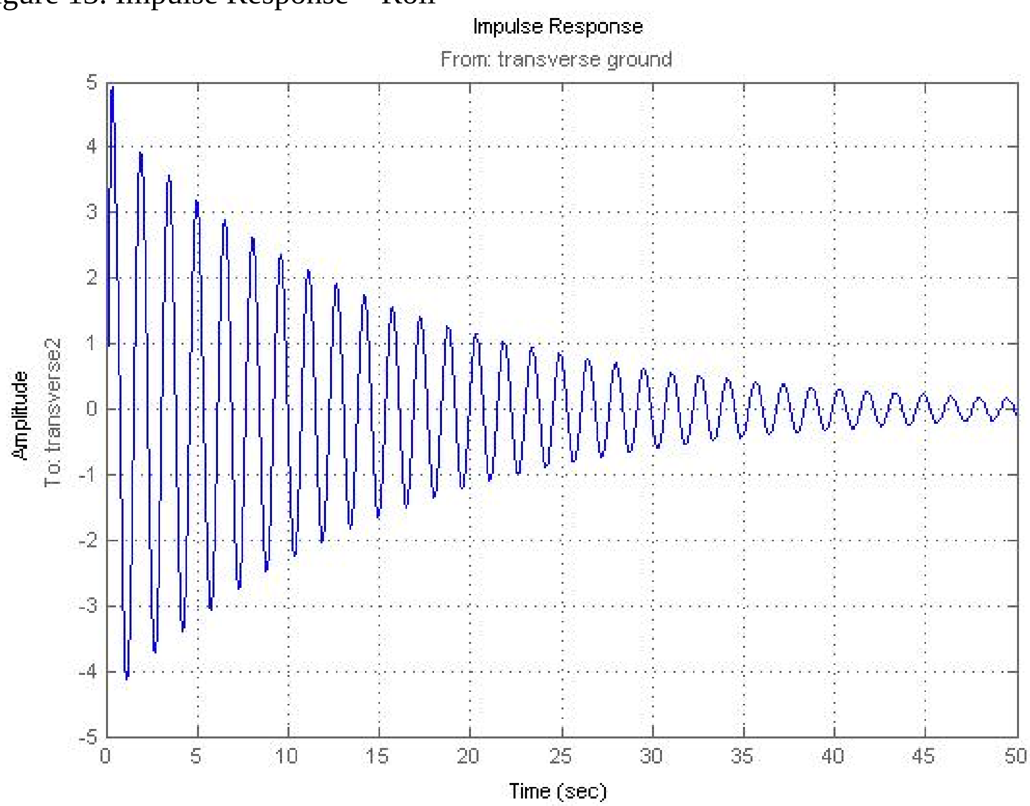

Figure 14. Impulse Response – Transverse

2.5 Support structure.

We have also considered the design of the support structure which could be used to mount the suspension on a HAM optics table. An adaptation (with slightly modified size) of the upper part of the test mass quadruple suspension support structure could be used, as shown in figure 15 below. The application of such a design is attractive for two reasons: a) the design already exists, and b) such a structure has been demonstrated to have a first resonant frequency of 200 Hz which minimises the impact on the control of the isolation table to which it is attached. Some modification of the position of the angled elements might be required for clearance for the optical beams.

