LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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Redesign of Blades for Improved Vertical Isolation for Triple Suspensions in Advanced LIGO

Norna A Robertson, Calum I Torrie

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This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1 Introduction

Recent work on the expected low frequency length noise in the Michelson and signal recycling cavity degrees of freedom and their impact on the GW channel by M Evans and P Fritschel, presented in “Displacement Noise in Advanced LIGO Triple Suspensions” (T080192-01-D), has led to a set of recommendations for revising the design of the triple pendulum suspensions for the beamsplitter/folding mirror and the small (HSTS) and large (HLTS) optics in the recycling cavities. One of these recommendations is to consider increasing the vertical seismic isolation for all of these suspensions. We present here the results of our considerations. We show that in principal we could gain a factor of ~2 to 3 improvement in vertical isolation with a modest amount of redesign work. We discuss these results and present our conclusions.

2 Background

The baseline designs for the beamsplitter (BS) suspension, input modecleaner suspension (now HAM small triple) and recycling mirror suspension (now HAM larger triple) were understood to give adequate vertical isolation in conjunction with the original specifications for residual seismic noise from the active platform which supports the suspensions. However regarding the HAM suspensions, the use of a more realistic seismic platform noise model based on performance data taken on the as-built LHO HAM-ISI shows that the platform noise, in combination with the transfer functions of the HAM triples, leads to vertical seismic noise exceeding the desired noise limit for the signal recycling cavity length below 20 Hz (see T080192-01 figure 4). This is due to a combination of two factors: vertical ground motion is much higher than horizontal in the 10-30 Hz region, and ii) resonances in the “gull-wing” supports lead to higher transmissibility. In the case of the beamsplitter the isolation does appear to be adequate. However we have been asked to consider providing more vertical isolation in the suspension to give more margin for potentially higher BSC-ISI platform noise in the 10-20 Hz band due to amplification from the BSC piers for example.

3 Modifications to Blade Design

All the suspension under discussion are triple suspensions with two sets of blades – one set of two at the top of the suspension and the second set of four within the top mass. The vertical isolation in the suspensions in the 10-20 Hz region is dominantly set by the resonant frequencies of the first two modes, whose uncoupled values are in the 2 to 3 Hz region. The third mode is much higher due to the wire suspension in the lowest stage, being ~18 Hz for the BS and ~28 Hz for the other triples. In the current designs for the triple pendulums the blades have been conservatively stressed to a level of around 600 to 800 MPa, corresponding to the typical stress levels we used in the GEO designs. For the quadruple pendulums in Advanced LIGO we decided to increase the stress level to ~ 1 GPa to gain isolation. This value is approximately 55% of yield stress, in line with what our VIRGO colleagues use. See T040108-03-K section 11 for further discussion on this. Using the same criteria in the triple blade designs as used for the quads we can gain some isolation. The most straightforward way to do this is to decrease the thickness of the blades, leaving the other dimensions unchanged. This has the minimum impact on the design of the suspensions which are in a mature state.

4 Results

We present vertical transfer functions from the MATLAB models for each of the three triple pendulum designs, using the most up-to-date parameter sets for each design*, as detailed in the appendix in section 6. See figures 1, 2 and 3. In each case the blue curve is using the original design of blades and the green curve is produced using the revised design of blades. Active damping is included to give a damping time to 1/e of ~ 10 s, using the "adapted geo active" functions included in the MATLAB model.

[* One recent change (Oct 2008) to the large triple parameter set is that the lowest wire has been made slightly thicker, now 135 μm radius compared to 120 μm listed previously, to make the highest vertical mode the same for the two suspension designs.]

Details of the masses in the suspensions and the blade parameters are as follows.

4.1 Masses, blade designs, uncoupled frequencies and stress.

4.1.1 Beamsplitter

<u>Masses</u> (from top to bottom)
m1 = 12.621 kg
m2 = 13.575 kg
m3 = 14.175 kg
(m3 corresponds to a beamsplitter optic of 370 mm diam. with a 0.04 degree symmetric wedge, and thickness of 60 mm at thick end).

