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1 APPLICABLE & REFERENCE DOCUMENTS

[RD1] CDR Planck Dynamic Analysis and Sine Test Prediction Report
H-P-3-ASPI-AN-0718, Issue 1.0

[RD2] Instrument Interface Document part B instrument HFI
SCI-PT-IIDB-HFI-04141 is 3,1 dated 05/03/04

[RD3] Planck PLM Mechanical and Thermoelastic Analyses
H-P-3-ASPI-AN-0329, Issue 2.0

[RD4] Instrument Interface Document
SCI-PT-IIDA-04624 is 3,1 dated 12/02/04

2 INTRODUCTION

In the space environment the 4K Cooler subsystem (placed in the Service Module) ensures the cooling of the Planck spacecraft's detectors. During its working the 4K Cooler generates dynamic loads propagating to the whole spacecraft structures and, in particular, to the FPU (Focal Plane Unit) optical instrument.

The purpose of the present document is to investigate the effects, in terms of acceleration levels, occurring at the support interfaces of the FPU. Computed acceleration levels are then compared to specification requirements (see [RD02] & §6.2).
Micro-vibration analysis have been carried out through the following steps:

- Numerical checks of the spacecraft finite element model (see §3.1.2),
- Stiffening of the SVM Panel +Y where 4K Cooler is mounted on,
- Modifying spacecraft damping from 2% (CDR analysis finite element model) to 0.5%,
- Sine analysis with free boundary conditions (see §6.3),
- Investigating effects over FPU responses of reducing the damping factor of the FPU supporting structures (see §6.4) to take into account the eventual cryo temperature effect.

Planck finite element model issued from Critical Design Review has been used to perform present analyses (see [RD01]). As Planck spacecraft is supposed to be in the space environment, dynamic analyses are performed with spacecraft free boundary conditions.

For more details about Planck configuration and definitions see [RD01].

3 PLANCK SPACECRAFT

The Planck spacecraft fem is shown in Figure 1.

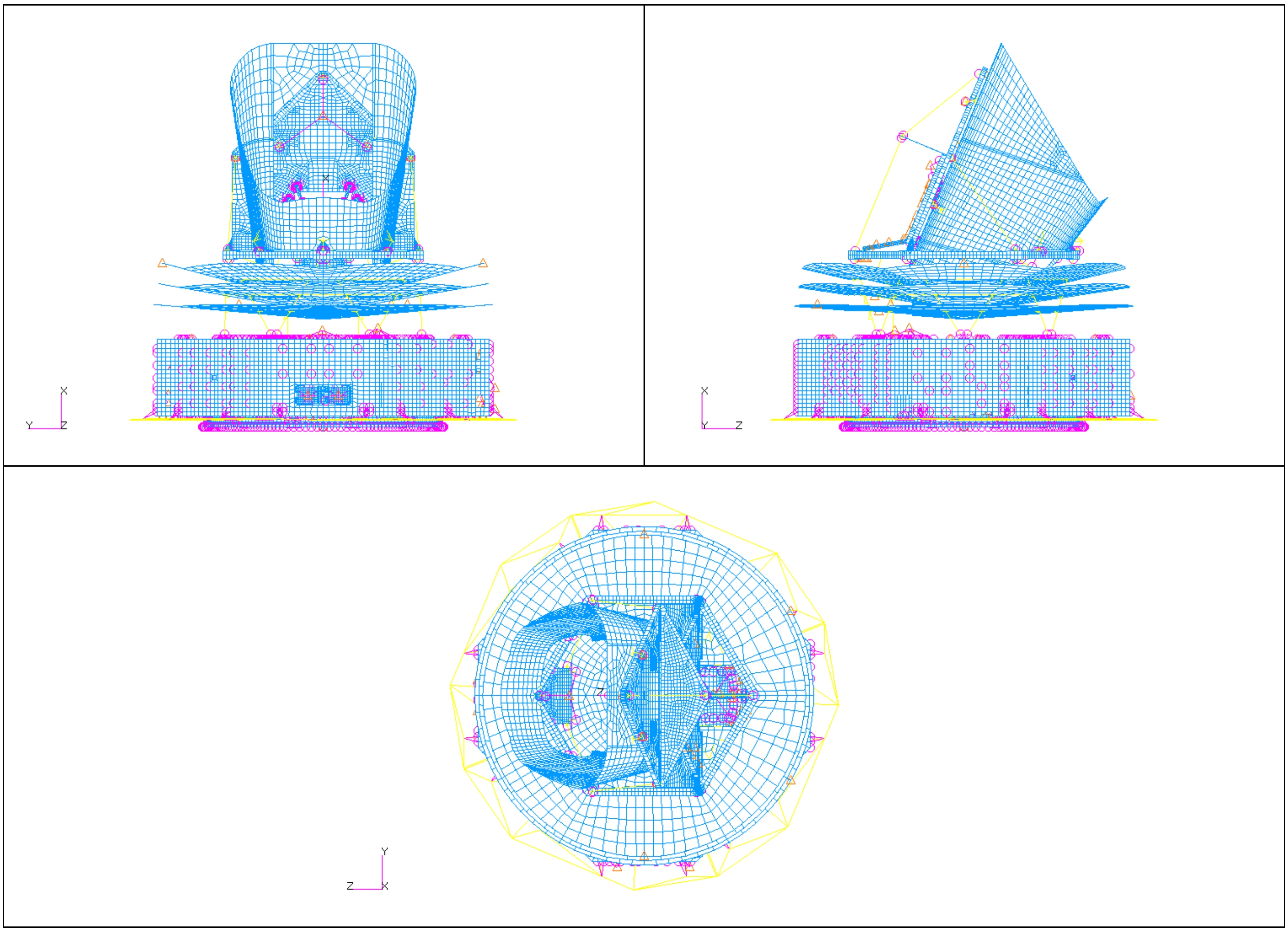


Figure 1:Planck spacecraft fem views

With respect to CDR model, the SVM Panel +Y (4K Cooler subsystem is just mounted on) has been reinforced changing sandwich panel skin thickness from 0.3 mm to 0.6 mm to be in accordance with design updates subsequent to FEM delivery. So doing the frequency of first mode shifts from 37.50Hz to 44.80Hz.
Also the structural damping factor has been changed. It has been set to 0.5% to consider a structural damping adapted to microvibration.

The Planck satellite reference frame (O, X_X, Y_X, Z_x) is defined as follows:

- Its origin O is located at the point of intersection of the longitudinal Launcher axis and Satellite /Launcher separation plane; the origin coincides with the centre of the Satellite /Launcher separation plane,
- Xs coincides with the nominal spin axis of Planck. Positive X_S axis is oriented opposite to the Sun in nominal operation. The X_S axis coincides with the launcher longitudinal axis,
- Zs is such that the Planck telescope line of sight is in the (X_S, Z_S) plane. The telescope is pointing in the $+Z_S$ half-plane,
- Ys completes the right-handed orthogonal reference frame.

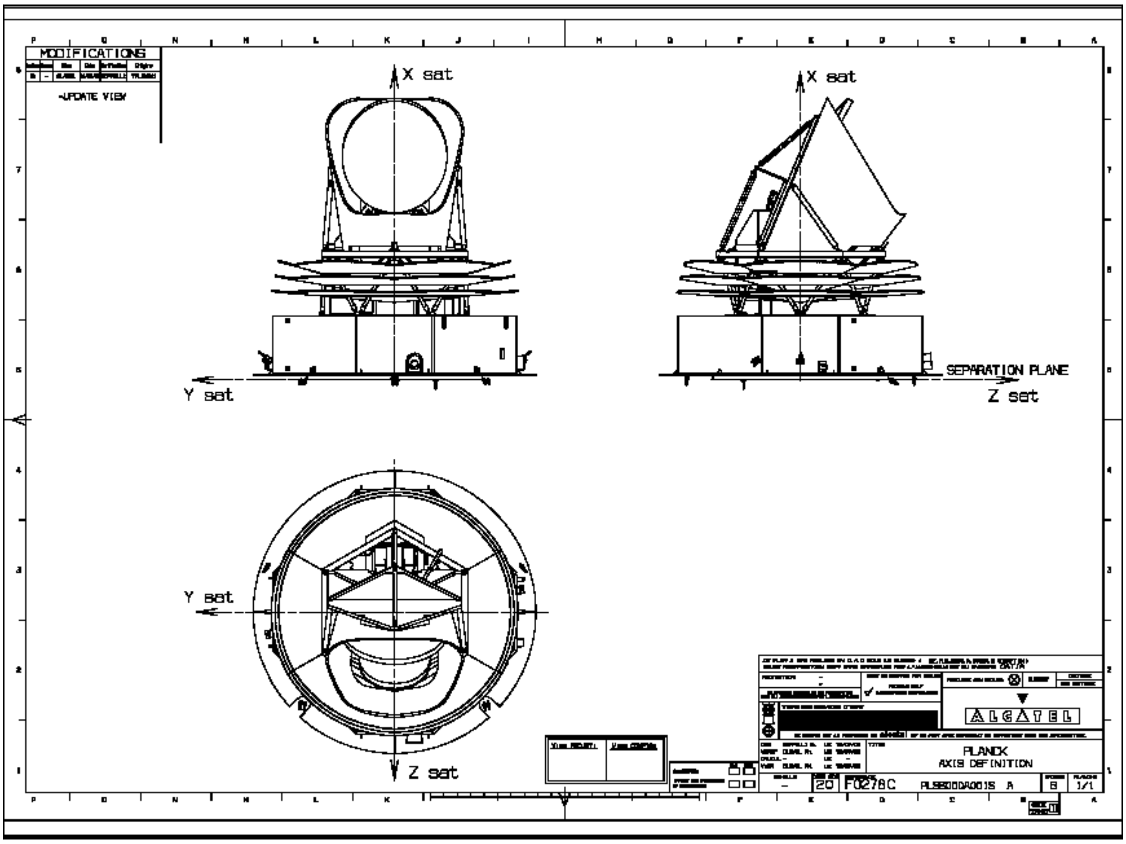


Figure 2: PLANCK Spacecraft Axes

3.1.1 MCI

The following table shows spacecraft cog and mass properties.

```
          O U T P U T   F R O M   G R I D   P O I N T   W E I G H T   G E N E R A T O R
0                                                     REFERENCE POINT =        0
                                                  M O
    *  1.926995E+03  9.159340E-16  2.220446E-16 -2.220446E-16  2.663320E+01 -5.150472E+01 *
    *  9.159340E-16  1.926995E+03  7.105427E-14 -2.470676E+01 -2.131628E-14  1.531172E+03 *
    *  2.220446E-16  7.105427E-14  1.926995E+03  5.145069E+01 -1.531172E+03  2.486900E-14 *
    * -2.220446E-16 -2.470676E+01  5.145069E+01  3.207727E+03 -2.004143E+01 -7.076578E+00 *
    *  2.663320E+01 -2.131628E-14 -1.531172E+03 -2.004143E+01  3.779446E+03  6.002093E+01 *
    * -5.150472E+01  1.531172E+03  2.486900E-14 -7.076578E+00  6.002093E+01  3.966282E+03 *
                                                   S
                         *  1.000000E+00  0.000000E+00  0.000000E+00 *
                         *  0.000000E+00  1.000000E+00  0.000000E+00 *
                         *  0.000000E+00  0.000000E+00  1.000000E+00 *
                                               DIRECTION
          MASS AXIS SYSTEM (S)     MASS              X-C.G.        Y-C.G.        Z-C.G.
             X            1.926995E+03     -1.152284E-19  2.672800E-02  1.382110E-02
             Y            1.926995E+03      7.945907E-01 -1.106193E-17  1.282139E-02
             Z            1.926995E+03      7.945907E-01  2.669996E-02  1.290558E-17
                                                 I(S)
                         *  3.206037E+03 -2.084081E+01 -1.255518E+01 *
                         * -2.084081E+01  2.562423E+03 -6.073278E+01 *
                         * -1.255518E+01 -6.073278E+01  2.748250E+03 *
                                                 I(Q)
                         *  2.543928E+03                             *
                         *                2.765606E+03               *
                         *                              3.207176E+03 *
                                                   Q
                         *  2.480107E-02  4.071877E-02  9.988628E-01 *
                         * -9.586715E-01 -2.823155E-01  3.531177E-02 *
                         *  2.834323E-01 -9.584571E-01  3.203419E-02 *
```

The spacecraft total mass is 1927 kg. A complete description of the Planck fem is given in [RD1].

