Section 10 Appendix 3

3A: Dynamic Analysis Of The BSM

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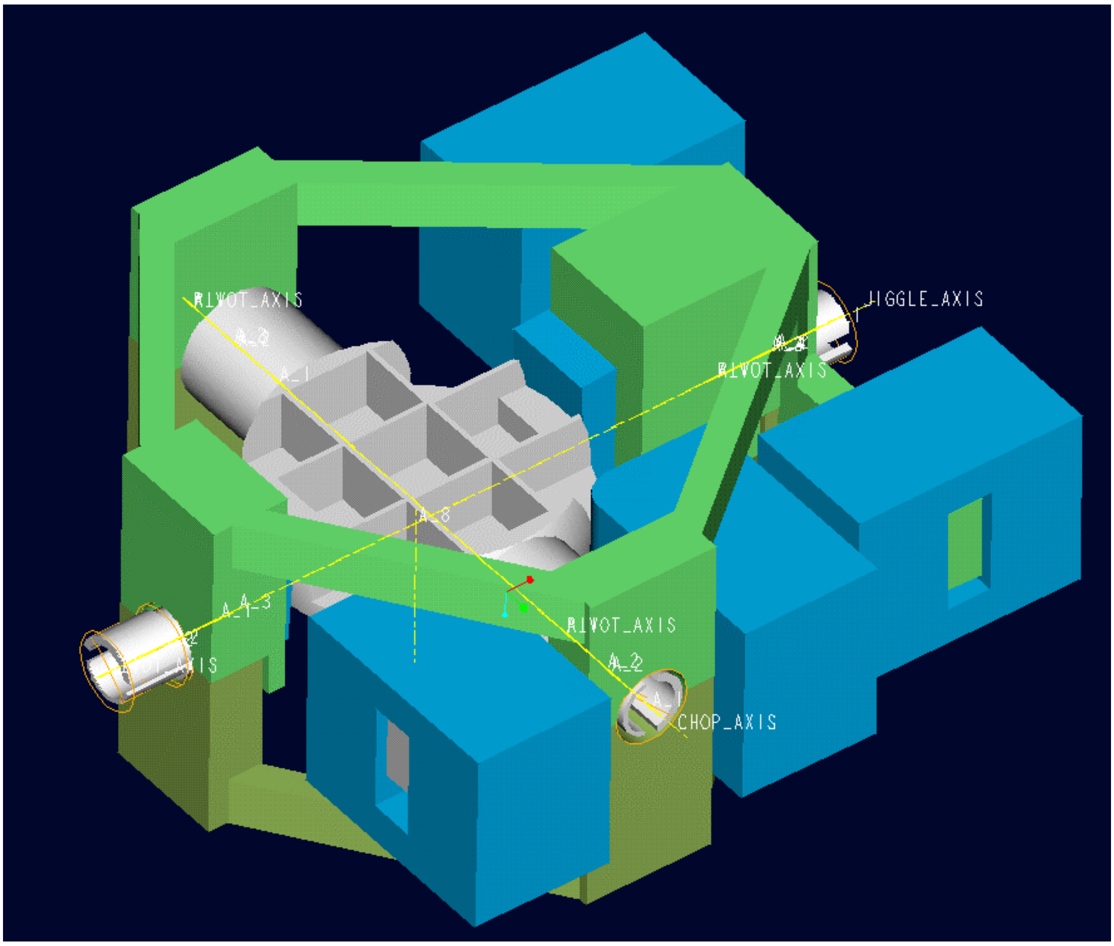
1 BSM Design

The SPIRE Beam Steering Mirror has been modelled for finite element analysis as a simplified representation of the Pro/E solid model shown below.

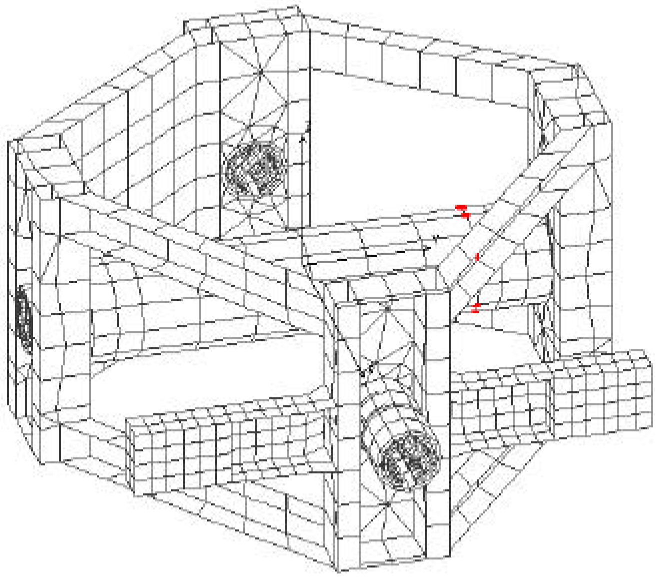


- The chop stage is monolithic. The underside of the mirror is lightweighted and has pockets for the iron plates for the sensors.
- The jiggle stage is split and clamps together around the flex pivots.
- Space envelopes for the coils and sensors (potted) are shown in blue.
- The outer rings of the flex-pivots are not shown for clarity.
- In this revision Lucas 5010-600 pivots have been used for the jiggle axis and 5010-800 for the chop axis. These have torsional stiffnesses of 0.0286 and 0.0036 lb.in/degree respectively.

2 FEA Model

2.1 Modelling

- The jiggle stage structure has been represented by thin shell elements;
- The chop stage has been represented by a tube of solid elements together with lumped masses (shown red in the illustration below) to give the same mass and moments of inertia as the solid model;
- The flex pivots have been modelled using a combination of solid and shell elements.



- The jiggle stage framework between the flex-pivot housings has been modelled as 5mm x 5mm x 0.5mm channel section.
- The pivots have been moved as far as reasonably practical towards the mirror to minimise the inertia and maximise the stiffness. To clear the coils this leads to an asymmetric arrangement.
- To balance the jiggle stage the framework in the opposite corner to the coils has been made solid. This also increases the stiffness of the structure. Due to the use of lumped masses which do not give the correct products of inertia and also because the jiggle stage has not been dynamically balanced their will be some inaccuracy in modelling coupling of the stages.

2.2 Load cases

The follwing analyses have been made:

- 50 g static load in X,Y and Z directions
- Frequency response analysis for excitation of the chop and jiggle stages by couples of 1 Newton forces at the centre of the drive magnets (equivalent forces for the chop stage.)