<u>Upper Blades</u>
width thick end = 62.5mm
length = 250 mm
thickness = 2.5mm (original design) 2.2 mm (revised design)
frequency = 2.93 Hz (original design), 2.42 Hz (revised design)
stress = 760 MPa (original design), 982 MPa (revised design)

<u>Lower Blades</u>
width thick end = 25.78mm
length = 140 mm
thickness = 1.6 mm (original design), 1.5mm (revised design)
frequency = 3.13 Hz (original design), 2.84 Hz (revised design)
stress = 866 MPa (original design) 986 MPa (revised design)

The frequencies quoted are the so-called "uncoupled frequencies" which are what would be obtained by taking the combined blade spring constant at one stage and the mass directly attached to those blades i.e. for the upper blades the appropriate mass is m1, and for the lower blades it is m2. Improvement in isolation is given approximately by comparing the square of the products of the frequencies = [(2.93*3.13)/(2.42*2.84)]^2 = 1.78. The actual ratio from the data in figure 1 gives a factor of 1.76 at 10 Hz.

4.1.2 HAM large triple suspension

<u>Masses</u> (from top to bottom)
m1 = 12.07 kg
m2 = 12.10 kg

m3 = 12.14 kg

(m3 corresponds to a large triple optic of 265 mm diam. with a 0.6 degree symmetric wedge, and thickness of 101.4 mm thick at thick end).

Upper Blades
width thick end = 65 mm
length = 250 mm
thickness = 2.3 mm (original design) 2.05 mm (revised design)
frequency = 2.70 Hz (original design), 2.27 Hz (revised design)
stress = 777 MPa (original design), 978 MPa (revised design)

Lower Blades
width thick end = 32 mm
length = 120 mm
thickness = 1.3 mm (original design), 1.17 mm (revised design)
frequency = 3.2 Hz (original design), 2.73 Hz (revised design)
stress = 791 MPa (original design) 977 MPa (revised design)

Improvement in isolation is given approximately by comparing the square of the products of the frequencies = [(2.7*3.2)/(2.27*2.73)]^2 = 1.94. The actual ratio from the data in figure 2 gives a factor of 2.0 at 10 Hz.

4.1.3 HAM small triple suspension

Masses (from top to bottom)
m1 = 3.125 kg
m2 = 2.967 kg
m3 = 2.8165 kg

(m3 corresponds to a small triple optic of 175 mm diam. with a 2.0 degree symmetric wedge, and thickness of 75 mm at thick end. This is the current design for use in the recycling cavity. The IMC optic has a smaller wedge of 0.5 degrees and hence a slightly smaller mass).

Upper Blades
width thick end = 39.878 mm
length = 250 mm
thickness = 1.5 mm (original design), 1.3 mm (revised design)
frequency = 2.19 Hz (original design), 1.76 Hz (revised design)
stress = 730 MPa (original design), 973 MPa (revised design)

Lower Blades
width thick end = 18 mm
length = 120 mm
thickness = 1.0 mm (original design), 0.76 mm (revised design)
frequency = 3.27 Hz (original design), 2.16 Hz (revised design)
stress = 567 MPa (original design), 982 MPa (revised design)

Improvement in isolation is given approximately by comparing the square of the products of the frequencies = [(2.19*3.27)/(1.76*2.16)]^2 = 3.5. The actual ratio from the data in figure 3 gives a factor of 3.7 at 10 Hz.