3.1.2 FEM Numerical Checks

3.1.2.1 Strain Energy

The numerical verifications of the PLANCK fem have been performed by computing conditioning matrices KRBG , KRBN and KRBF (see Table 1, Table 2 & Table 3) which are representative of the residual strain energy inside the model.

```
0       MATRIX KRBG      (GINO NAME 101 ) IS A DB  PREC             6 COLUMN X                6 ROW
SQUARE   MATRIX.
0COLUMN      1       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -6.0639D-05 -1.4903D-05 -4.8816D-05  3.0801D-05  1.9556D-04 -2.4532D-05
0COLUMN      2       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -4.5604D-06 -1.4147D-05 -2.9187D-05  1.4686D-04  5.3970D-05  1.6536D-05
0COLUMN      3       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -1.2530D-05  1.4993D-05 -8.0587D-05 -6.4191D-05  1.2200D-04  1.1201D-05
0COLUMN      4       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)     9.7827D-06  1.1272D-04 -4.8150D-05  3.9714D-04  8.0484D-05  1.3623D-04
0COLUMN      5       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)     1.0289D-04  6.4207D-05  1.6307D-04 -1.4814D-04 -4.6232D-04  3.0235D-04
0COLUMN      6       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)     -4.6470D-05 -2.2110D-04 -6.8851D-05  3.2363D-06  2.1980D-04 -6.2197D-05
```

Table 1: Spacecraft KRBG matrix

```
0       MATRIX KRBN      (GINO NAME 101 ) IS A DB  PREC             6 COLUMN X                6 ROW
SQUARE   MATRIX.
0COLUMN      1       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -9.6305D-05 -2.1461D-05 -4.5997D-05  2.9767D-05  2.0500D-04 -4.8762D-05
0COLUMN      2       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -5.5034D-06 -4.1187D-05 -2.9102D-05  1.5617D-04  5.6304D-05 -1.0966D-05
0COLUMN      3       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -2.3010D-05  1.7299D-05 -7.7607D-05 -5.1751D-05  1.0265D-04  1.1987D-05
0COLUMN      4       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)     7.3820D-06  1.1785D-04 -4.1731D-05  3.9821D-04  7.8365D-05  1.1524D-04
0COLUMN      5       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)     1.2140D-04  6.6212D-05  1.6773D-04 -1.4655D-04 -4.5864D-04  2.9992D-04
0COLUMN      6       ROWS       1 THRU       6     ----------------------------------------------
    ROW
      1)    -5.1670D-05 -2.2706D-04 -6.1035D-05 -2.5926D-05  1.6584D-04 -2.1059D-05
```

Table 2: Spacecraft KRBN matrix

```
0       MATRIX KRBF      (GINO NAME 101 ) IS A DB  PREC             6 COLUMN X              6 ROW
SQUARE   MATRIX.
0COLUMN      1       ROWS       1 THRU      6     ----------------------------------------------
    ROW
      1)   -9.6305D-05 -2.1461D-05 -4.5997D-05  2.9767D-05  2.0500D-04 -4.8762D-05
0COLUMN      2       ROWS       1 THRU      6     ----------------------------------------------
    ROW
      1)   -5.5034D-06 -4.1187D-05 -2.9102D-05  1.5617D-04  5.6304D-05 -1.0966D-05
0COLUMN      3       ROWS       1 THRU      6     ----------------------------------------------
    ROW
      1)   -2.3010D-05  1.7299D-05 -7.7607D-05 -5.1751D-05  1.0265D-04  1.1987D-05
0COLUMN      4       ROWS       1 THRU      6     ----------------------------------------------
    ROW
      1)    7.3820D-06  1.1785D-04 -4.1731D-05  3.9821D-04  7.8365D-05  1.1524D-04
0COLUMN      5       ROWS       1 THRU      6     ----------------------------------------------
    ROW
      1)    1.2140D-04  6.6212D-05  1.6773D-04 -1.4655D-04 -4.5864D-04  2.9992D-04
0COLUMN      6       ROWS       1 THRU      6     ----------------------------------------------
    ROW
      1)   -5.1670D-05 -2.2706D-04 -6.1035D-05 -2.5926D-05  1.6584D-04 -2.1059D-05
```

Table 3: Spacecraft KRBF matrix

3.1.2.2 Free-Free Modes

With free boundary conditions, the first seven frequencies of the spacecraft model are described hereafter.

MODE NR.	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1.35E-07	3.67E-04	5.84E-05	1.00E+00	1.35E-07
2	2.80E-07	5.29E-04	8.43E-05	1.00E+00	2.80E-07
3	3.55E-07	5.96E-04	9.48E-05	1.00E+00	3.55E-07
4	6.65E-07	8.15E-04	1.30E-04	1.00E+00	6.65E-07
5	1.10E-06	1.05E-03	1.67E-04	1.00E+00	1.10E-06
6	1.73E-06	1.31E-03	**2.09E-04**	1.00E+00	1.73E-06
7	1.56E+02	1.25E+01	**1.99E+00**	1.00E+00	1.56E+02

4 FOCAL PLANE UNIT OPTICAL INSTRUMENT

The FPU fem is shown in Figure 3.

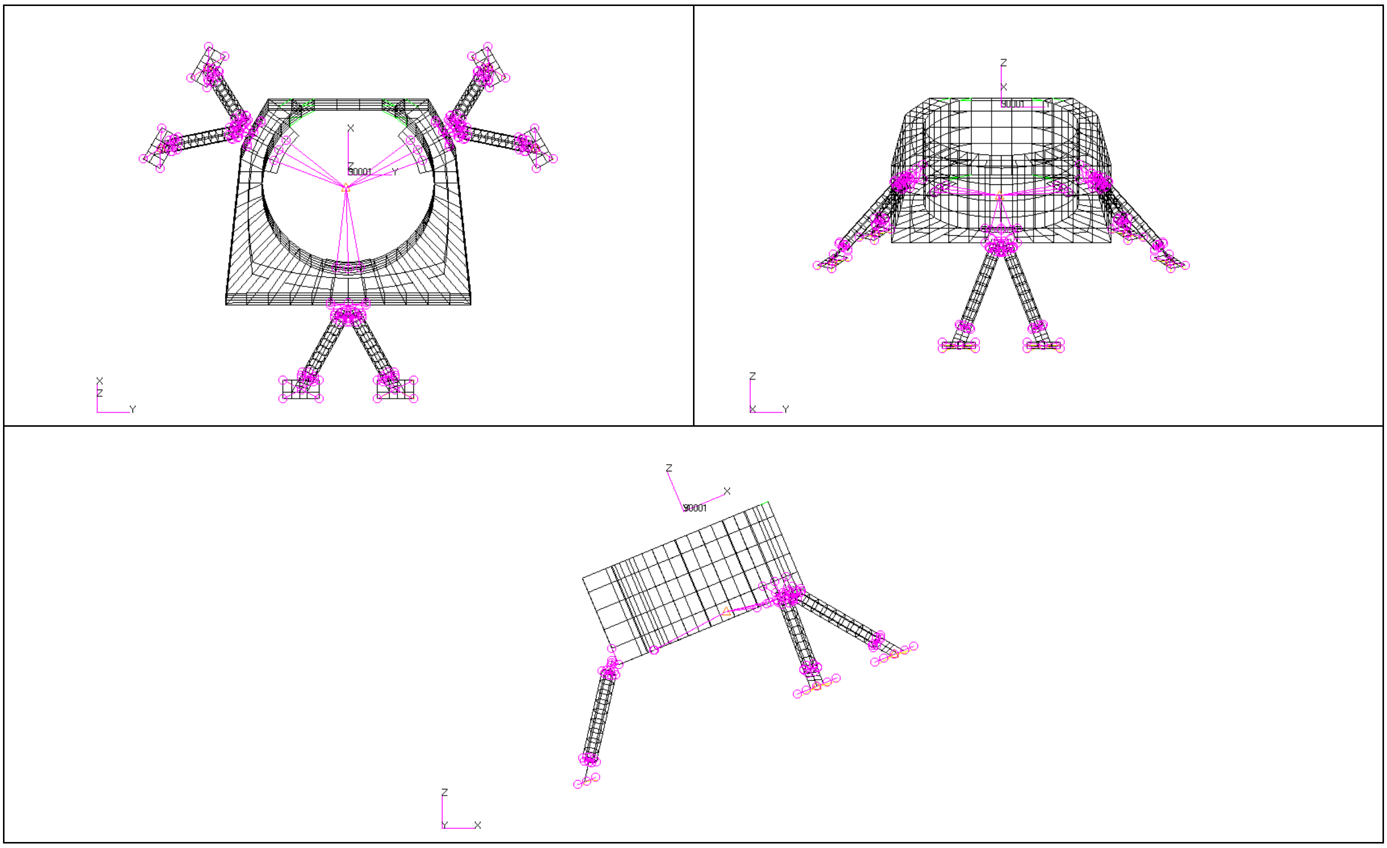


Figure 3: FPU fem view

FPU is hinged (RBE2 123) at the primary reflector support panel level (see Figure 4) by six interfaces.

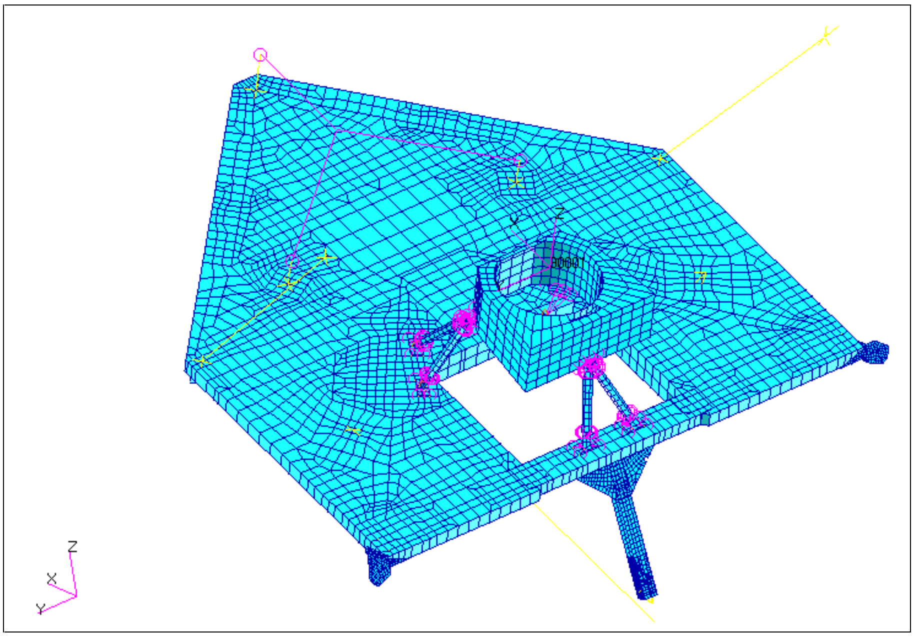


Figure 4: Primary Reflector & FPU femsview

Figure 5 shows how FPU is connected to primary reflector support panel.

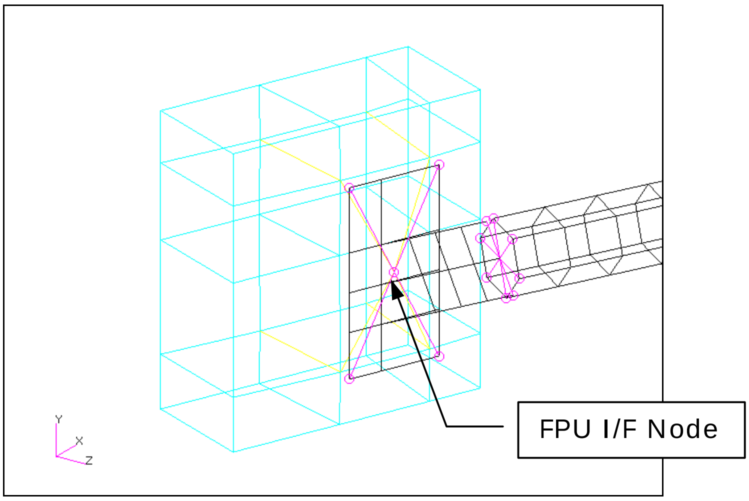


Figure 5: FPU interfaces detailed view

Sine response levels (see §6.3) are computed at the central node of the 4-node rigid element (RBE2) shown in the figure above as required by specification requirements.

5 4K COOLER SUBSYSTEM & LOADING CONDITIONS

The 4K Cooler is mounted on SVM Panel +Y and is modeled by a rigid element (MSC/NASTRAN RBE2) with a lumped mass (CONM2 MSC/NASTRAN element). A view of SVM Panel +Y is shown in Figure 6.