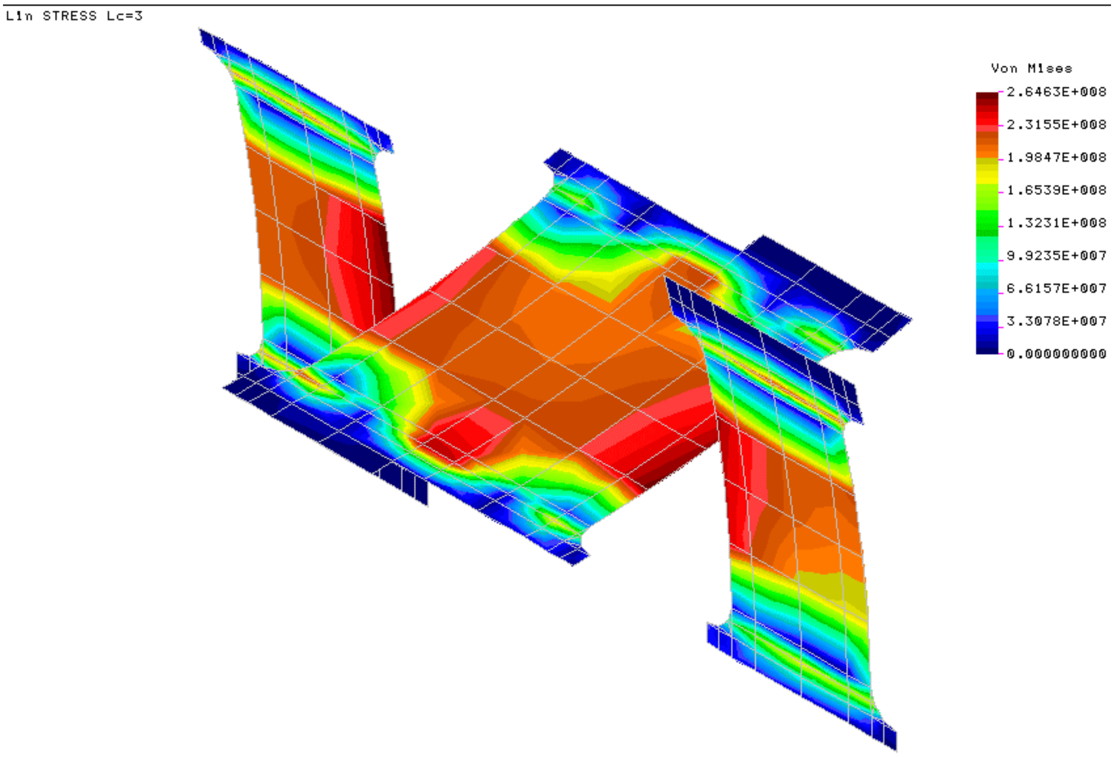
3 Results

3.1 Static stress analysis

The three load cases (50g in X, Y and Z) lead to stresses in the flexures of similar magnitude.

The highest stress, 265 MPa, occurrs in the jiggle axis flex-pivots. The 0.2% proof and ultimate tensile stresses and of 420S29 equivalent to the stainless steel used for these items are 555 MPa and 755 MPa respectively so the design appears relatively safe. It should be noted however that the model is a simplified representation for dynamic analysis and would need refinement for accurate stress calculation.

The load capacity of each of the pivots is 245 N (55 lb) and the weight of the jiggle and chop stages at 50g is 27 N.



3.2 Dynamic Analysis

3.2.1 *Frequency analysis*

The model was analysed to obtain the first 50 natural frequencies. The resonant frequencies of the chop and jiggle stages are 23 and 18 Hz respectively.

The first parasitic resonance occurs at 729 Hz.

FREQUENCY NUMBER	FREQUENCY (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SECONDS)
1	.1142200E+03	.1817867E+02	.5500952E-01
2	.1454493E+03	.2314898E+02	.4319844E-01
3	.4577739E+04	.7285698E+03	.1372552E-02
4	.5822649E+04	.9267033E+03	.1079094E-02
5	.7800567E+04	.1241499E+04	.8054781E-03
6	.9250813E+04	.1472313E+04	.6792036E-03
7	.1019618E+05	.1622772E+04	.6162294E-03
8	.1030486E+05	.1640069E+04	.6097305E-03
9	.1129106E+05	.1797028E+04	.5564743E-03
10	.1459196E+05	.2322382E+04	.4305923E-03

3.2.2 *Damping*

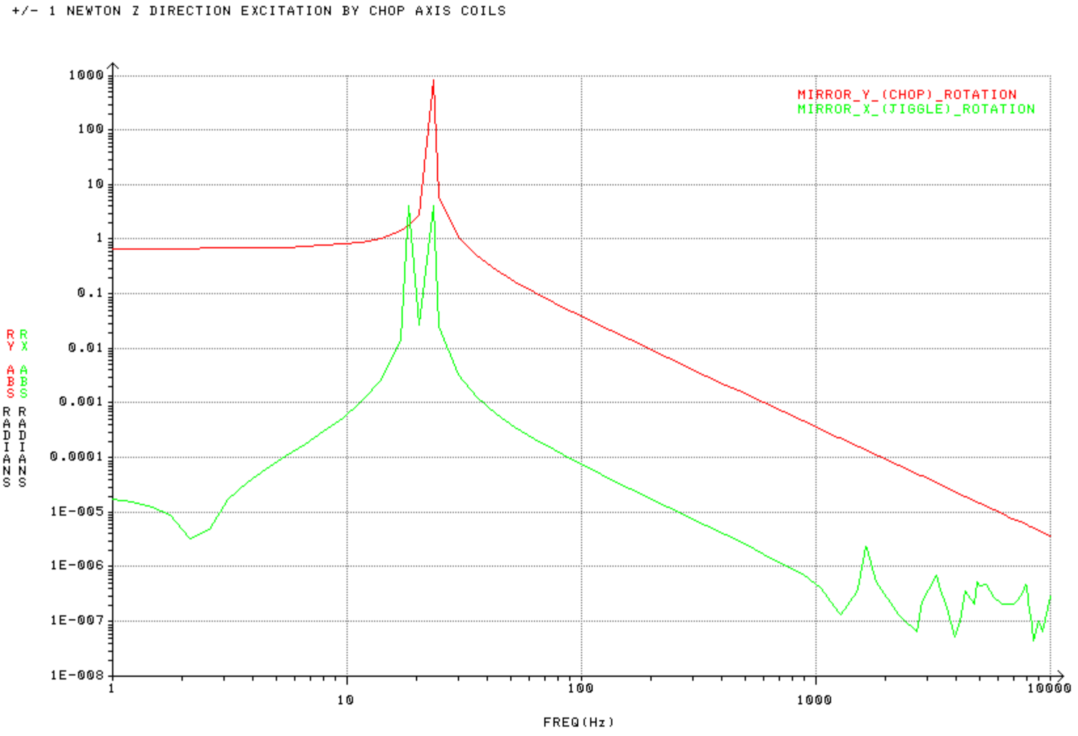
The damping ratio for the near rigid-body modes (chop and jiggle) were set to 0.0004 based on data in the Lucas flex-pivot catalogue. For the higher frequency where the flexure of the jiggle-stage framework is significant the ratio was set to 0.02 which is typical of a well engineered bolted structure.

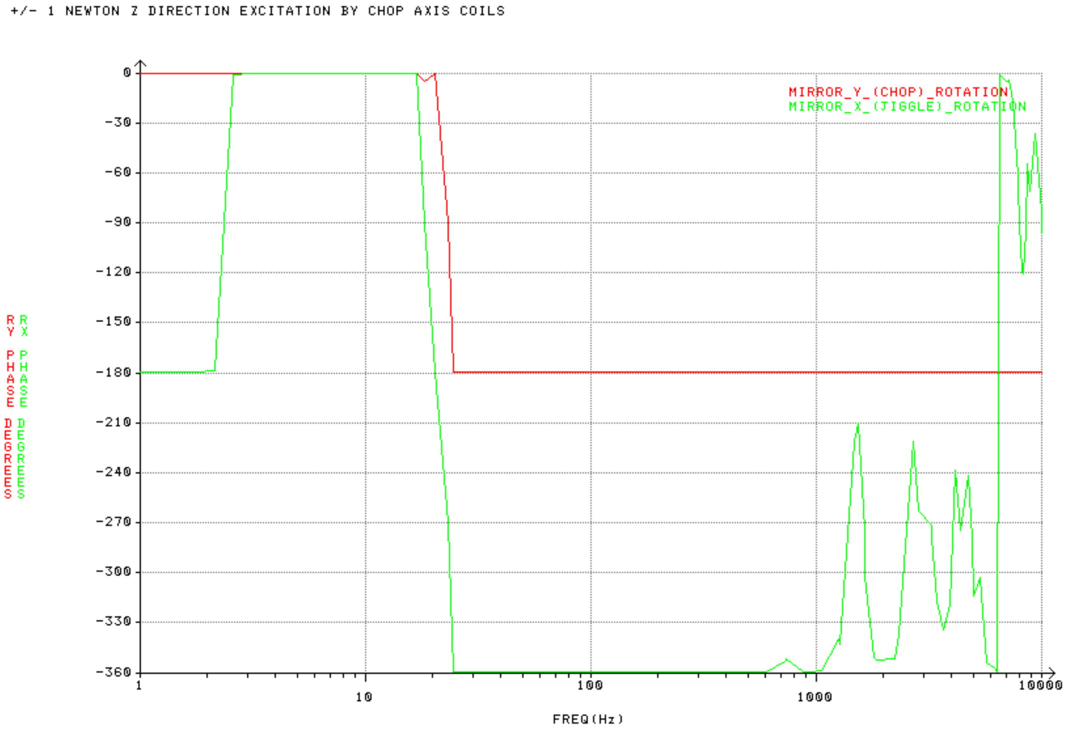
```
Set no.       First Mode      Last Mode       Damping Ratio
1               1                2           .4000E-03
2               3               50           .2000E-01
```

3.2.3 Chop axis excitation

Forces were applied equivalent to a couple of 1Newton forces acting at the chop magnet radius (15mm from the axis).

