CAU ieap Christian-Albrechts-Universität zu Kiel	Solar Orbiter EPD Energetic Particles Detector RFW/RFD	Number: SO-EPD-KIE-RD-0017 Issue: 1.1 Date: 09.05.2016

Business Agreement: N/A
Order: N/A

Classification: Minor

Originator site: CAU – Kiel (D)

Item designation: N/A	**Model: PQM, FM** **S/N: N/A**
Affected item(s): **STEP(PQM, FM)**	**Affected document(s):** **Experiment Interface Document-Part A (EID-A), Issue 5.** **SOL.EST.RCD.0050**

Short Description:
We request to perform notching for the new vibration levels provided by Cliff Ashcroft (ESA).

Detailed Description:

- See Annex A for detailed description of the notching plan.
- See Annex B which is a Technical Note from IDR/UP including FEM analysis for stress, acceleration and RV responses. This TN includes the QSLs required by Cliff Ashcroft (ESA) during EPD IQR co-location meeting at ESTEC on 17.02.2016.

Reason for Request:
The main resound for notching request is to avoid HW damage to the flight HW.
In the scope of EPTHET PFM vibration, the following system requirements for QSL was received from ESA via an email sent on 11.03.2016 by Cliff Ashcroft:
" Xurf Axes : System QSL Requirement is 42.5 g-pk()
Yurf Axes : System QSL Requirement is 42.5 g-pk()
Zurf Axes : System QSL Requirement is 40.0 g-pk()"

According to the results seen on page 59 of Annex B, the following QSL levels were obtained for STEP PQM RV tests with the notching:
Xurf Axes : 61.29 g-pk()
Yurf Axes : 46.35 g-pk()
Zurf Axes : 54.71 g-pk()

The above notching plan applied on STEP PQM was confirmed by Cliff Ashcroft (ESA) during the telecom on 28.04.2016 and as STEP also will follow the PFM approach, we request to perform the RV tests on STEP PFM (acceptance duration) with the same notching plan as STEP PQM.

Adverse Effects:
N/A

PRESENTING INSTITUTION

Engineering	PA	PM	PI
Ali Ravanbakhsh	Michael Richards	César Martín	Robert Wimmer

CONSORTIUM

SE	PA	EM	PI

ESA APPROVAL

Engineering	PA	PM	PI

Annex A

Detailed Description:

Back ground

During post vibration functional tests of EPT-HET PQM on “20.05.2015” anomalies were observed. EPT-HET PQM was inspected at CAU Kiel and hardware damage to LVPS, Digital and Analog boards was observed.

The details can be found in: “SO-EPD-KIE-NC-0016-postVibFTanomalies.pdf”.

STEP PQM vibration test planning

After this failure and in the scope of an NRB with ESA, as EPT-HET and STEP structural design philosophy are quite similar, three simultaneous strategies were planned before starting the STEP PQM vibration tests:

1) ESA provided new load levels for STEP PQM vibration tests based on new definition of In-plane and out-of-plane axes.
   The details can be found in:
   “SO-EPD-KIE-RD-0011_iss1_rev1_qualification_random_vibration_levels.pdf”

2) CAU/OHB reviewed the board population verification with.

3) CAU reviewed the STEP PQM structural design focusing on electronics board’s failure during EPT-HET RV vibration tests.

As a result of the above strategies, CAU proceeded with the following steps before the STEP PQM vibration tests:

1) To design, manufacture and implement stiffeners to include more support to the electronic boards.
2) To perform a low-level vibration test in order to obtain data for FEM correlation.
3) To consider a notching plan during the vibration tests based on the FEM analysis.

Notching plan

The notching frequencies for different axes were selected based on the RV analysis on correlated FEM and the electronic board responses. As it was not possible to read out the boards responses directly during the vibration test (no access to put control accelerometers on the boards), the notching profile was set in advance. With the following characteristics:

Table 1- (from TR: SO-EPD-KIE-TR-0020, iss1/rev0)

Manual notching properties performed during STEP PQM random vibration tests.

Axis		Start-Stop frequency	-12dB notched frequency band	-3dB notched frequency band	Applied grms	Required grms
X	1st notch	335 Hz – 600 Hz	450 Hz – 480Hz		13.13 grms	15.20 grms
	2nd notch	700 Hz – 1100 Hz		750 Hz – 1050Hz		
Y	one notch	480 Hz – 642 Hz	540 Hz – 570Hz		10.09 grms	10.43 grms
Z	one notch	462 Hz – 845 Hz	520 Hz – 750 Hz		13.04 grms	15.20 grms

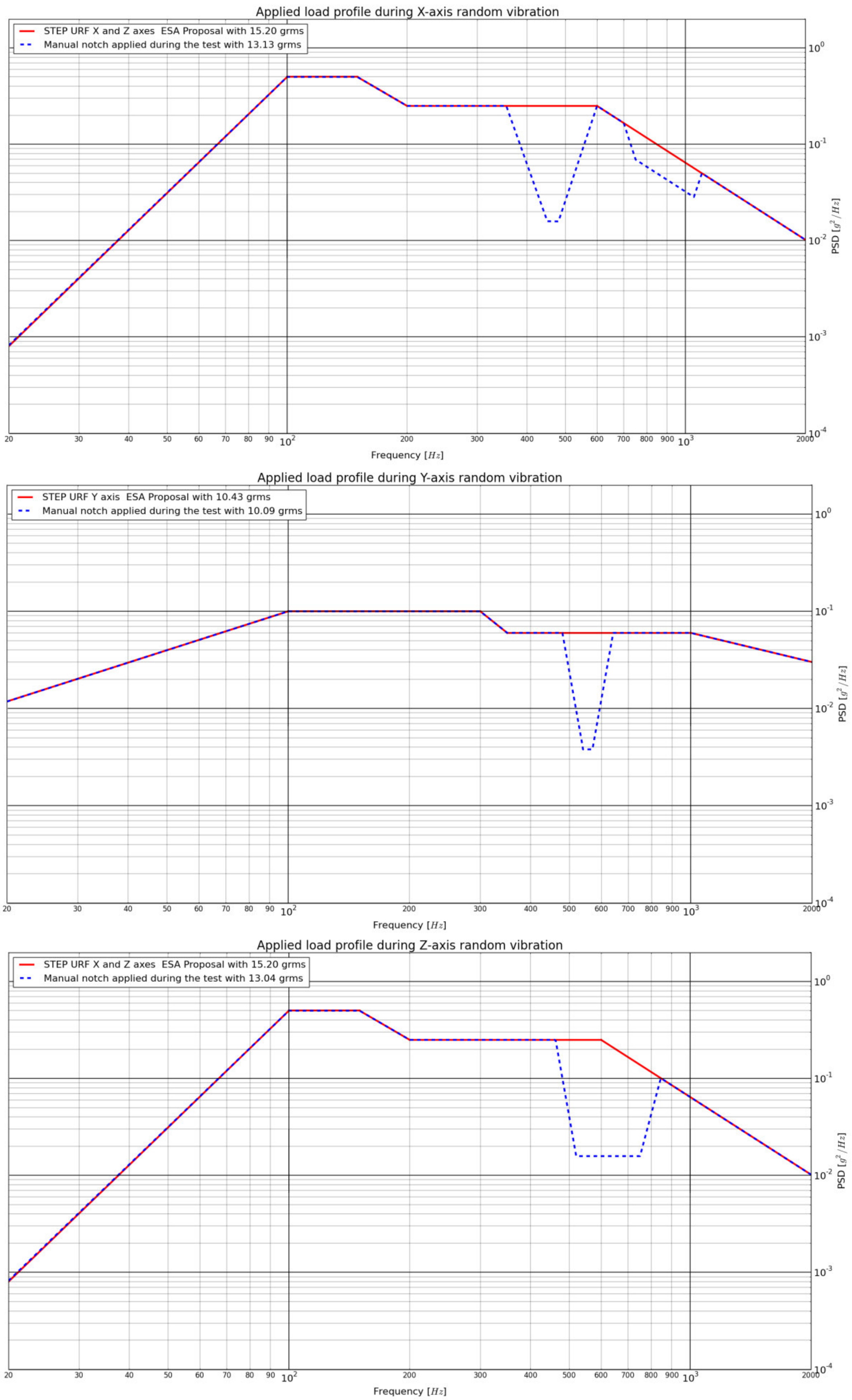

Figure 6-3 (from TR: SO-EPD-KIE-TR-0020, iss1/rev0).

Manual notching performed during STEP PQM random vibration tests.

RV analysis results for boards

X-axis (from Annex B)

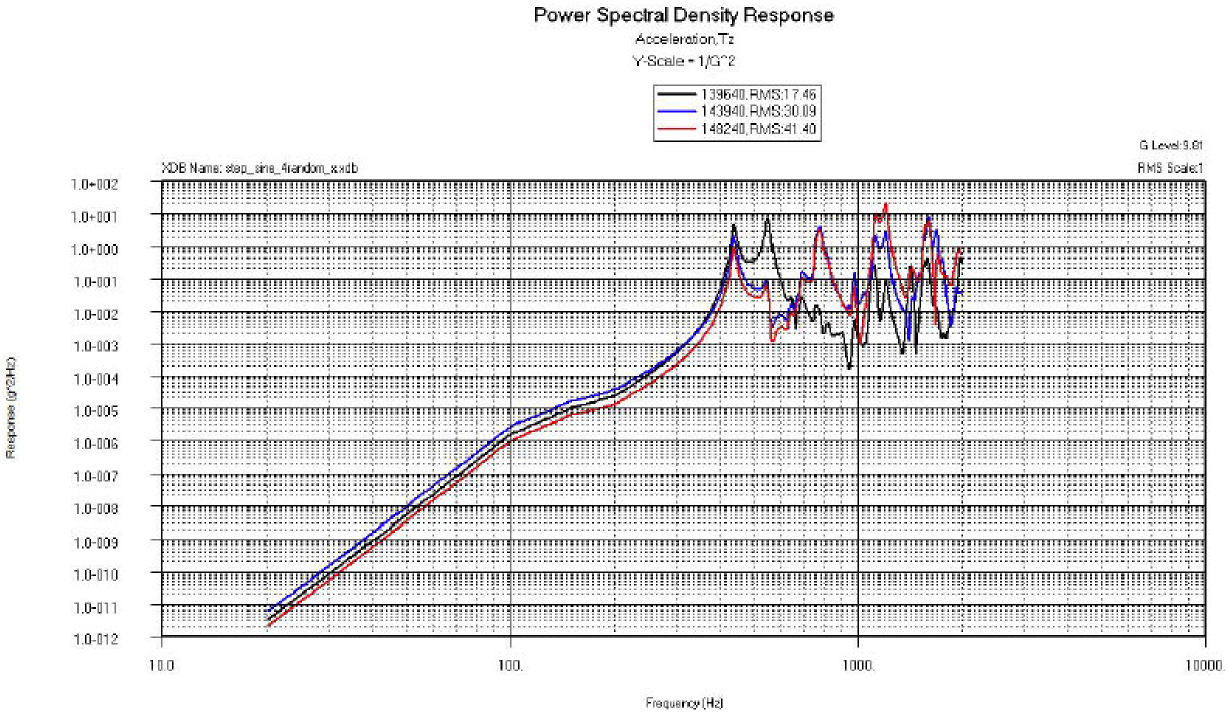

Figure 5-13: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

Y-axis (from Annex B)

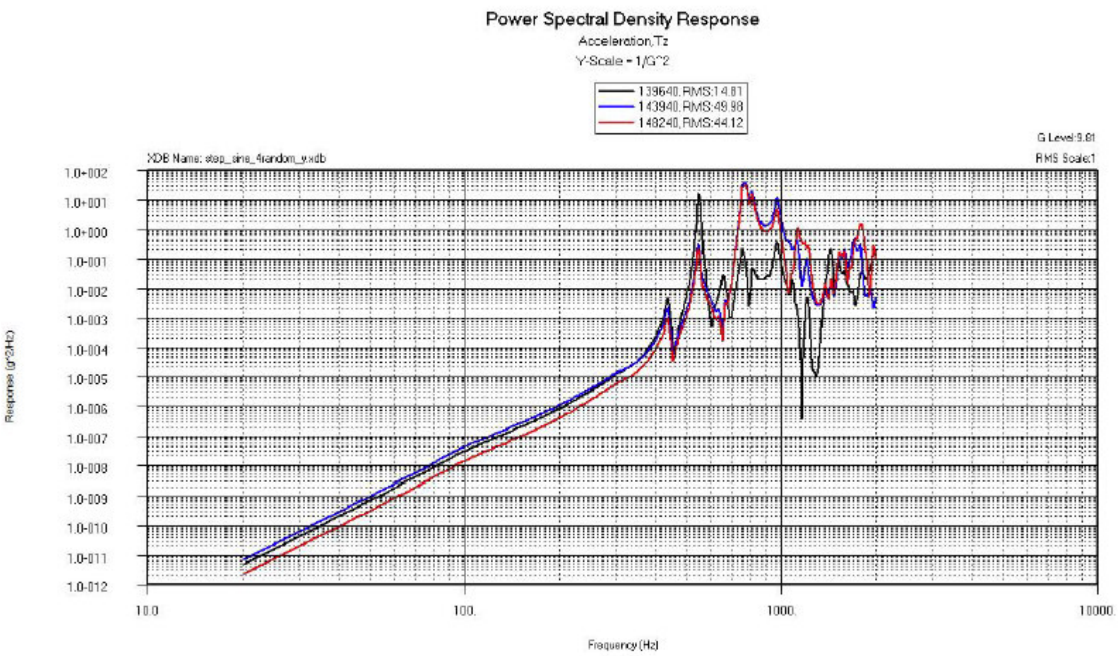

Figure 5-24: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

Z-axis (from Annex B)

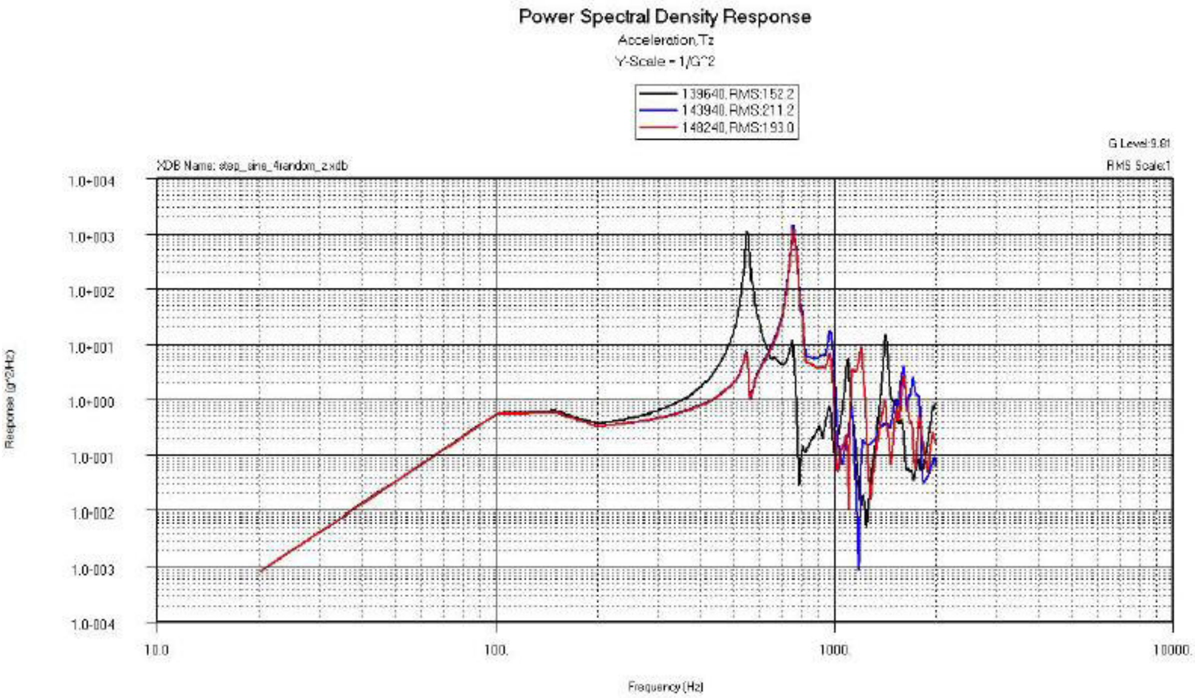

Figure 5-35: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

STEP_Random_Analysis_QSL_Technical Note_1.2.docx

Prepared by: Andrés García Pérez
Revised by: Gustavo Alonso Rodrigo, Félix Sorribes Palmer

1 SCOPE

The scope of this technical note is to provide additional information about the STEP structural analysis.
The STEP FE model has been udpated to include the PCBs stiffeners according to [RD1].
In this document, stress and accelerations from random vibration analysis are provided.

2 REFERENCES

2.1 Applicable documents

ID.	Title	Reference	Iss./Rev.	Date
AD1	Experiment Interface Document part A	SOL.EST.RCD.0050_05	5/0	16/03/2015
AD2	Experiment Interface Document part B	SO-EPD-PO-IF-00001	3/2 DRAFT	05/03/2013
AD3	ECSS-E-30_Part-2A-Mechanical_Part-2-Structural	-	-	25/04/2000
AD4	SOLAR ORBITER: Mechanical FEM Requirement Specification	SOL.S.ASTR.RS.00011	2/0	30/09/2011
AD5	Generic Mechanical FEM Specification	ADS.E.0787	2/0	24/01/2008
AD6	Data for selection of space materials and processes	ECSS-Q-70-71A	rev 1	18/06/2004
AD7	STEP Structural Analysis Report: Strength and stiffness	SO-EPD-KIE_RP-0042	2/3	27/02/2015
AD8	EPD-STEP (PQM) Evaluation of Post S/C STM Random Environment PI Extract	CAA/15_06_2015/SO/EUI-OBS/RV/DTEC	3/2	07/07/2015

Table 2-1: Applicable Documents.

2.2 Reference documents

ID.	Title	Reference	Iss./Rev.	Date
RD1	17sep2015_so-step-c4_top_upm-export.stp			17/09/2015
RD2	Bill of materials and mass budget	So-step-c4_top		06/11/2014
RD3	20130904_STEP_FEM_analysis_tradeoff_interface.pdf			04/09/2013
RD4	Experiment Interface Document part A	SOL.EST.RCD.0050_02	2/8	10/04/2011

RD5	STEP Mechanical Interface Control Drawing	SO-EPD-KIE-DR-0003_c4	3/3	09/01/2015
RD6	STEP PQM Low Vibration Test Report	SO-EPD-KIE-TR-0018	1/0	18/09/2015
RD7	Random Vibrations in Spacecraft Structures Design	-	-	2009
RD8	STEP PQM Random-Sine Vibration Test Plan and Procedure	SO-EPD-KIE-TP-0022	1/1	27/09/2015
RD9	STEP PQM Vibration Test Report	SO-EPD-KIE-TR-0020	1/0	13/12/2015
RD10	Vibration Analysis for Electronic Equipment, D. Steinberg	-	3/0	2000

Table 2-2: Reference Documents.

3 Material characteristics

These are the materials that have been used in the model. The reference temperature for all the materials is 20ºC.

Material Name	Property	Value	Units
Al_6061-T6	Density	2710	kg/m^3
	Modulus of Elasticity	68.9E+09	Pa
	Poisson's ratio	0.330	N/A
	Yield tensile strength	276	MPa
	Ultimate tensile strength	310	MPa
	Thermal expansion coefficient	23.5	µm/mK
Ti_6Al_4V	Density	4430	kg/m^3
	Modulus of Elasticity	113.8E+09	Pa
	Poisson's ratio	0.342	N/A
	Yield tensile strength	847	MPa
	Ultimate tensile strength	924	MPa
	Thermal expansion coefficient	8.6	µm/mK
PCB (FR4)	Density	1850	kg/m^3
	Modulus of Elasticity	24.8E+09	Pa
	Poisson's ratio	0.118	N/A
	Yield tensile strength	310	MPa
	Ultimate tensile strength	345	MPa
	Thermal expansion coefficient	16	µm/mK
Ultem	Density	1270	kg/m^3
	Modulus of Elasticity	3.2E+09	Pa
	Poisson's ratio	0.3	N/A
	Yield tensile strength	155	MPa
	Ultimate tensile strength	165	MPa
	Thermal expansion coefficient	30	µm/mK
Copper	Density	8960	kg/m^3
	Modulus of Elasticity	110.0E+09	Pa
	Poisson's ratio	0.34	N/A
	Yield tensile strength	333	MPa
	Ultimate tensile strength	343	MPa
	Thermal expansion coefficient	17	µm/mK

Table 3-1: Material properties

4 NORMAL MODES ANALYSIS

A normal modes analysis of the constrained FEM was performed. The first modes are shown and some figures of them are depicted below. The first eigenfrequency has a value of 439.1 Hz.