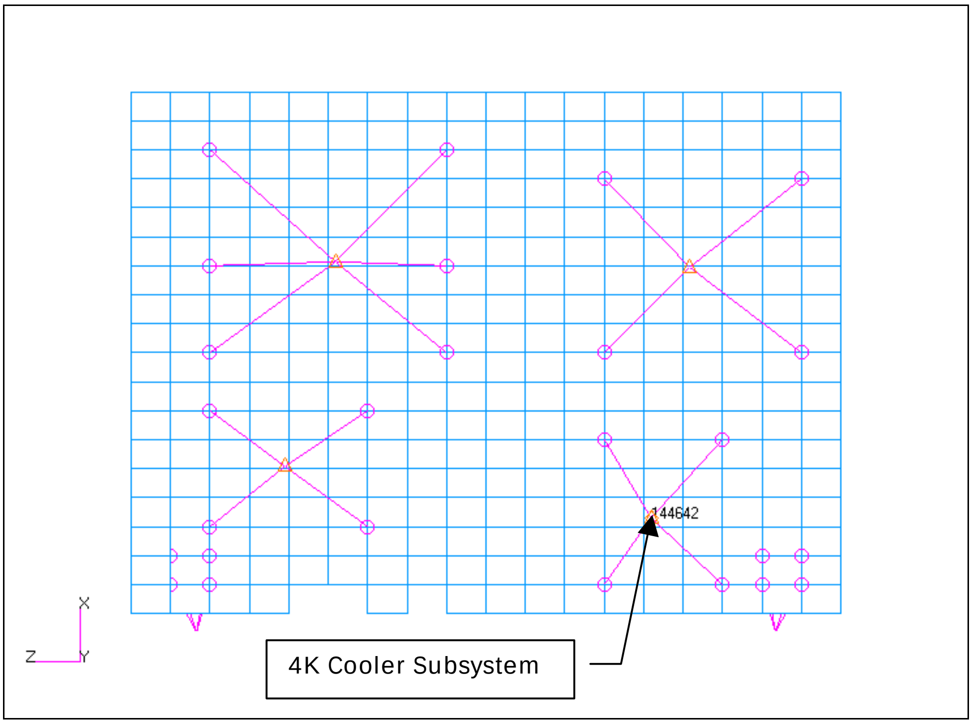


Figure 6: 4K Cooler view (SVM Panel +Y)

The 4K Cooler is hinged (RBE2 123 MSC/NASTRAN rigid element) at the SVM Panel +Y (see Figure 4) by 4 interfaces and aligned with spacecraft Z-axis.
During its working, the 4K Cooler generates a dynamic load along the Spacecraft Z-axis. The load magnitude is 40 mN at the 4K Cooler fundamental frequency and harmonics up to 200 Hz. Load amplitude above 200Hz is assumed to be 0. Noise outside the fundamental and harmonics is assumed to be 0..
The 4K Cooler fundamental frequency may be adjusted in between 35Hz and 45Hz.

The dynamic load is applied to the 4K Cooler center of gravity (node 144642).

6 MICRO-VIBRATION ANALYSIS

6.1 METHODOLOGY

6.1.1 Micro-Vibration Analysis

To compute the dynamic responses at FPU feet level a sine analysis has been performed in the frequency range [0-200 Hz] and free boundary conditions. The results of this analysis have been compared with specification requirements (see §6.2).

To evaluate the eventual damping evolution for the structure at cryo temperature, the following procedure has been followed:

- Identification of the peaks in the FPU sine responses (see §6.3),
- Evaluation of the deformation of the substructures supporting FPU by modal and strain energy analyses (see APPENDIX B),
- Reduction of the damping of the primary reflector support panel (see §6.4),
- New sine analysis and final comparison with specifications.

6.1.2 Post-Processing

Post-processing has been carried out by MATLAB v6.0r13 software. MSC/Nastran output file containing the magnitude and phase spectrum at the FPU interfaces and cog level is transformed in a MATLAB variable using FETools software.
The steps followed to post-process data are described hereunder:

- For each direction and interface node, the acceleration is computed by modal superposition using MSC/Nastran between 0 and 200 Hz. A constant perturbation force of 40 mN is assumed on the entire frequency band. This force is applied at the center of gravity of the 4K cooler compressor in the spacecraft Z-direction (see § 5).
- The RMS value of the acceleration is computed for each direction and interface node:

$$L\_RMS(f)=\frac{L(f)}{\sqrt{2}},$$

  where L(f) is the peak level response and f the corresponding frequency.
- Once set the 4K working frequency fun, the harmonic magnitudes of the responses have to be seek. As dynamic analysis has been performed up to 200Hz, at most 5 harmonics can contribute to the computation of the FPU response levels.
- For taking into account spacecraft fem uncertainty, the highest values of the harmonic magnitudes L_RMS_{MAX}(H*fun), where H is the harmonic order (at most H = 5), have been seek in a +/-5% or +/-10% range around the corresponding harmonic frequency (f = H*fun), depending on the frequency f is respectively lower or greater than 100Hz.

$$L\_RMS_{MAX}(H*fun)=Max_{Freq\_Range}[L\_RMS(H*fun)].$$

  For example if 35Hz is 4K Cooler working frequency (corresponding to the fundamental frequency fun), for each node and direction the maximum values of the response are to be seek in the frequency ranges reported in the table hereunder.

Harmonic ID	Harmonic Frequency [Hz]	Uncertainty Range [%]	Freq. Range [Hz]
#1	35.0	5 (< 100Hz)	33.25 – 38.25
#2	70.0	5 (< 100Hz)	66.50 – 73.50
#3	105.0	10 (> 100Hz)	99.75 – 110.25
#4	140.0	10 (> 100Hz)	133.00 – 147.00
#5	175.0	10 (> 100Hz)	166.25 – 183.75

- Then, the RMS value of the acceleration for one FPU interface node and one direction is computed as the quadratic sum over the maximum values of the harmonics:

$$L\_RMS_{TOT}(fun)=\sqrt{\sum_H L\_RMS_{MAX}(H,fun)^2}.$$

Moreover, if the 3-axis resultant R(fun) has to be computed, the L_RMS_{TOT}(fun) values computed for each direction have to combine again as follows:

$$R(fun)=\sqrt{L\_RMS_{TOT}\_X(fun)^2+L\_RMS_{TOT}\_Y(fun)^2+L\_RMS_{TOT}\_Z(fun)^2}$$

Shifting the fundamental frequency from 35Hz to 45Hz, the ranges for other harmonics change and they are shown in table 4.

Harmonic Nr.	Frequency Range [Hz]	Uncertainty Frequency Range [%]	Min-Max Freq. Range [Hz]	Contribution to Spec#2	Contribution to Spec#3	Contribution to Spec#4
#1	35-45	+/-5%	33.25 - 47.25	YES	-	-
#2	70-90	+/-5%	66.50 - 94.50	YES	YES	-
#3	105-135	+/-10%	94.50 - 148.50	YES	-	YES
#4	140-180	+/-10%	126.00 - 198.00	YES	-	YES
#5	175-200	+/-10%	157.50 - 220.00	YES	-	-

Table 4: FPU harmonics frequency ranges

6.2 SPECIFICATION REQUIREMENTS

The FPU interfaces should withstand the specification requirements reported in Table 5

Specification Nr.	Frequency Range [Hz]	Acceleration Level [g]	Output Acceleration Description
#2	30-200	2.0E-03	XYZ-Axis Resultant (RMS Value)
#3	50-70	0.2E-03	XY-Axis Resultant (RMS Value)
#4	120-160	0.2E-03	Z-Axis (RMS Value)

Table 5 : Micro-vibration Specification Requirements

Remark:

§ The spacecraft modal analysis with free boundary conditions shows lateral modes of the FPU occurring in the range 50Hz-70Hz as the longitudinal mode in the range 120Hz-160Hz.

§ As respect to the global specification #2 the resultant of the 3-axis acceleration levels have to be computed.

§ The specification #3 concerning the FPU lateral mode frequency range involve the in-plane resultant (2-axis acceleration levels used).

§ The specification #3 does not involve any resultant but just out-of-plane value has to be considered.

§ For each frequency step resultants are computed considering one-axis rms value.

6.3 SINE RESPONSE LEVELS

The FPU nodes used in the sine response are listed in Table 6 and shown in Figure 7.

GRID ID	COORD. FRAME ID	DESCRIPTION
69010	90001	+X+Y TOP I/F FPU
69011	90001	+X-Y TOP I/F FPU
69012	90001	+X+Y BOTTOM I/F FPU
69013	90001	+X-Y BOTTOM I/F FPU
69017	90001	-X RIGHT I/F FPU
69018	90001	-X LEFT I/F FPU
100007	90001	X I/F HFI
100353	90001	-Y I/F HFI
100363	90001	+Y I/F HFI
102000	90001	CoG HFI

Table 6: Sine output node Ids

They include FPU and HFI interfaces, and FPU center of gravity.

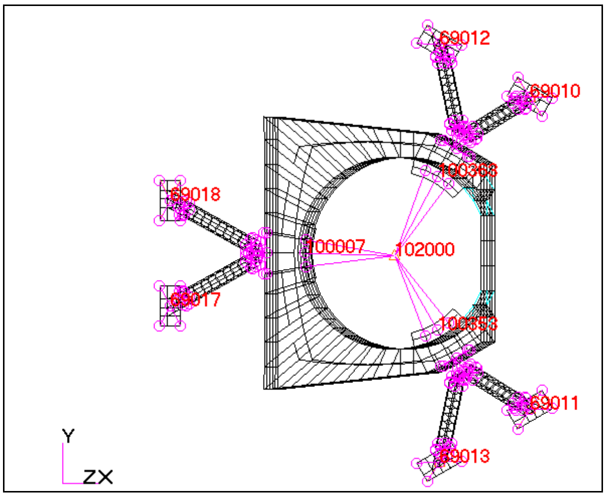


Figure 7: Sine output node locations

All the sine response levels are expressed in the local coordinate frame 90001.
It is defined as follows:

- Z-axis is perpendicular to the FPU support plane,
- Y-axis lies in the support plane and coincides with spacecraft Y-axis,
- X-axis lies in the support plane and completes the right-handed orthogonal reference frame.

X-axis sine responses are shown in Figure 8.

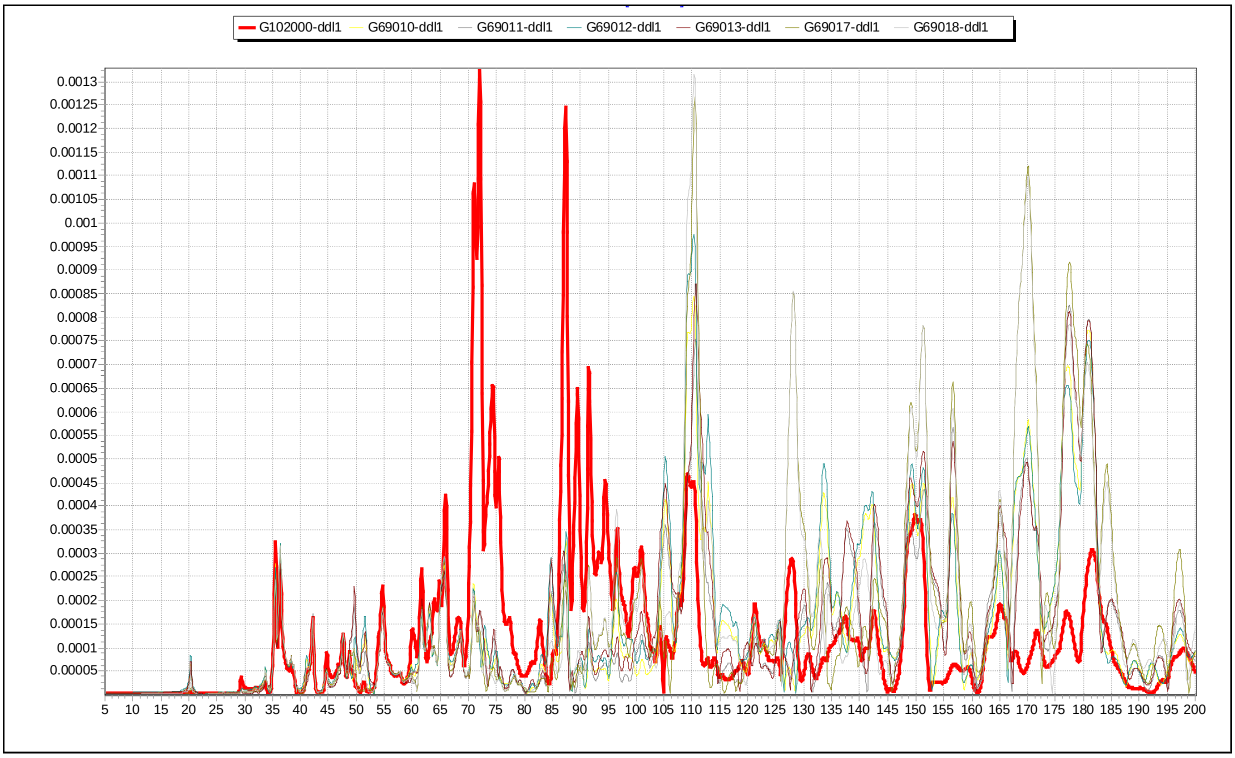


Figure 8: FPU sine response levels along X-axis vs frequency (PR damping = 0.5%)

The highest peaks for X-axis responses are summarized in Table 7.

Sine Analysis		Modal & S.E. Analysis		Remarks
Peak Node	Freq. [Hz]	Mode Nr.	Freq. [Hz]	
FPU CoG	66.0	81	65.8	FPU Lateral Mode Not Excited
FPU CoG	71.5	93	72.1	Telescope structure strain energy % not significant
FPU CoG	87.5	123	87.4	Telescope structure strain energy % not significant
FPU Feet	110.0	180	110.6	Telescope structure strain energy % not significant
FPU Feet	170.0	344	169.5	Telescope structure strain energy % not significant

Table 7: Highest peaks on FPU sine response (X-axis)

Remark:

- Mode #81 is not excited as the largest 2nd harmonic frequency range [66.50Hz - 94.50Hz] (see table 4) does not include the frequency 65.8 Hz.
- In the other modes there is not a significant level of strain energy accumulated in the telescope structure[1].