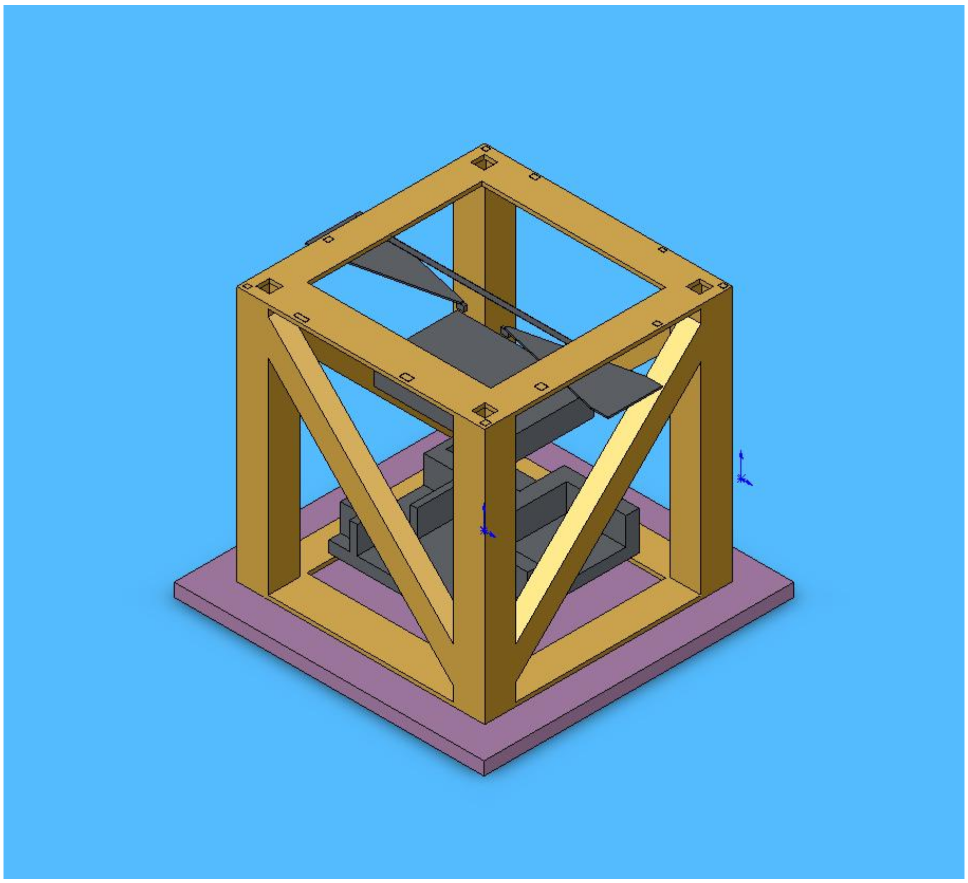

Figure 15 Possible support structure for the output modecleaner.

3. Conclusions

We have presented a conceptual design for a double pendulum suspension of an output modecleaner. The normal mode frequencies all lie in a range of ~0.3 to ~4 Hz apart from the highest vertical and roll modes. The low frequency modes can all be adequately damped by applying forces at the top mass. The isolation at 10 Hz in longitudinal is ~5 x 10^{-4} and in vertical ~4 x 10^{-2} (which assuming 0.1% coupling gives a vertical to longitudinal isolation of 4 x 10^{-5}). The blade design is conservative. If more vertical isolation is needed, longer blades could be used by either angling the top wires or by crossing the blades as is done in the quadruple suspension.

Appendix A.

Parameters for Output Mode Cleaner (SI)

m1: 20
ux: 2.7000e-001
uy: 4.4200e-001
uz: 6.2070e-002
I1x: 3.3203e-001
I1y: 1.2792e-001
I1z: 4.4711e-001
m2: 40
ix: 5.0000e-001
iy: 5.0000e-001
iz: 1.6000e-001
I2x: 9.1867e-001
I2y: 9.1867e-001
I2z: 1.6667e+000
l1: 1.9400e-001
l2: 4.4295e-001
nw1: 2
nw2: 4
r1: 3.7488e-004
r2: 2.2860e-004
Y1: 2.1200e+011
Y2: 2.1200e+011
ufc1: 2.4907
d0: 6.0000e-003
d1: 1.0000e-003
d2: 1.0000e-003
su: 0
si: 1.5000e-002
n0: 2.2100e-001
n1: 2.2100e-001
n2: 2.2100e-001
n3: 2.5000e-001

