Note on Design of the ETM Reaction Chain and ITM Reaction Chain in Advanced LIGO

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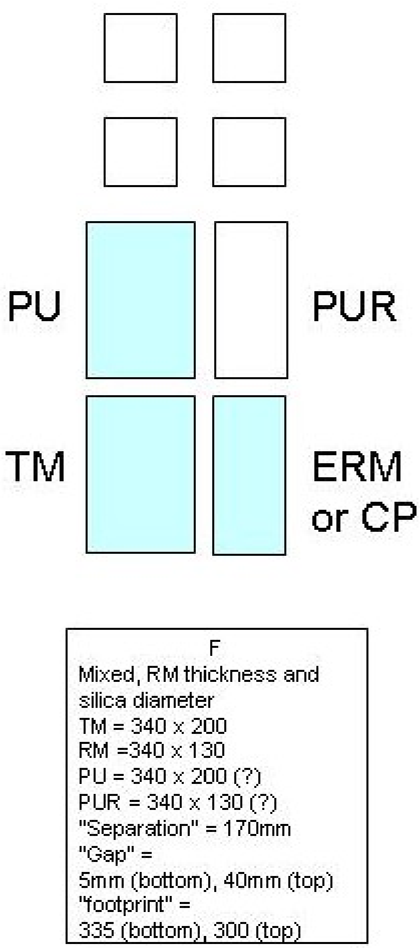
LIGO DCC T060283-02-R

Note: version 02 supercedes version 01. The MATLAB code was not set up correctly to change from ribbons in the main chain to wires in the reaction chain in version 01, and hence the mode frequencies were incorrect. The results are slightly different but the conclusions remain essentially the same.

1. Introduction

The conceptual design for the main chains (ETM and ITM) is given in the Conceptual Design Document T010103-04-D. The conceptual sizes (footprints) of masses for the reaction chain for the ETM is given in the document entitled “Separation of Chains in Quad Suspensions” T050077-05-K, see in particular the diagram in section 4. Option F is the chosen option – see figure 1 below (slightly modified), where the left hand chain is the main chain and the right hand chain is the reaction chain. That document explains the background to the choice of sizes, which stems from the requirement to leave open the option of returning to a sapphire test mass while minimising the redesign effort.



Note that the final mass in the reaction chain has previously been called RM in T0500077 and other documentation. This could cause confusion with the power and signal recycling mirrors, also called RM. Thus we have renamed the reaction mass for the ETM chain the ERM (end reaction mass) and advocate that this nomenclature is used in all future documentation. The bottom mass in the ITM reaction chain is the compensator plate, CP.

To minimize differences in the mechanical design between the two chains, we choose to make the sum of the penultimate and test masses in the main chain be equal to the sum of the bottom two masses in the reaction chain. This ensures that the blade designs can be common.

2. 1 ETM Reaction Chain

We note that the ETM mass, TM, and its reaction mass, ERM, are the same diameter but different thicknesses. The TM is made of silica, density 2200 kg/m^3 and mass 39.57 kg (allowing for flats on the side for bonding). The penultimate mass, PU, is the same size and mass as the TM. Electrostatic drive is used between the TM and the ERM, and our baseline design has been to make these two masses have similar mass. This has led to the use of a high density glass for the ERM. For the noise prototype we have chosen to use Schott F2 which has a density of 3610 kg/m^3. Given the dimensions shown, and allowing for flats, its mass is 42.2 kg. The penultimate reaction mass PUR, which is made of metal, will be consequently slightly lighter than the PU.

The two chains are not identical and for completeness we have checked that the mode frequencies and damping behaviour are similar, so that other design features (for example the spacing of wires) can be the same in each chain.

2.2 Comparison of mode frequencies for ETM main chain and reaction chain.

These analyses have been done using the most recent MATLAB quad noise prototype model which can be found on Mark Barton's web site at

http://www.ligo.caltech.edu/~e2e/

following links to "Suspension by Mark Barton" and then "MATLAB versions" to find

20060914quadnoise.zip

The ETM main chain frequencies are

longpitch1: [**0.3234** 0.4392 0.9868 **1.2026**]
longpitch2: [**1.5008** 1.9869 **2.9339** 3.4112]
yaw: [0.5969 1.3443 2.3972 3.0277]
transroll1: [0.4626 0.8245 1.0445 2.1082]
transroll2: [2.6911 3.3111 5.0980 12.8494]
vertical: [0.5814 2.3376 3.7591 8.9885]