[1] Telescope structure includes baffle, primary reflector, secondary reflector and support frame (see [RD3]).

Y-axis sine responses are shown in Figure 9.

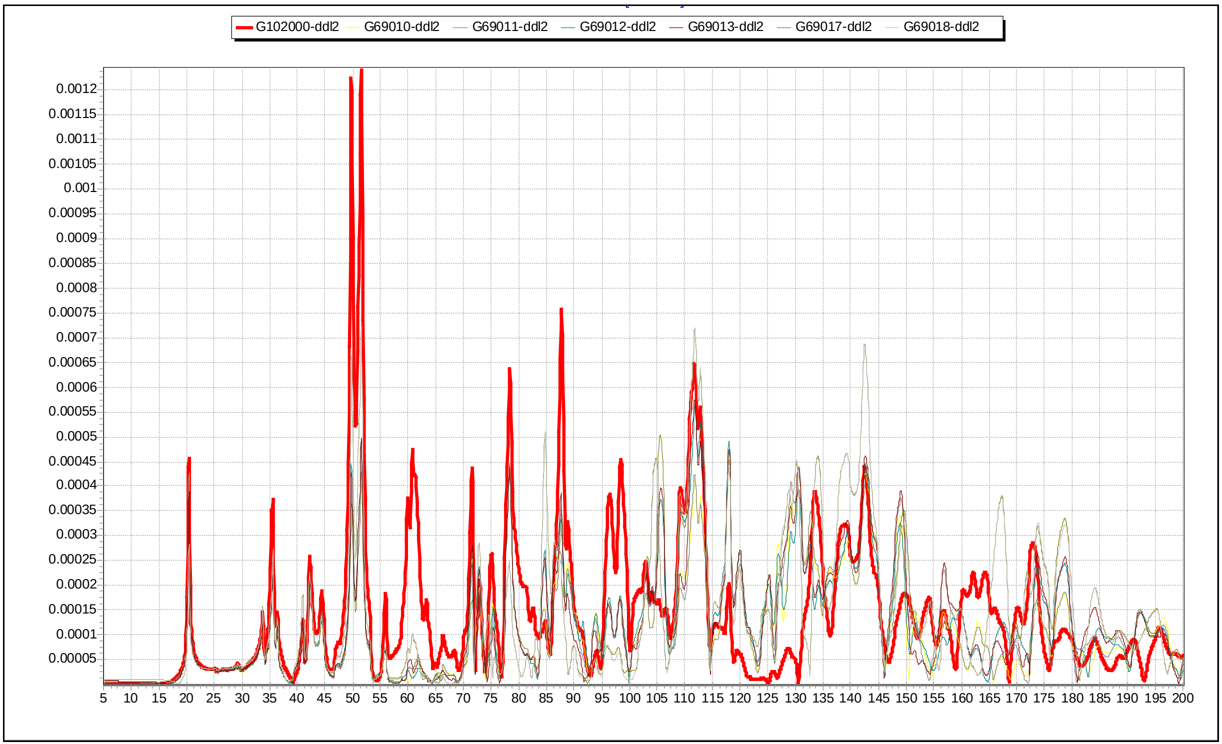


Figure 9: FPU sine response levels along Y-axis vs frequency (PR damping = 0.5%)

The highest peaks for Y-axis responses are summarized in Table 8.

Sine Analysis		Modal & S.E. Analysis		Remarks
Peak Node	Freq. [Hz]	Mode Nr.	Freq. [Hz]	
FPU CoG	50	58	49.7	FPU Lateral Mode Not Excited
FPU CoG	61	73	60.6	FPU Lateral Mode Not Excited
FPU CoG	71	90	71.3	Telescope structure strain energy % not significant
FPU CoG	78	107	78.4	Telescope structure strain energy % not significant
FPU CoG	88	125	88.2	Telescope structure strain energy % not significant

Table 8: Highest peaks on FPU sine response (Y-axis)

Remark:

§ Modes #58 & #73 are not excited as the largest frequency ranges for the 1st and 2nd harmonics are respectively [33.25Hz - 47.25Hz] and [66.50Hz - 94.50Hz].

§ In the other modes there is not a significant level of strain energy accumulated in the telescope.

Z-axis sine responses are shown in Figure 10.

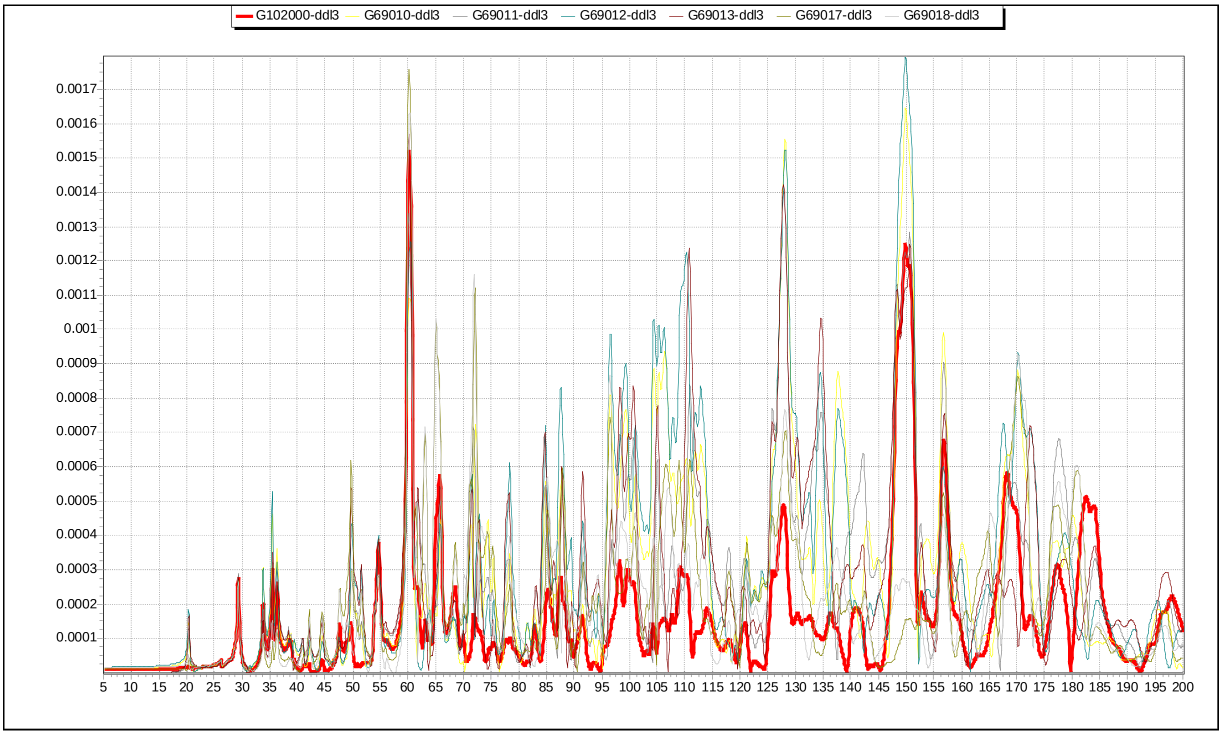


Figure 10: FPU sine response levels along Z-axis vs frequency (PR damping = 0.5%)

The highest peaks for Z-axis responses are summarized in Table 9.

Sine Analysis		Modal & S.E. Analysis		Remarks
Peak Node	Freq. [Hz]	Mode Nr.	Freq. [Hz]	
FPU Feet	110	180	110.6	Telescope SE % not significant
FPU Feet	127.5	230	127.1	FPU Longitudinal Mode Excited
FPU Feet	150	289	150.7	Telescope structure strain energy % not significant
FPU Feet	157	301	156.8	Telescope structure strain energy % not significant
FPU Feet	170	346	170.4	Telescope structure strain energy % not significant

Table 9: Highest peaks on FPU sine response (Z-axis)

Remark:

§ Only the mode #230 at 127Hz risks to be impacted by the eventual damping evolution. Strain energy distribution is shown hereunder.

```
MODE =  230 - FREQUENCY = 127.102 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :
     MX        MY        MZ        IX        IY        IZ
     0.000     0.000     0.000     0.000     0.000     0.000
____________________________________________________________
SUBSTRUCTURE OR SUBSYSTEM                  % SE      SUM

 PLM Primary reflector                      21.646    21.646
 SVM Lower closure panel                    14.497    36.143
 PLM Baffle                                 13.478    49.621
 PLM Groove3                                 8.699    58.320
 PLM Groove2                                 7.892    66.212
 PLM Struts_Blades_Brace                     5.649    71.861
 SVM Central cone                            4.678    76.539
 PLM Frame                                   3.882    80.421
E_BEXT                                       3.037    83.459
 SVM Payload subplatform                     2.309    85.768
 SVM Panel -Y+Z                              2.215    87.983
 SVM Panel +Z                                1.702    89.685
 PLM Groove1                                 1.506    91.191
 SVM Panel +Y+Z                              1.427    92.618
 SVM Upper closure panel                     1.347    93.965
```

§ In the other modes there is not a significant level of strain energy accumulated in the telescope structure.

6.4 STRUCTURAL DAMPING FACTOR

To estimated an eventual damping evolution at cryo temperature, the structural damping factor of the primary reflector support panel has been reduced to 0.05% (very unfavourable).

The sine responses shown in §6.3 change as reported in Figure 11-Figure 13.

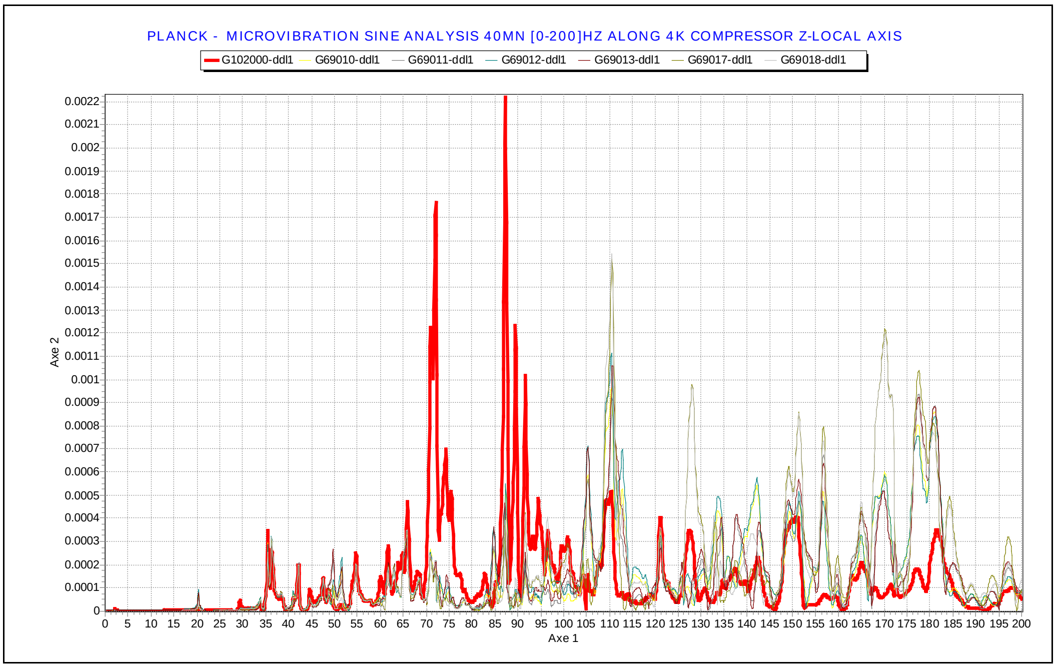


Figure 11: FPU sine response levels along X-axis vs frequency (PR damping = 0.05%)