Mode	Frequency (Hz)	Mode	Frequency (Hz)	Mode	Frequency (Hz)
1	439.1	8	685.7	15	972.5
2	548.0	9	753.7	16	985.0
3	552.5	10	779.4	17	1028.1
4	632.1	11	808.5	18	1045.6
5	638.8	12	831.4	19	1078.7
6	658.9	13	912.4	20	1081.7
7	668.3	14	931.2	21	1085.6

Table 4-1: Normal modes

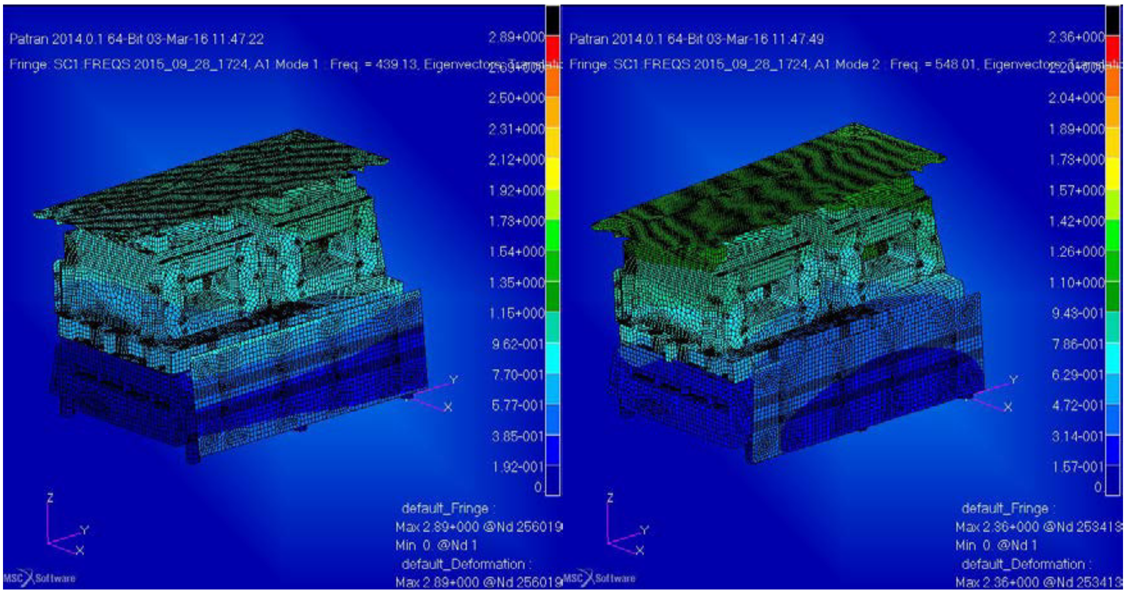

Figure 4-1: Modes 1 (439.1 Hz) and 2 (548.0 Hz)

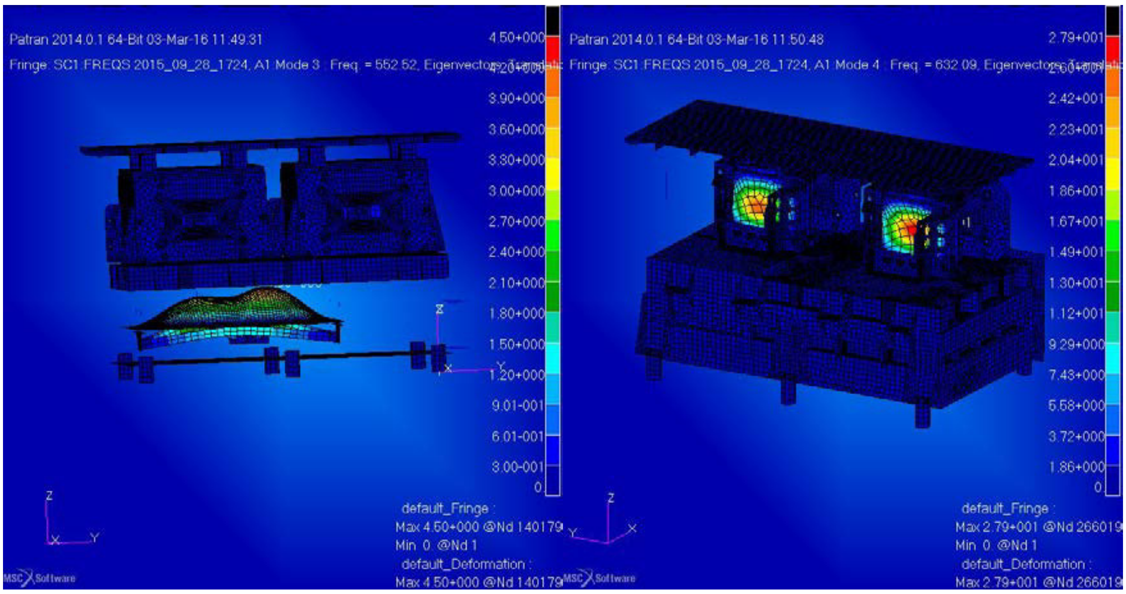

Figure 4-2: Modes 3 (552.5 Hz) and 4 (632.1 Hz)

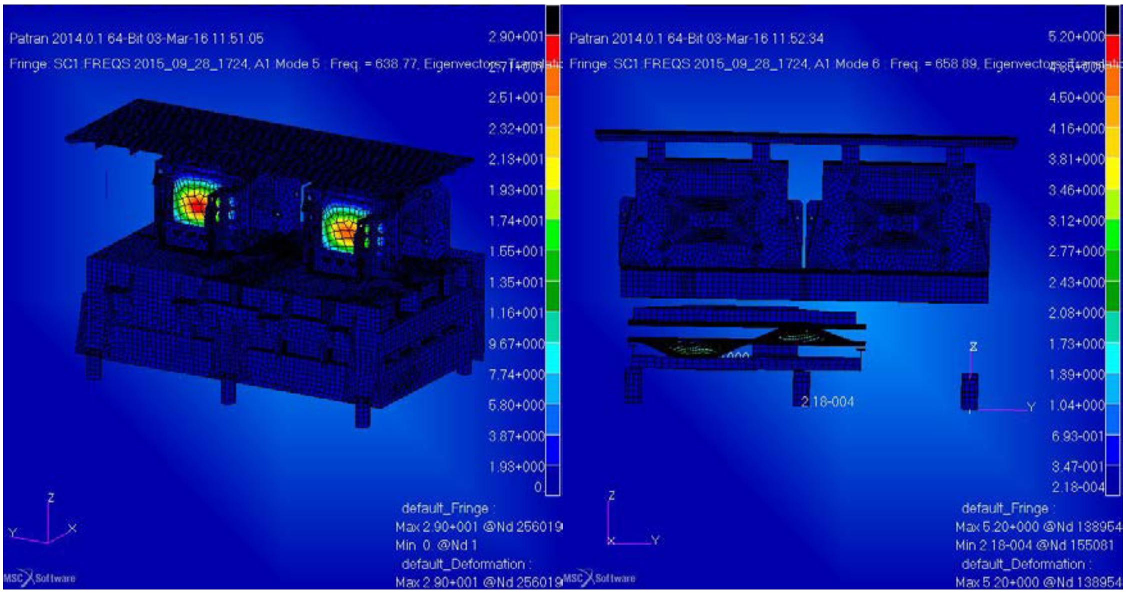

Figure 4-3: Modes 5 (638.8 Hz) and 6 (658.9 Hz)

5 RANDOM VIBRATION ANALYSIS

A random vibration analysis has been carried on with the random specification according to [AD8]. The qualification levels for random test can been seen in Table 5-1, Figure 5-1 and Figure 5-2.

Axis	Frequency (Hz)	Qualification
X & Z EPD-STEP	20 – 100	+12 dB/Oct
	100 – 150	0.5 g^2/Hz
	200 – 600	0.25 g^2/Hz
	600 – 2000	-8 dB/Oct
		15.20 g rms
Y EPD-STEP	20 – 100	+4 DB/Oct
	100 – 300	0.1 g^2/Hz
	350 – 1000	0.06 g^2/Hz
	1000 – 2000	-3dB/Oct
		10.43 g rms

Table 5-1: Random vibration test levels

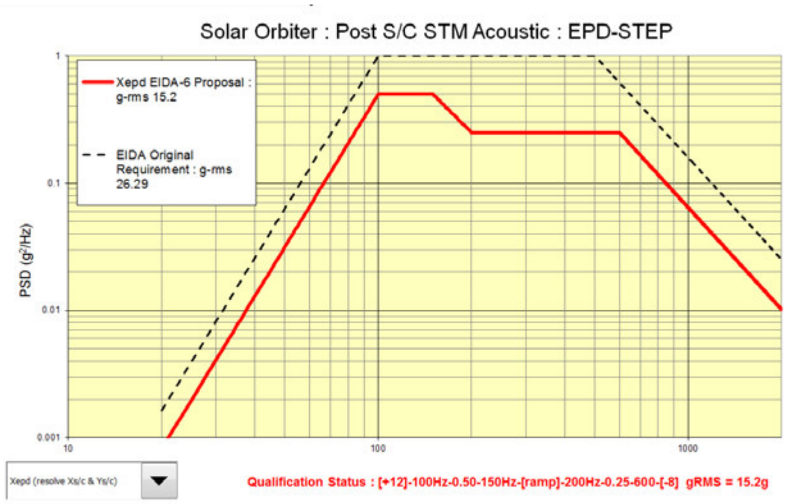

Figure 5-1: Random vibration test levels - X & Z STEP axis

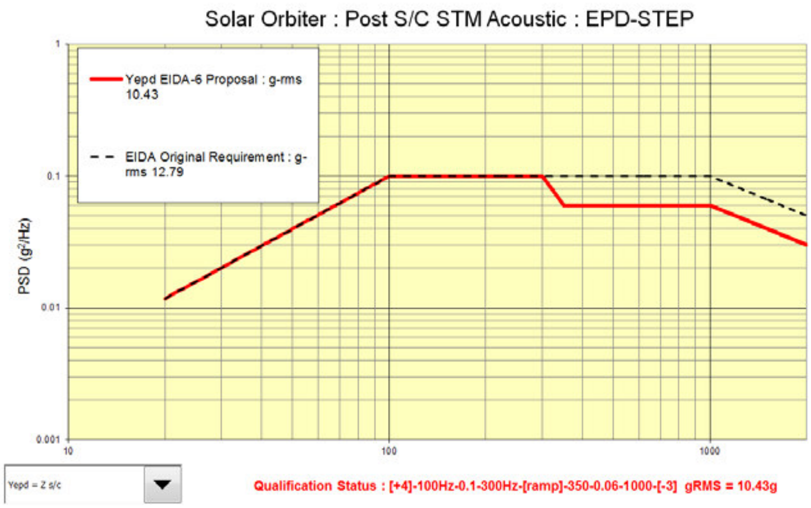

Figure 5-2: Random vibration test levels - Y STEP axis

The damping factor for dynamic analysis has been obtained taking into account the Low Level vibration test results [RD6], and it's shown in Figure 5-3.

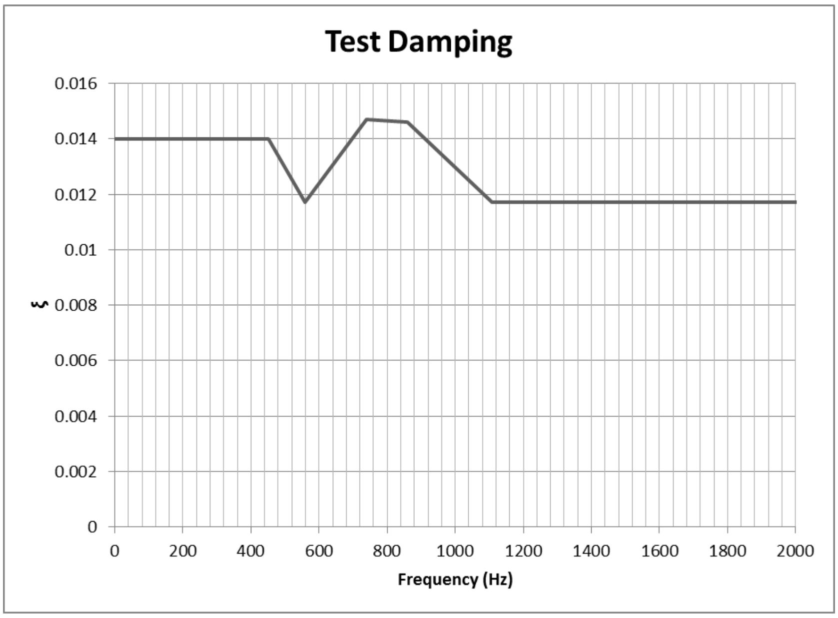

Figure 5-3: Damping factor

The results summary is shown in Table 5-2, Table 5-3 and Table 5-4.

Part	Maximum 3xRMS stress (MPa)		
	Random X	Random Y	Random Z
Al6061-T6	167.0	80.7	73.8
Ti 6Al4V	212.0	68.9	84.2
Ultem	26.3	11.7	7.2
Copper	110.0	49.8	32.9
Power Board	22.1	7.5	79.1
Digital Board	36.4	14.9	63.4
Analogic Board	27.0	10.8	51.6
idefx unit P	80.9	24.6	40.4
idefx unit i	58.0	20.6	19.1

Table 5-2: Maximum 3xRMS stress values

Part	Maximum 3xRMS acceleration (m/s^2)		
	Random X	Random Y	Random Z
Power Board (Tz)	793	608	6010
Digital Board (Tz)	2060	1770	6900
Analogic Board (Tz)	1740	1300	5700
Bottom plate (Tz)	650	1350	4120
Idefx carriers (Tx)	8480	5350	7410

Table 5-3: Maximum 3xRMS acceleration values

Part	Maximum 3xRMS relative displacement (m)		
	Random X	Random Y	Random Z
Power Board (Tz)	7.023E-05	4.392E-05	4.902E-04
Digital Board (Tz)	6.240E-05	6.555E-05	3.012E-04
Analogic Board (Tz)	6.393E-05	5.160E-05	2.516E-04
idefx carrier unit P (Tx)	6.042E-04	1.541E-04	2.400E-04
idefx carrier unit i (Tx)	4.062E-04	1.285E-04	1.221E-04

Table 5-4: Maximum 3xRMS relative displacement values

5.1 Random vibration analysis – X axis

5.1.1 Stress plots

The units of the following plots are **Pa**.

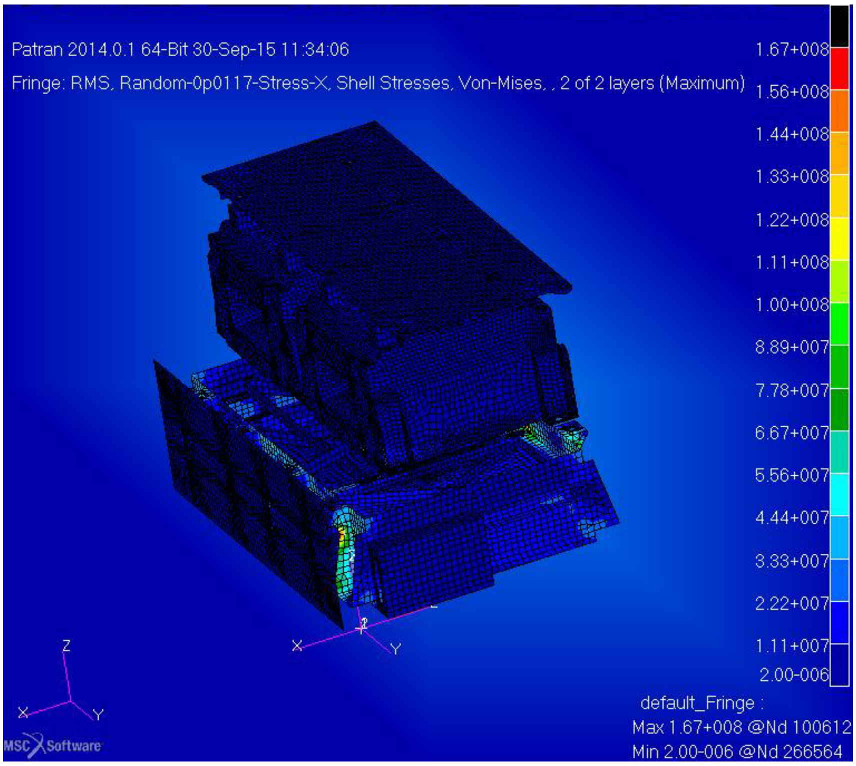

Figure 5-4: 3xRMS Stress - Al6061 Structure - Random X

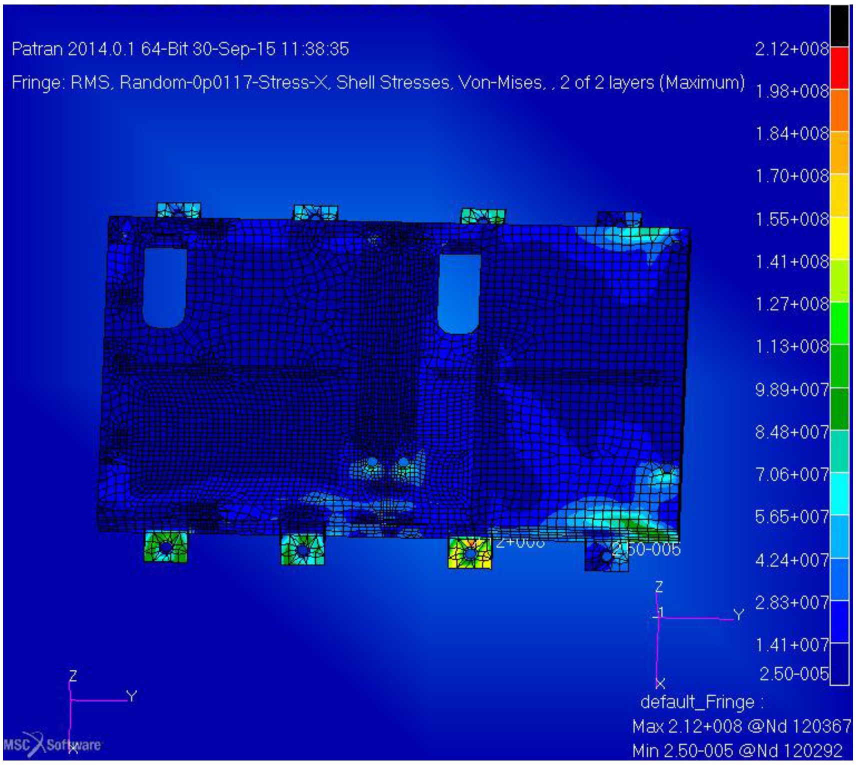

Figure 5-5: 3xRMS Stress - Titanium Structure - Random X

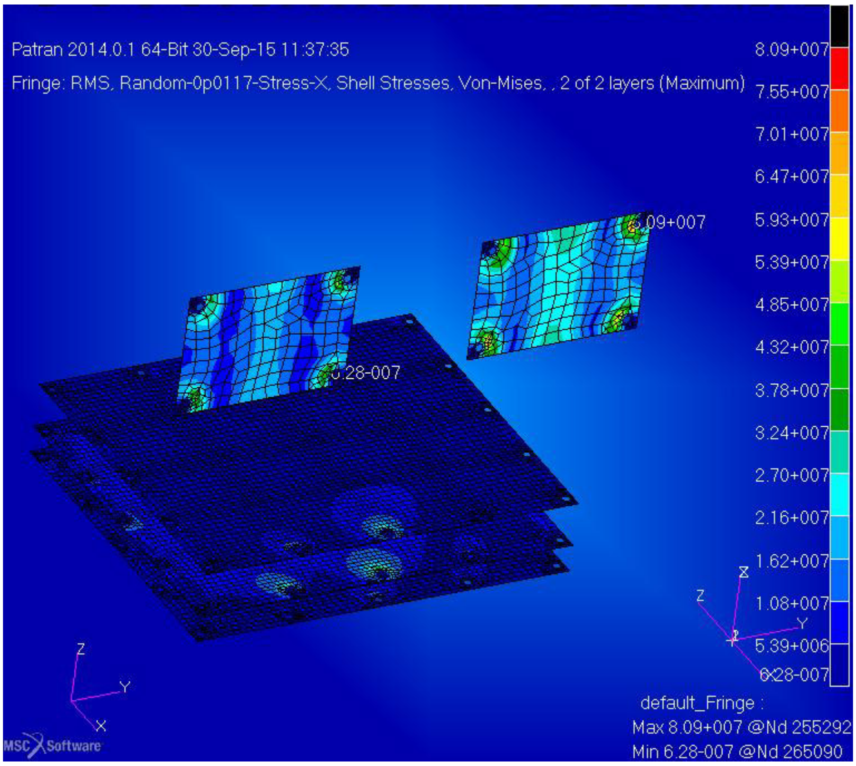

Figure 5-6: 3xRMS Stress - PCBs - Random X

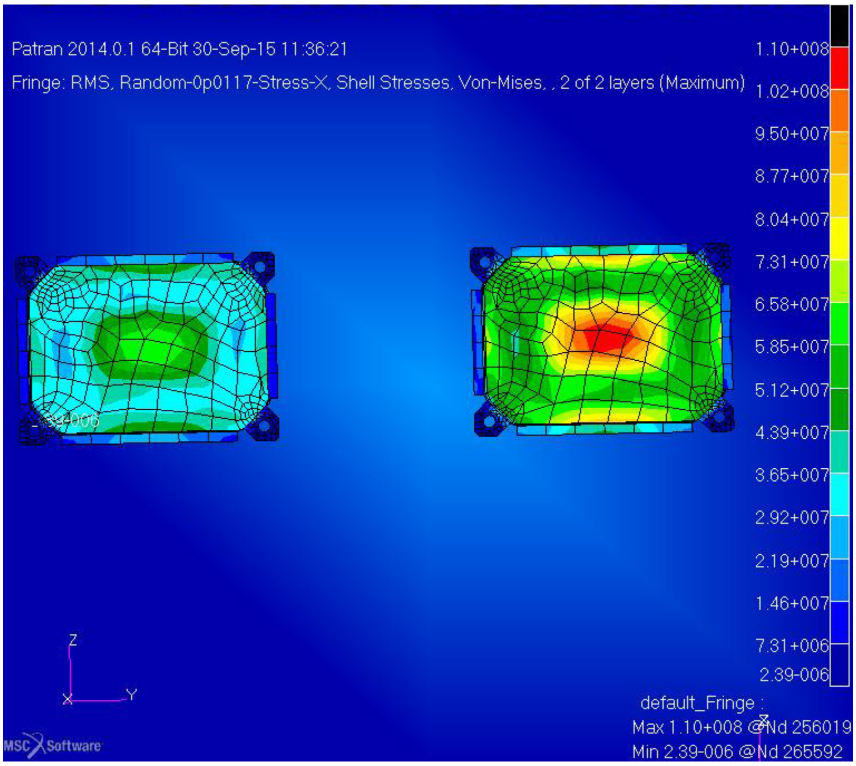

Figure 5-7: 3xRMS Stress – Copper parts - Random X

5.1.2 Acceleration plots

The units of the following plots are **m/s²**.