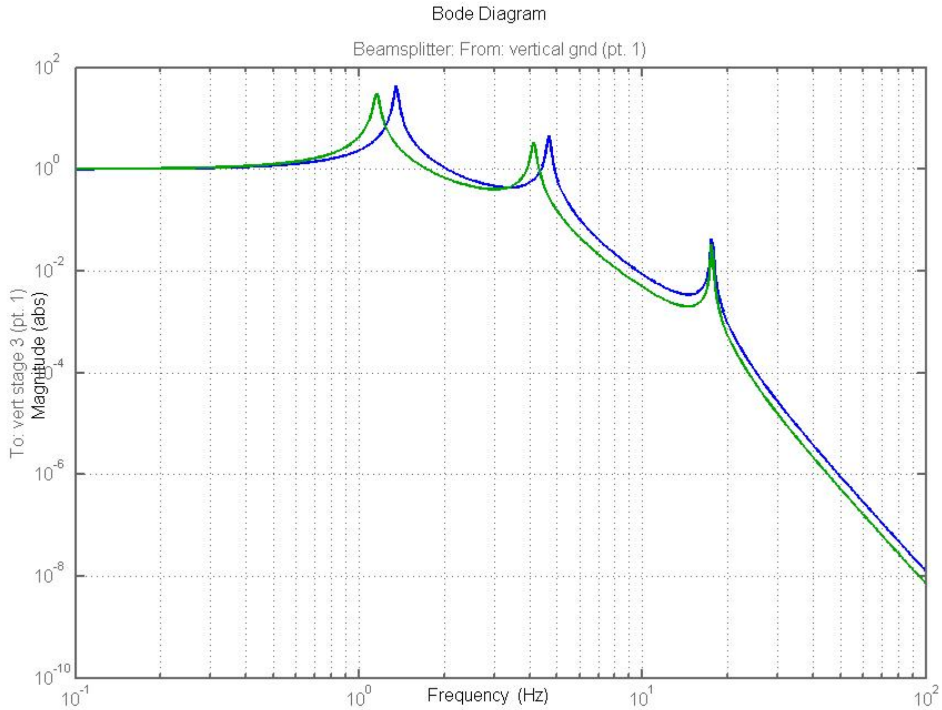


Figure 1. Vertical transfer functions for the beamsplitter triple suspension. The blue curve corresponds to the original blade design and the green curve to the revised design.