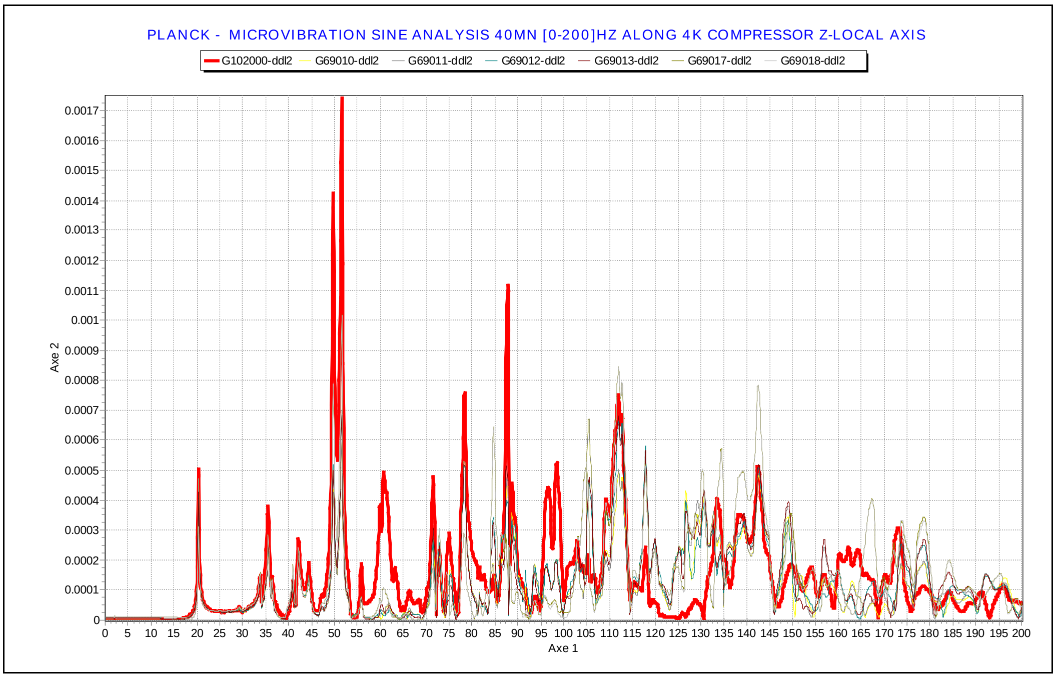


Figure 12: FPU sine response levels along Y-axis vs frequency (PR damping = 0.05%)

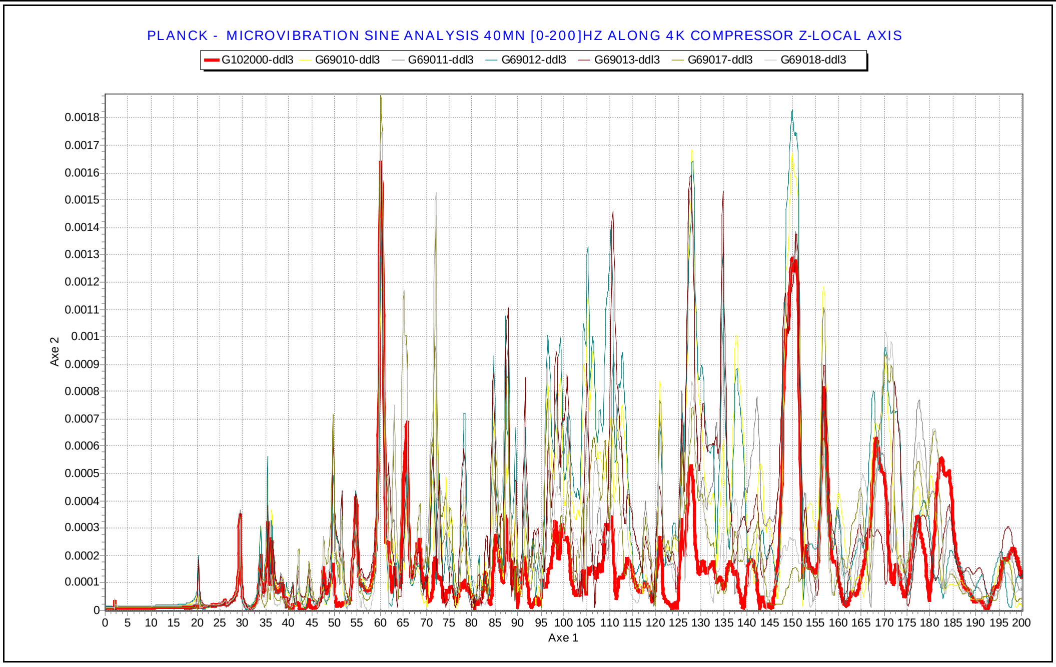


Figure 13: FPU sine response levels along Z-axis vs frequency (PR damping = 0.05%)

Remark:

In the new PR support panel configuration (damping factor = 0.05%) the peak at 127Hz is higher.
The peak at 134.6Hz has near the same level but the corresponding mode presents a more significant percentage of strain energy going to the primary reflector (49%) and baffle (10%).

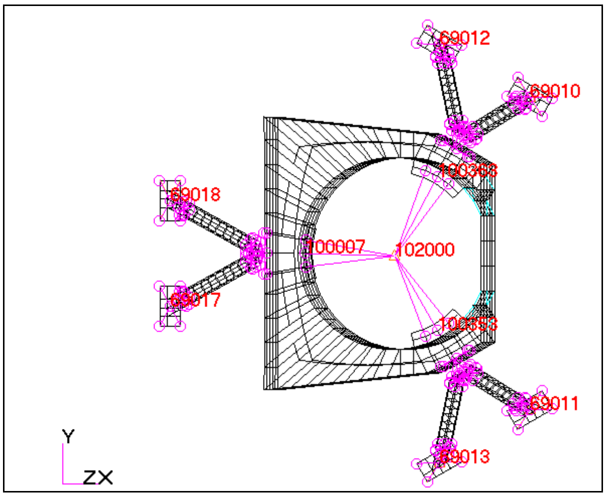
```
MODE =  246 - FREQUENCY = 134.620 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :
     MX         MY         MZ         IX         IY         IZ
     0.000      0.000      0.000      0.000      0.000      0.000
____________________________________________________________
SUBSTRUCTURE OR SUBSYSTEM                      % SE       SUM

 PLM Primary reflector                          48.901     48.901
 PLM Baffle                                      9.646     58.547
 PLM Groove3                                     8.184     66.731
 SVM Central cone                                4.964     71.695
 PLM Groove2                                     4.534     76.229
 PLM Struts_Blades_Brace                         4.160     80.389
 SVM Payload subplatform                         3.066     83.455
 SVM Lower closure panel                         2.296     85.751
 PLM Groove1                                     2.104     87.854
 PLM Frame                                       1.859     89.713
E_BEXT                                           1.516     91.228
 SVM Panel +Y+Z                                  1.294     92.522
 SVM Upper closure panel                         1.003     93.525
```

6.5 RESULTS

The results for FPU interfaces are presented as follows:

- for all the interfaces,
- for every working frequency of the 4K Cooler (that is from 35Hz to 45Hz with a 0.1Hz step),
- for both nominal and reduced damping factors,

The locations of the FPU interfaces is just reminded hereunder.



Results are presented in Figure 11, Figure 12 and Figure 13.

The 3-axis resultant (necessary to verify specification #2) is shown in Figure 14.

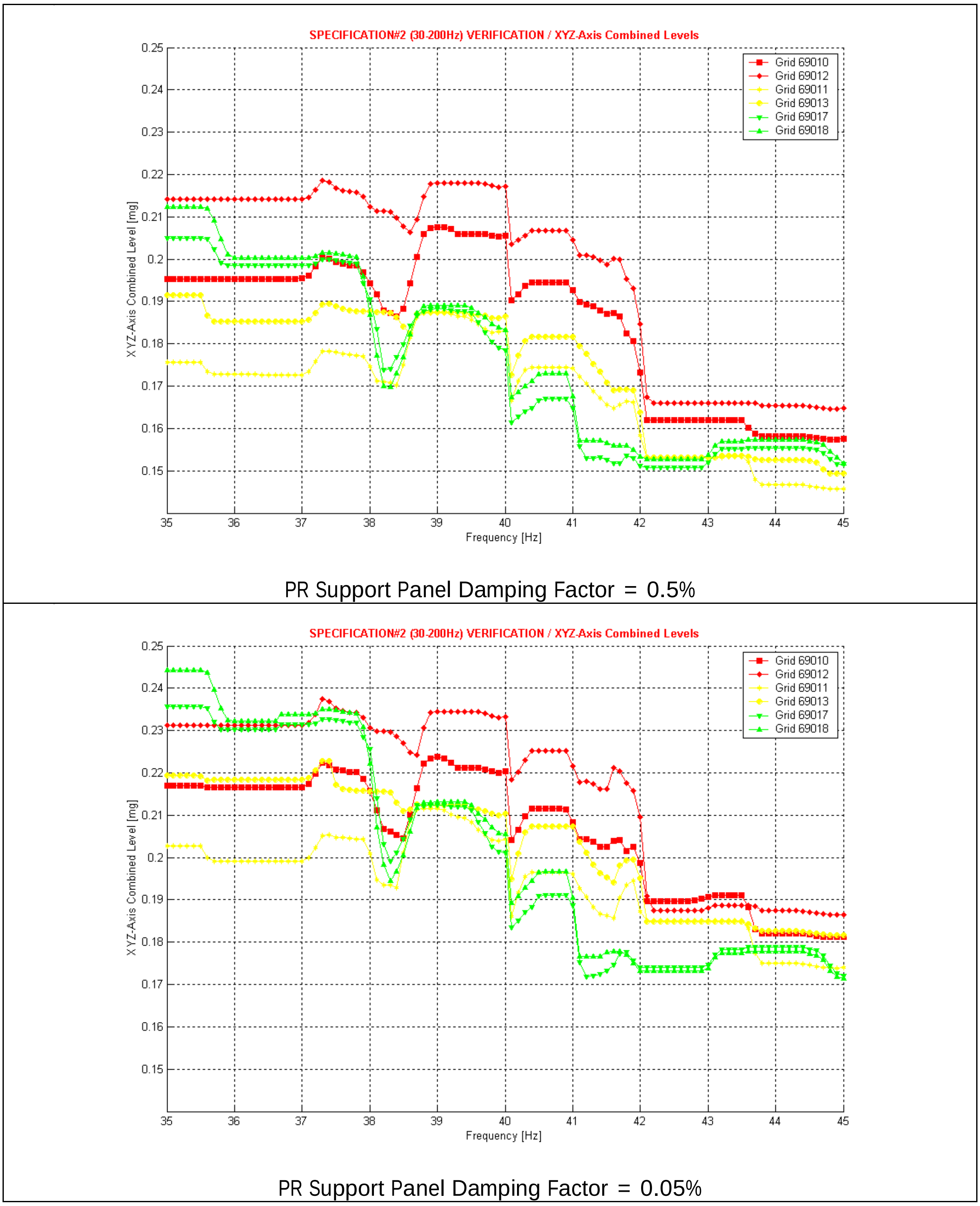


Figure 14: 3-axis acceleration resultant in the range [30Hz-200Hz])

Specification #2 requires levels being lower than $2*10^{-3}$ g.

<u>Remark:</u>

1. The highest combined level is ~$0.22*10^{-3}$ g and it occurs for the FPU I/F (node 69012) working the 4K Cooler at 37.2Hz.

2. Reduction of the damping factor does not produce significant changes in the resultant levels. Maximum levels occur at 35-36Hz rather than 37-38Hz and shift from top FPU interfaces to bottom ones (nodes 69017 & 69018).

The 2-axis resultant (necessary to verify specification #3) is shown in Figure 15.