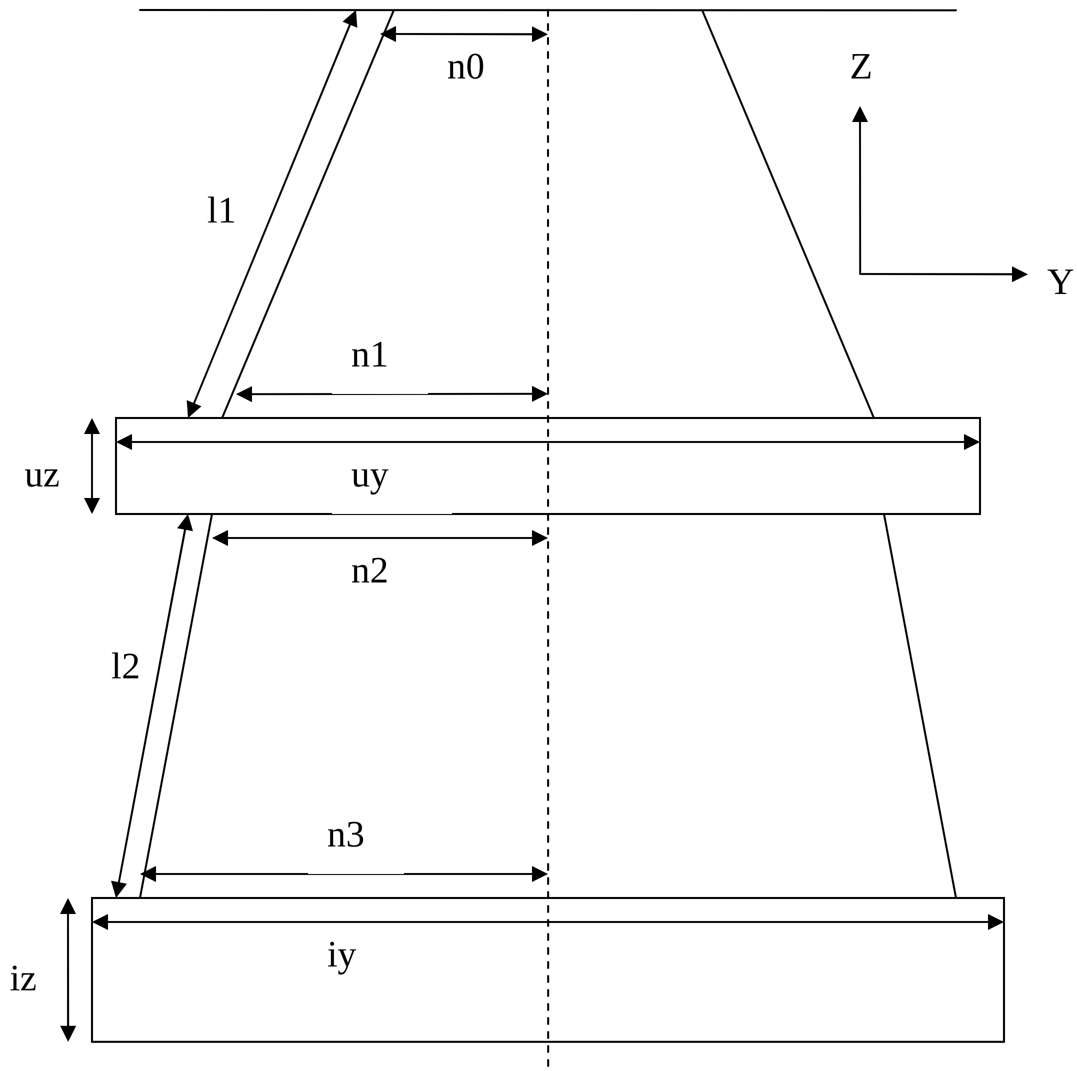

Figure 15. Parameters for a double pendulum (face on view)