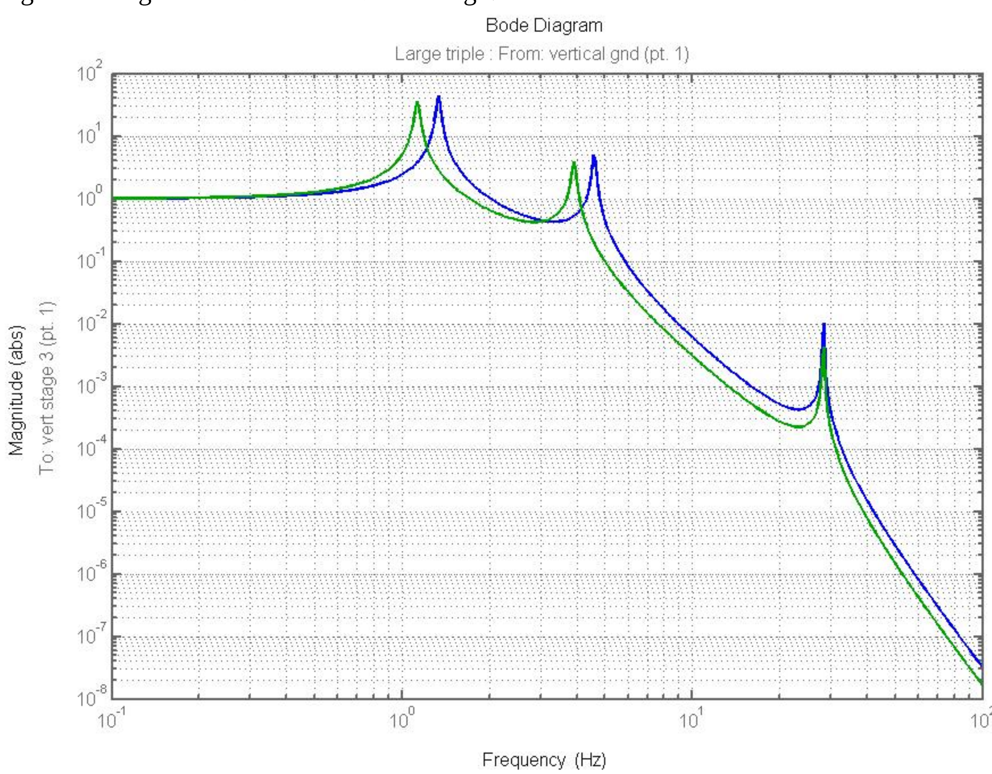


Figure 2. Vertical transfer functions for the HAM large triple suspension. The blue curve corresponds to the original blade design and the green curve to the revised design.

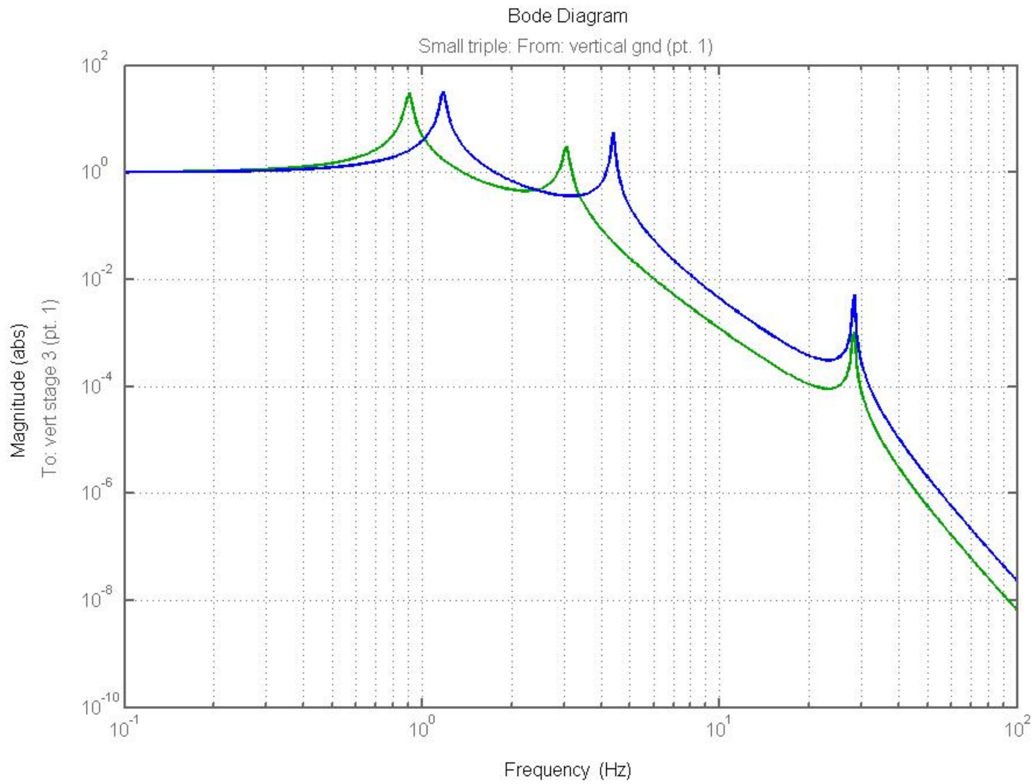


Figure 3. Vertical transfer functions for the HAM small triple suspension. The blue curve corresponds to the original blade design and the green curve to the revised design.

5 Conclusions

We have seen that by reducing the thicknesses of the blades in the designs of the triple pendulum suspensions we can enhance the vertical isolation by factors of ~2 to 3. The change to the thickness increases the stress in the blades. We have increased the stress to the same level as has been accepted for use in the blades for the test mass quadruple suspensions. Changing the blade thickness is the simplest way to achieve a modest increase in isolation without significantly adding to the design effort for these suspensions which are now in a mature state. Regarding the beamsplitter suspension, the designs for the blades need to be fixed very soon to allow the UK to proceed with manufacture. We therefore propose that the redesigned values as given above are accepted for use in the beamsplitter. Regarding the large and small triples, we will propose these modifications at the upcoming preliminary design review. We recognise that the lower blades for the small triple have a proposed thickness of 0.76 mm and that this value is thinner than any blades we have previously had manufactured. Thus for those particular blades we will propose a further round of prototyping before accepting such a change to the design.