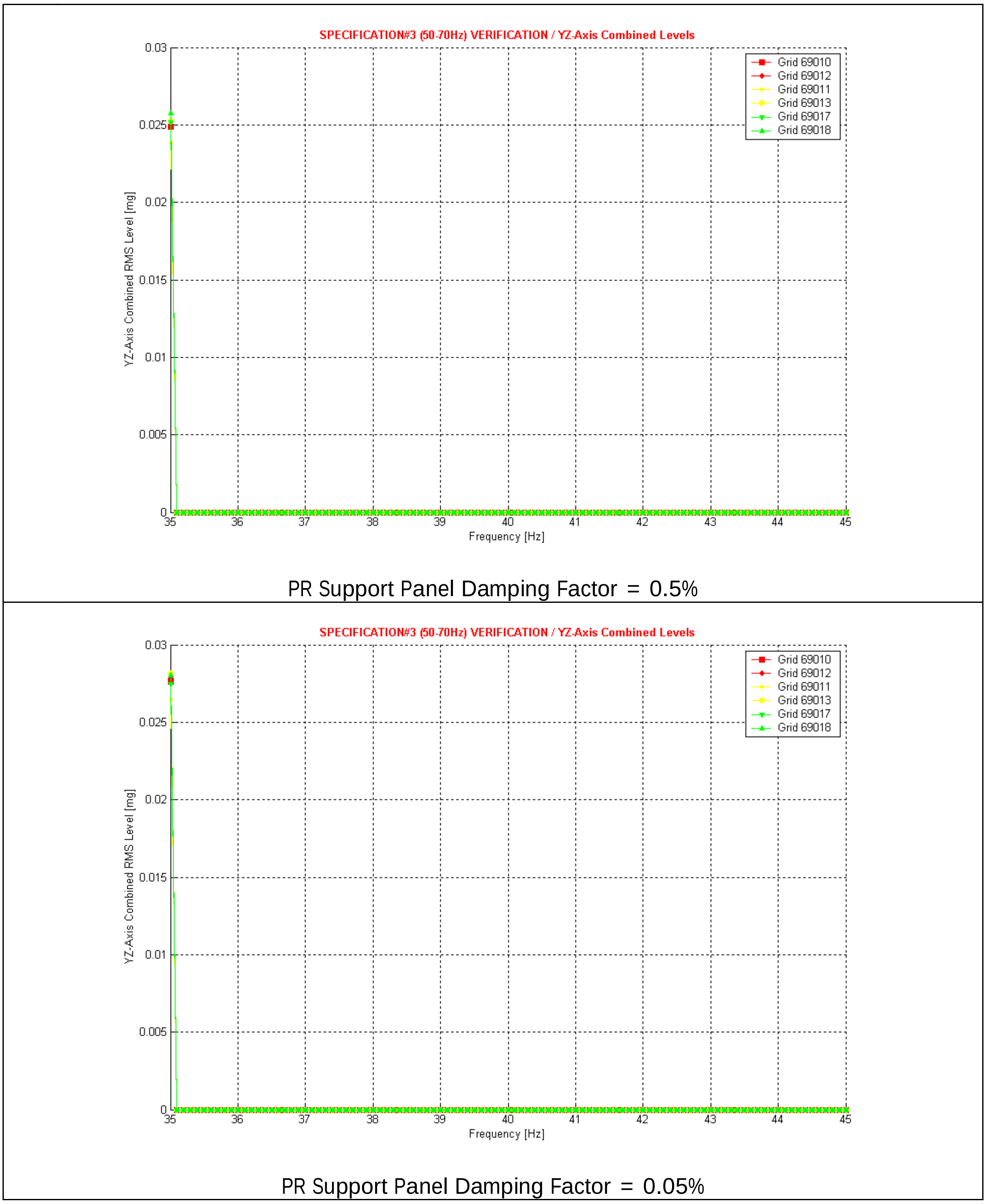
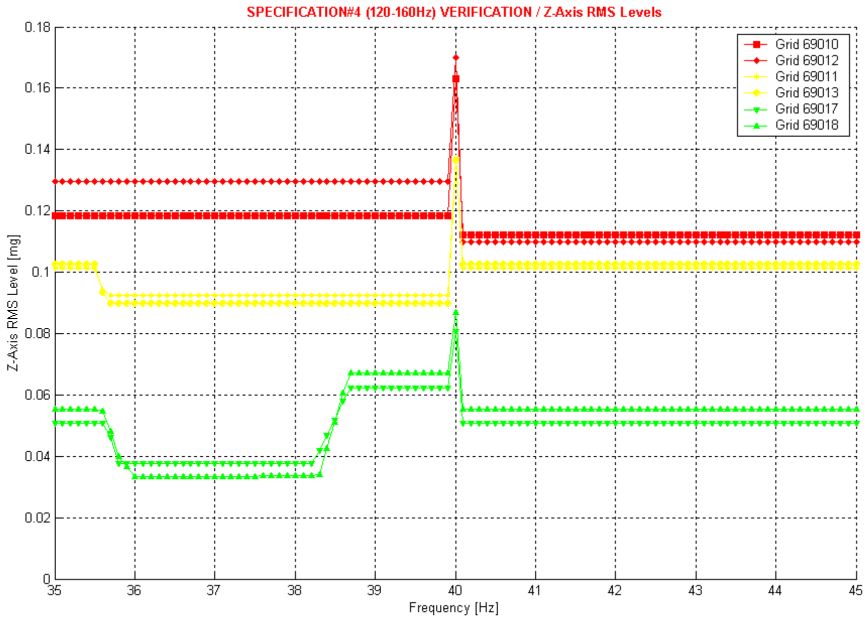


Figure 15: In-plane acceleration resultant in the range [50Hz-70Hz]

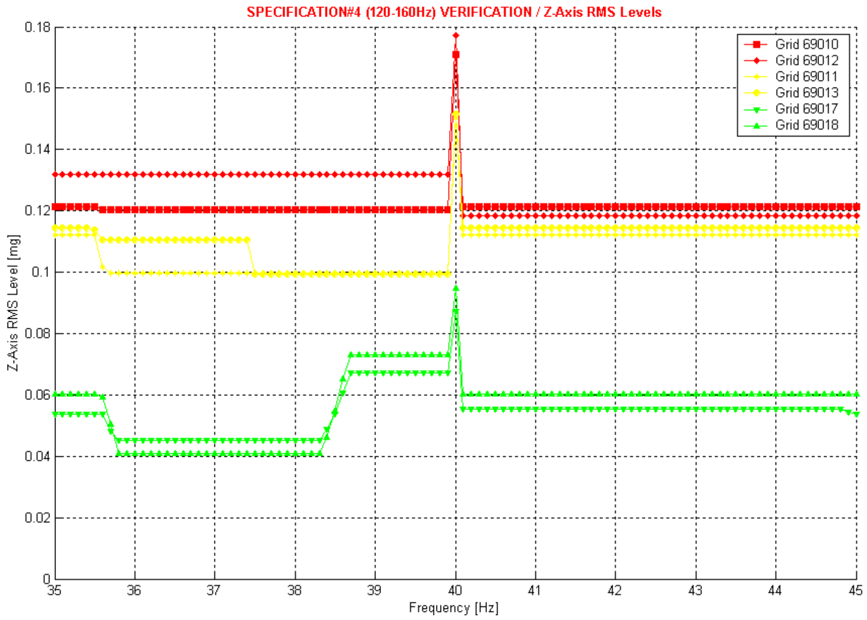
Remark:

1. In this case only 2nd harmonic at the 4K Cooler working frequency of 35Hz can contribute to the resultant computation. That is why only one value can be observed at 35Hz.
2. All the interfaces reach the same level and the maximum level is $0.025*10^{-3}$ g and it is quite lower than specification requirement ($0.2*10^{-3}$ g).
3. Reduction of the damping factor does not produce significant changes in the in-plane resultant levels.

The Z-axis rms level (necessary to verify specification #4) is shown in Figure 16.



PR Support Panel Damping Factor = 0.5%



PR Support Panel Damping Factor = 0.05%

Figure 16: Z-axis rms levels in the range [120Hz-160Hz]

Specification #4 requires levels being lower than $0.2*10^{-3}$ g.

Remark:

1. For each axis, 3rd harmonic contributes in the range [40Hz – 45Hz] as 4th harmonic does in the range [35Hz – 40Hz].
2. Only at the frequency of 40Hz the 3rd and 4th harmonics combine. Thus, a significant peak of $\sim 0.17*10^{-3}$ g can be observed for the FPU I/F (node 69012) just at 40Hz.

3. Reduction of the damping factor does not produce significant changes in the Z-axis rms levels. All the curves translate slightly upward. Maximum level occur still at 40Hz.
4. Mode #230 at 127.1Hz (see Figure 10 and Table 9) corresponds to a 4K Cooler working frequency of ~42Hz.
   At this frequency no peak appears in Figure 16. The constant values after 40Hz corresponds to the peak values at 127.1Hz shown in Figure 10 since they are always inside the +/-10% bandwidth when maximum values are searched (see §6.1.2 for details).

7 CONCLUSIONS

Three specifications have been studied and results are fully compliant for all the specifications. Results are summarised in Table 10 - Table 12.

Node ID	Description	SPECIFICATION #2 [30Hz-200Hz]	PR SUPPORT PANEL DAMPING 0.5%		PR SUPPORT PANEL DAMPING 0.05%	
			Max Acceleration Level [mg]	4K Cooler Working Frequency [Hz]	Max Acceleration Level [mg]	4K Cooler Working Frequency [Hz]
69010	+X+Y TOP I/F	$2*10^{-3}$	0.21	39.0	0.22	39.0
69011	+X-Y TOP I/F		0.19	38.8	0.21	38.8
69012	+X+Y BOTTOM I/F		0.22	37.3	0.24	37.3
69013	+X-Y BOTTOM I/F		0.19	35.0	0.22	37.4
69017	-X RIGHT I/F		0.20	35.0	0.24	35.0
69018	-X LEFT I/F		0.21	35.0	0.24	35.0

Table 10: Results (Specification #2)

Node ID	Description	SPECIFICATION #3 [50Hz-70Hz]	PR SUPPORT PANEL DAMPING 0.5%		PR SUPPORT PANEL DAMPING 0.05%	
			Max Acceleration Level [mg]	4K Cooler Working Frequency [Hz]	Max Acceleration Level [mg]	4K Cooler Working Frequency [Hz]
69010	+X+Y TOP I/F	$0.2*10^{-3}$	0.02	35.0	0.03	35.0
69011	+X-Y TOP I/F		0.03	35.0	0.03	35.0
69012	+X+Y BOTTOM I/F		0.02	35.0	0.03	35.0
69013	+X-Y BOTTOM I/F		0.03	35.0	0.03	35.0
69017	-X RIGHT I/F		0.03	35.0	0.03	35.0
69018	-X LEFT I/F		0.03	35.0	0.03	35.0

Table 11: Results (Specification #3)

Node ID	Description	SPECIFICATION #4 [120Hz-160Hz]	PR SUPPORT PANEL DAMPING 0.5%		PR SUPPORT PANEL DAMPING 0.05%	
			Max Acceleration Level [mg]	4K Cooler Working Frequency [Hz]	Max Acceleration Level [mg]	4K Cooler Working Frequency [Hz]
69010	+X+Y TOP I/F	$0.2*10^{-3}$	0.16	40.0	0.17	40.0
69011	+X-Y TOP I/F		0.14	40.0	0.15	40.0
69012	+X+Y BOTTOM I/F		0.17	40.0	0.18	40.0
69013	+X-Y BOTTOM I/F		0.14	40.0	0.15	40.0
69017	-X RIGHT I/F		0.08	40.0	0.09	40.0
69018	-X LEFT I/F		0.09	40.0	0.09	40.0

Table 12: Results (Specification #4)

APPENDIX A : SINE RESPONSE LEVELS

3-AXIS RMS RESPONSES (0.5% DAMPING)

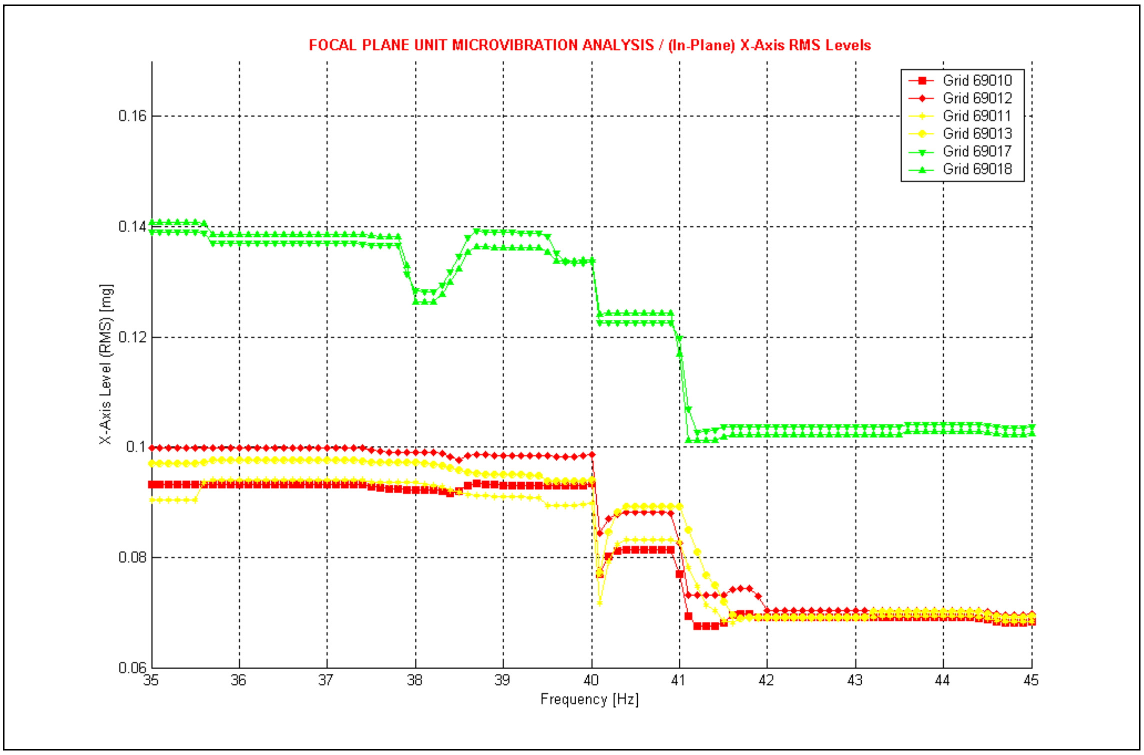


Figure 17: X-axis rms levels in the range [30Hz-200Hz]