The ETM reaction chain frequencies are

longpitch1: [**0.3633** 0.4371 1.0195 **1.3501**]
longpitch2: [2.0133 **2.7117** **3.0147** 3.4146]
yaw: [0.6375 1.4289 2.5243 3.1641]
transroll1: [0.4590 0.7987 1.0791 2.1309]
transroll2: [2.6964 3.3200 5.0985 24.2292]
vertical: [0.5821 2.3460 3.7719 17.0151]

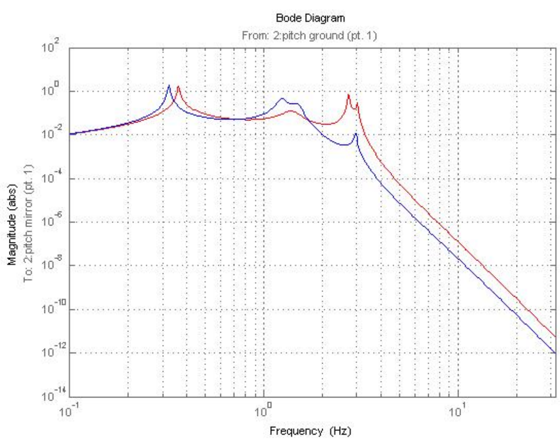
The reaction chain results have been produced making the following assumptions.

i) the ERM has been assumed to be cylindrical with no flats.

ii) The PUR has been assumed to be cylindrical with no flats and with an average density such that its mass when summed with the ERM equals the mass of the bottom two stages in the main chain.

iii) The only other change made between the two parameter sets has been to replace the silica ribbons/fibres in the main chain with steel wires of suitable radius to give safety factor of 3 (thus r3 and Y3 change in the parameter set).

We note that the biggest frequency changes are in the high frequency vertical and roll modes, which are higher due to the higher Young's modulus of steel wire compared to silica. Other than that the modes are in general within a few percent, except for the third pitch mode which has risen from ~1.5 to ~2.7 Hz (pitch modes indicated in bold above) The bode magnitude plots for pitch are shown in figure 2a, where the magnitude of the applied damping is unchanged between the two plots. It can be seen that the 2.7 Hz pitch mode is less well damped showing that it is less well coupled to the other pitch modes. However the overall decay time is similar (see figure 2b) and so the damping is still acceptable. The pitch isolation is also less, but the noise requirements for the reaction chain are substantially less than for the main chain and so this is not a problem.



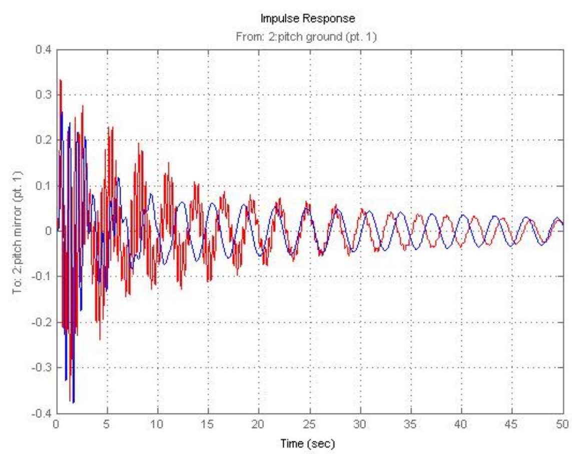


Figure 2a (on left): Transfer function for pitch ground to pitch of bottom mass.
Figure 2b (on right): Impulse response for pitch.
Blue = ETM main chain. Red = ETM reaction chain.
Damping is "adapted GEO active" with gain unchanged between blue and red graphs (gain of 0.3 in gain box in pende model).

3.1 ITM Reaction Chain

The ITM reaction chain incorporates the compensator plate (CP) as its bottom mass. The size of this optic has been the subject of much discussion over the past few years as the design of the thermal compensation scheme for Advanced LIGO has been developed. See for example T040038-01-R in which various options in size are considered. Health warning: the analyses covered in that document predate the sapphire/silica downselect and predate the new physics added to the MATLAB model following findings with the quad controls prototype. Thus the parameters and frequencies quoted in that document should not be directly compared to the numbers given here. However the general findings are still valid, and in particular, when a thin (65 mm) light (11kg) CP was under consideration it looked like we would want to change the spacing of the wires at the final stage to increase pitch coupling. Now (Dec 06) the baseline size and mass for the compensator plate is 130 mm thick, 340mm diameter, silica, which gives a mass of 26.0 kg (without flats). We wish to check that no change in wire spacing is necessary for this size.