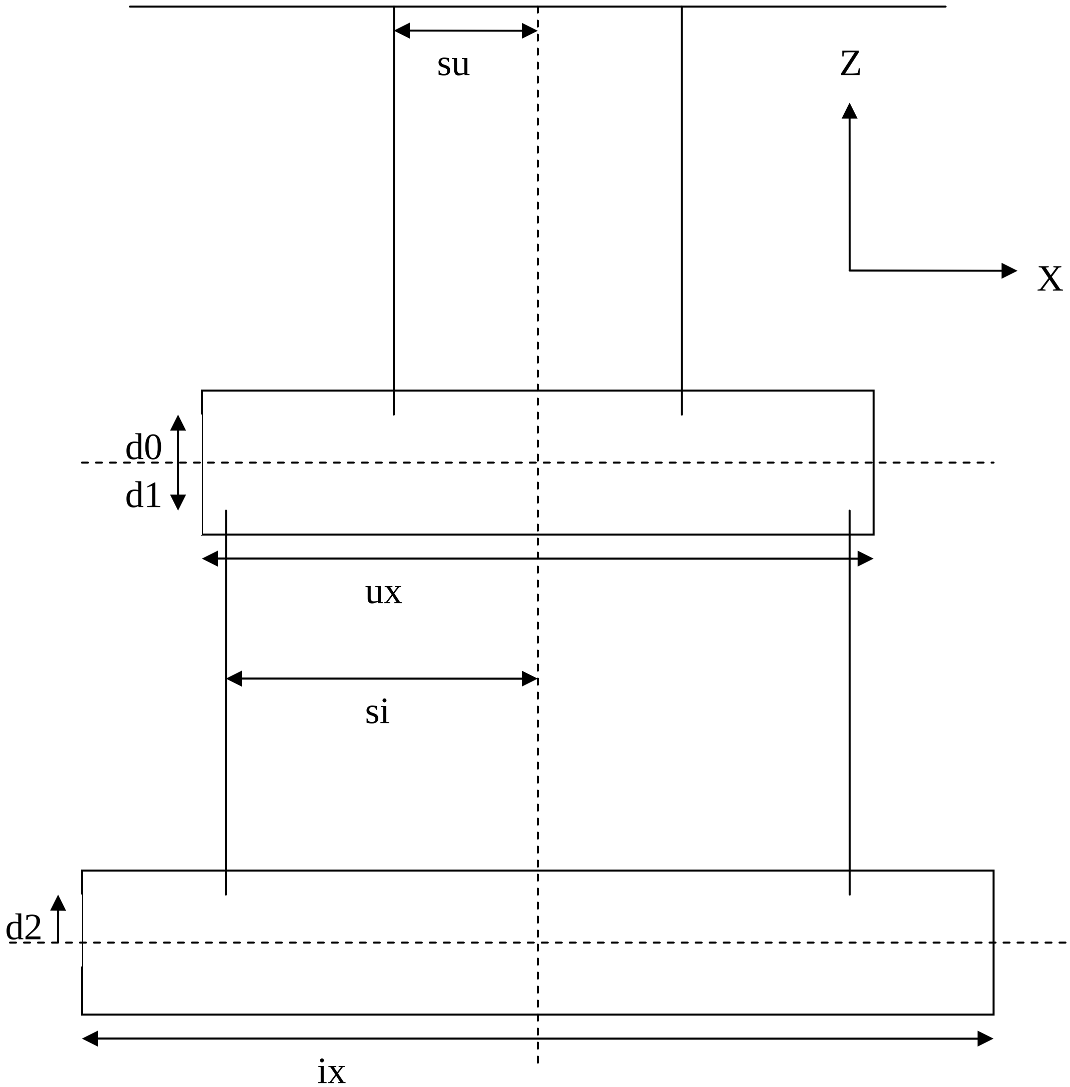

Figure 16. Parameters for a double pendulum (side view)

Appendix B
Blade Dimension Details.

(simplified shape shown: connection for wire attachment at tip not included)