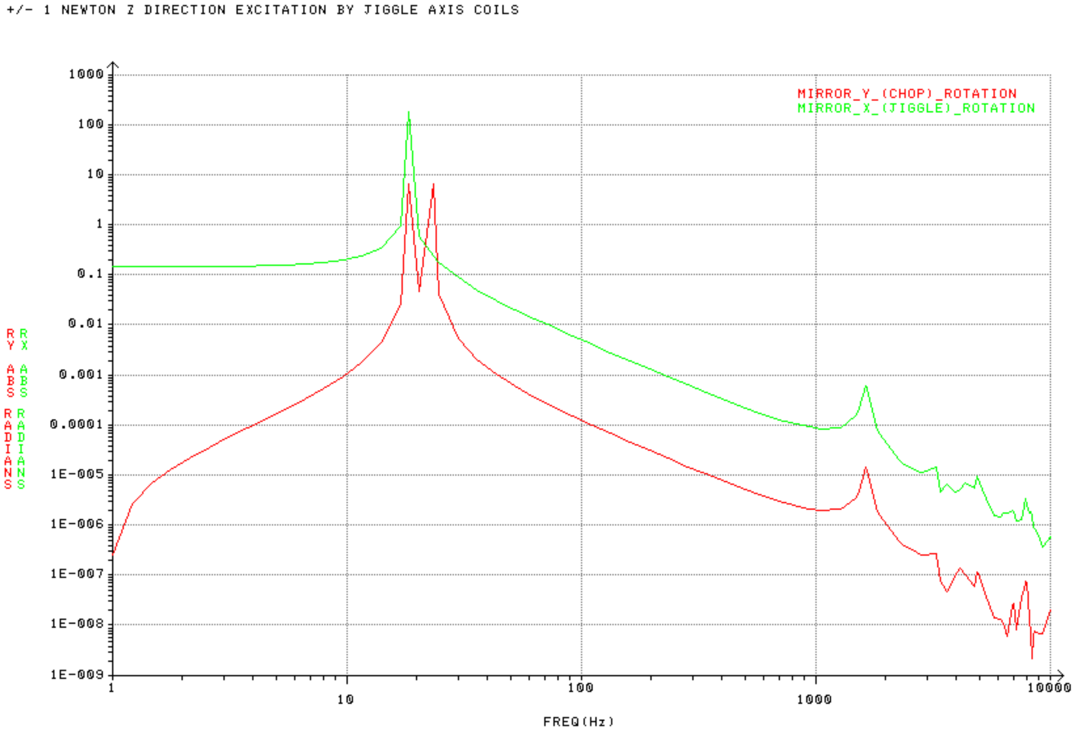
Below the resonance the response tends to the static case; a rotation of 0.086 radian.

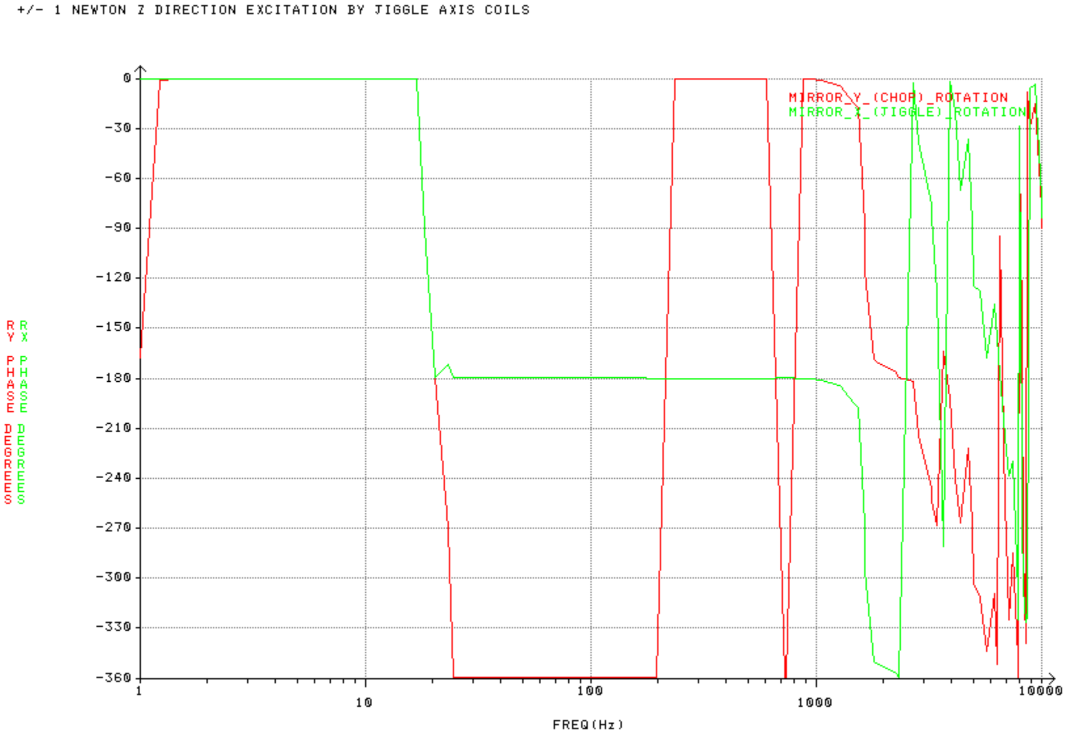

+/- 1 NEWTON Z DIRECTION EXCITATION BY CHOP AXIS COILS


+/- 1 NEWTON Z DIRECTION EXCITATION BY CHOP AXIS COILS

3.2.4 *Jiggle axis excitation*

A couple of 1Newton forces acting at the centre of the jiggle magnets. Below the resonance the response tends to the static case; a rotation of 0.14 radian.





4 References

4.1 Mass properties

The following parameters are derived from the FEA model. The section dimensions used will be fed back into the solid model and more accurate values obtained in due course.

Stage	Parameter	Value
Chop	Mass	0.018 Kg
	Moment of Inertia	2.1 $Kg.mm^2$
Jiggle	Mass	0.054 Kg
	Moment of Inertia	27 $Kg.mm^2$

Appendix 3B: Structural Interface FEA Results

1 Scope

This document records a Finite Element Analysis performed on the SPIRE Beam Steering Mirror structure component,

2 Model

2.1 Design

The model is based on Pro/Engineer drawing number BSM-02-001-001 dated Rev 1 (WIP) 29.May.01.

2.2 FEA representation

The FEA was performed as a solid model in integrated Pro/Mechanica. Multi-pass adaptive meshing was used, with convergence set at 10%. Small fillets and holes were generally suppressed, with the exception of connector pin and base mounting features. Material was assigned as Aluminium 6082

2.3 Software

- Pro/Engineer 2000i2
- Pro/MECHANICA STRUCTURE Version 22.3(305) (integrated mode)

3 Results

3.1 50 G acceleration load case

3.1.1 Deflection results

Maximum displacement is predicted at 43 microns under this load case, with prime deflections occuring in a twisting mode (from the side loading) and a pistoning mode around the front mounting hole (from vertical and fore-aft loads).