3.2 Comparison of mode frequencies for ITM main chain and ITM reaction chain incorporating CP.

The ITM main chain frequencies are

longpitch1: [**0.3234** 0.4392 0.9868 **1.2026**]
longpitch2: [**1.5008** 1.9869 **2.9339** 3.4112]
yaw: [0.5969 1.3443 2.3972 3.0277]
transroll1: [0.4626 0.8245 1.0445 2.1082]
transroll2: [2.6911 3.3111 5.0980 12.8494]
vertical: [0.5814 2.3376 3.7591 8.9885]

The ITM reaction chain frequencies are

longpitch1: [**0.3493** 0.4553 0.8575 **1.3536**]
longpitch2: [1.9096 **2.2865 2.9383** 3.4016]
yaw: [0.6519 1.3433 2.3097 2.9810]
transroll1: [0.4802 0.7936 0.8983 2.0413]
transroll2: [2.6977 3.3092 5.0968 20.0025]
vertical: [0.5824 2.3475 3.7738 14.0462]

The reaction chain results have been produced making the following assumptions.

i) the CP, has been assumed to be cylindrical with no flats.
ii) The PUR has been assumed to be cylindrical with no flats and with an average density such that its mass when summed with the CP equals the mass of the bottom two stages in the main chain.
iii) The only other change made between the two parameter sets has been to replace the silica ribbons/fibres in the main chain with steel wires of suitable radius to give safety factor of 3 (thus r3 and Y3 change in the parameter set).

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Once again the pitch modes are the low frequency modes most affected (highlighted in bold above) In particular the mode at 2.29 Hz is less coupled and hence less well damped. See figures 3a and 3b. The green curve has the same gain in the damping loop for the ITM and its reaction chain. If the ringing at 2.29 Hz were too large in the reaction chain, increased pitch damping could be used, an example of which is shown in the red curve.

4. Conclusions.

We have looked at the behaviour of the ETM and ITM reaction chains in terms of their mode frequencies and damping behaviour. We conclude that the behaviour of these chains is acceptable with a substitution of new masses at the penultimate and bottom stages whose sum equals that of the penultimate and test mass in the main chain and whose dimensions are as given above, and with replacement of the silica suspensions with steel wire. No other changes have been made. We note that the real design of the penultimate masses for the reaction chains will differ from the simple model assumed above of a cylinder with suitable average density to give the required mass. When those penultimate masses have been designed, the models should be checked again. However from our experience to date we do not anticipate any problems arising from such changes.

Finally we note that it has been suggested for commonality of design that the ETM reaction mass beyond the noise prototype could be made of silica rather than F2, with size and mass the same as the CP, hence making the reaction chains for the ETM and ITM essentially the same from a mechanical viewpoint. This is certainly an attractive option to consider.