6 Appendix – parameters used in MATLAB models

In all cases parameters are as designed at 10 Oct 2008. The parameter values correspond to the revised blade design. Minor changes may still occur especially in the large and small triples when these designs are reviewed. Note that the MATLAB models assume right circular cylinders for the optics. The thicknesses have been chosen to give the same masses as the real optics with their appropriate wedge values.

Note that rounding in the lists below has in some cases reduced the number of significant figures. Where there is an apparent discrepancy with the numbers in section 4, the numbers in section 4 should be used.

6.1 Beamsplitter

```
pend =

            m1: 12.6210
     material1: 'steel'
           I1x: 0.1659
           I1y: 0.0247
           I1z: 0.1643
            m2: 13.5750
            ix: 0.0571
            ir: 0.1850
           I2x: 0.2592
           I2y: 0.1298
           I2z: 0.1359
            m3: 14.1749
     material3: 'silica'
            tx: 0.0599
            tr: 0.1850
           I3x: 0.2426
           I3y: 0.1255
           I3z: 0.1255
            l1: 0.6120
            l2: 0.6015
            l3: 0.5000
           nw1: 2
           nw2: 4
           nw3: 4
            r1: 3.1250e-004
            r2: 2.0000e-004
```

r3: 1.2500e-004
Y1: 2.1190e+011
Y2: 2.1190e+011
Y3: 2.1190e+011
l1b: 0.2500
a1b: 0.0625
h1b: 0.0022
ufc1: 2.4200
l2b: 0.1400
a2b: 0.0258
h2b: 0.0015
ufc2: 2.8400
su: 0
si: 0.0150
sl: 0.0050
n0: 0.0770
n1: 0.1300
n2: 0.0600
n3: 0.1915
n4: 0.1865
n5: 0.1865
stage2: 1
d0: -0.0018
d1: -9.0670e-004
d2: 0.0081
d3: -8.1100e-005
d4: -8.1100e-005
tl1: 0.6079
tl2: 0.5941
tl3: 0.4998
l_cofm: 1.7019
l_total: 1.8869
ribbon: 0

```
                    db: 0
                     g: 9.8100
                   kc1: 1.4590e+003
                   kc2: 2.1613e+003
  l_suspoint_to_centreofoptic: 1.7019
  l_suspoint_to_bottomofoptic: 1.8869
                 flex1: 0.0028
                 flex2: 0.0019
                 flex3: 0.0011
               flex3tr: 0.0011
            longpitch1: [0.4197 0.4875 1.0418]
            longpitch2: [1.0575 1.3874 1.6928]
                   yaw: [0.4893 1.3738 2.1332]
            transroll1: [0.4229 1.0503 1.5707]
            transroll2: [2.2646 3.4999 24.3361]
              vertical: [1.1494 4.0733 17.5544]
```

6.2 Large Triple

```
pend =

        m1_parameters: 'Calculated from SWorks Assem 2008'
            material1: 'combination steel+alum'
                   m1: 12.0700
                  I1x: 0.1225
                  I1y: 0.0181
                  I1z: 0.1237
        m2_parameters: [1x48 char]
            material2: 'alum + s/stl inserts + s/stl clamps'
                   m2: 12.1000
                  I2x: 0.0821
                  I2y: 0.0200
                  I2z: 0.0819
        m3_parameters: [1x48 char]
```