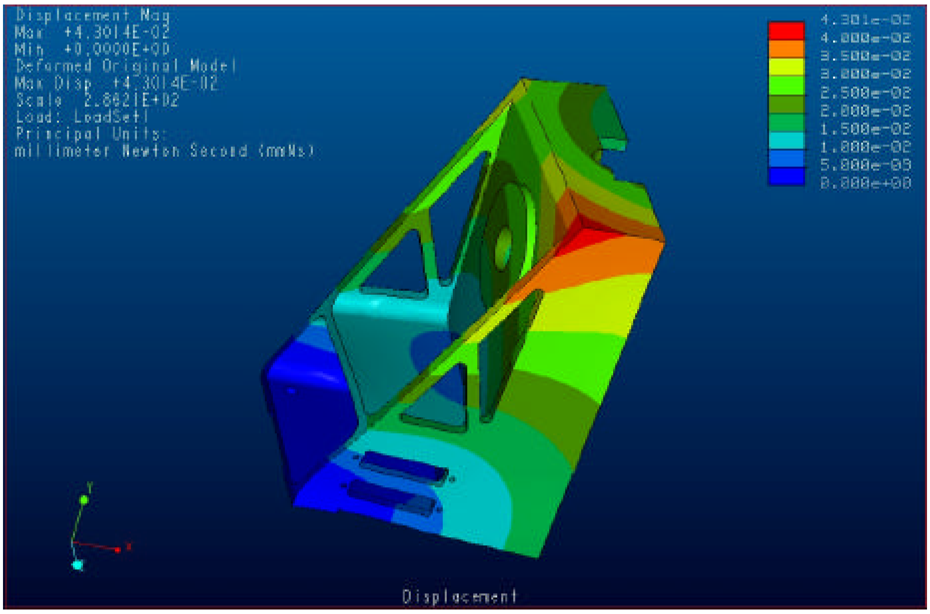


Figure 1 : displacement results (millimetres)

3.1.2 Von Mises Stress results

stresses peak at 36 MPa.

Permissible is per BS8118 (IP's design log no 9, p57)

For fatigue with FoS of 1.0

- 67 MPa friction grip bolted zones (not strictly applicable here as loads are not construction level friction grip)
- 96MPa for re-entrant features
- 76MPa small holes (dia < 3t)

For parent plate
240 MPa with suggested load factor of 2.5, ie a target of 96 MPa in this case