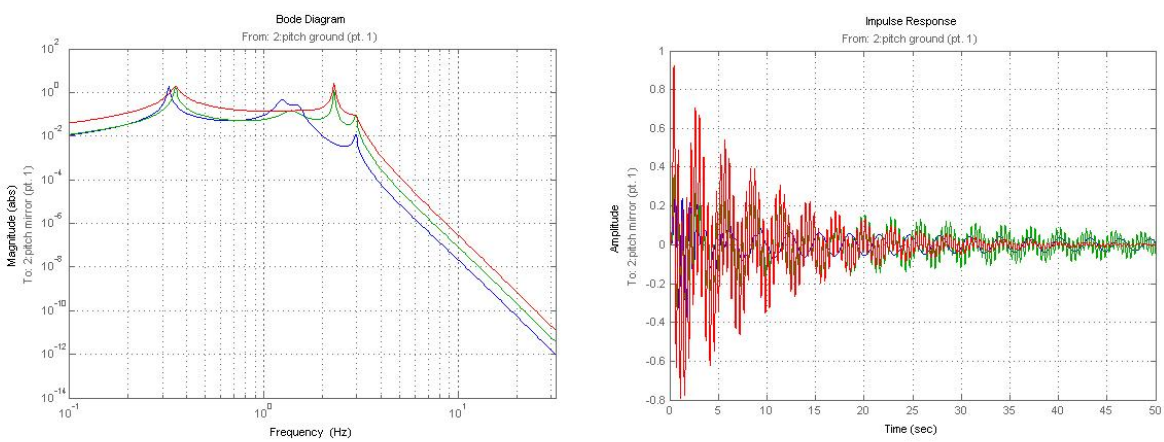

Figure 3a (on left): Transfer function for pitch ground to pitch of bottom mass.
Figure 3b (on right): Impulse response for pitch.
Blue = ITM main chain. Green and Red = ITM reaction chain.
Damping is “adapted GEO active” with gain unchanged between blue and green graphs (gain of 0.3 in gain box in pende model) and gain three times larger for red graph.

Appendix.

Parameter set for models.

1) ETM/ITM main chain

```
pend =
              ribbon: 1
              stage2: 1
                   g: 9.8100
                  nx: 0.1300
                  ny: 0.5000
                  nz: 0.0840
                denn: 4000
                  mn: 22.1100
                 Inx: 0.4558
                 Iny: 0.0712
                 Inz: 0.4547
                  ux: 0.1300
                  uy: 0.5000
                  uz: 0.0840
                den1: 4000
                  m1: 21.0110
                 I1x: 0.5174
                 I1y: 0.0598
                 I1z: 0.5205
                  ix: 0.2000
                  ir: 0.1700
                den2: 2200
                  m2: 39.5700
                 I2x: 0.5666
                 I2y: 0.4204
                 I2z: 0.4101
                  tx: 0.2000
                  tr: 0.1700
                den3: 2200
                  m3: 39.5700
                 I3x: 0.5666
                 I3y: 0.4204
                 I3z: 0.4101
             tlnspec: 0.4160
             tl1spec: 0.2770
             tl2spec: 0.3410
             tl3spec: 0.6020
                 nwn: 2
                 nw1: 4
```

nw2: 4
nw3: 4
bd: 0
rn: 5.2000e-004
r1: 3.5000e-004
r2: 3.1000e-004
t3: 1.1500e-004
W3: 0.0012
Yn: 2.1200e+011
Y1: 2.1200e+011
Y2: 2.1200e+011
Y3: 7.0000e+010
twistlength: 0
d3tr: 1.0000e-003
d4tr: 1.0000e-003
sn: 0
su: 0.0030
si: 0.0030
sl: 0.0150
nn0: 0.2500
nn1: 0.0900
n0: 0.2000
n1: 0.0600
n2: 0.1400
n3: 0.1762
n4: 0.1712
n5: 0.1712
kxn: 100000
kx1: 100000
kx2: 80000
stage2: 1
ribbon: 1
ln: 0.4486
l1: 0.3090
l2: 0.3417
l3: 0.6006
dm: -0.0031
dn: 0.0032
d0: -0.0017
d1: 0.0031
d2: -0.0018
d3: 6.7576e-004
d4: 6.7576e-004
kcn: 1.6111e+003
kc1: 1.8114e+003
kc2: 2.6303e+003

ufcn: 1.9213
ufc1: 2.0899
ufc2: 1.8351
tln: 0.4160
tl1: 0.2770
tl2: 0.3410
tl3: 0.6020
l_suspoint_to_centreofoptic: 1.6360
l_suspoint_to_bottomofoptic: 1.8060
flexn: 0.0041
flex1: 0.0027
flex2: 0.0028
flex3: 3.2424e-004
flex3tr: 0.0032

2) ETM reaction chain where different from above

ribbon: 0

ix: 0.1300
ir: 0.1700
den2: 3096
m2: 36.5420
I2x: 0.5280
I2y: 0.3155
I2z: 0.3155
tx: 0.1300
tr: 0.1700
den3: 3610
m3: 42.6087
I3x: 0.6157
I3y: 0.3679
I3z: 0.3679

r3: 2.2500e-004

Y3: 2.1200e+011

3) ITM (CP) reaction chain where different from 1).

ribbon: 0

ix: 0.1300
ir: 0.1700
den2: 4502
m2: 53.1369

I2x: 0.7678
I2y: 0.4587
I2z: 0.4587
tx: 0.1300
tr: 0.1700
den3: 2200
m3: 25.9665
I3x: 0.3752
I3y: 0.2242
I3z: 0.2242

r3: 1.7500e-004

Y3: 2.1200e+011