material3: 'silica'
tx: 0.1000
tr: 0.1325
m3: 12.1395
I3x: 0.1066
I3y: 0.0634
I3z: 0.0634
l1: 0.2025
l2: 0.2036
l3: 0.2552
nw1: 2
nw2: 4
nw3: 4
r1: 3.0000e-004
r2: 1.7000e-004
r3_parameters: 'Spring Steel Wires'
r3: 1.3500e-004
Y1: 2.1200e+011
Y2: 2.1200e+011
Y3_parameters: 'Spring Steel Wires'
Y3: 2.1200e+011
ufc1: 2.2700
l1b: 0.2500
a1b: 0.0650
h1b: 0.0021
ufc2: 2.7300
l2b: 0.1200
a2b: 0.0320
h2b: 0.0012
su: 0
si: 0.0300
sl: 0.0050
n0: 0.0770

n1: 0.1300
n2: 0.0700
n3: 0.1375
n4: 0.1455
n5: 0.1455
stage2: 1
d0: 1.0000e-003
d1: 1.0000e-003
d2: 1.0000e-003
d3: 1.0000e-003
d4: 1.0000e-003
ribbon: 0
db: 0
g: 9.8100
kc1: 1.2277e+003
kc2: 1.7801e+003
tl1: 0.1964
tl2: 0.1941
tl3: 0.2572
l_suspoint_to_centreofoptic: 0.6477
l_suspoint_to_bottomofoptic: 0.7802
flex1: 0.0026
flex2: 0.0014
flex3: 0.0014
flex3tr: 0.0014
longpitch1: [0.6724 0.7726 1.5858]
longpitch2: [2.2854 2.8528 3.8050]
yaw: [1.0198 2.3427 3.3912]
transroll1: [0.6931 1.5246 2.1522]
transroll2: [2.5845 4.0594 47.0153]
vertical: [1.1236 3.8588 28.2667]

6.3 Small Triple

pend =

```
m1_parameters: 'Calculated'
   material1: 'combination steel+alum'
          m1: 3.1250
         I1x: 0.0238
         I1y: 0.0024
         I1z: 0.0238
m2_parameters: 'Controls P-type: Calculated'
   material2: 'alum with holes + s/steel clamps'
          ix: 0.0750
          ir: 0.0750
          m2: 2.9670
         I2x: 0.0086
         I2y: 0.0056
         I2z: 0.0057
m3_parameters: [1x48 char]
   material3: 'silica'
          tx: 0.0724
          tr: 0.0750
          m3: 2.8165
         I3x: 0.0079
         I3y: 0.0052
         I3z: 0.0052
          l1: 0.2950
          l2: 0.1670
          l3: 0.2200
         nw1: 2
         nw2: 4
         nw3: 4
          r1: 1.8000e-004
          r2: 1.0000e-004
```

r3_parameters: 'Spring Steel Wires'

r3: 6.0000e-005

Y1: 2.2000e+011

Y2: 2.2000e+011

Y3_parameters: 'Spring Steel Wires'