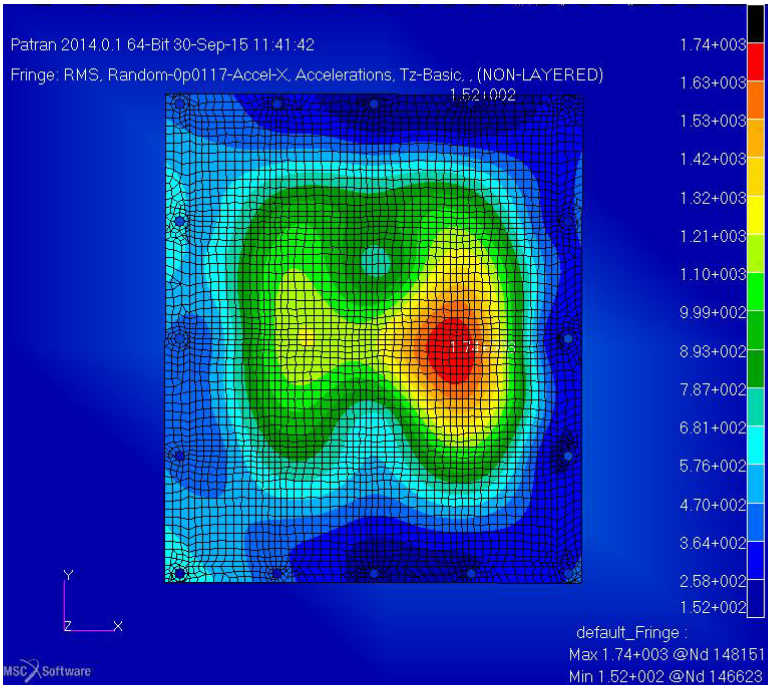

Figure 5-8: 3xRMS Tz component acceleration - Analogic Board

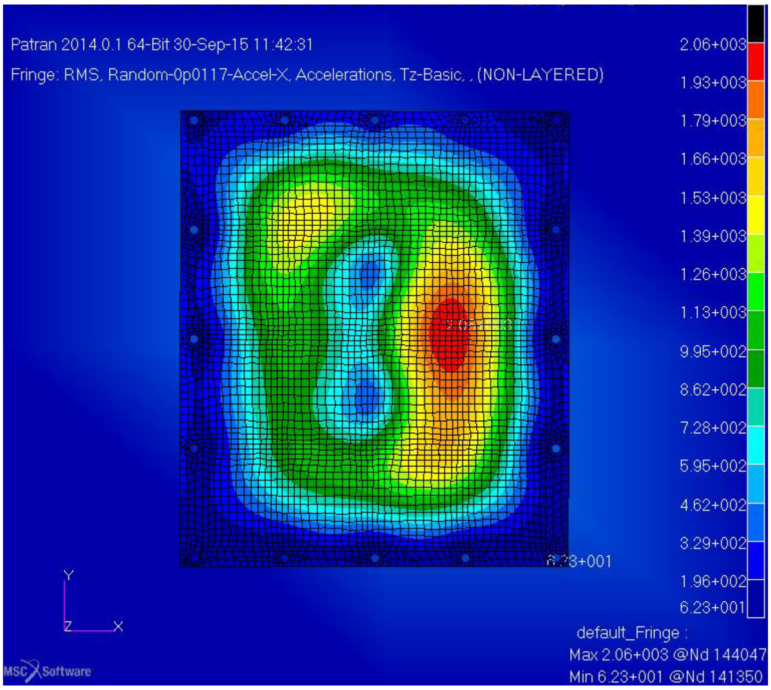

Figure 5-9: 3xRMS Tz component acceleration - Digital Board

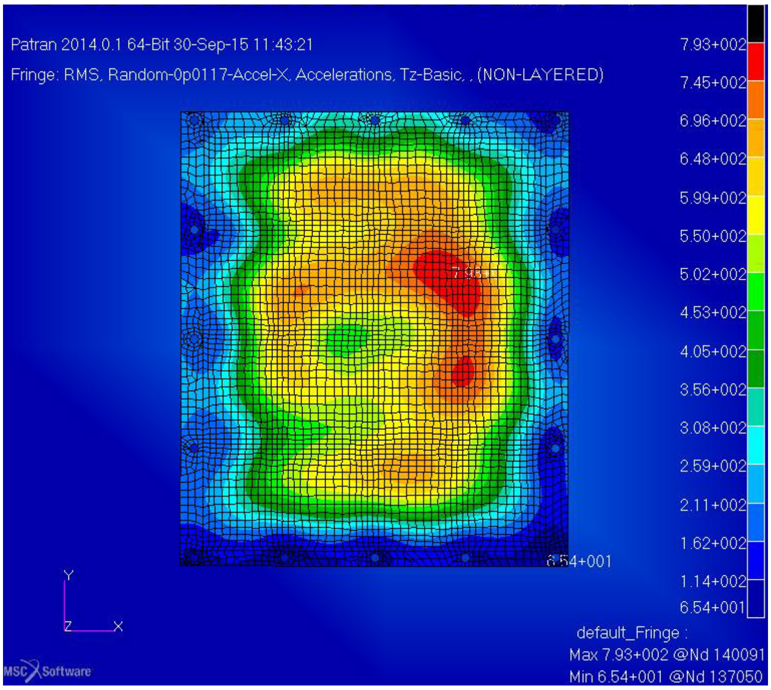

Figure 5-10: 3xRMS Tz component acceleration - LVPS Board

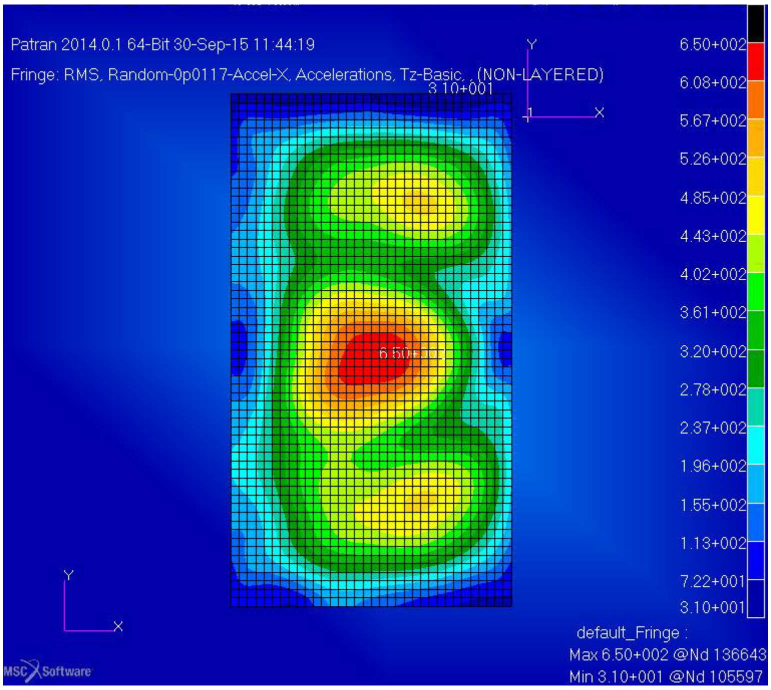

Figure 5-11: 3xRMS Tz component acceleration - Bottom Plate

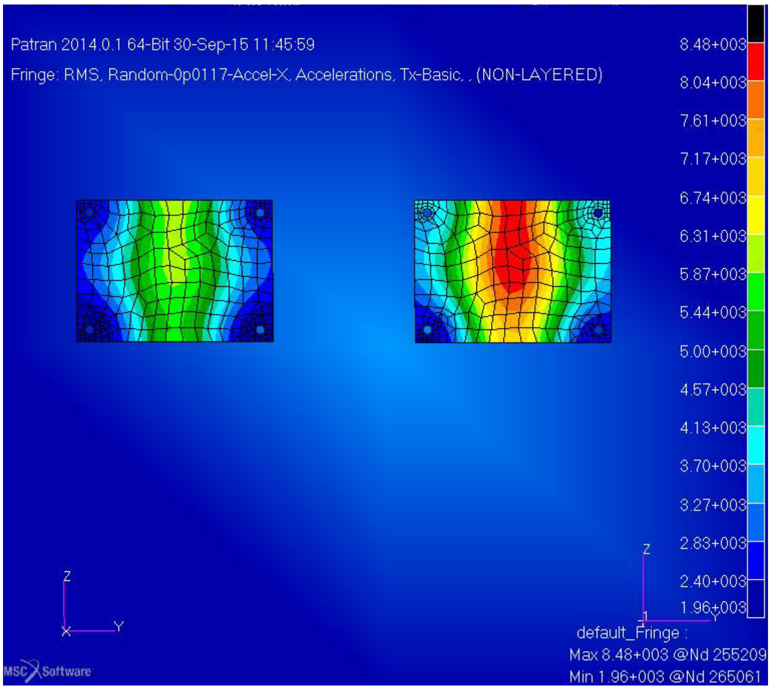

Figure 5-12: 3xRMS Tx component acceleration - idefx carriers

5.1.3 Acceleration PSD curves

The units of the following curves are **g^2/Hz**. These curves show centre node responses of each PCB (the acceleration direction is perpendicular to each PCB), and nodes responses at the accelerometers locations.

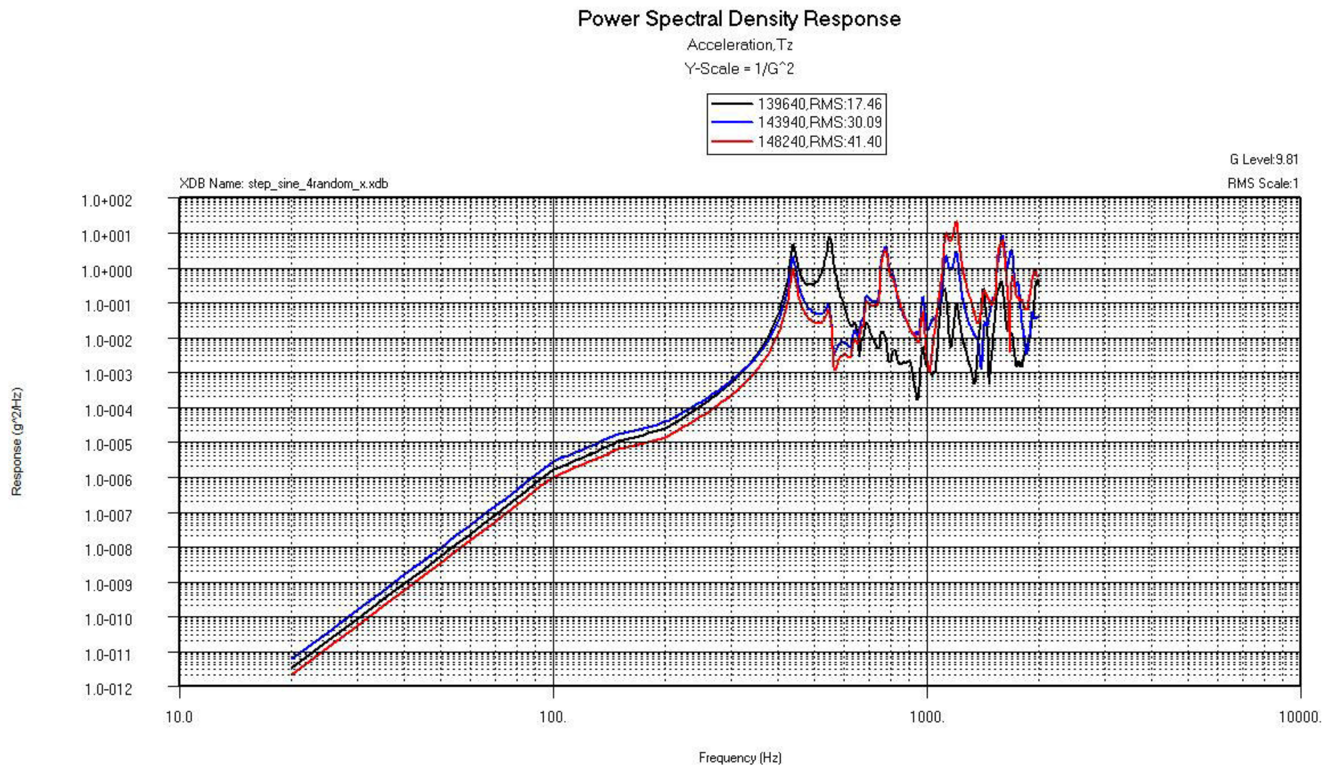

Figure 5-13: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

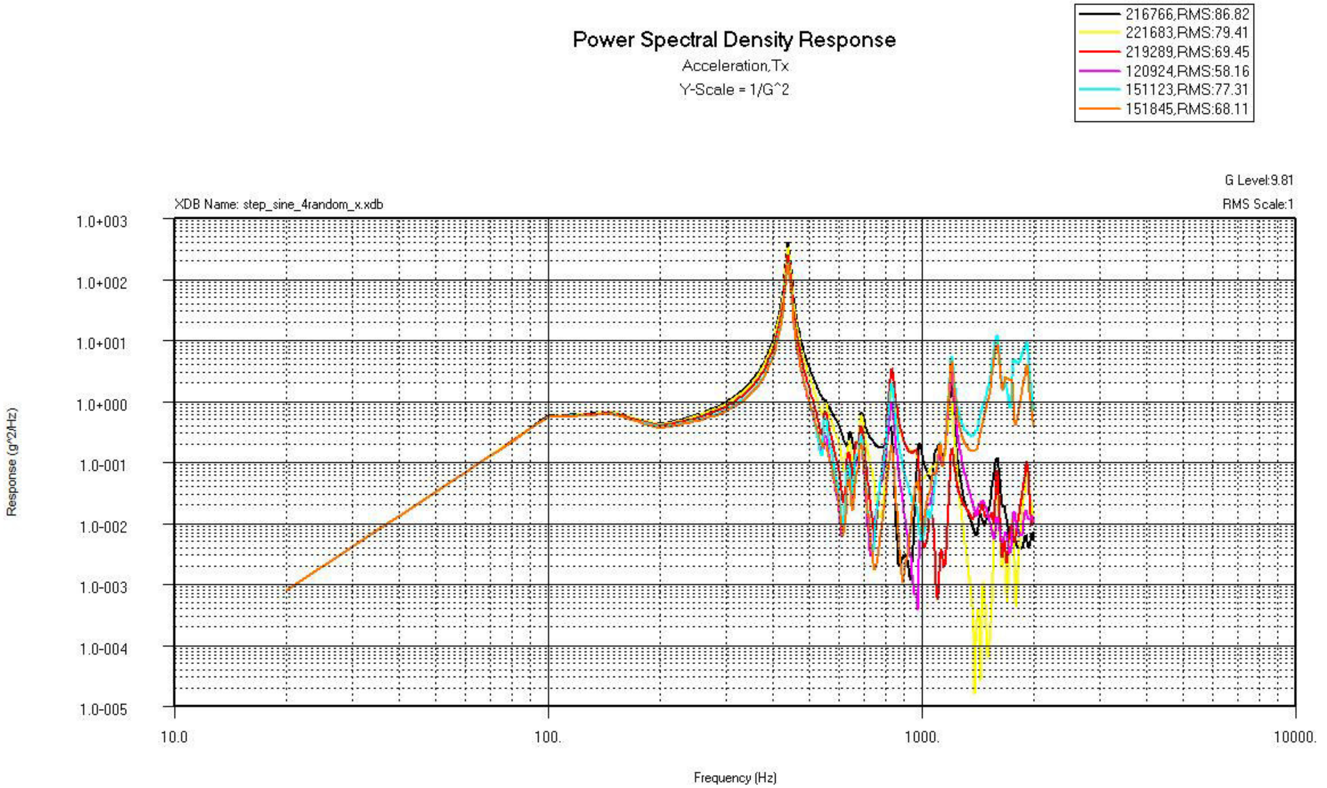

Figure 5-14: Acceleration PSD – A1x (black), A5x (yellow), A6x (red), A7x (pink), A9x (green) and A11x (orange)

5.2 Random vibration analysis – Y axis

5.2.1 Stress plots

The units of the following plots are **Pa**.

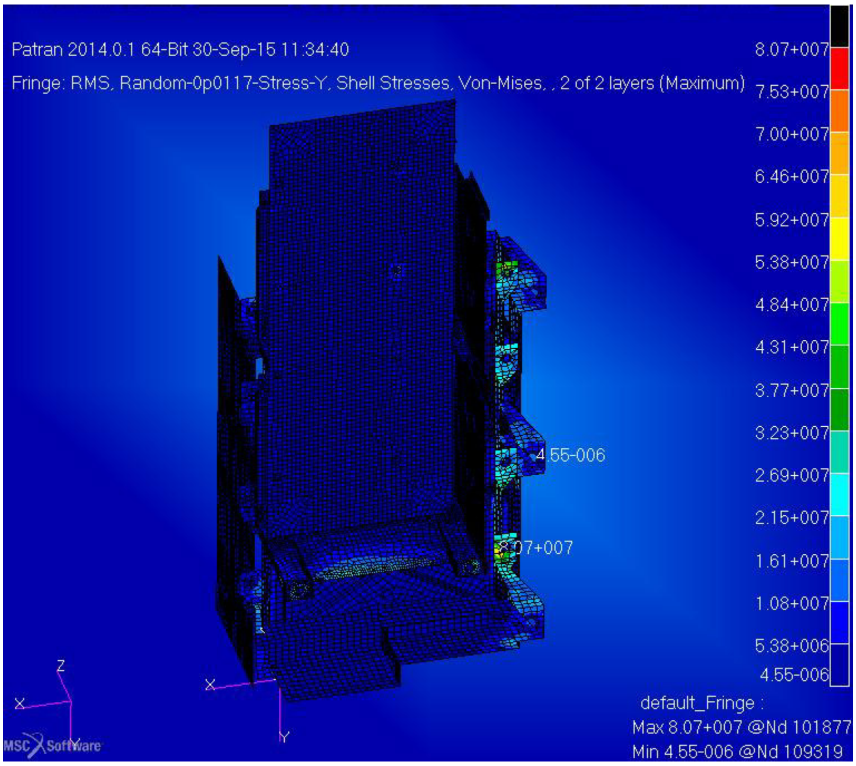

Figure 5-15: 3xRMS Stress - Al6061 Structure - Random Y

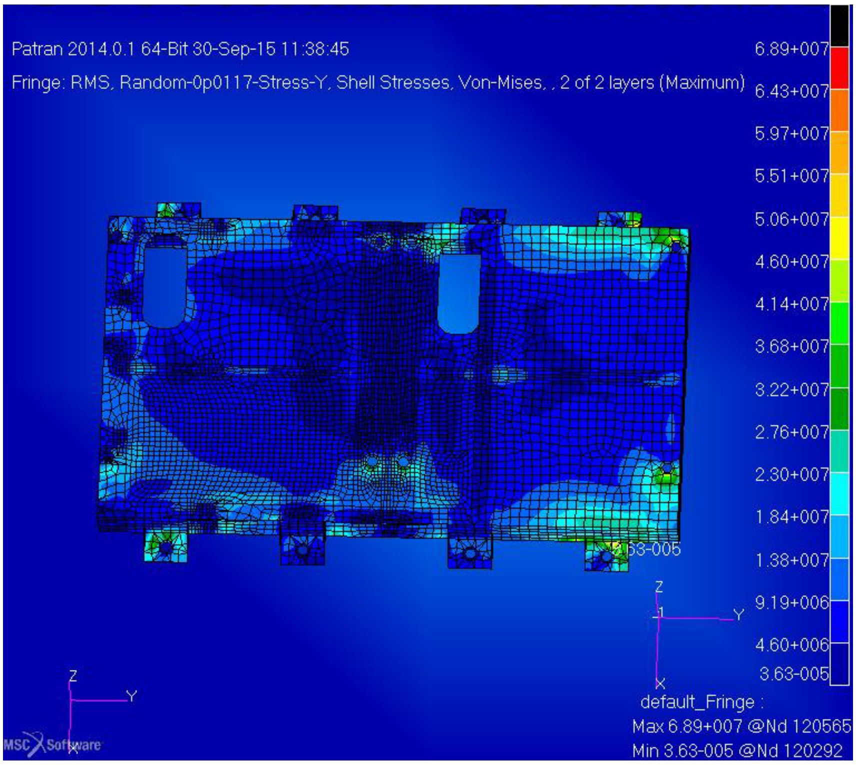

Figure 5-16: 3xRMS Stress - Titanium Structure - Random Y

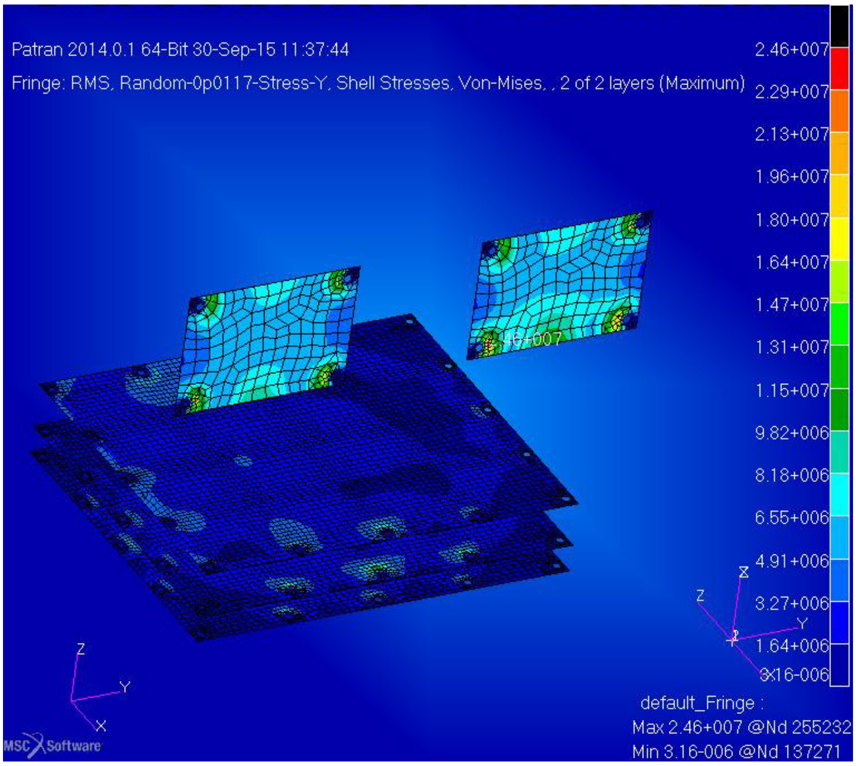

Figure 5-17: 3xRMS Stress - PCBs - Random Y

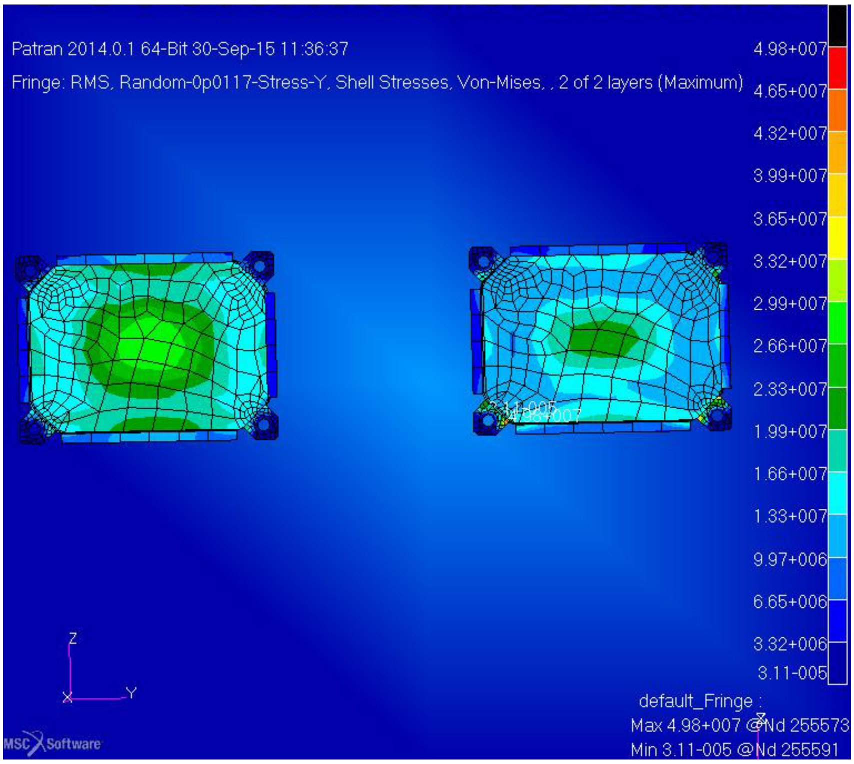

Figure 5-18: 3xRMS Stress – Copper parts - Random Y

5.2.2 Acceleration plots

The units of the following plots are **m/s^2**.