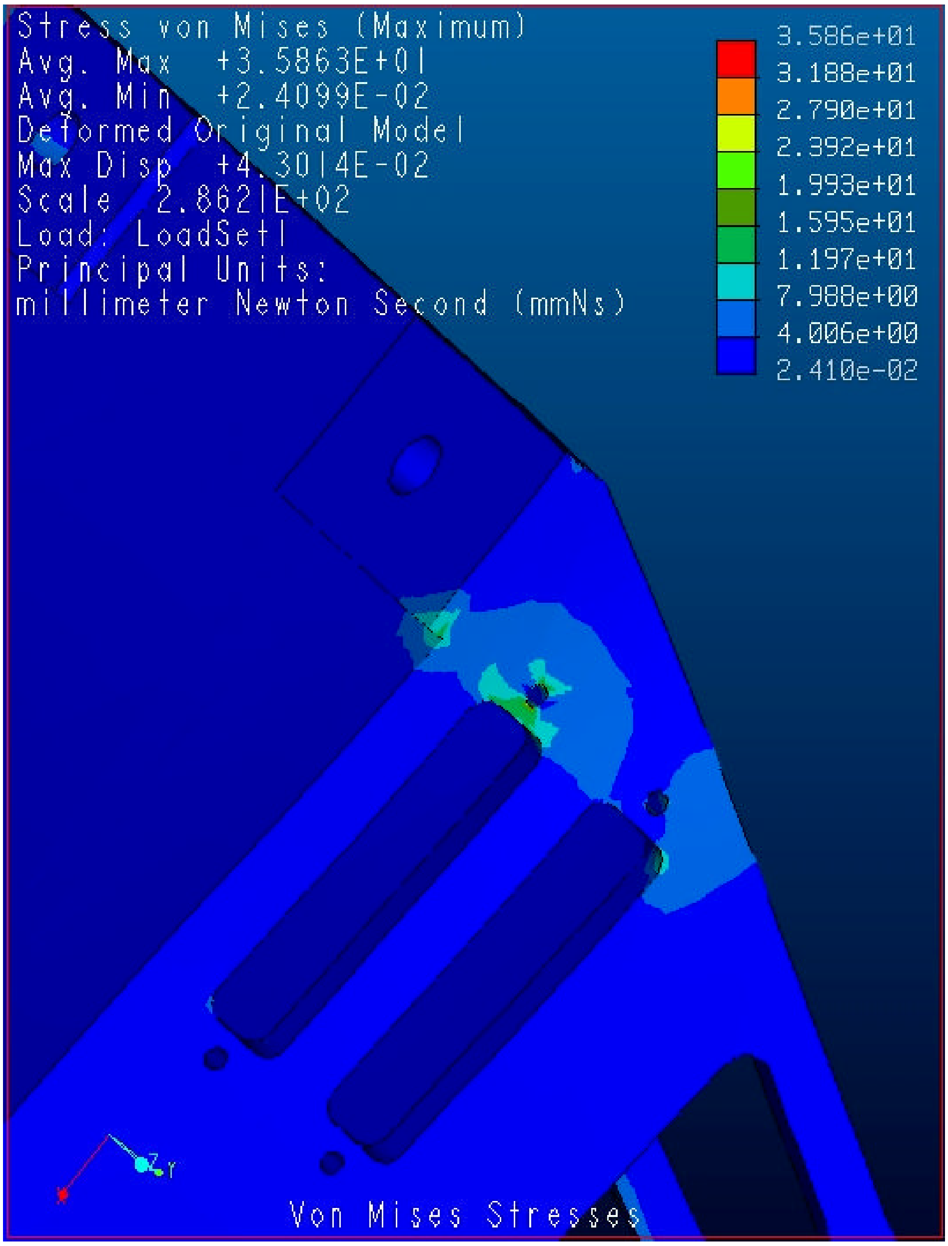


Figure 2 stress distribution around connector cut out and mounting feet

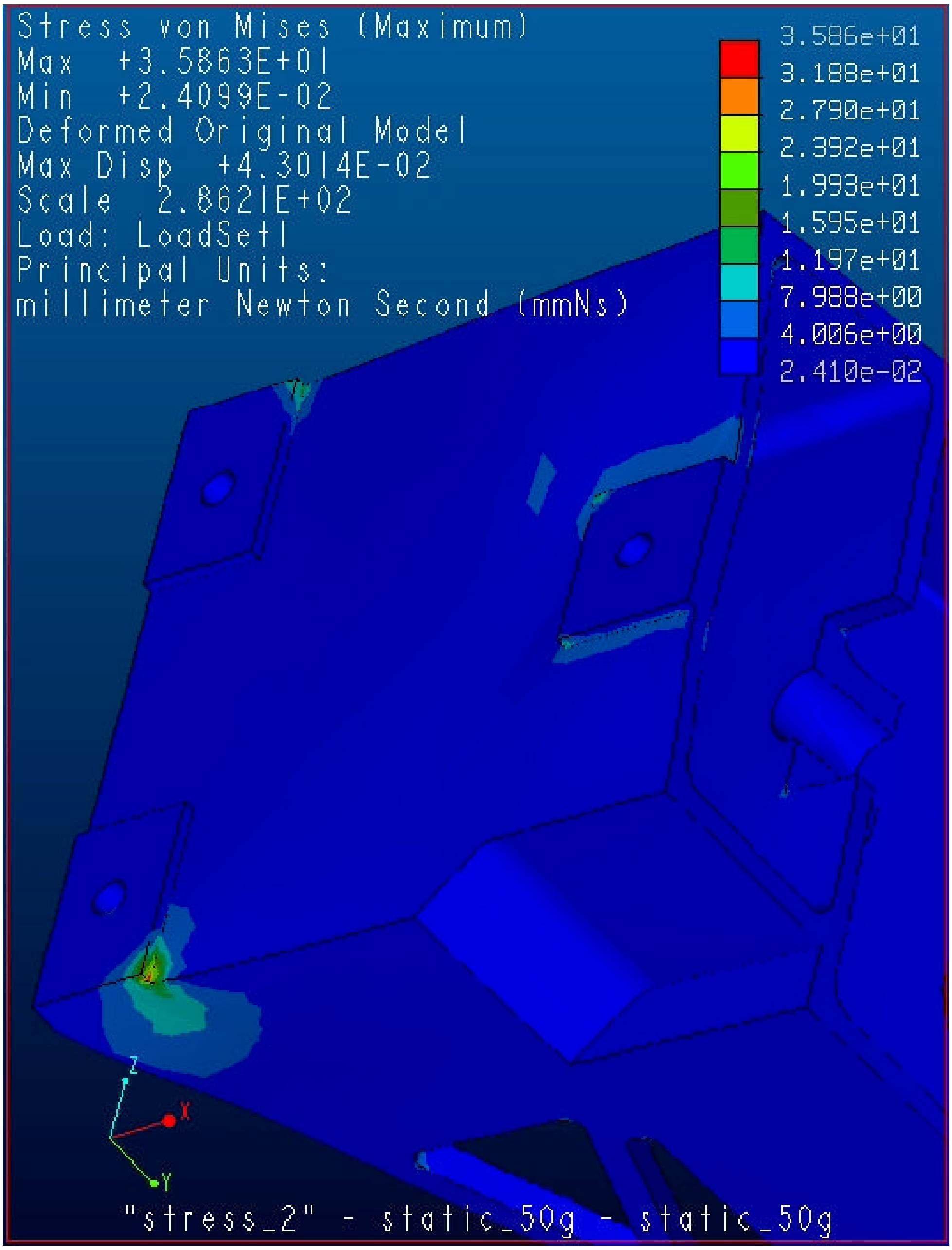


Figure 3 stress distribution around rear mounting foot

3.1.3 Analysis report (extracts)

```
------------------------------------------------------------
Pro/MECHANICA STRUCTURE Version 22.3(305)
Summary for Design Study "static_50g"
Mon Jun 04, 2001   19:10:01
------------------------------------------------------------
No errors were found in the model.

Pro/MECHANICA STRUCTURE Model Summary

  Principal System of Units: millimeter Newton Second (mmNs)

  Length:        mm
  Force:         N
  Time:          sec
  Temperature:    C

  Model Type: Three Dimensional

  Points:     1146
  Edges:       5435
  Faces:      7465

  Springs:       0
  Masses:         0
  Beams:          0
  Shells:       0
  Solids:     3189

  Elements:    3189

------------------------------------------------------------

Standard Design Study

Description:
  50G loads applied in x,y,z

Static Analysis "static_50g":

  Convergence Method: Multiple-Pass Adaptive
  Plotting Grid:     4

  >> Pass  1 <<

         Total Number of Equations:   3330
          Maximum Edge Order:           1

         Elements Not Converged:      3189
         Edges Not Converged:        5435
         Local Disp/Energy Index:   100.0%
         Global RMS Stress Index:   100.0%
>> Pass  2 <<

         Total Number of Equations:  19418
          Maximum Edge Order:           2

Elements Not Converged:      1956
         Edges Not Converged:        4627
         Local Disp/Energy Index:   100.0%
         Global RMS Stress Index:    84.8%
  >> Pass  3 <<
         Total Number of Equations:  63723
          Maximum Edge Order:           4
         Elements Not Converged:      1639
         Edges Not Converged:        2628
         Local Disp/Energy Index:   100.0%
         Global RMS Stress Index:    80.9%

  >> Pass  4 <<
         Total Number of Equations: 117789
          Maximum Edge Order:           5
```

```
          Elements Not Converged:        815
          Edges Not Converged:          207
          Local Disp/Energy Index:    100.0%
          Global RMS Stress Index:     36.4%

     >> Pass  5 <<
          Total Number of Equations:  174100
          Maximum Edge Order:             6
          Elements Not Converged:        146
          Edges Not Converged:            0
          Local Disp/Energy Index:     54.9%
          Global RMS Stress Index:     13.1%

     >> Pass  6 <<
          Total Number of Equations:  199893
          Maximum Edge Order:             6
          Elements Not Converged:         22
          Edges Not Converged:            0
          Local Disp/Energy Index:     30.1%
          Global RMS Stress Index:     12.0%

        RMS Stress Error Estimates:

        Load Set          Stress Error  % of Max Prin Str
        ----------------  ------------  -----------------
        LoadSet1            4.56e-01       1.3% of  3.63e+01

  ** Warning: Convergence was not obtained because the maximum
          polynomial order of 6 was reached.

     The analysis did not converge to within 10% on
     edge displacement and element strain energy.

     Total Mass of Model:  2.943847e-04

     Mass Moments of Inertia about WCS Origin:

       Ixx:  1.41233e+00
       Ixy: -2.35807e-01  Iyy:  3.84633e-01
       Ixz: -4.52996e-03  Iyz:  1.01220e-03  Izz:  1.29888e+00

     Principal MMOI and Principal Axes Relative to WCS Origin:

          Max Prin          Mid  Prin          Min  Prin
        1.46399e+00       1.29874e+00       3.33110e-01

     WCS X:  9.76566e-01       2.74581e-02       2.13461e-01
     WCS Y: -2.13377e-01      -5.97632e-03       9.76952e-01
     WCS Z: -2.81010e-02       9.99605e-01      -2.26723e-05

     Center of Mass Location Relative to WCS Origin:
                 ( 1.02862e+01,  4.89316e+01, -5.38177e-02)

     Mass Moments of Inertia about the Center of Mass:

       Ixx:  7.07486e-01
       Ixy: -8.76379e-02  Iyy:  3.53484e-01
       Ixz: -4.69293e-03  Iyz:  2.36968e-04  Izz:  5.62882e-01

     Principal MMOI and Principal Axes Relative to COM:

          Max Prin          Mid  Prin          Min  Prin
        7.28123e-01       5.62755e-01       3.32974e-01

     WCS X:  9.73328e-01       2.64026e-02       2.27892e-01
     WCS Y: -2.27705e-01      -9.92492e-03       9.73680e-01
     WCS Z: -2.79695e-02       9.99602e-01       3.64820e-03

     Constraint Set: ConstraintSet1

     Load Set: LoadSet1

       Resultant Load on Model:
```

```
    in global X direction:  1.451317e+02
    in global Y direction:  1.451317e+02
    in global Z direction:  1.451317e+02

  Measures:

      Name            Value      Convergence
  --------------    -------------  -----------
  max_disp_mag:       4.301418e-02      0.8%
  max_disp_x:       3.048651e-02      0.8%
  max_disp_y:      -1.805561e-02      0.9%
  max_disp_z:       2.839908e-02      0.8%
  max_prin_mag:      3.626618e+01      3.8%
  max_stress_prin:   3.626618e+01      3.8%
  max_stress_vm:      3.586344e+01      0.2%
  max_stress_xx:     2.019206e+01     15.5%
  max_stress_xy:     1.101872e+01     15.7%
  max_stress_xz:     7.227989e+00      0.5%
  max_stress_yy:     3.609924e+01      2.9%
  max_stress_yz:    -7.932948e+00      0.6%
  max_stress_zz:    -1.609714e+01      0.5%
  min_stress_prin:  -3.532419e+01      1.2%
       strain_energy:      9.345811e-01      0.6%
```