Y3: 2.2000e+011

ufc1: 1.7600

l1b: 0.2500

a1b: 0.0399

h1b: 0.0013

ufc2: 2.1600

l2b: 0.1200

a2b: 0.0180

h2b: 7.6000e-004

su: 0

si: 0.0285

sl: 0.0050

n0: 0.0773

n1: 0.1000

n2: 0.0390

n3: 0.0765

n4: 0.0800

n5: 0.0800

stage2: 1

d0: 0.0050

d1: 0.0020

d2: 1.0000e-003

d3: 1.0000e-003

d4: 1.0000e-003

ribbon: 0

db: 0

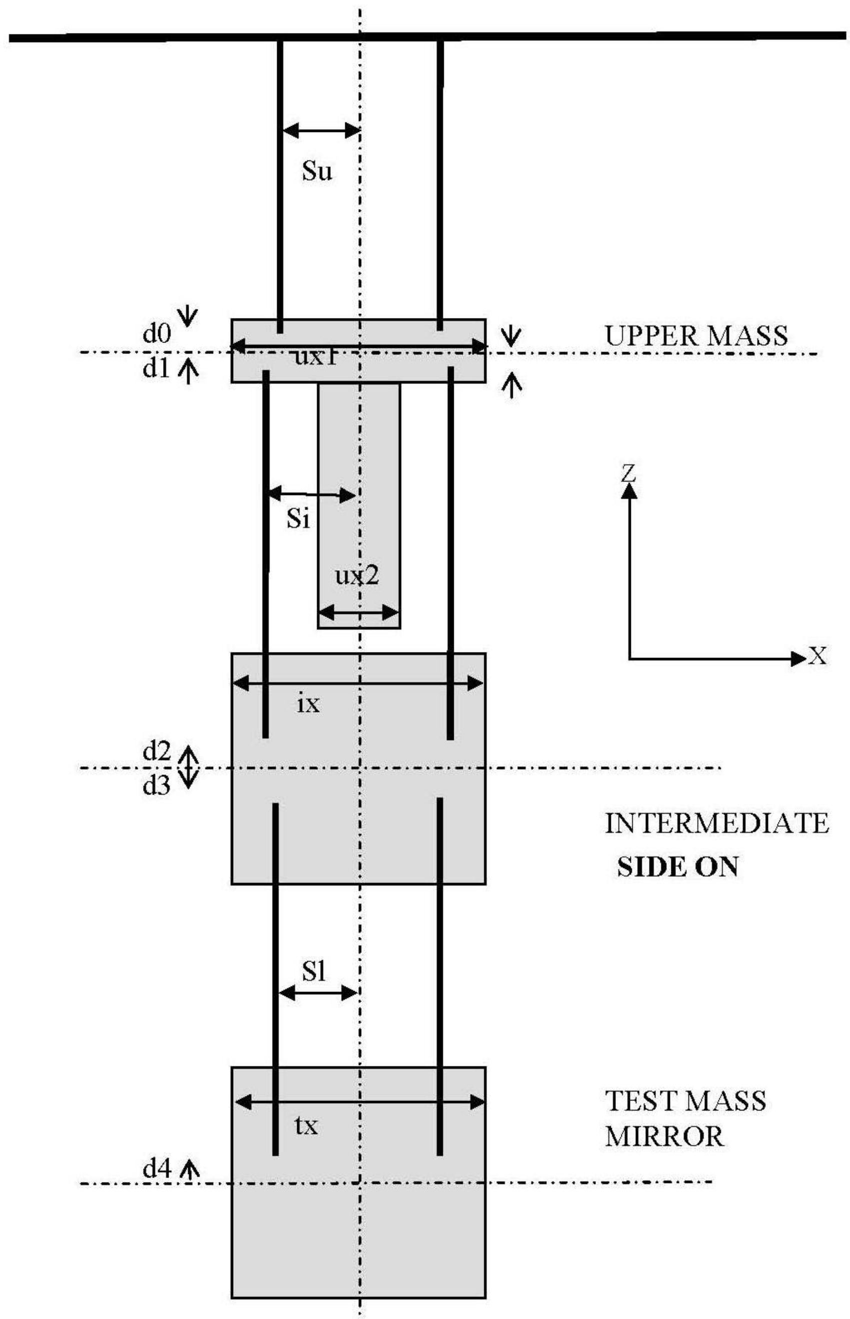
g: 9.8100

kc1: 191.0755

kc2: 273.2466
tl1: 0.2991
tl2: 0.1657
tl3: 0.2220
l_suspoint_to_centreofoptic: 0.6869
l_suspoint_to_bottomofoptic: 0.7619
flex1: 0.0020
flex2: 0.0011
flex3: 5.6938e-004
flex3tr: 5.6938e-004
longpitch1: [0.6741 1.0299 1.5090]
longpitch2: [2.7876 3.2308 3.9035]
yaw: [1.1045 1.9885 3.5237]
transroll1: [0.6782 1.5050 1.7313]
transroll2: [2.1783 3.0235 42.1554]
vertical: [0.9007 3.0097 28.2022]

Appendix E

E.1 The parameters of a triple pendulum (side on view)



E.2 The parameters for a triple pendulum (face on view)