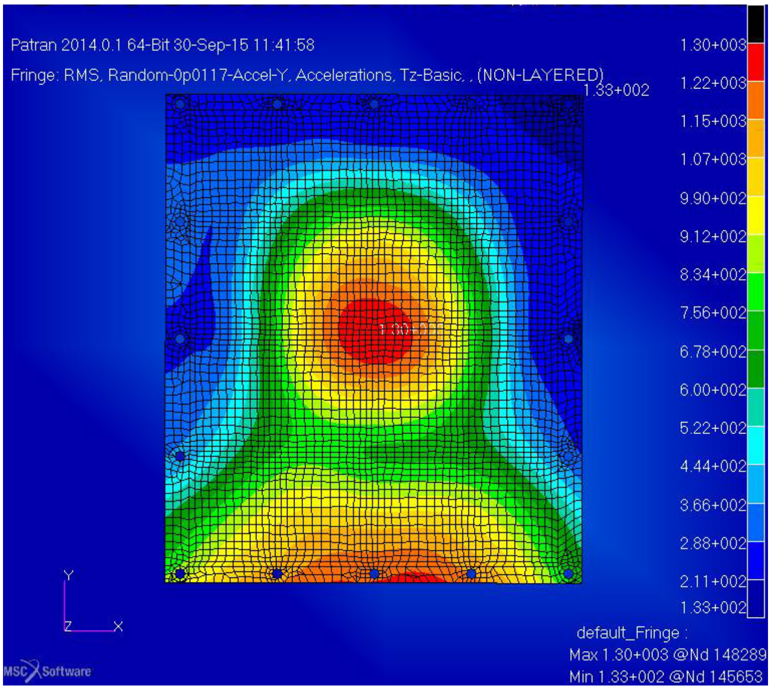

Figure 5-19: 3xRMS Tz component acceleration - Analogic Board

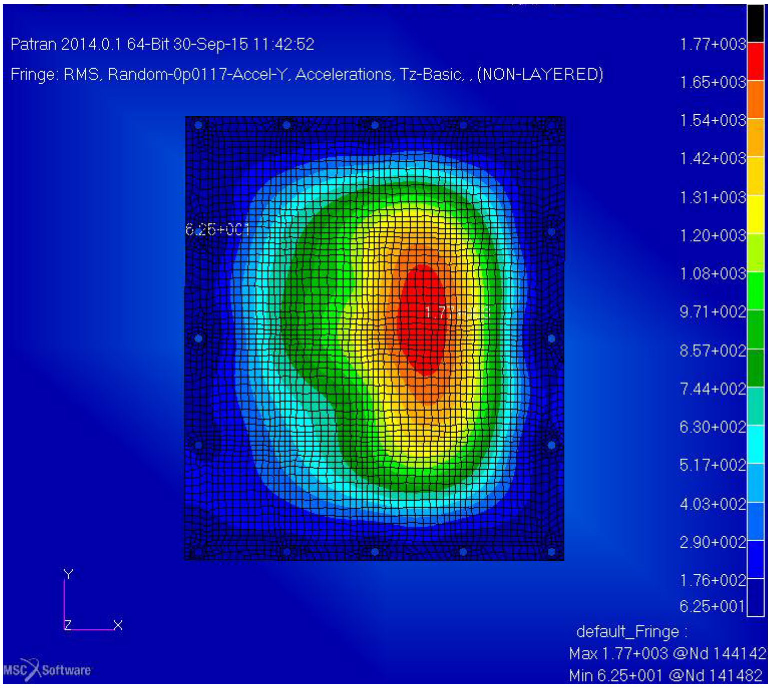

Figure 5-20: 3xRMS Tz component acceleration - Digital Board

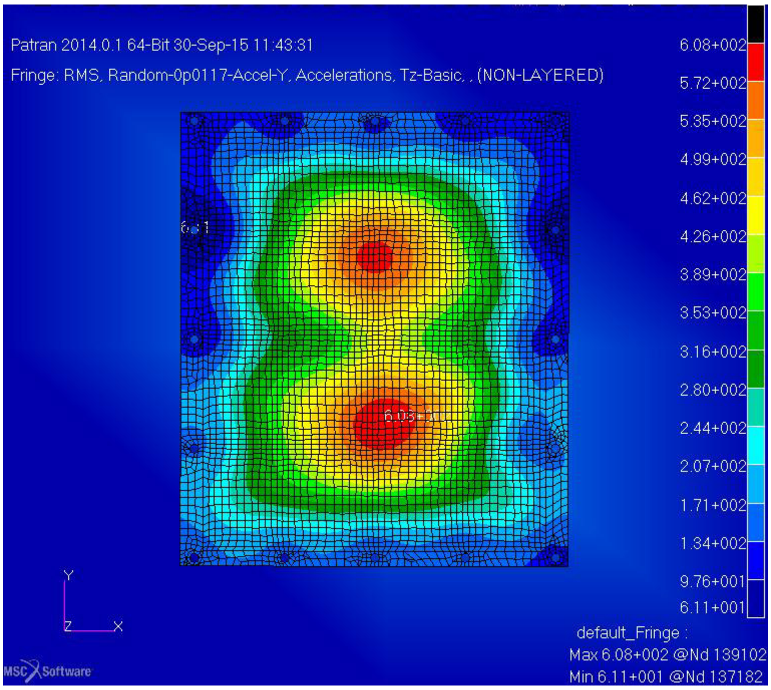

Figure 5-21: 3xRMS Tz component acceleration - LVPS Board

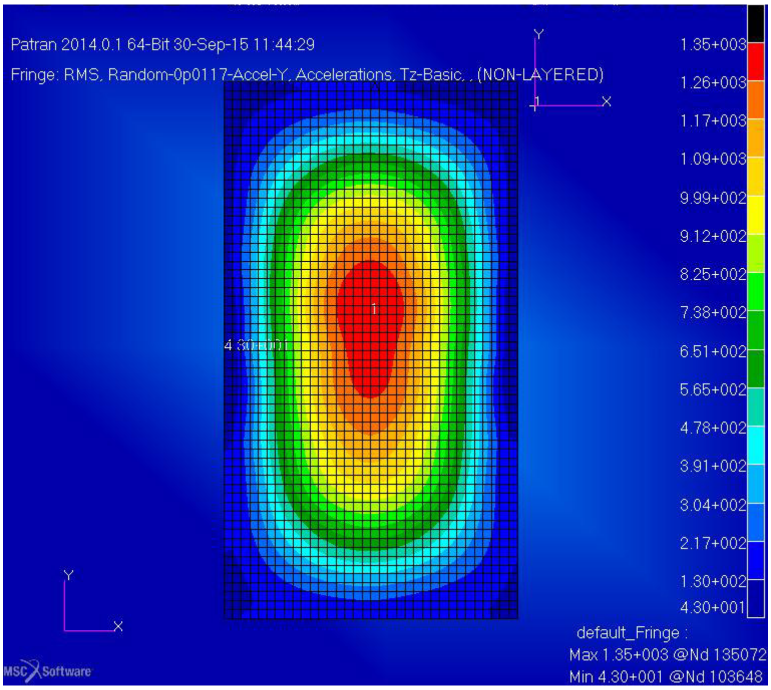

Figure 5-22: 3xRMS Tz component acceleration - Bottom Plate

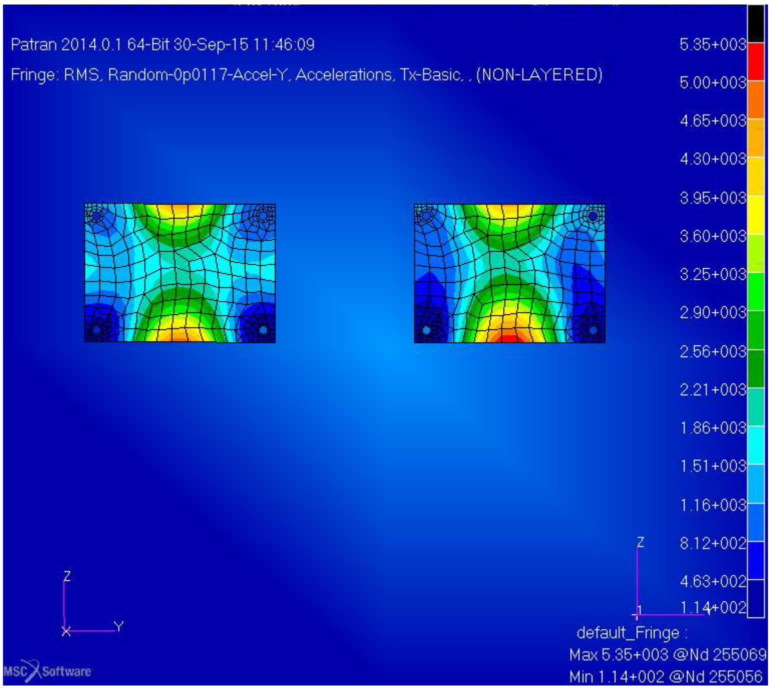

Figure 5-23: 3xRMS Tx component acceleration - idefx carriers

5.2.3 Acceleration PSD curves

The units of the following curves are **g^2/Hz**. These curves show centre node responses of each PCB (the acceleration direction is perpendicular to each PCB), and nodes responses at the accelerometers locations.

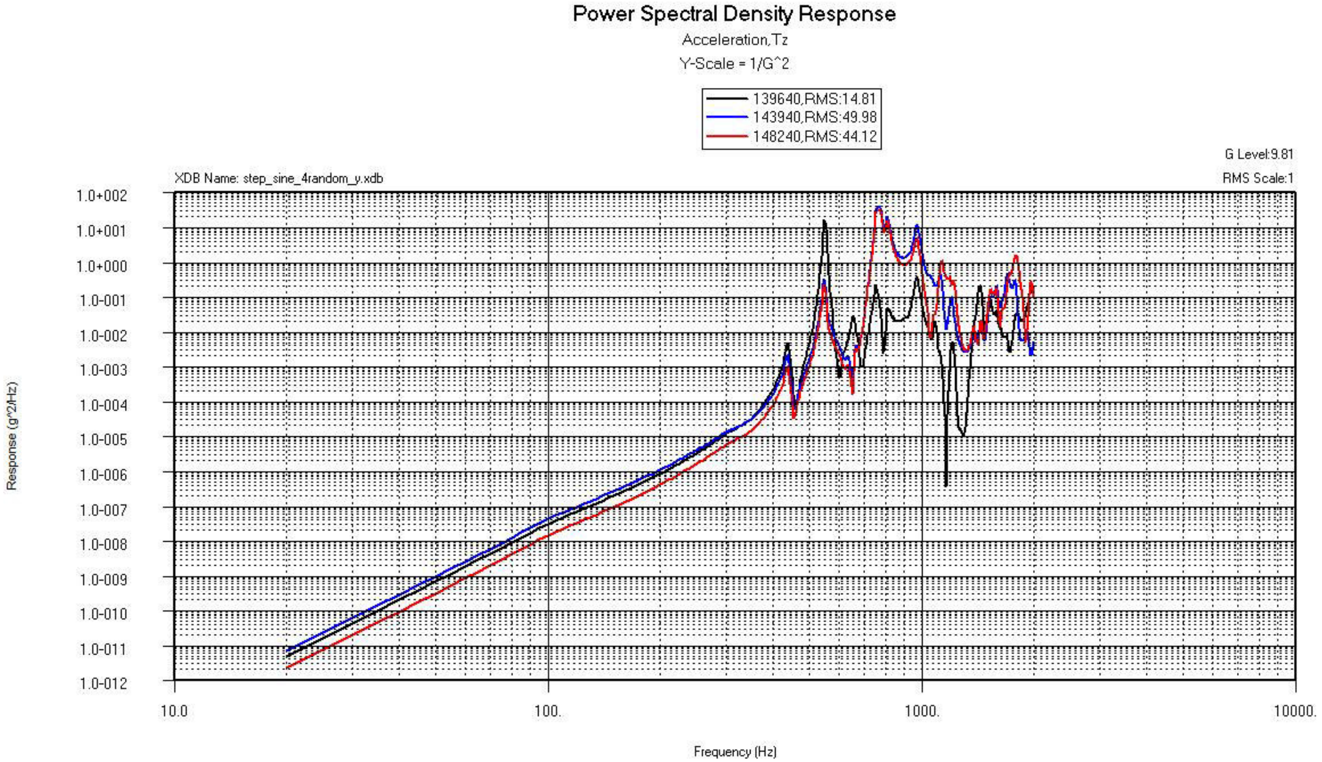

Figure 5-24: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

Figure 5-25: Acceleration PSD – A1y (black), A2y (Yellow), A3y (red) and A4y (pink)

5.3 Random vibration analysis – Z axis

5.3.1 Stress plots

The units of the following plots are **Pa**.

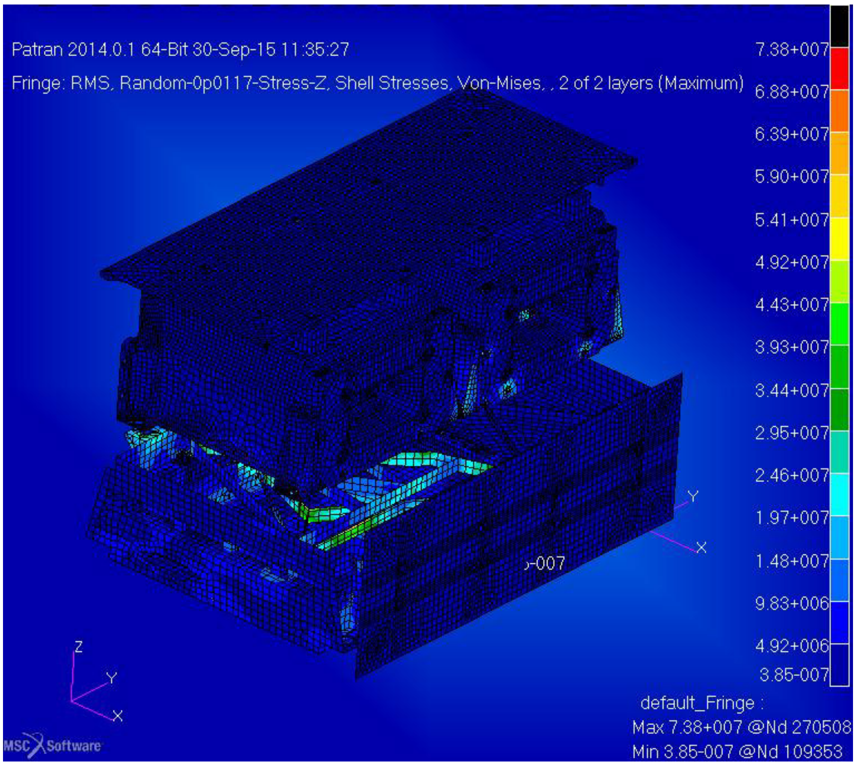

Figure 5-26: 3xRMS Stress - Al6061 Structure - Random Z

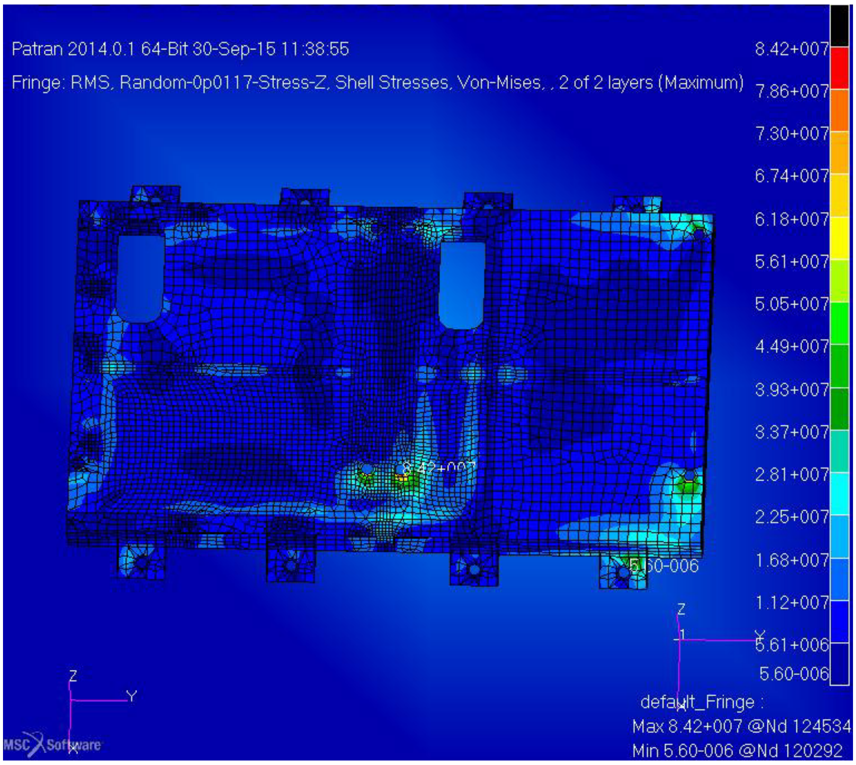

Figure 5-27: 3xRMS Stress - Titanium Structure - Random Z

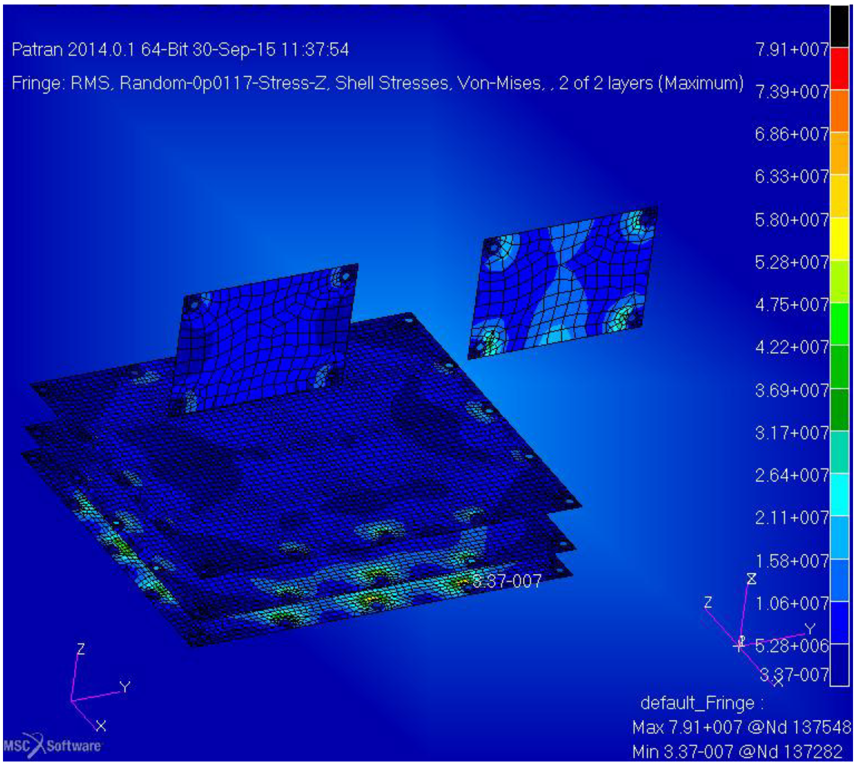

Figure 5-28: 3xRMS Stress - PCBs - Random Z

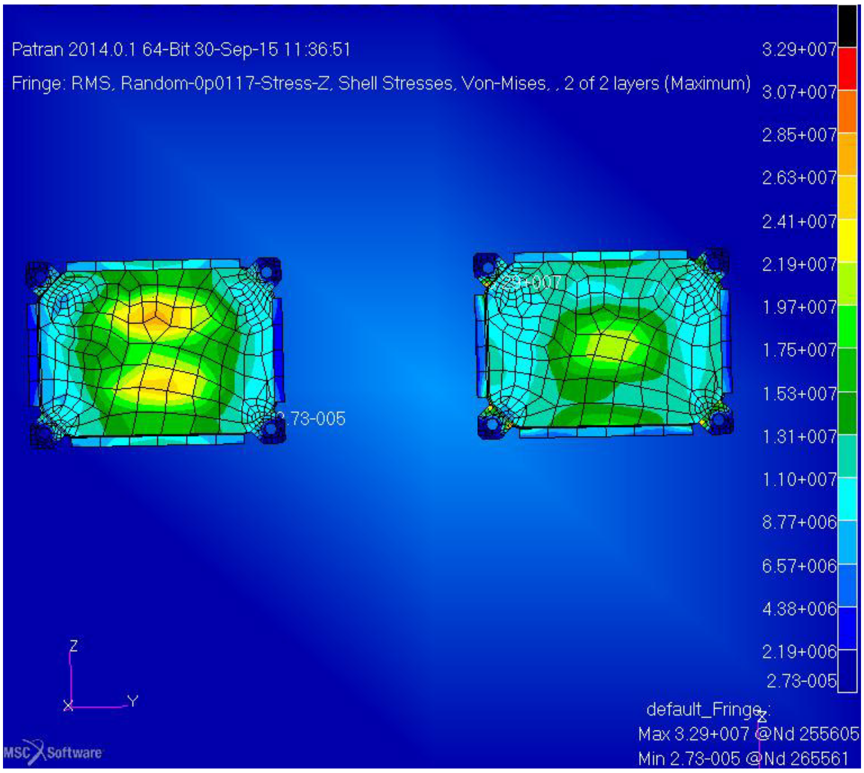

Figure 5-29: 3xRMS Stress – Copper parts - Random Z

5.3.2 Acceleration plots

The units of the following plots are **m/s^2**.