3.1.4 Verification

Reaction loads

- need checking

Manual verification

- required,

3.2 Modal Analysis

3.2.1 Modal Analysis Results

To limit run time, the maximum number of modes to sweep for was set to 12. The results were:

Mode	Frequency
1	6.881738e+02
2	8.638142e+02
3	1.780816e+03
4	2.715497e+03
5	3.058290e+03
6	3.283797e+03
7	3.344646e+03
8	3.614443e+03
9	3.957047e+03
10	4.096691e+03
11	4.676689e+03
12	5.185199e+03

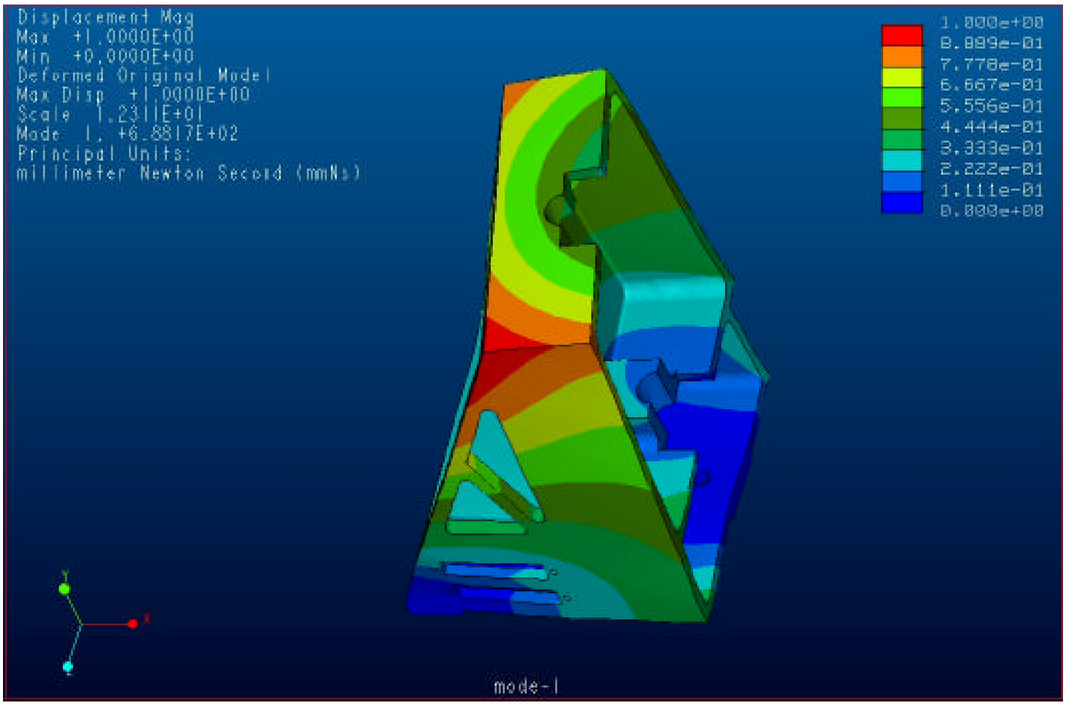


Figure 4 First resonant mode, twisting of entire structure, 688 Hz

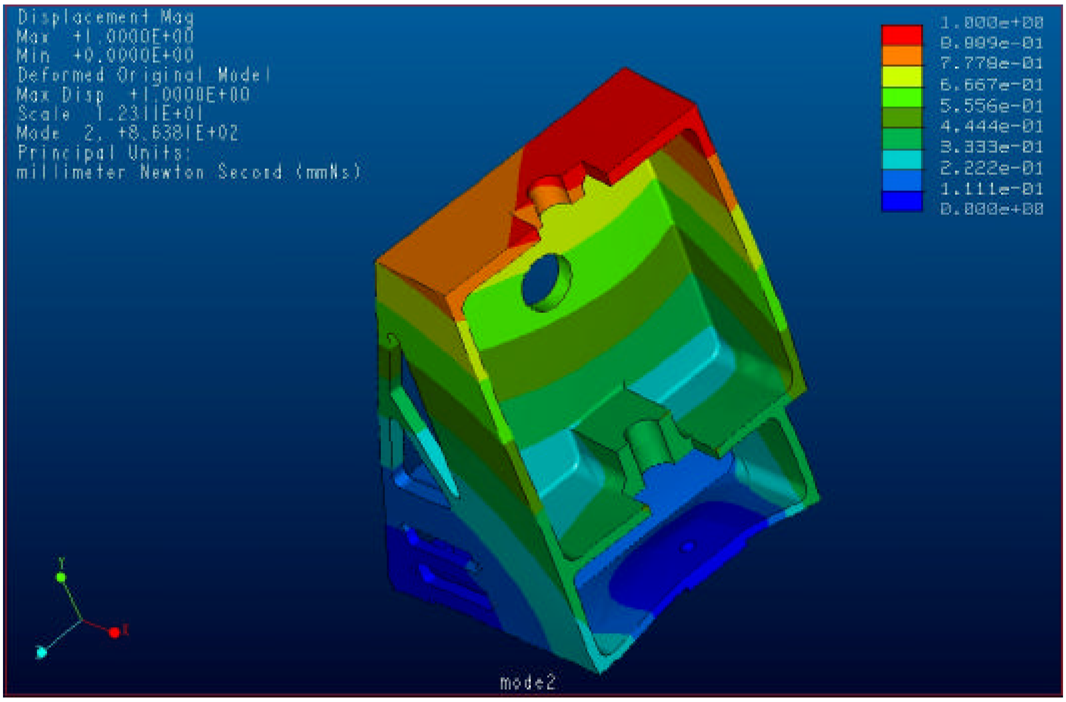


Figure 5 mode 2 , 864Hz. Piston and twist of whole structure

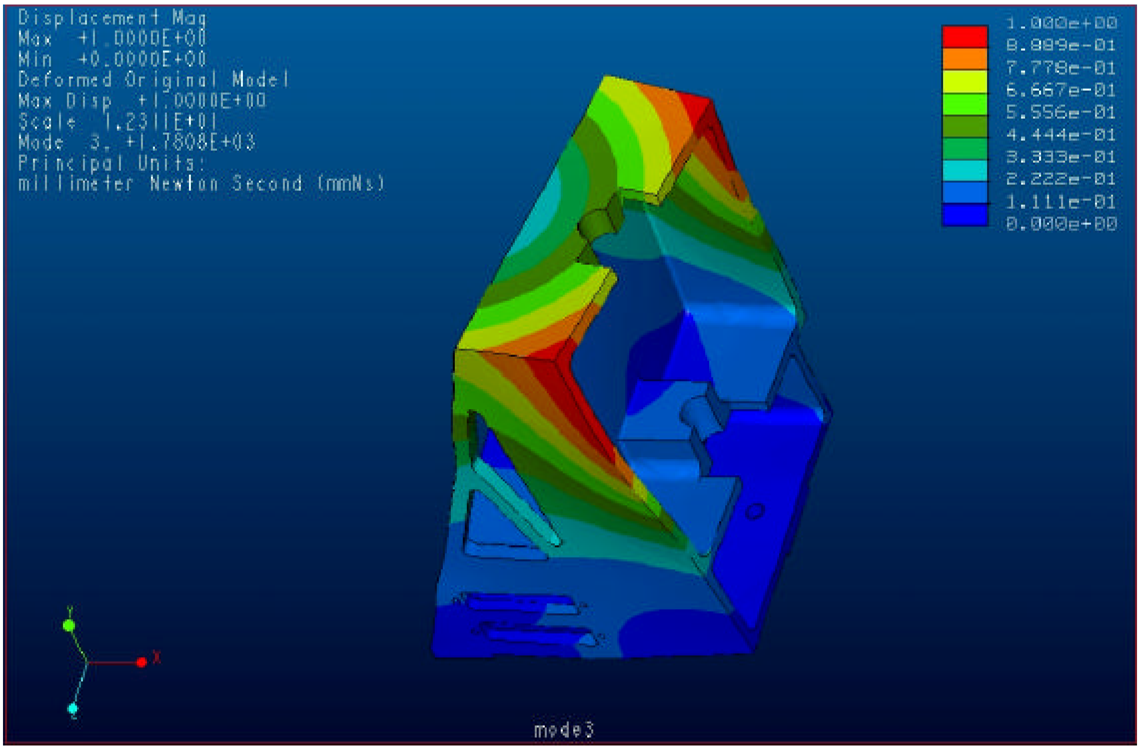


Figure 6 Mode 3 , 1780- Hz, rocking forward of whole structure

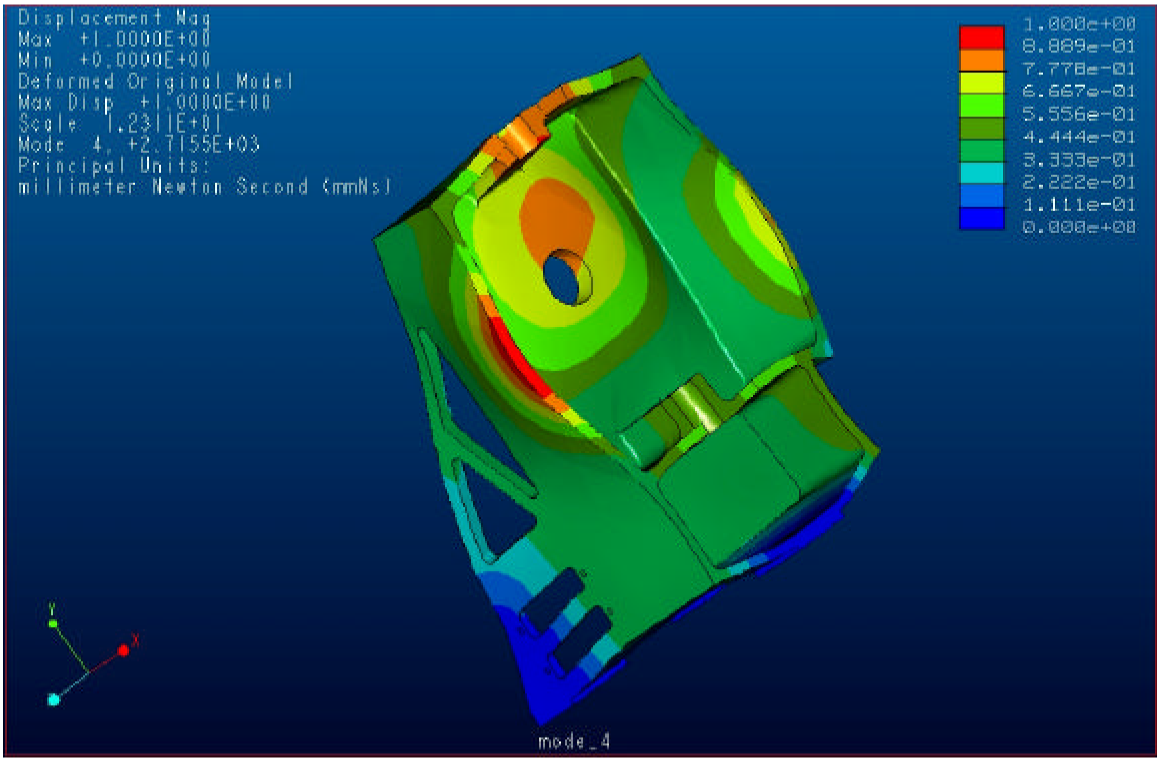


Figure 7 Mode 4, 2716 Hz, local resonance of plates

3.2.2 Model report (extracts)

```
------------------------------------------------------------
Pro/MECHANICA STRUCTURE Version 22.3(305)
Summary for Design Study "modal"
Tue Jun 05, 2001   08:32:47
------------------------------------------------------------

No errors were found in the model.

Pro/MECHANICA STRUCTURE Model Summary

  Principal System of Units: millimeter Newton Second (mmNs)

  Length:         mm
  Force:          N
  Time:           sec
  Temperature:    C

  Model Type: Three Dimensional

  Points:      1146
  Edges:        5435
  Faces:        7465

  Springs:        0
  Masses:          0
  Beams:           0
  Shells:        0
  Solids:      3189

  Elements:     3189

------------------------------------------------------------

Standard Design Study

Description:
  basic modal analysis

Modal Analysis "modal":

  Convergence Method: Single-Pass Adaptive
  Plotting Grid:      4

  Convergence Loop Log:                    (08:33:15)

  >> Pass  1 <<
       Calculating Element Equations           (08:33:15)
         Total Number of Equations:   57792
         Maximum Edge Order:             3


  >> Pass  2 <<
       Calculating Element Equations           (08:36:33)
         Total Number of Equations:   65469
         Maximum Edge Order:             5