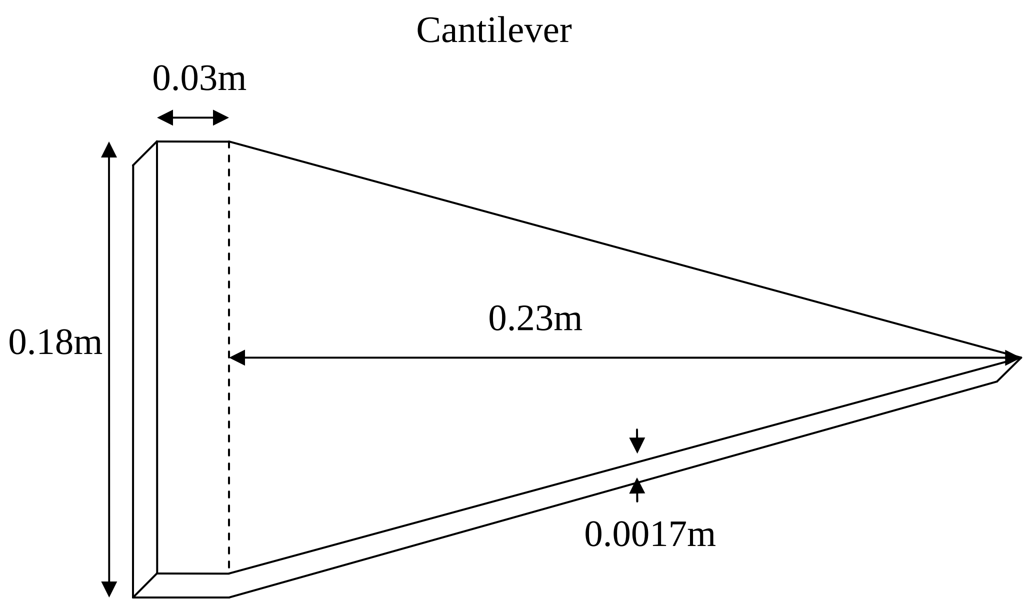

Figure 17. Cantilever parameters

Uncoupled frequency =2.49 Hz
Stress level 7.8 x 10^8 N/m^2

(assumes alpha factor of 1.38)

Appendix C Actuator positions

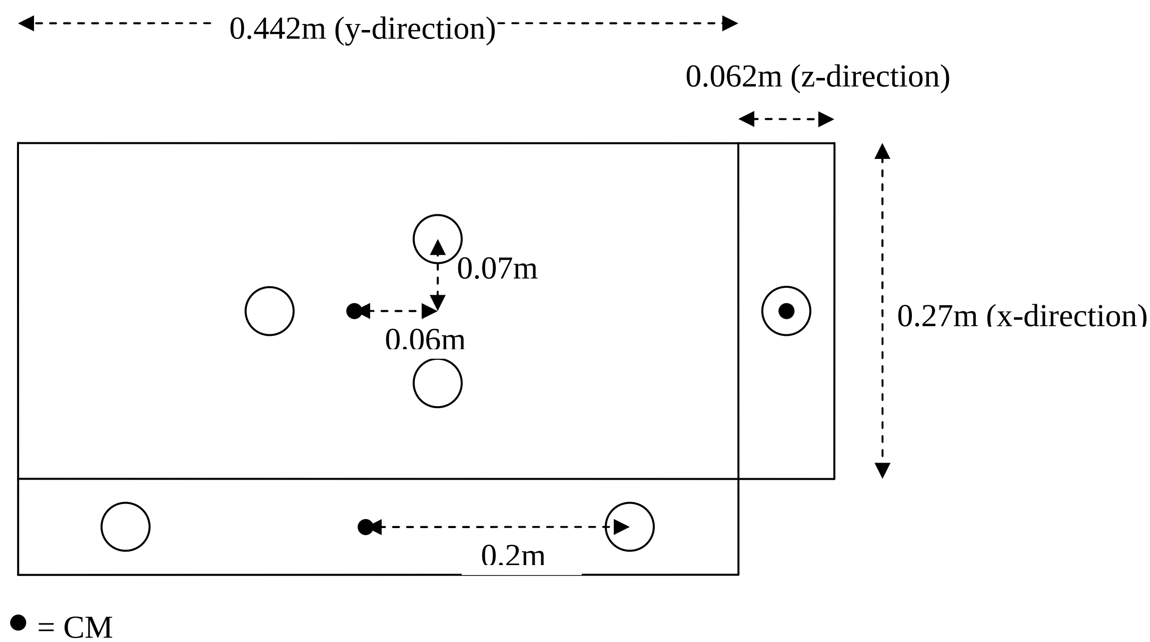

Figure 18. Damping coil placement on top mass

Gain parameters:
Torque Gain = (gain factor) x (number of magnets) x (lever arm)^2
Force Gain = (gain factor) x (number of magnets)

gain factor = 3/2
Torque-rotation Gain = 0.12
Force-longitudinal Gain = 3

gain factor = 1
Force-vertical Gain = 3
Torque-pitch Gain = 0.0098
Torque-roll Gain = 0.0108

gain factor = 3
Force-transverse Gain = 3

Eddy current damping function veldamp = zpk([0],-1000,30000)