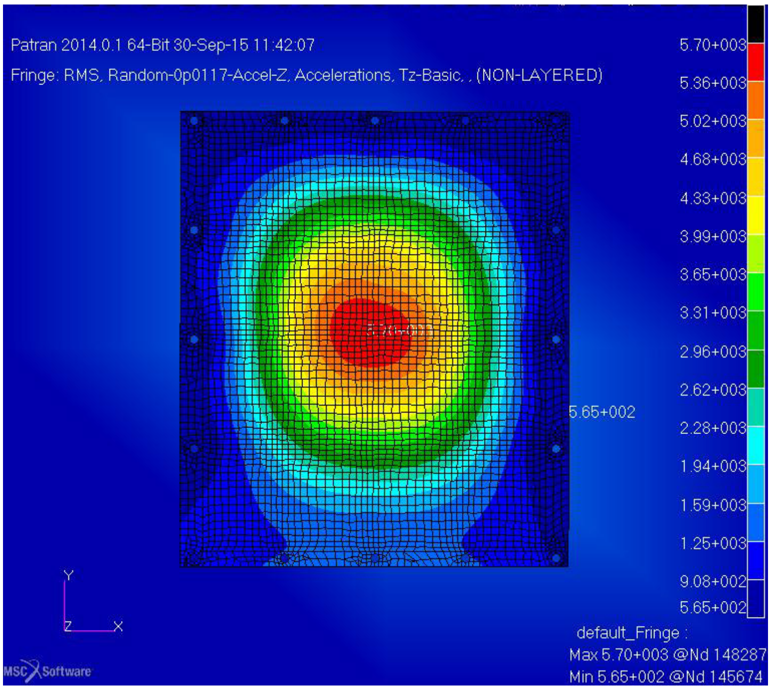

Figure 5-30: 3xRMS Tz component acceleration - Analogic Board

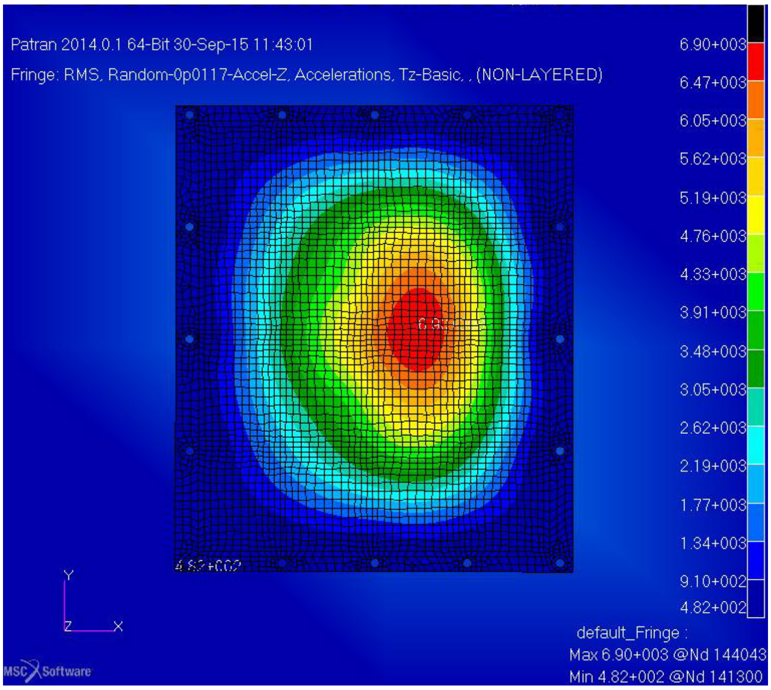

Figure 5-31: 3xRMS Tz component acceleration - Digital Board

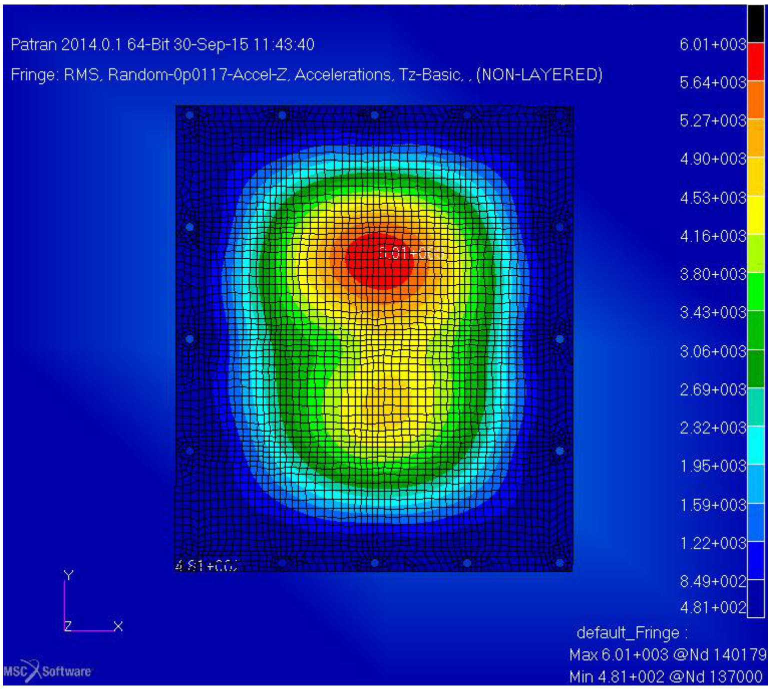

Figure 5-32: 3xRMS Tz component acceleration - LVPS Board

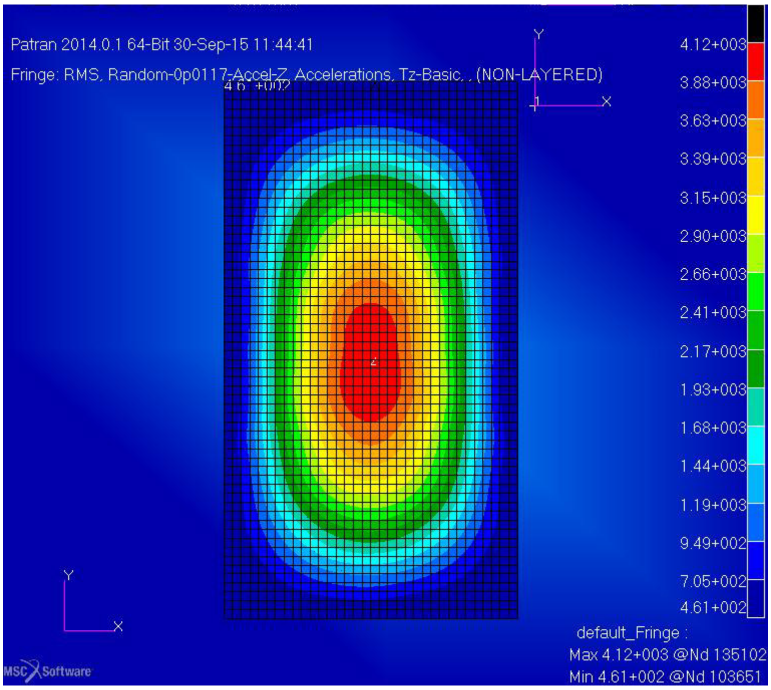

Figure 5-33: 3xRMS Tz component acceleration - Bottom Plate

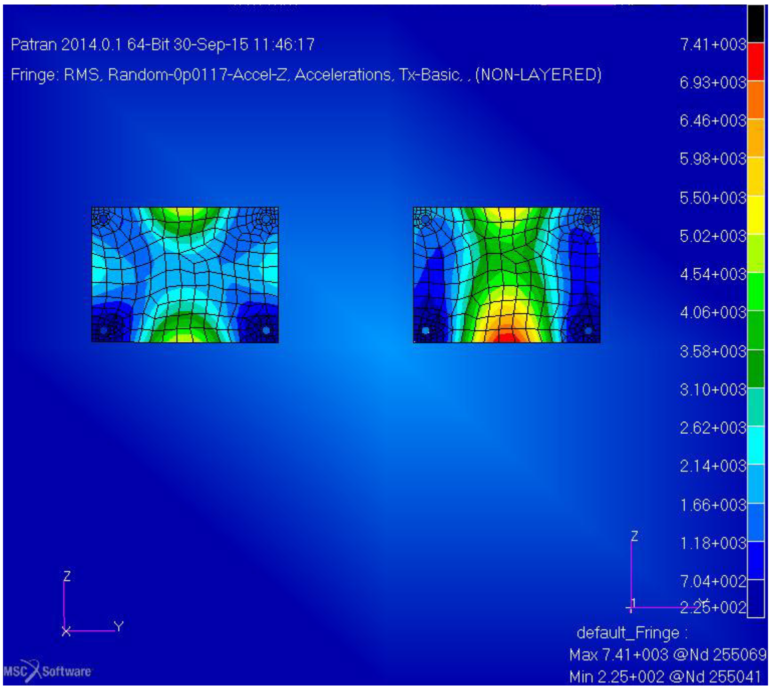

Figure 5-34: 3xRMS Tx component acceleration - idefx carriers

5.3.3 Acceleration PSD curves

The units of the following curves are **g^2/Hz**. These curves show centre node responses of each PCB (the acceleration direction is perpendicular to each PCB), and nodes responses at the accelerometers locations.

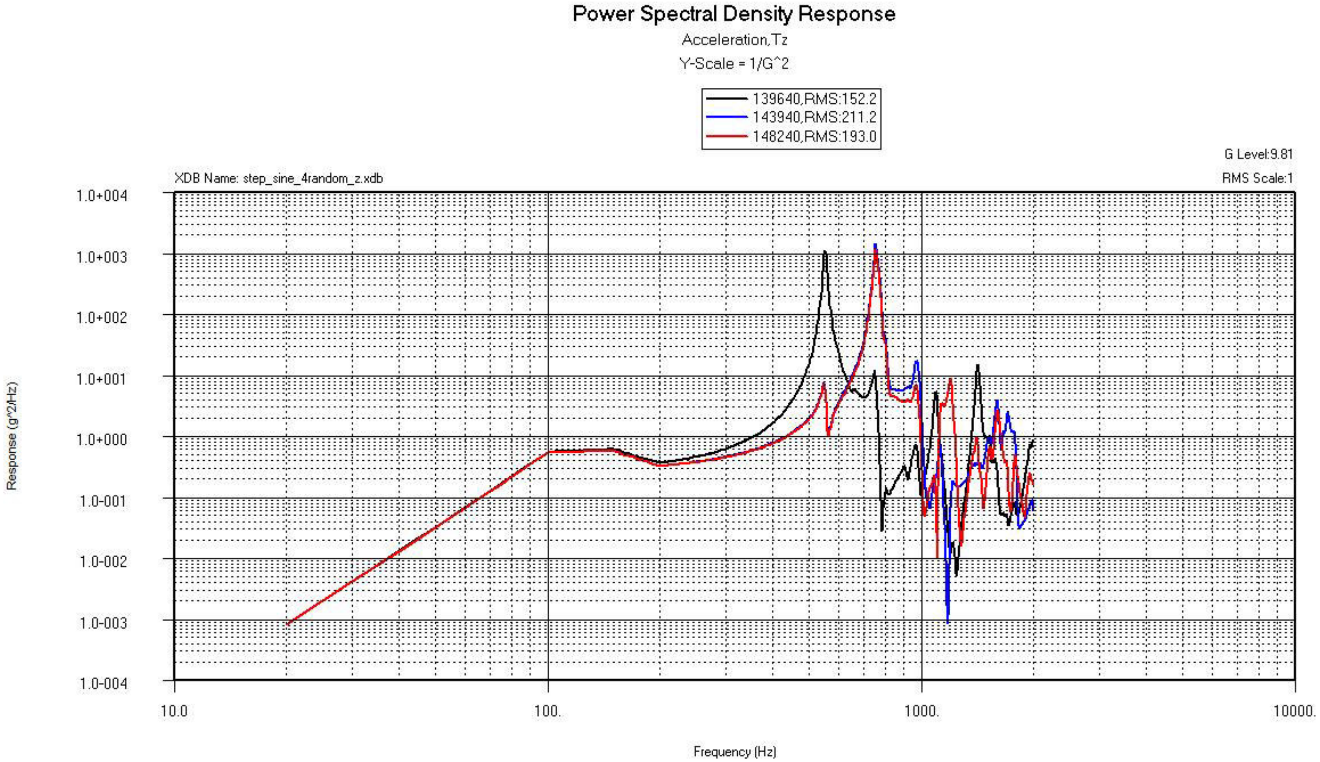

Figure 5-35: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

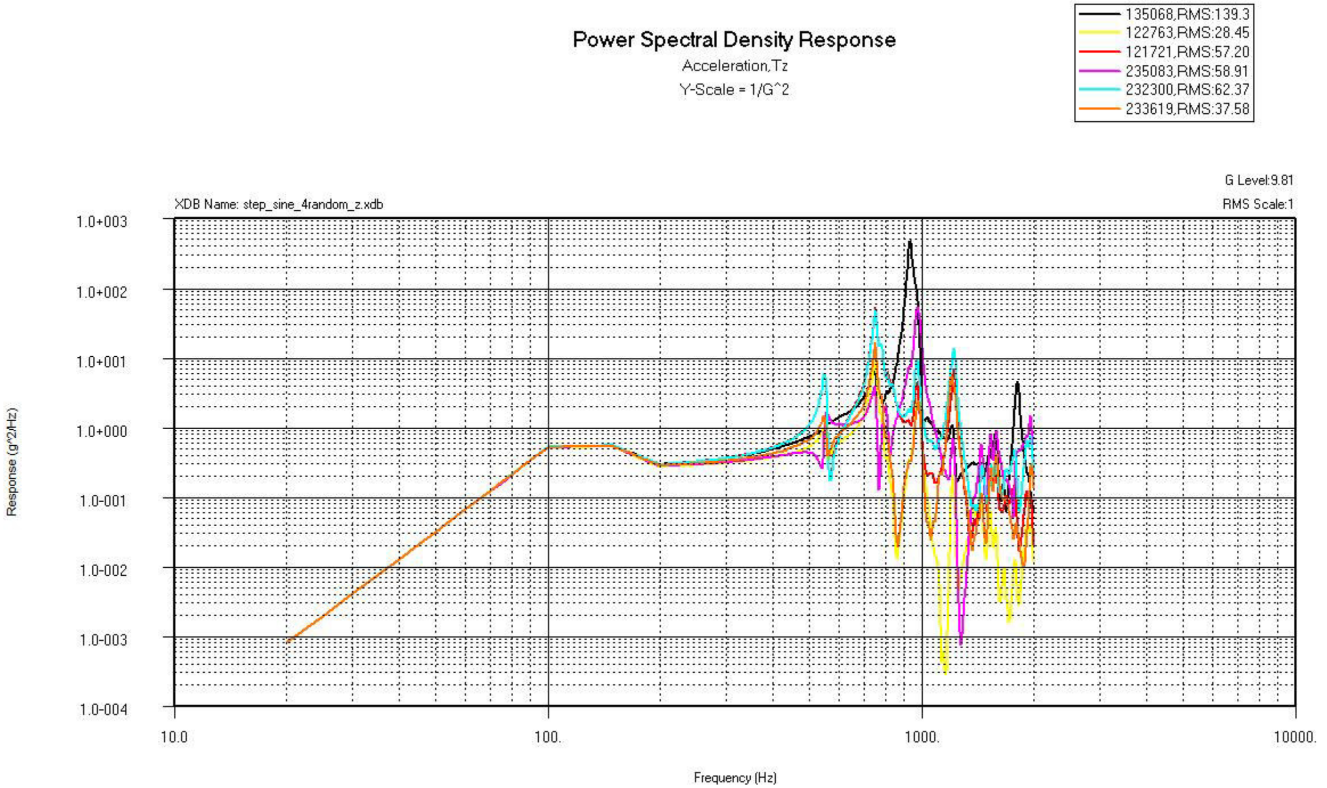

Figure 5-36: Acceleration PSD – A1z (black), A5z (yellow), A6z (red), A8z (pink), A9z (green) and A10z (orange)

5.4 Random IF forces

The forces and the moments at the interfaces have been recovered with CBUSH elements. The values, with a model factor (K_M) of 1.2, have been gathered from Table 5-5 to Table 5-7.

IF	Random X		
	CBUSH ID	Axial force (N)	Shear force (N)
STEP IF	10001	778.22	659.19
	10002	537.89	478.09
	10003	749.98	604.44
	10004	621.15	700.14
	10005	601.02	549.94
	10006	838.00	635.63
Ebox housing – Ebox cover IF	51031	413.30	323.52
	51032	275.57	373.18
	51033	334.90	282.58
	51034	527.99	398.50
	51035	423.12	647.19
	51036	326.78	470.90
	51037	251.81	859.06
	51038	514.08	308.32
Ebox cover – Senhousing basis	51121	384.02	339.69
	51122	418.75	471.83
	51123	255.77	377.92
	51124	248.27	296.84
	51125	220.50	276.70
	51126	258.68	252.13
	51127	369.32	238.23
	51128	283.70	283.92
Senhousing basis – Unit p support	91001	90.06	123.31
	91002	127.79	146.01
	91003	105.80	123.26
	91004	102.87	137.96
Senhousing basis – Unit i support	92001	33.20	48.59
	92002	28.41	47.27
	92003	31.43	41.09
	92004	27.40	41.58

Table 5-5: Random X (original specification) resultant loads - IF Forces

IF	Random Y		
	CBUSH ID	Axial force (N)	Shear force (N)
STEP IF	10001	449.29	327.34
	10002	110.66	296.00
	10003	515.23	311.12
	10004	525.79	334.66
	10005	144.35	306.00
	10006	457.65	347.93
Ebox housing – Ebox cover IF	51031	450.77	162.38
	51032	97.21	259.45
	51033	79.26	244.70
	51034	404.60	286.23
	51035	398.96	225.41
	51036	60.69	238.56
	51037	55.63	266.59
	51038	357.78	108.38
Ebox cover – Senhousing basis	51121	261.99	115.68
	51122	230.42	205.69
	51123	108.91	195.83
	51124	114.67	200.58
	51125	223.91	257.86
	51126	95.25	227.98
	51127	258.19	101.52
	51128	261.66	164.74
Senhousing basis – Unit p support	91001	121.03	79.89
	91002	186.08	118.99
	91003	79.18	69.86
	91004	96.54	88.43
Senhousing basis – Unit i support	92001	42.40	32.93
	92002	56.74	38.21
	92003	28.94	19.65
	92004	25.34	20.43

Table 5-6: Random Y (original specification) resultant loads - IF Forces

IF	Random Z		
	CBUSH ID	Axial force (N)	Shear force (N)
STEP IF	10001	288.46	131.75
	10002	424.87	141.79
	10003	334.30	146.78
	10004	297.55	141.45
	10005	446.32	146.93
	10006	300.19	157.44
Ebox housing – Ebox cover IF	51031	317.59	94.52
	51032	224.09	92.81
	51033	193.43	86.21
	51034	287.28	98.76
	51035	287.33	78.89
	51036	154.42	72.06
	51037	177.02	82.64
	51038	294.12	76.54
Ebox cover – Senhousing basis	51121	196.92	99.11
	51122	235.57	89.35
	51123	244.10	100.81
	51124	98.37	66.28
	51125	159.63	75.01
	51126	233.12	63.43
	51127	157.88	77.88
	51128	209.51	69.93
Senhousing basis – Unit p support	91001	78.64	47.17
	91002	120.33	55.08
	91003	121.72	55.71
	91004	198.44	100.09
Senhousing basis – Unit i support	92001	46.05	22.61
	92002	50.95	23.85
	92003	28.82	13.27
	92004	25.15	13.33

Table 5-7: Random Z (original specification) resultant loads - IF Forces

6 RANDOM VIBRATION ANALYSIS

A random vibration analysis has been carried on with the random specification with a notching for the vibration levels according to [RD9]. The qualification levels for random analysis can been seen in Table 6-1 and Figure 6-1.