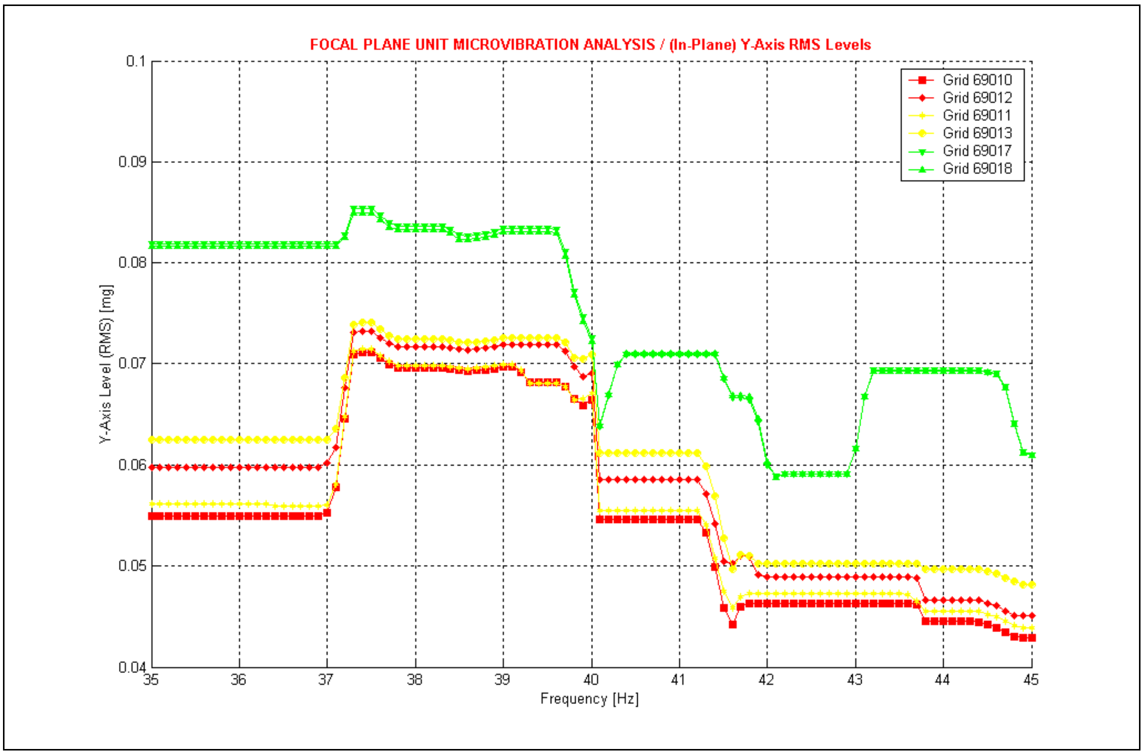


Figure 18: Y-axis levels in the range [30Hz-200Hz]

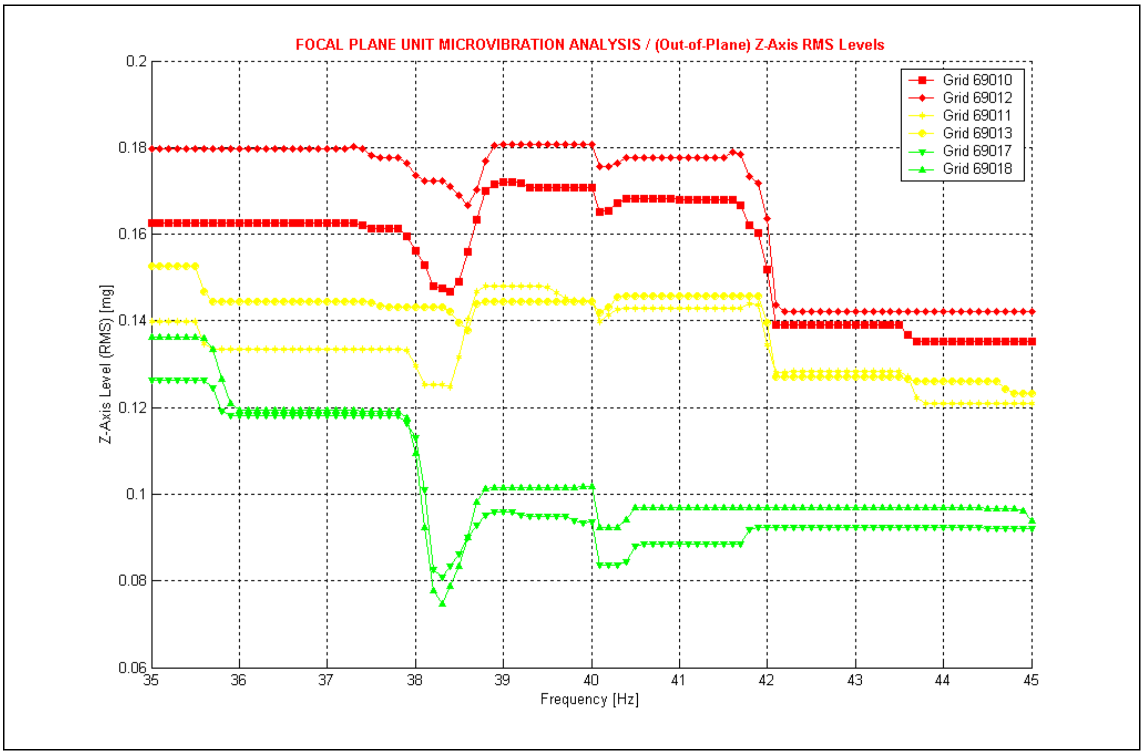


Figure 19: Z-axis rms levels in the range [30Hz-200Hz]

3-AXIS RMS RESPONSES (0.05% DAMPING)

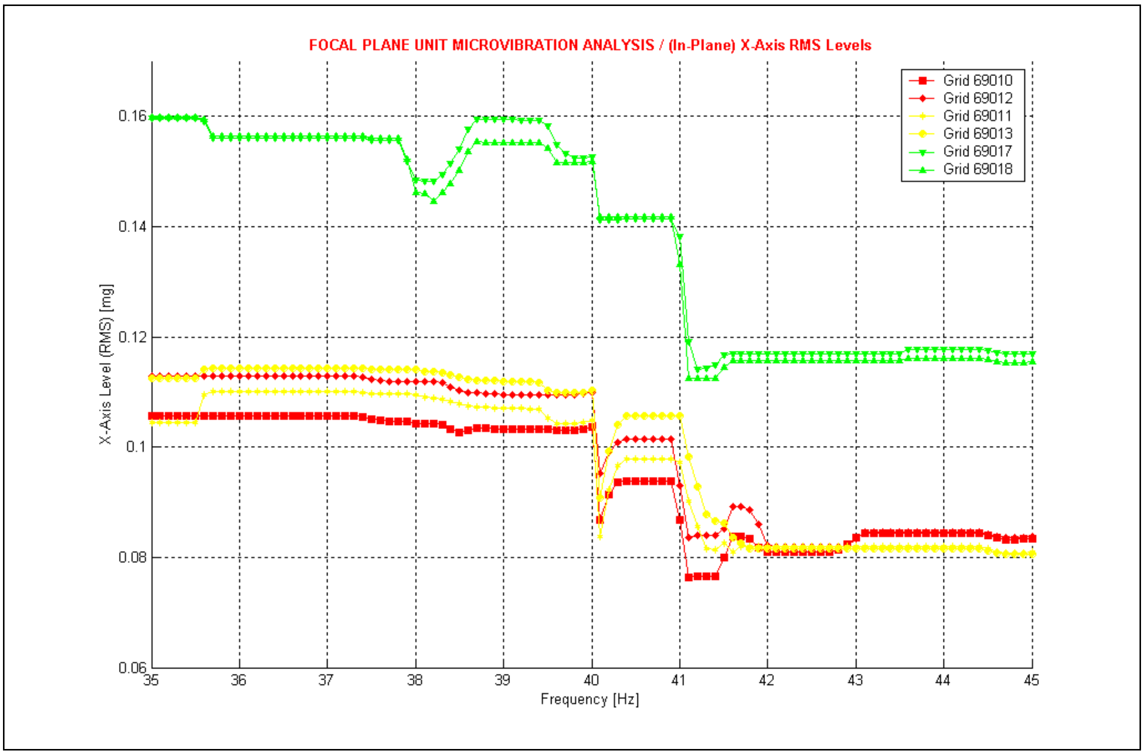


Figure 20: X-axis rms levels in the range [30Hz-200Hz]

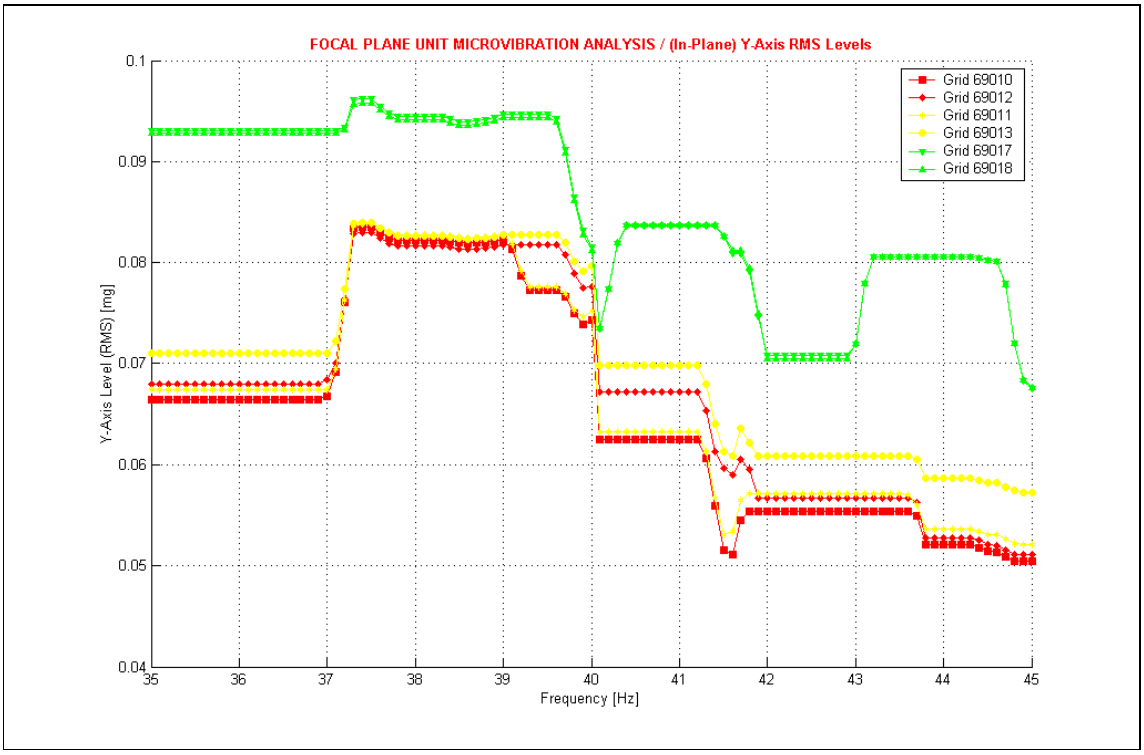


Figure 21: Y-axis rms levels in the range [30Hz-200Hz]

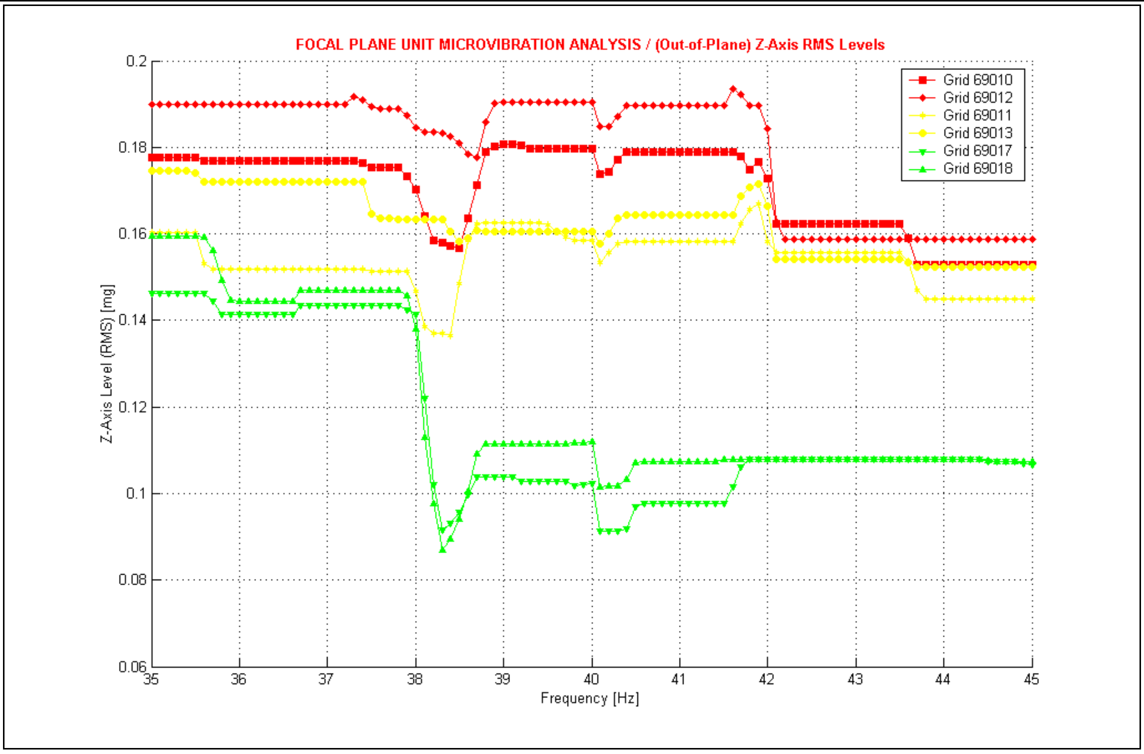


Figure 22: Z-axis rms levels in the range [30Hz-200Hz]