       RMS Stress Error Estimates:

       Mode   Stress Error  (% of Max Modal Stress)
       ----  --------------
         1       0.8%
         2       0.7%
         3       2.4%
         4       1.3%
         5       1.1%
```

```
         6      0.8%
         7      0.9%
         8      1.6%
         9      4.3%
        10       2.4%
        11       2.0%
        12       1.0%

Total Mass of Model:  2.943847e-04


Mass Moments of Inertia about WCS Origin:

  Ixx:  1.41233e+00
  Ixy: -2.35807e-01  Iyy:  3.84633e-01
  Ixz: -4.52996e-03  Iyz:  1.01220e-03  Izz:  1.29888e+00

Principal MMOI and Principal Axes Relative to WCS Origin:

         Max Prin          Mid  Prin          Min  Prin
       1.46399e+00       1.29874e+00       3.33110e-01

WCS X:  9.76566e-01       2.74581e-02       2.13461e-01
WCS Y: -2.13377e-01      -5.97632e-03       9.76952e-01
WCS Z: -2.81010e-02       9.99605e-01      -2.26723e-05

Center of Mass Location Relative to WCS Origin:
            ( 1.02862e+01,  4.89316e+01, -5.38177e-02)

Mass Moments of Inertia about the Center of Mass:

  Ixx:  7.07486e-01
  Ixy: -8.76379e-02  Iyy:  3.53484e-01
  Ixz: -4.69293e-03  Iyz:  2.36968e-04  Izz:  5.62882e-01

Principal MMOI and Principal Axes Relative to COM:

         Max Prin          Mid  Prin          Min  Prin
       7.28123e-01       5.62755e-01       3.32974e-01

WCS X:  9.73328e-01       2.64026e-02       2.27892e-01
WCS Y: -2.27705e-01      -9.92492e-03       9.73680e-01
WCS Z: -2.79695e-02       9.99602e-01       3.64820e-03

Constraint Set: ConstraintSet1

Number of Modes: 12

   Mode   Frequency
  ----  ------------
     1  6.881738e+02
     2  8.638142e+02
     3  1.780816e+03
     4  2.715497e+03
     5  3.058290e+03
     6  3.283797e+03
     7  3.344646e+03
     8  3.614443e+03
     9  3.957047e+03
    10  4.096691e+03
    11  4.676689e+03
    12  5.185199e+03
```

3.2.3 Verification

- need checking manually

Appendix 3C: Structural Interface Manual Calculations

1 Scope

This document records a calculation performed on the SPIRE Beam Steering Mirror flex pivots and structure mounting bolts.