Axis	Frequency (Hz)	Qualification
X EPD-STEP	20 - 100	12 dB/oct
	100 - 150	0.5 g2/Hz
	150 - 200	-7.3 dB/oct
	200 - 335	0.25 g2/Hz
	335 - 450	-28.2 dB/oct
	450 - 480	0.0158 g2/Hz
	480 - 600	37.3 dB/oct
	600 - 700	-8 dB/oct
	700 - 750	-38.2 dB/oct
	750 - 1050	-8 dB/oct
	1050 - 1100	36.7 dB/oct
	1100 - 2000	-8 dB/oct
		13.13 grms
Y EPD-STEP	20 - 100	4 dB/oct
	100 - 300	0.1 g2/Hz
	300 - 350	-10 dB/oct
	350 - 480	0.06 g2/Hz
	480 - 540	-70.6 dB/oct
	540 - 570	0.0038 g2/Hz
	570 - 642	69.9 dB/oct
	642 - 1000	0.06 g2/Hz
	1000 - 2000	-3 dB/oct
		10.09 grms
Z EPD-STEP	20 - 100	6 dB/oct
	100 - 150	0.5 g2/Hz
	150 - 200	-7.3 dB/oct
	200 - 462	0.25 g2/Hz
	462 - 520	-70.3 dB/oct
	520 - 750	0.0158 g2/Hz
	750 - 845	46.7 dB/oct
	845 - 2000	-8 dB/oct
		13.04 grms

Table 6-1: Random vibration test levels with notching

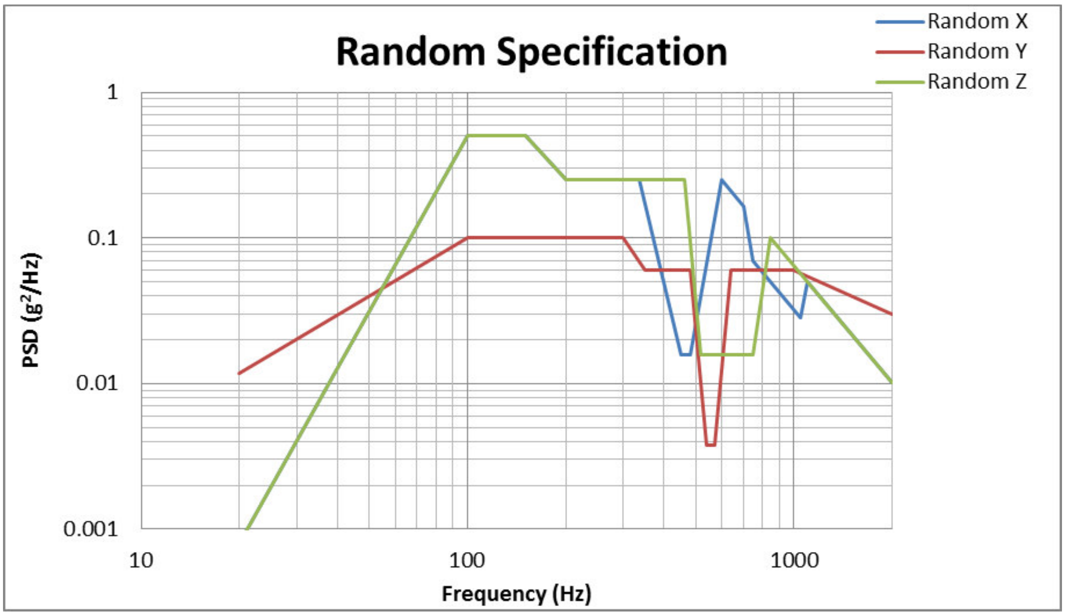

Figure 6-1: Random vibration test levels with notching – X, Y & Z STEP axes

The damping factor for dynamic analysis have been obtained taking into account the test results [RD6], and it's shown in Figure 5-3.

The results summary is shown in Table 6-2, Table 6-3 and Table 6-4.

Part	Maximum 3xRMS stress (MPa)		
	Random X	Random Y	Random Z
Al6061-T6	59.1	44.6	38.5
Ti 6Al4V	74.8	34.0	44.3
Ultem	10.0	4.7	5.1
Copper	82.8	33.3	28.3
Power Board	9.3	3.6	27.0
Digital Board	17.5	14.8	27.4
Analogic Board	11.4	10.7	21.7
idefx unit P	50.3	24.3	26.7
idefx unit i	35.9	18.3	16.3

Table 6-2: Maximum 3xRMS stress values

Part	Maximum 3xRMS acceleration (m/s^2)		
	Random X	Random Y	Random Z
Power Board (Tz)	645	406	1900
Digital Board (Tz)	2020	1760	3150
Analogic Board (Tz)	1730	1300	2450
Bottom plate (Tz)	612	1350	4060
Idefx carriers (Tx)	5870	5340	6500

Table 6-3: Maximum 3xRMS acceleration values

Part	Maximum 3xRMS relative displacement (m)		
	Random X	Random Y	Random Z
Power Board (Tz)	2.752E-05	2.049E-05	1.503E-04
Digital Board (Tz)	4.041E-05	6.525E-05	1.261E-04
Analogic Board (Tz)	2.691E-05	5.061E-05	1.033E-04
idefx carrier unit P (Tx)	3.447E-04	1.536E-04	1.774E-04
idefx carrier unit i (Tx)	2.396E-04	1.197E-04	4.707E-05

Table 6-4: Maximum 3xRMS relative displacement values

6.1 Random vibration analysis – X axis

6.1.1 Stress plots

The units of the following plots are **Pa**.

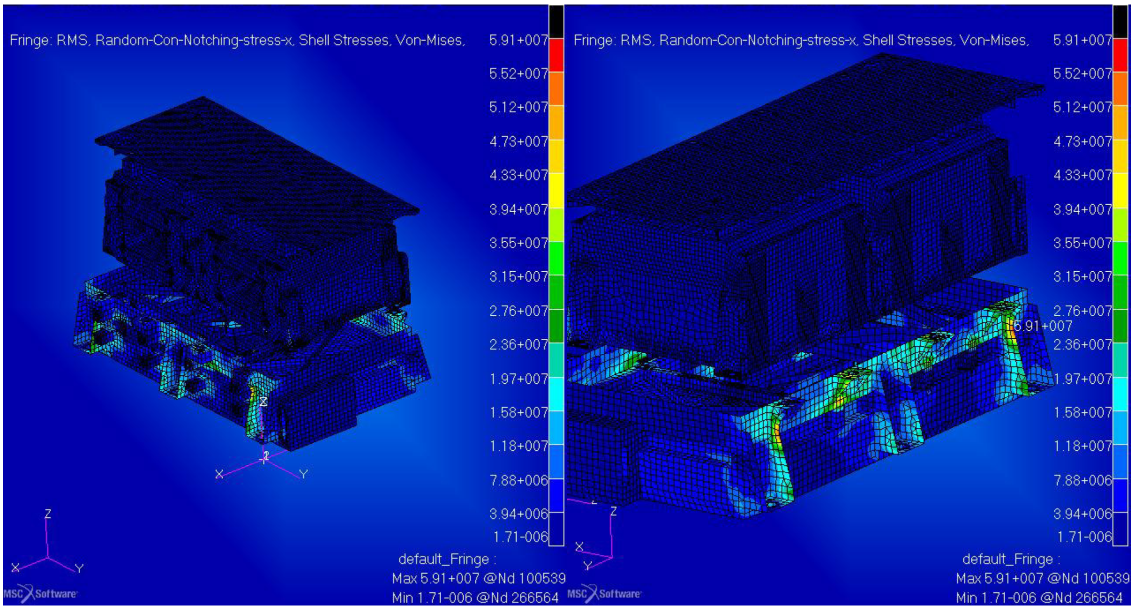

Figure 6-2: 3xRMS Stress - Al6061 Structure - Random X

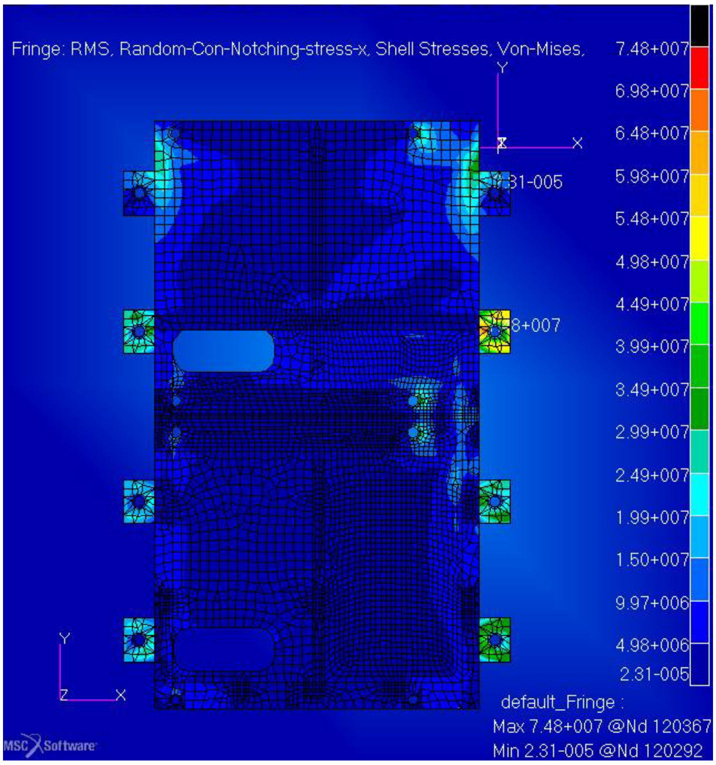

Figure 6-3: 3xRMS Stress - Titanium Structure - Random X

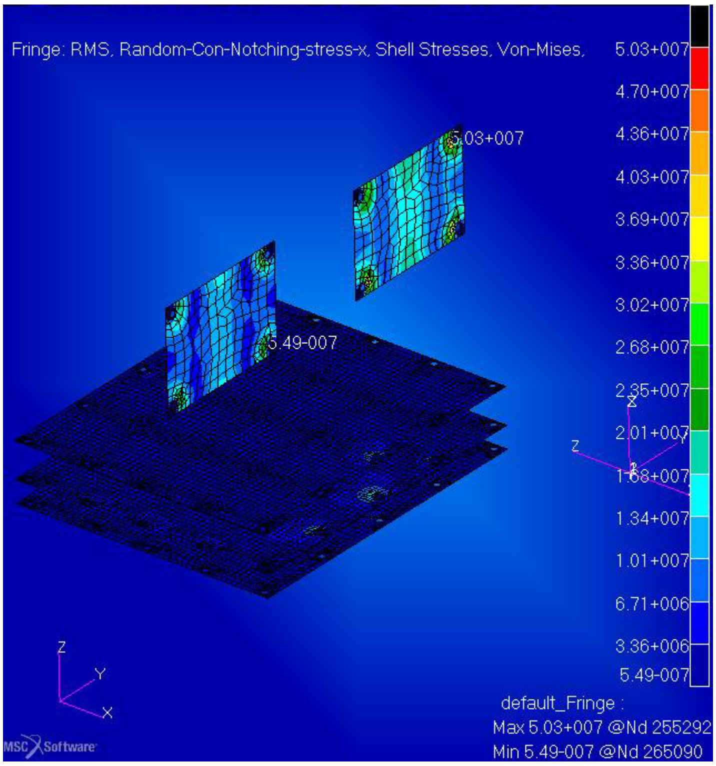

Figure 6-4: 3xRMS Stress - PCBs - Random X

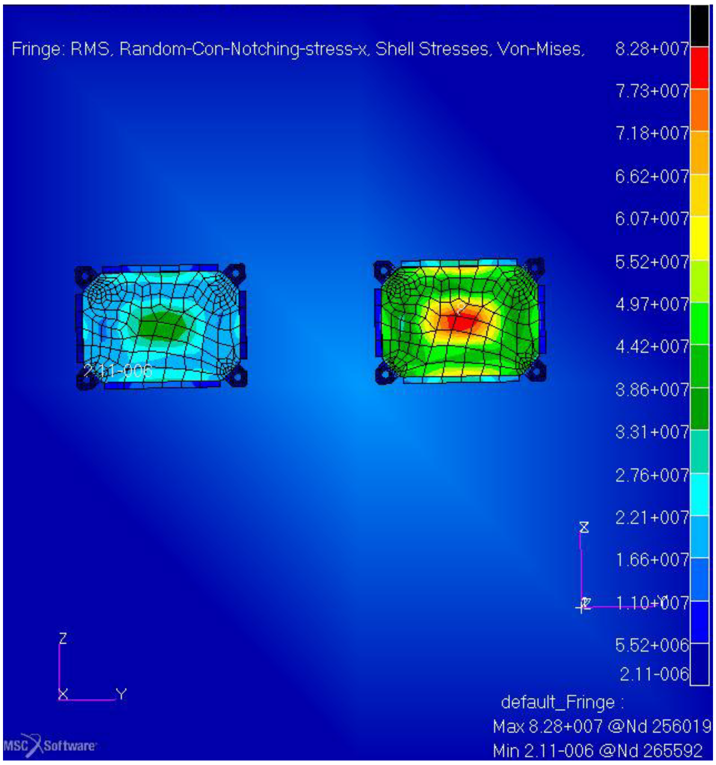

Figure 6-5: 3xRMS Stress – Copper parts - Random X

6.1.2 Acceleration plots

The units of the following plots are **m/s^2**.

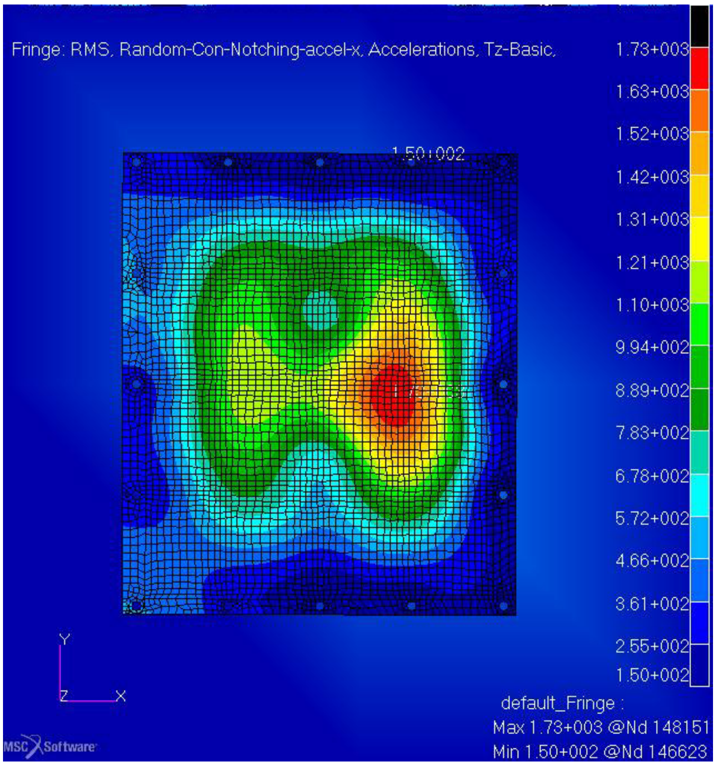

Figure 6-6: 3xRMS Tz component acceleration - Analogic Board

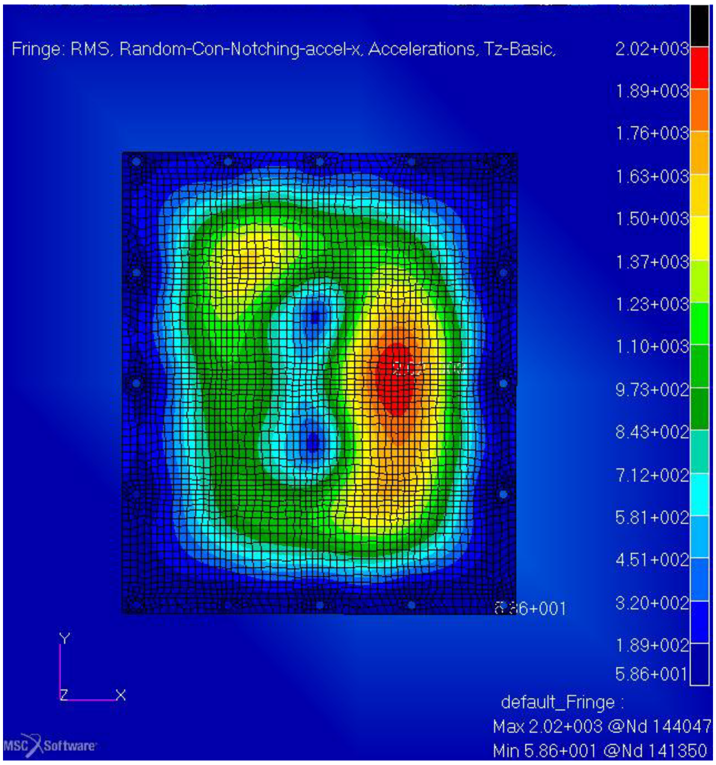

Figure 6-7: 3xRMS Tz component acceleration - Digital Board

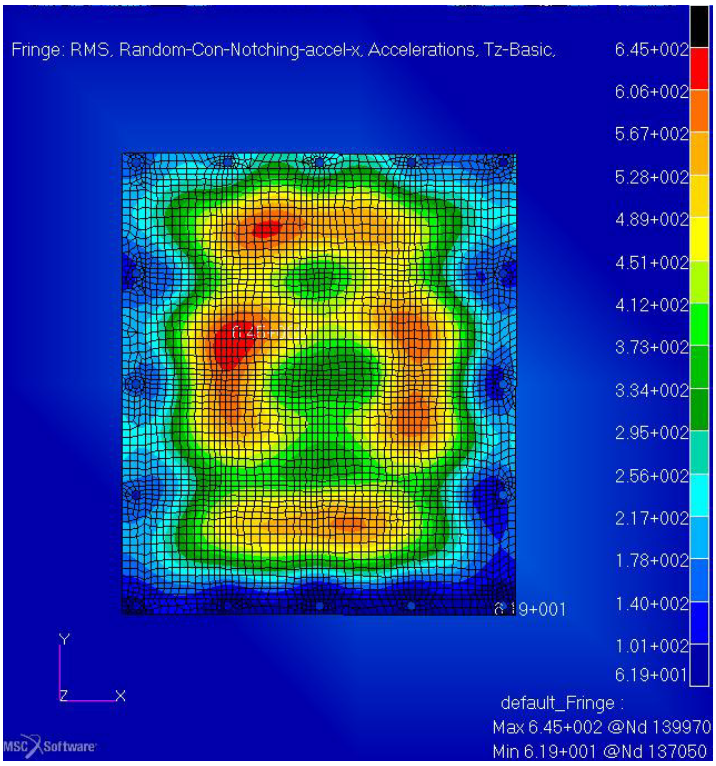

Figure 6-8: 3xRMS Tz component acceleration - LVPS Board

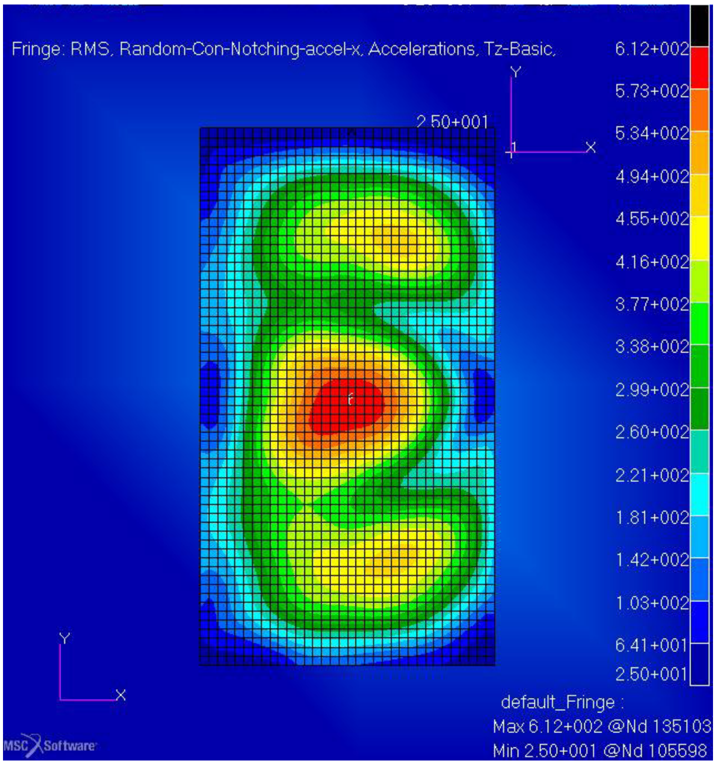

Figure 6-9: 3xRMS Tz component acceleration - Bottom Plate

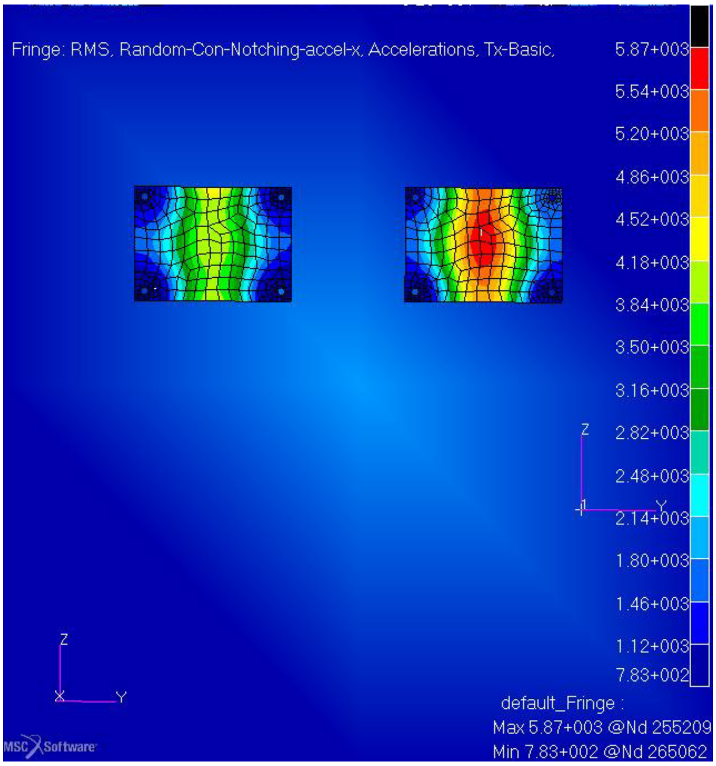

Figure 6-10: 3xRMS Tx component acceleration - idefx carriers

6.1.3 Acceleration PSD curves

The units of the following curves are **g^2/Hz**. These curves show centre node responses of each PCB (the acceleration direction is perpendicular to each PCB), and nodes responses at the accelerometers locations.