APPENDIX B : STRAIN ENERGY COMPUTATION

X-axis

MODE = 81 - FREQUENCY = 65.821 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Struts_Blades_Brace	21.122	21.122
PLM Primary reflector	16.210	37.333
PLM Frame	9.770	47.103
PLM Groove3	7.442	54.545
SVM Links	7.142	61.686
SVM Central cone	5.009	66.695
PLM Baffle	4.803	71.498
PLM Secondary reflector	3.882	75.380
SVM Tanks	3.317	78.697
SVM Payload subplatform	3.301	81.998
SVM Panel +Y+Z	2.711	84.709
PLM Groove2	2.423	87.132
PLM Groove1	2.192	89.324
PLM FPU	1.860	91.184
SVM Lower closure panel	1.828	93.012
SVM Shear panels	1.815	94.827
SVM Upper closure panel	1.227	96.054

MODE = 93 - FREQUENCY = 72.075 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Primary reflector	24.702	24.702
PLM Baffle	15.219	39.921
PLM FPU	8.896	48.817
PLM Frame	7.791	56.607
PLM Struts_Blades_Brace	5.428	62.036
PLM Groove1	4.483	66.519
PLM Groove2	3.891	70.410
PLM Secondary reflector	3.670	74.080
SVM Links	3.524	77.604
SVM Central cone	3.045	80.649
SVM Lower closure panel	2.928	83.577
SVM Shear panels	2.147	85.724
SVM Payload subplatform	1.821	87.546
SVM Tanks	1.514	89.059
SVM Panel -Z	1.502	90.561
SVM Upper closure panel	1.476	92.037
SVM Panel +Y+Z	1.352	93.389
SVM Panel -Y	1.071	94.460

MODE = 123 - FREQUENCY = 87.385 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Primary reflector	35.647	35.647
PLM Groove3	18.213	53.860
SVM Links	12.089	65.949
PLM Baffle	6.785	72.734
PLM Struts_Blades_Brace	4.533	77.267
PLM FPU	4.512	81.779
SVM Lower closure panel	2.802	84.580
SVM Shear panels	2.637	87.217
SVM Panel -Y+Z	1.862	89.079
SVM Central cone	1.652	90.732
SVM Upper closure panel	1.418	92.150
PLM Frame	1.357	93.507
SVM Panel -Z+Y	1.204	94.711

MODE = 180 - FREQUENCY = 110.571 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Baffle	40.956	40.956

```
 SVM Central cone                           14.831    55.788
 PLM Primary reflector                      14.012    69.800
E_BINT                                       6.887    76.687
 SVM Lower closure panel                     4.239    80.926
 SVM Panel -Y+Z                              2.371    83.297
 PLM FPU                                     1.775    85.071
 PLM Struts_Blades_Brace                     1.665    86.736
 PLM Groove3                                 1.422    88.158
 PLM Frame                                   1.308    89.466
 SVM Links                                   1.222    90.688
 SVM Upper closure panel                     1.145    91.833
E_BEXT                                       1.093    92.926
____________________________________________________________

MODE =  344 - FREQUENCY = 169.528 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :
     MX        MY        MZ        IX        IY        IZ
     0.000     0.000     0.000     0.000     0.000     0.000
____________________________________________________________
SUBSTRUCTURE OR SUBSYSTEM                 % SE      SUM

 PLM Groove1                                54.359    54.359
 PLM Baffle                                  8.820    63.179
 PLM Struts_Blades_Brace                     7.756    70.935
 PLM Primary reflector                       4.754    75.690
 SVM Upper closure panel                     4.168    79.857
 SVM Central cone                            4.086    83.944
 PLM Groove3                                 3.392    87.335
 PLM FPU                                     2.164    89.499
 PLM Groove2                                 1.833    91.332
 SVM Payload subplatform                     1.617    92.949
 PLM Frame                                   1.429    94.378
 SVM Lower closure panel                     1.184    95.562
____________________________________________________________
```

Y-axis

MODE = 58 - FREQUENCY = 49.710 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Primary reflector	16.070	16.070
PLM Frame	12.320	28.390
SVM Central cone	12.024	40.414
PLM Secondary reflector	9.378	49.792
PLM Baffle	7.025	56.817
SVM Payload subplatform	7.008	63.825
PLM Struts_Blades_Brace	6.836	70.661
SVM Lower closure panel	4.830	75.491
SVM Upper closure panel	4.181	79.672
SVM Tanks	4.089	83.761
SVM Panel -Y+Z	2.176	85.937
PLM Groove1	1.714	87.651
PLM FPU	1.661	89.312
SVM Links	1.492	90.804
PLM Groove2	1.413	92.216
SVM Panel +Y	1.382	93.598
SVM Shear panels	1.226	94.824
E_BEXT	1.024	95.848

MODE = 73 - FREQUENCY = 60.622 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Baffle	20.990	20.990
PLM Frame	12.796	33.786
SVM Central cone	12.048	45.834
PLM Primary reflector	8.825	54.659
SVM Tanks	5.614	60.273
PLM Struts_Blades_Brace	5.442	65.715
PLM Secondary reflector	4.571	70.286
SVM Lower closure panel	4.203	74.489
PLM Groove3	3.638	78.127
SVM Upper closure panel	2.917	81.044
SVM Panel +Y	2.728	83.772
SVM Links	2.553	86.325
SVM Payload subplatform	2.300	88.625
PLM Groove2	2.036	90.661
SVM Panel +Y+Z	1.496	92.157
SVM Panel -Z+Y	1.161	93.318

MODE = 90 - FREQUENCY = 71.345 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
SVM Central cone	12.957	12.957
SVM Lower closure panel	12.796	25.753
PLM Primary reflector	8.960	34.713
E_BINT	8.907	43.621
PLM Baffle	8.769	52.389
PLM Struts_Blades_Brace	4.840	57.230
PLM Groove1	4.778	62.008
PLM Secondary reflector	4.501	66.509
PLM Frame	4.322	70.831
PLM Groove3	4.177	75.007
SVM Links	3.028	78.035
SVM Tanks	2.951	80.986
PLM Groove2	2.684	83.670
SVM Panel +Y+Z	2.542	86.212
SVM Panel -Z	2.420	88.633
SVM Payload subplatform	2.330	90.963
PLM FPU	2.054	93.017
SVM Upper closure panel	1.781	94.798
SVM Shear panels	1.377	96.175

MODE = 107 - FREQUENCY = 78.373 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Struts_Blades_Brace	24.731	24.731
PLM Secondary reflector	21.659	46.390
PLM Primary reflector	14.335	60.725
PLM Groove1	9.958	70.683
PLM Groove3	5.119	75.802
PLM Frame	4.812	80.614
SVM Central cone	2.192	82.806
SVM Lower closure panel	2.142	84.948
PLM Baffle	1.991	86.939
SVM Upper closure panel	1.853	88.792
SVM Panel -Z+Y	1.495	90.287
PLM FPU	1.424	91.711
SVM Panel +Y	1.395	93.106
PLM Groove2	1.304	94.411
SVM Panel -Y+Z	1.244	95.654
SVM Panel +Y+Z	1.169	96.823

MODE = 125 - FREQUENCY = 88.164 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Primary reflector	62.771	62.771
PLM Baffle	10.281	73.052
PLM Frame	4.532	77.584
PLM Struts_Blades_Brace	3.098	80.682
PLM Groove2	2.317	82.999
SVM Lower closure panel	2.149	85.147
SVM Links	1.557	86.705
SVM Panel -Y+Z	1.481	88.186
SVM Upper closure panel	1.445	89.631
PLM Groove3	1.298	90.929
SVM Central cone	1.220	92.150
PLM FPU	1.217	93.367

Z-axis

MODE = 180 - FREQUENCY = 110.571 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Baffle	40.956	40.956
SVM Central cone	14.831	55.788
PLM Primary reflector	14.012	69.800
E_BINT	6.887	76.687
SVM Lower closure panel	4.239	80.926
SVM Panel -Y+Z	2.371	83.297
PLM FPU	1.775	85.071
PLM Struts_Blades_Brace	1.665	86.736
PLM Groove3	1.422	88.158
PLM Frame	1.308	89.466
SVM Links	1.222	90.688
SVM Upper closure panel	1.145	91.833
E_BEXT	1.093	92.926

MODE = 180 - FREQUENCY = 110.571 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Baffle	40.956	40.956
SVM Central cone	14.831	55.788
PLM Primary reflector	14.012	69.800
E_BINT	6.887	76.687
SVM Lower closure panel	4.239	80.926
SVM Panel -Y+Z	2.371	83.297
PLM FPU	1.775	85.071
PLM Struts_Blades_Brace	1.665	86.736
PLM Groove3	1.422	88.158
PLM Frame	1.308	89.466
SVM Links	1.222	90.688
SVM Upper closure panel	1.145	91.833
E_BEXT	1.093	92.926

MODE = 230 - FREQUENCY = 127.102 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Primary reflector	21.646	21.646
SVM Lower closure panel	14.497	36.143
PLM Baffle	13.478	49.621
PLM Groove3	8.699	58.320
PLM Groove2	7.892	66.212
PLM Struts_Blades_Brace	5.649	71.861
SVM Central cone	4.678	76.539
PLM Frame	3.882	80.421
E_BEXT	3.037	83.459
SVM Payload subplatform	2.309	85.768
SVM Panel -Y+Z	2.215	87.983
SVM Panel +Z	1.702	89.685
PLM Groove1	1.506	91.191
SVM Panel +Y+Z	1.427	92.618
SVM Upper closure panel	1.347	93.965

MODE = 289 - FREQUENCY = 150.718 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
E_BEXT	12.767	12.767
PLM Groove2	12.758	25.525
SVM Central cone	11.576	37.101
PLM Groove1	11.013	48.114
SVM Lower closure panel	7.708	55.821
PLM Groove3	5.884	61.706
PLM Struts_Blades_Brace	5.105	66.811

PLM Baffle	4.004	70.815
SVM Payload subplatform	3.564	74.379
SVM Panel +Y	3.449	77.828
SVM Panel -Z+Y	2.934	80.762
SVM Panel -Y+Z	2.480	83.242
SVM Upper closure panel	2.344	85.586
SVM Tanks	2.231	87.817
PLM Primary reflector	1.751	89.568
SVM Links	1.626	91.194
SVM Shear panels	1.457	92.652
SVM Panel +Y+Z	1.426	94.077
SVM Panel -Y	1.250	95.328
SVM Panel -Y-Z	1.100	96.428

MODE = 301 - FREQUENCY = 156.793 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
SVM Central cone	19.884	19.884
PLM Baffle	13.236	33.120
E_BEXT	9.377	42.497
PLM Primary reflector	9.124	51.621
SVM Panel -Y+Z	6.688	58.309
SVM Lower closure panel	4.869	63.178
E_BINT	4.527	67.705
SVM Payload subplatform	3.942	71.647
SVM Upper closure panel	3.857	75.505
PLM Groove1	3.697	79.202
PLM Struts_Blades_Brace	3.350	82.552
SVM Shear panels	2.475	85.027
SVM Panel +Y+Z	1.823	86.850
SVM Panel -Y	1.814	88.663
SVM Tanks	1.743	90.406
SVM Links	1.585	91.990
PLM Groove2	1.411	93.401
PLM Frame	1.325	94.726
SVM Panel +Z	1.277	96.003
PLM FPU	1.196	97.199

MODE = 346 - FREQUENCY = 170.375 Hz

EFFECTIVE MASS & INERTIA (KG, KG.M2) :

MX	MY	MZ	IX	IY	IZ
0.000	0.000	0.000	0.000	0.000	0.000

SUBSTRUCTURE OR SUBSYSTEM	% SE	SUM
PLM Groove2	22.653	22.653
PLM Groove3	12.673	35.327
PLM Struts_Blades_Brace	7.849	43.175
SVM Central cone	7.748	50.923
E_BEXT	6.107	57.030
SVM Panel +Y	5.994	63.024
SVM Payload subplatform	4.976	68.001
PLM Baffle	3.832	71.832
PLM Groove1	3.143	74.976
SVM Upper closure panel	3.109	78.085
SVM Lower closure panel	3.016	81.101
SVM Panel -Z+Y	2.685	83.785
SVM Shear panels	2.389	86.175
SVM Panel +Y+Z	2.348	88.523
PLM Primary reflector	2.337	90.860
SVM Links	1.909	92.769
SVM Panel +Z	1.665	94.434
SVM Panel -Y+Z	1.229	95.663
PLM Frame	1.113	96.776

END OF DOCUMENT