2 Calculation

The Input load is as provided in the table below. A static equivalent acceleration load is applied by assuming a Single Degree of Freedom system and using the Miles approximation:

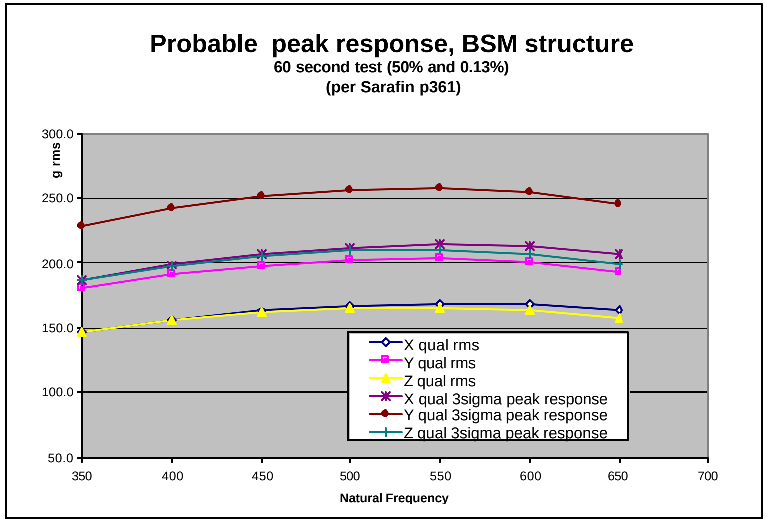
rms accel = (pi . Fn. Wx(Fn)) / 4L)^0.5

where,

Fn = natural frequency
Wx(Fn) = structure input accel from the PSD at the frequency
L = damping ratio = 1/sqrt(Frequency)

BSM random Specification			**Ref. instrument co-ordinate system**				**supplied by B.Winters, 26.Jun.01**			
X 60 sec	**X g^2/hz**	**X g^2/hz**		**Y 60 sec**	**Y g^2/hz**	**Y g^2/hz**		**Z 60 sec**	**Z g^2/hz**	**Z g^2/hz**
f	**Accept**	**Qual**		**f**	**Accept**	**Qual**		**f**	**Accept**	**Qual**
20	0.004	0.008		20	0.006	0.011		20	0.005	0.01
40	0.016	0.032		40	0.022	0.044		40	0.02	0.039
60	0.036	0.072		60	0.05	0.1		60	0.044	0.089
80	0.064	0.128		80	0.089	0.177		80	0.079	0.158
100	0.1	0.2		85	0.1	0.2		90	0.1	0.2
150	0.1	0.2		100	0.7	1.399		200	0.1	0.2
155	0.1	0.2		150	0.7	1.399		210	0.1	0.2
230	0.1	0.2		160	0.15	0.3		250	0.1	0.2
235	0.1	0.2		165	0.15	0.3		255	0.1	0.2
350	0.1	0.2		300	0.15	0.3		300	0.1	0.2
800	0.019	0.038		800	0.021	0.042		800	0.014	0.028
1000	0.012	0.024		1000	0.013	0.027		1000	0.009	0.018
1500	0.005	0.011		1500	0.006	0.012		1500	0.004	0.008
2000	0.003	0.006		2000	0.003	0.007		2000	0.002	0.004
g-rms	8.1	11.4		g-rms	11.1	15.7		g-rms	7.7	10.9

BSM Response				**calculated 10.Jul.01**	**I.Pain**			**version 2.0**		
fn	freq	interpolate spec		damping = 1/freq^0.5	rms accel (Miles)	multiplier: probable peak response, 60 sec test		50 % peak response	X qual 3sigma peak response	
					X qual rms					
350	350	0.200		0.053452	32.1	4.6		147.2	187.0	
400	400	0.182		0.05	33.8	4.6		156.2	198.4	
450	450	0.164		0.04714	35.1	4.6		162.9	206.9	
500	500	0.146		0.044721	35.8	4.7		167.1	212.3	
550	550	0.128		0.04264	36.0	4.7		168.8	214.4	
600	600	0.110		0.040825	35.6	4.7		167.7	213.0	
650	650	0.092		0.039223	34.6	4.7		163.5	207.6	
					Y qual rms				Y qual 3sigma peak response	
350	350	0.300		0.053452	39.3	4.6		180.3	229.0	
400	400	0.271		0.05	41.3	4.6		190.7	242.3	
450	450	0.243		0.04714	42.7	4.6		198.1	251.6	
500	500	0.214		0.044721	43.3	4.7		202.3	257.0	
550	550	0.185		0.04264	43.3	4.7		203.1	258.0	
600	600	0.157		0.040825	42.5	4.7		200.2	254.2	
650	650	0.128		0.039223	40.8	4.7		192.8	244.9	
					Z qual rms				Z qual 3sigma peak response	
350	350	0.200		0.053452	32.1	4.6		147.2	187.0	
400	400	0.181		0.05	33.7	4.6		155.7	197.8	
450	450	0.162		0.04714	34.8	4.6		161.8	205.5	
500	500	0.143		0.044721	35.4	4.7		165.2	209.8	
550	550	0.124		0.04264	35.4	4.7		165.9	210.6	
600	600	0.104		0.040825	34.7	4.7		163.4	207.5	
650	650	0.085		0.039223	33.3	4.7		157.4	199.9	



BSM margin - flex pivots & structural bolt				**calculated 10.Jul.01 I.Pain**		**version 2.0**	
Component	mass (incl contingency)	load limit of component (N)	required margin	survival load (in g) for 2 pivots	margin on rms response	margin on 50% peak response	margin on 3-sigma peak response
chop axis flex pivot 5010-800	20	25.4	1.5	172.6	4.0	**0.8**	**0.7**
jiggle axis flex pivot 5010-600	97	245.0	1.5	343.3	7.9	1.7	1.3
structure bolt (1 M4 only)	909	400	1.5	293.4	6.8	1.4	1.1

3 Discussion

This analysis does not cover

(a) flex pivots at their resonant frequency (approx >1000hz)
(b) flex pivots at resonant frequencies of rotating masses (approx 15 and 30 Hz), as these are not the driving design case

The load limits are as per the catalogue data for 429 grade stainless steel components.

The 5010 type BSM flex pivots do not have a positive survival margin for qualification. This however applies both a 1.5x qualification load factor and includes a 1.5x margin on the component loads. Reducing the required margin on the loads to unity (accepting that the qualification load factor provides adequate reserve, but that there is thus a risk of failure on qualification) the margin on 3-sigma peak response for the flex pivots would be 0.7 x 1.5 = 1.05

The inconel grade pivots are manufactured in a higher grade material and have additional margin. They do not have an equivalent catalogue rated load, but stress calculations have been performed, summarised below.

The rated life for these flexures, from data supplied by Lucas is given in section 7.2.4 of the Design Description Document

Based on this data, the load for inconel pivots with a fatigue margin of 1.0 would be:

chop axis warm (7010-800) - 292g (fatigue) (TBC)
chop axis cold (7010-800) - 830g (fatigue) (TBC)

These values are conservative, as they are for infinite fatigue life wheras the vibration test would generate a significantly reduced number of cycles (max 120000 if 2kHz for 60 sec).

The difference between warm and cold fatigue life properties will require careful test design to account for this in performing warm and cold vibration tests.

However, buckling overload of the flexures would place a cap on the survivable load. Based on correspondence with TRW, the highest combined stress in any of the cases is less than 19,000 psi in the flexures. Critical buckling stress is quoted by TRW as 34,040 psi for a, i.e. a margin of 1.8 on bucking failure. Based on linear extrapolation from the 9.9lb load and the 20 grammes mass of the chop stage the maximum gravity loading with a buckling safety factor of 1.0 would thus be:

chop axis (7010-800) - worst of warm and cold - 405g (buckling)

4 Conclusion :

The factors of safety are:

Stainless steel flex pivots (420 grade)

• chop axis flex pivots	1.05
• jiggle axis fl;ex pivots	1.95

This allows for the 1.5 qualification load factor but assumes a component safety factor of 1.0

However, this grade of pivots is known to be brittle at cryogenic temperatures and is not recommended.

Inconel 718 flex pivots

Fatigue - warm	1.1
Fatigue cold	3.2
3-sigma peak response	1.6

Structure bolts

3-sigma peak response	1.65 (any one of three bolts alone)

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