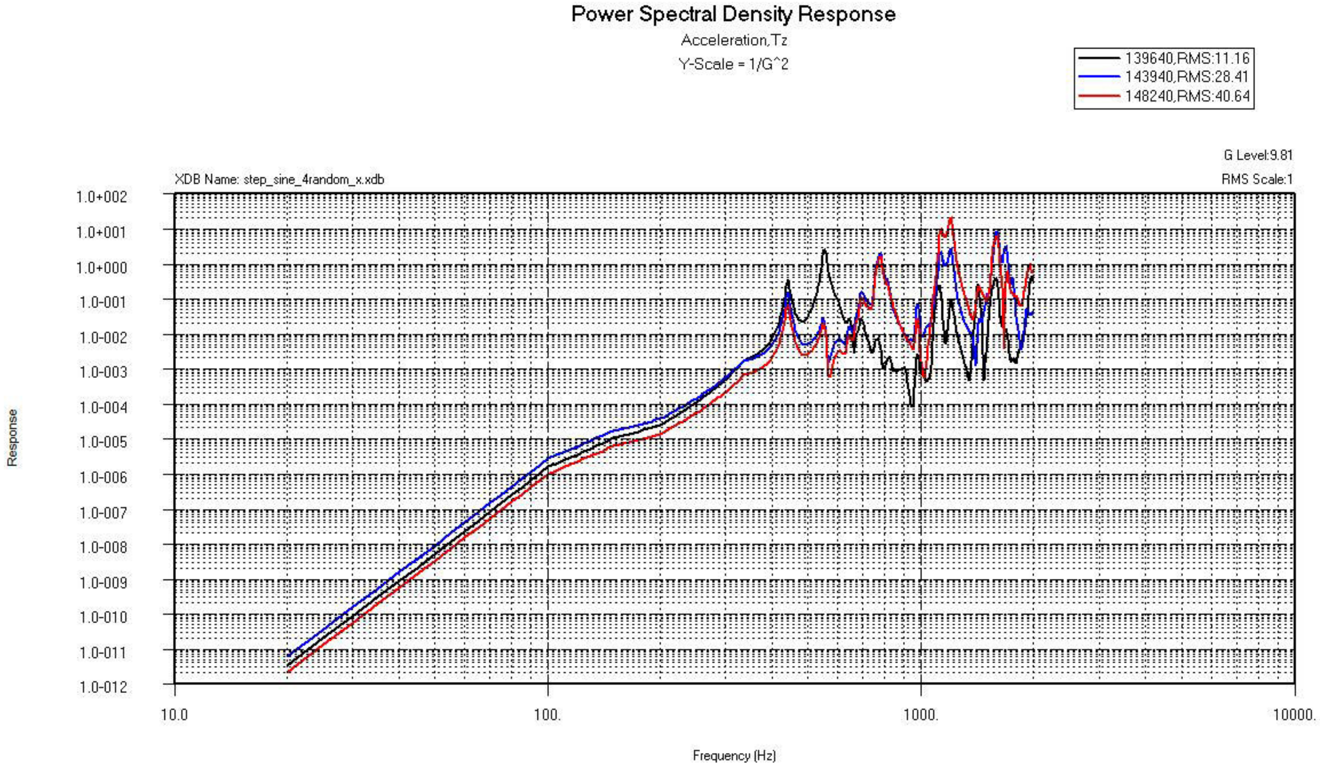

Figure 6-11: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

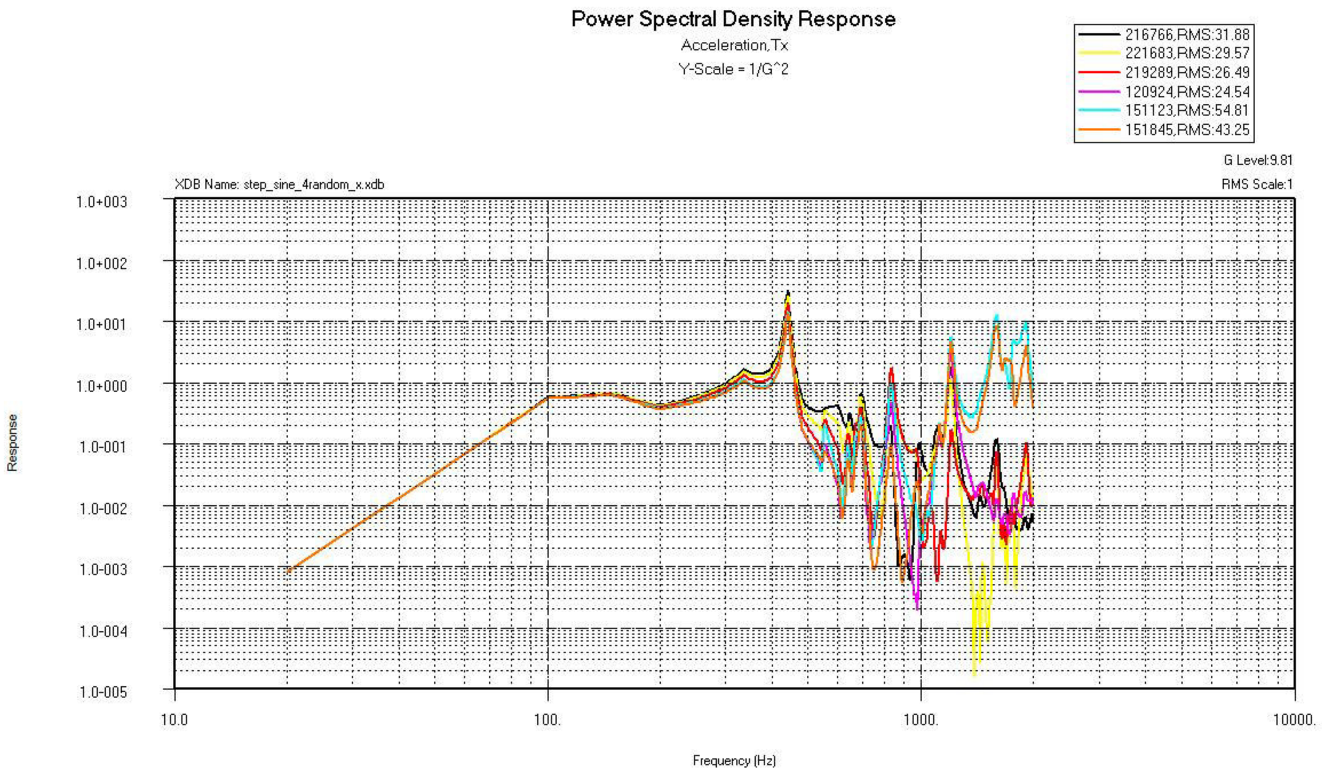

Figure 6-12: Acceleration PSD – A1x (black), A5x (yellow), A6x (red), A7x (pink), A9x (green) and A11x (orange)

6.2 Random vibration analysis – Y axis

6.2.1 Stress plots

The units of the following plots are **Pa**.

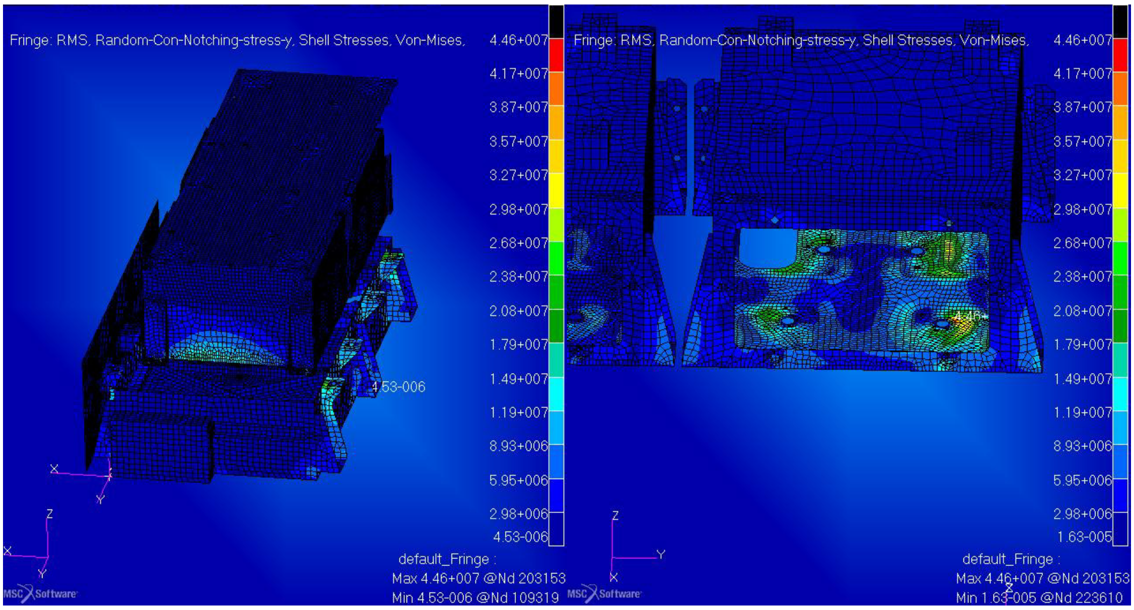

Figure 6-13: 3xRMS Stress - Al6061 Structure - Random Y

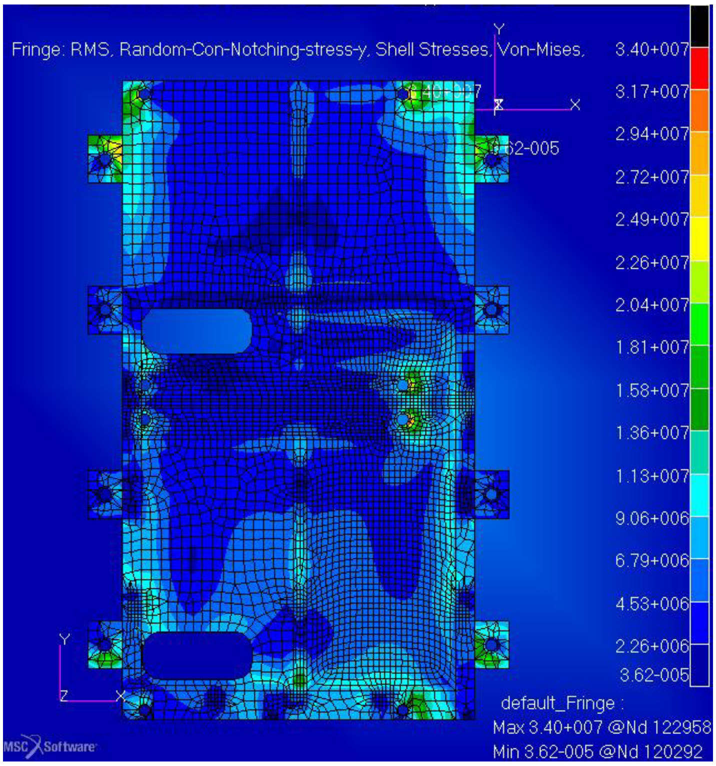

Figure 6-14: 3xRMS Stress - Titanium Structure - Random Y

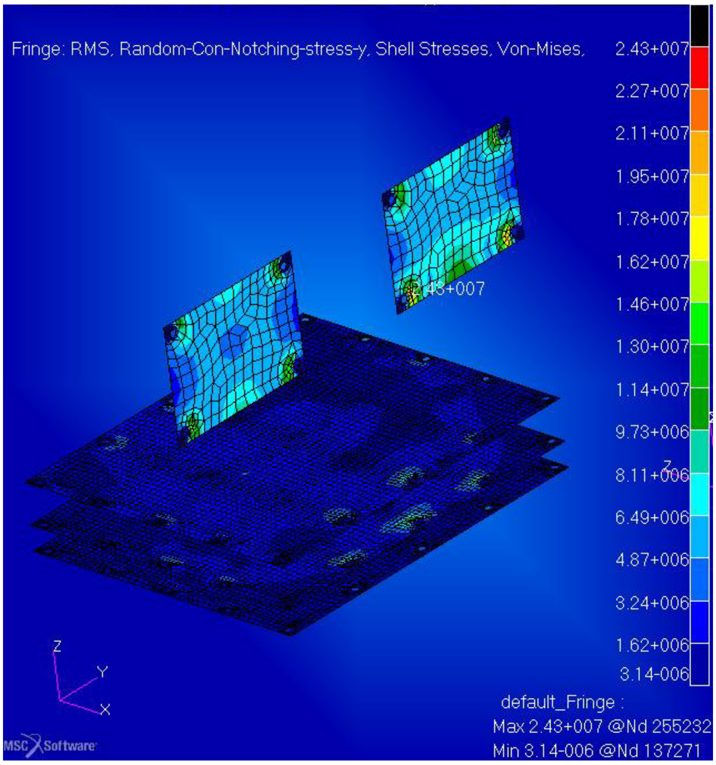

Figure 6-15: 3xRMS Stress - PCBs - Random Y

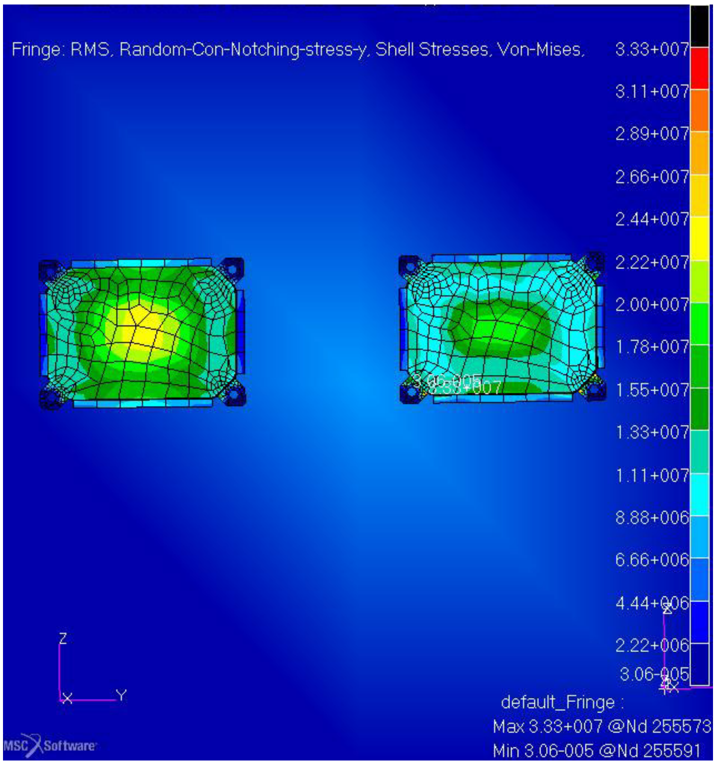

Figure 6-16: 3xRMS Stress – Copper parts - Random Y

6.2.2 Acceleration plots

The units of the following plots are **m/s^2**.

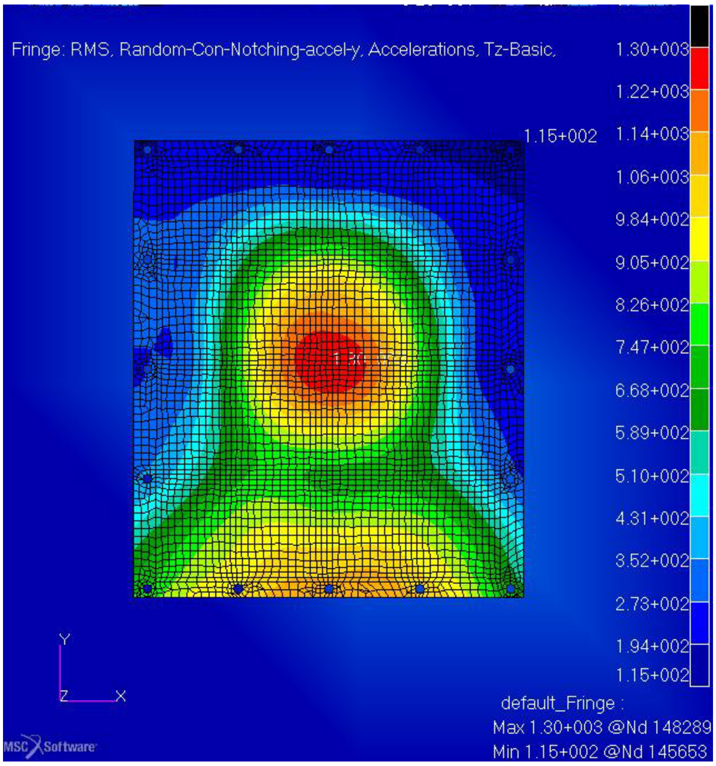

Figure 6-17: 3xRMS Tz component acceleration - Analogic Board

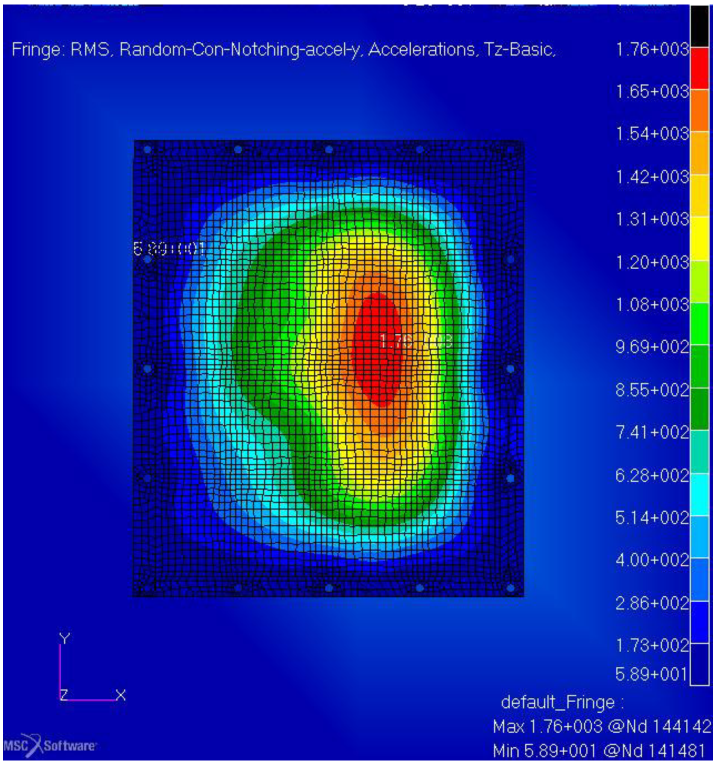

Figure 6-18: 3xRMS Tz component acceleration - Digital Board

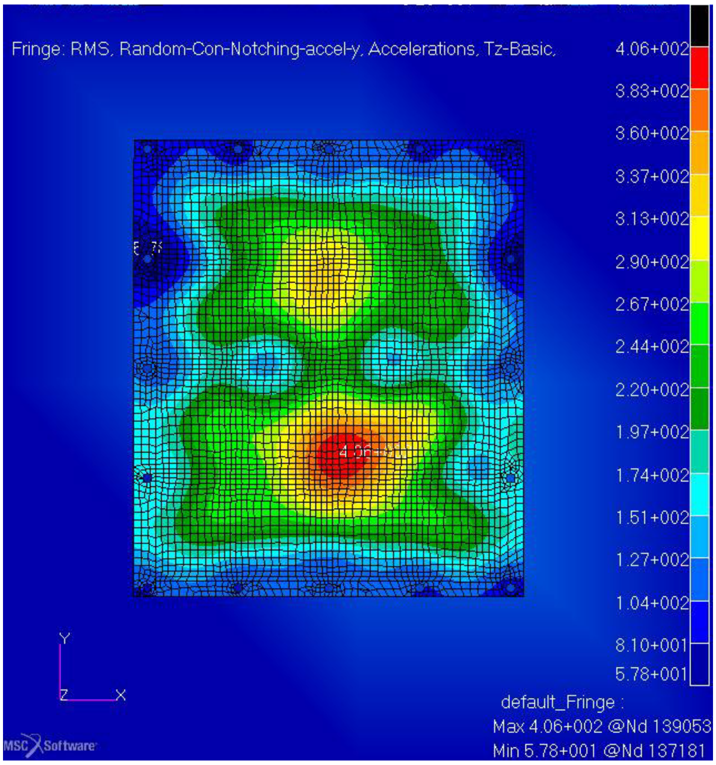

Figure 6-19: 3xRMS Tz component acceleration - LVPS Board

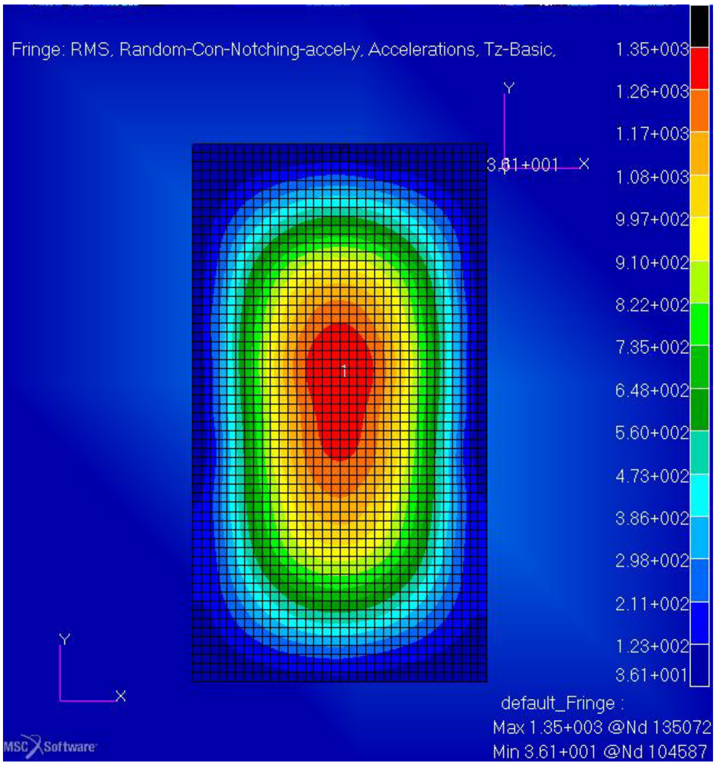

Figure 6-20: 3xRMS Tz component acceleration - Bottom Plate

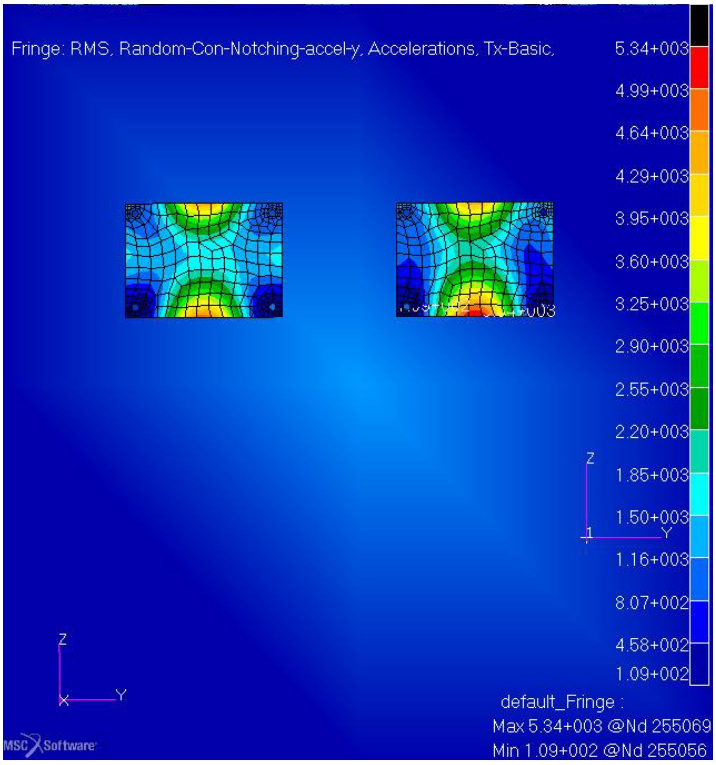

Figure 6-21: 3xRMS Tx component acceleration - idefx carriers

6.2.3 Acceleration PSD curves

The units of the following curves are **g^2/Hz**. These curves show centre node responses of each PCB (the acceleration direction is perpendicular to each PCB), and nodes responses at the accelerometers locations.

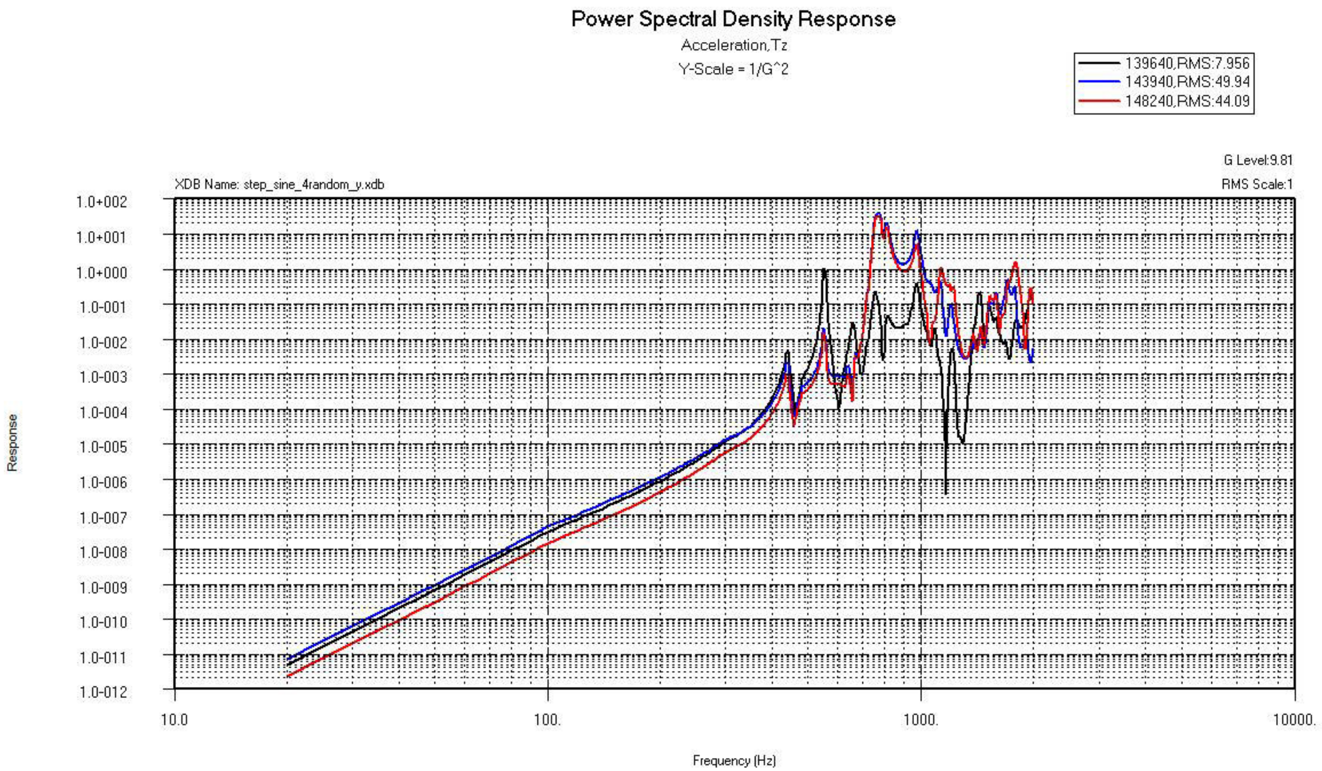

Figure 6-22: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

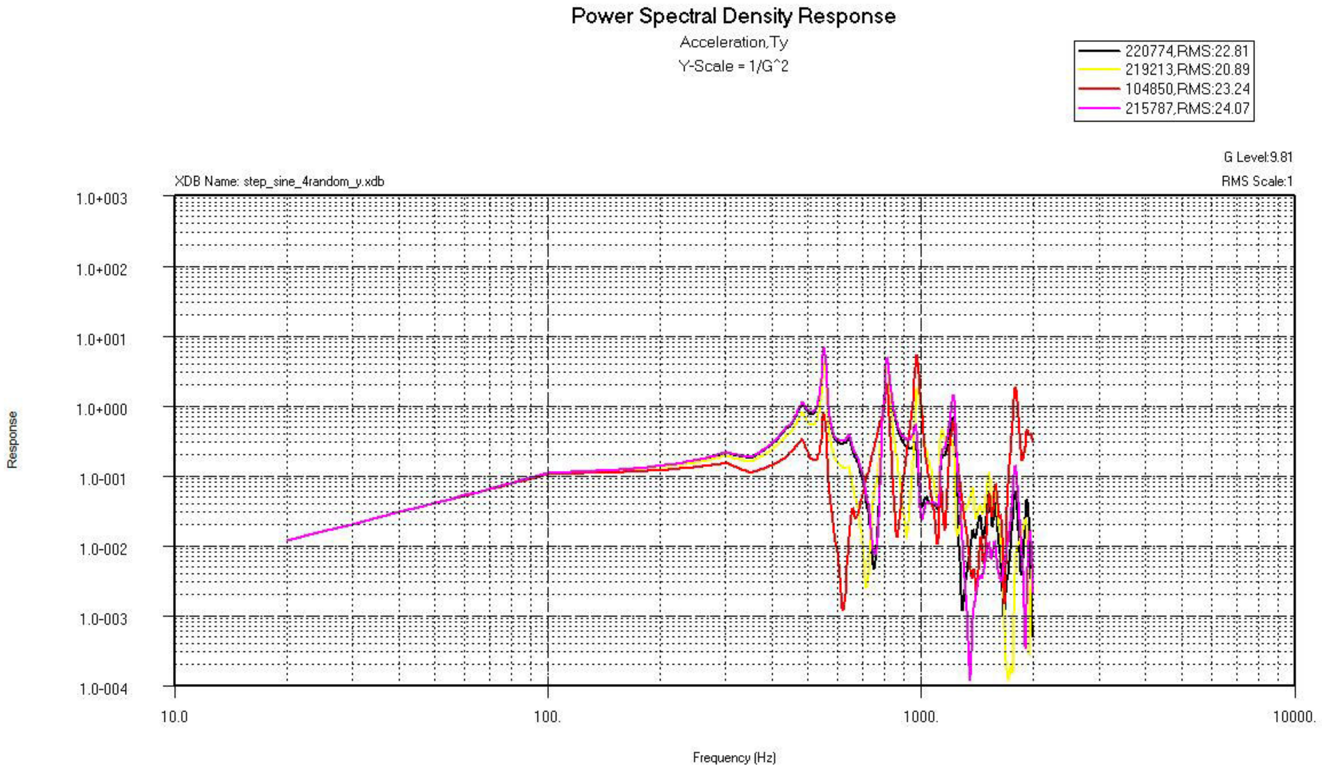

Figure 6-23: Acceleration PSD – A1y (black), A2y (Yellow), A3y (red) and A4y (pink)

6.3 Random vibration analysis – Z axis

6.3.1 Stress plots

The units of the following plots are **Pa**.

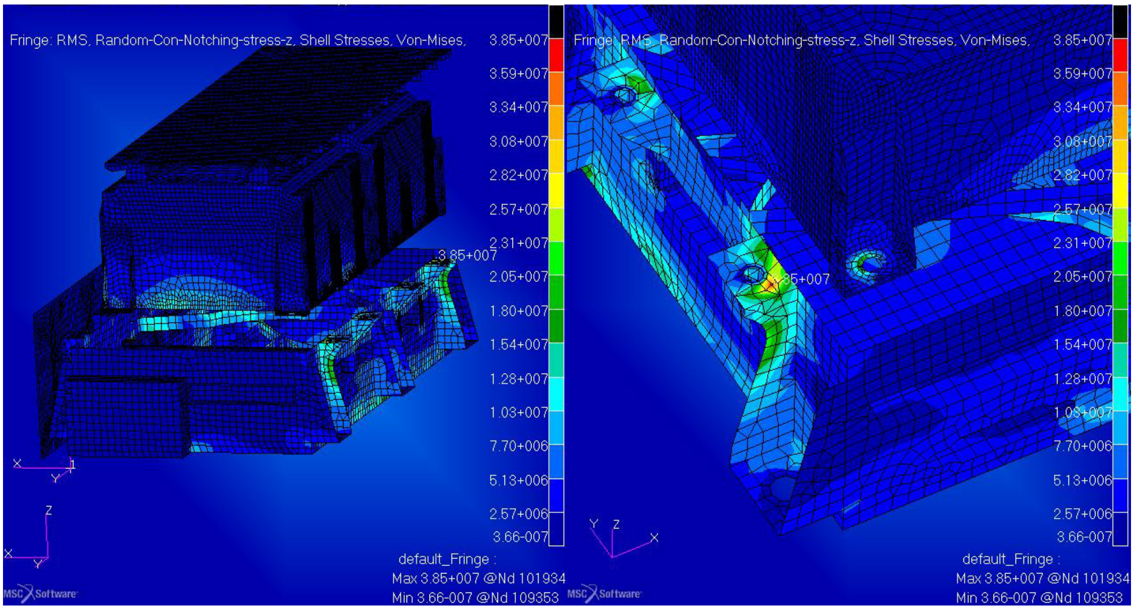

Figure 6-24: 3xRMS Stress - Al6061 Structure - Random Z

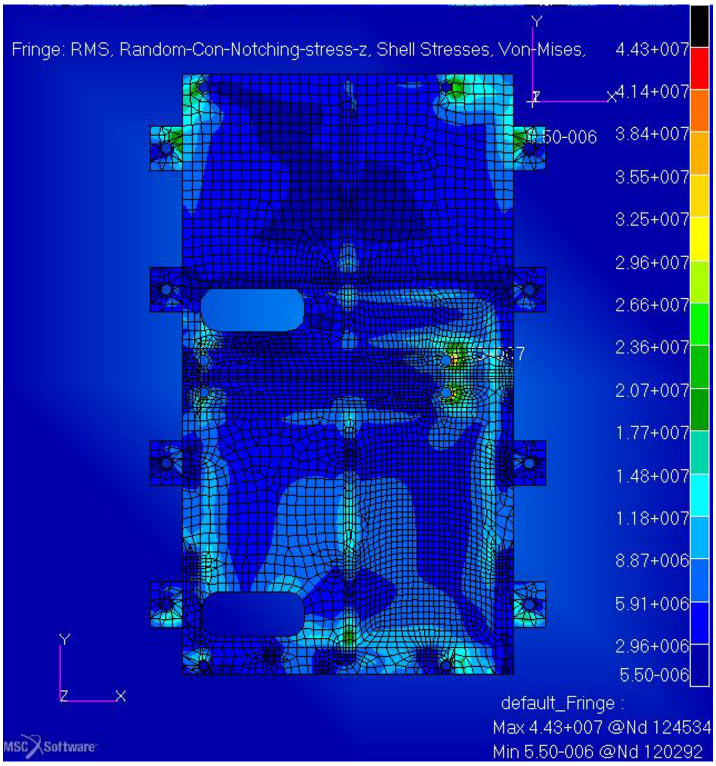

Figure 6-25: 3xRMS Stress - Titanium Structure - Random Z

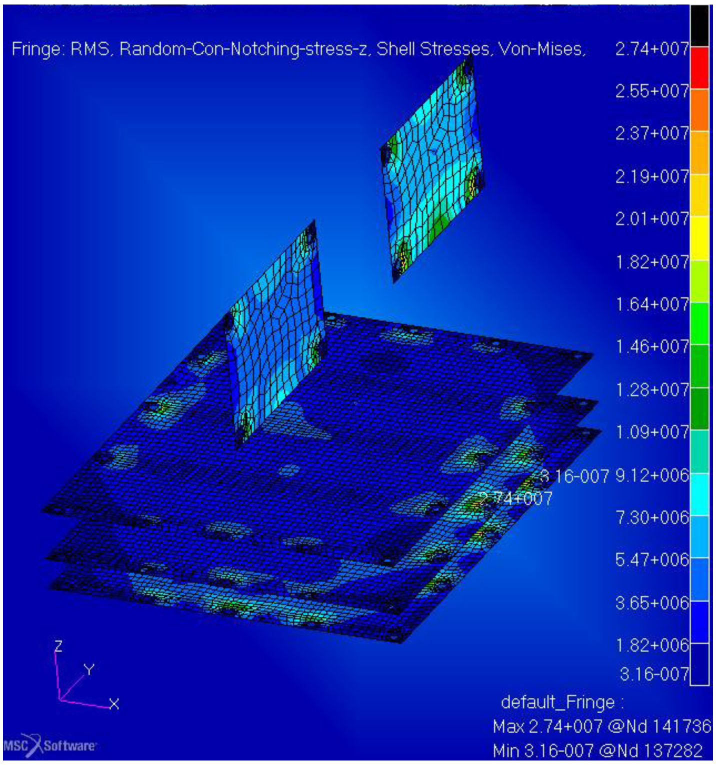

Figure 6-26: 3xRMS Stress - PCBs - Random Z

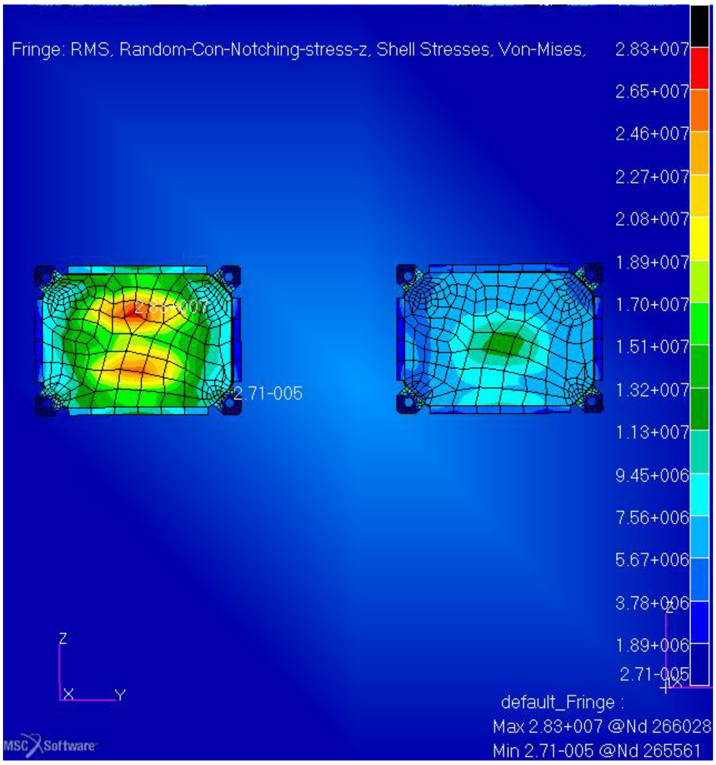

Figure 6-27: 3xRMS Stress – Copper parts - Random Z

6.3.2 Acceleration plots

The units of the following plots are **m/s²**.

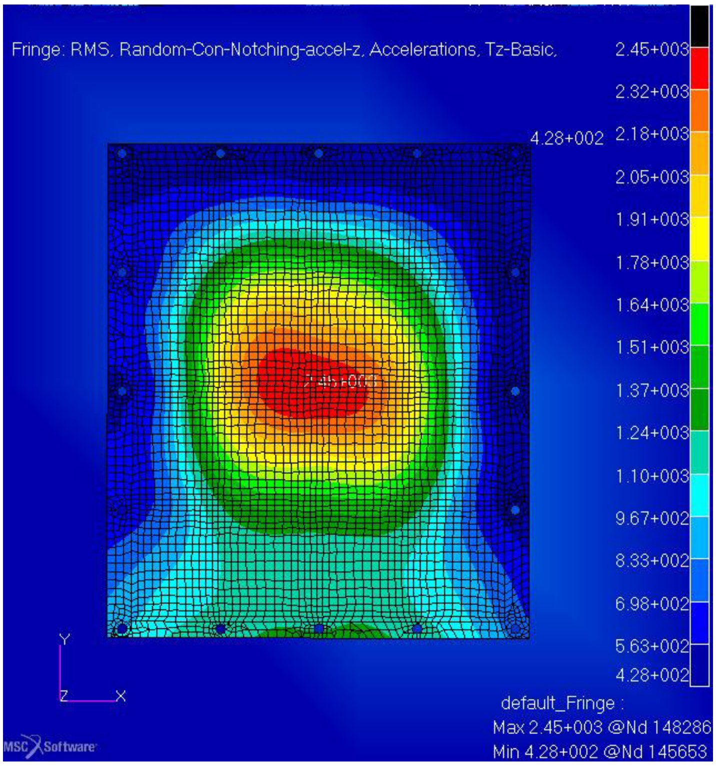

Figure 6-28: 3xRMS Tz component acceleration - Analogic Board

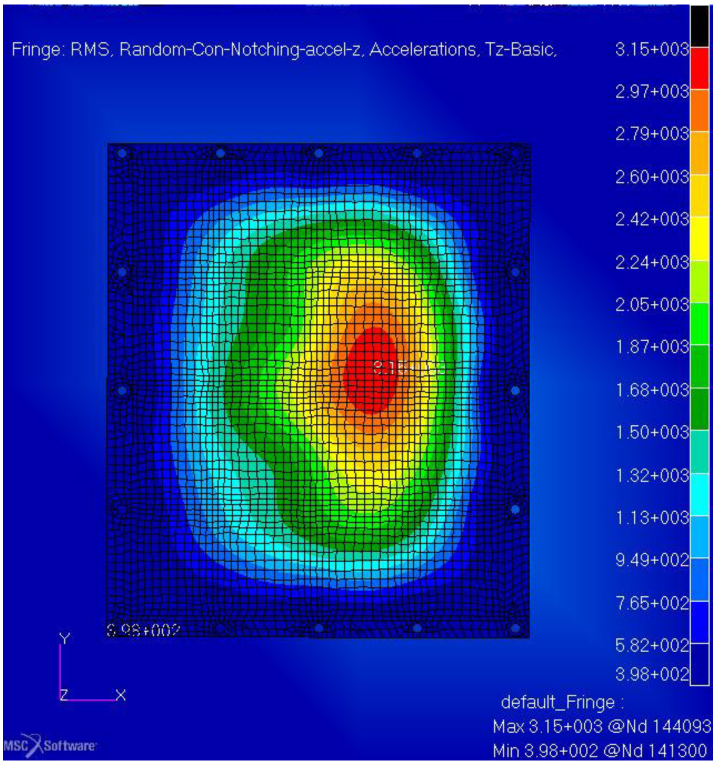

Figure 6-29: 3xRMS Tz component acceleration - Digital Board

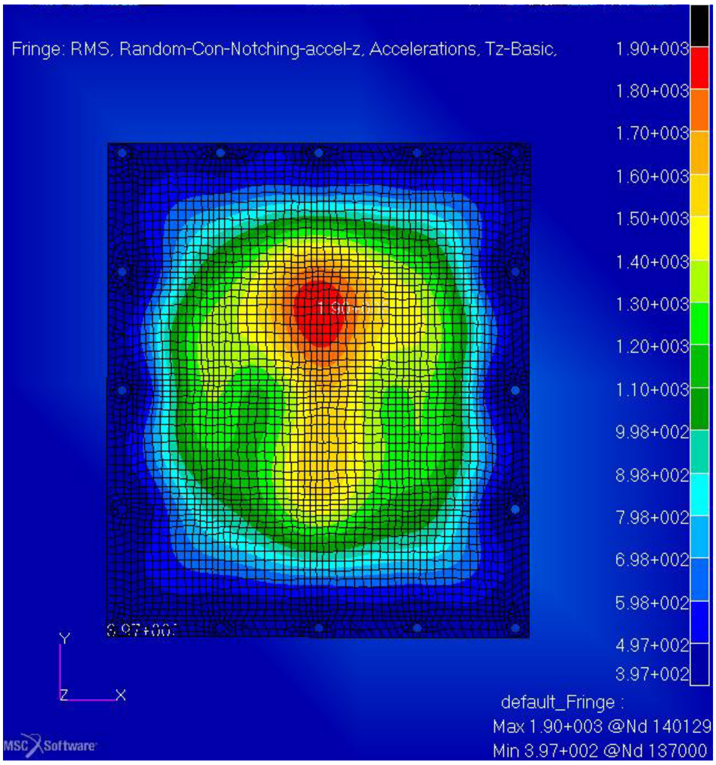

Figure 6-30: 3xRMS Tz component acceleration - LVPS Board

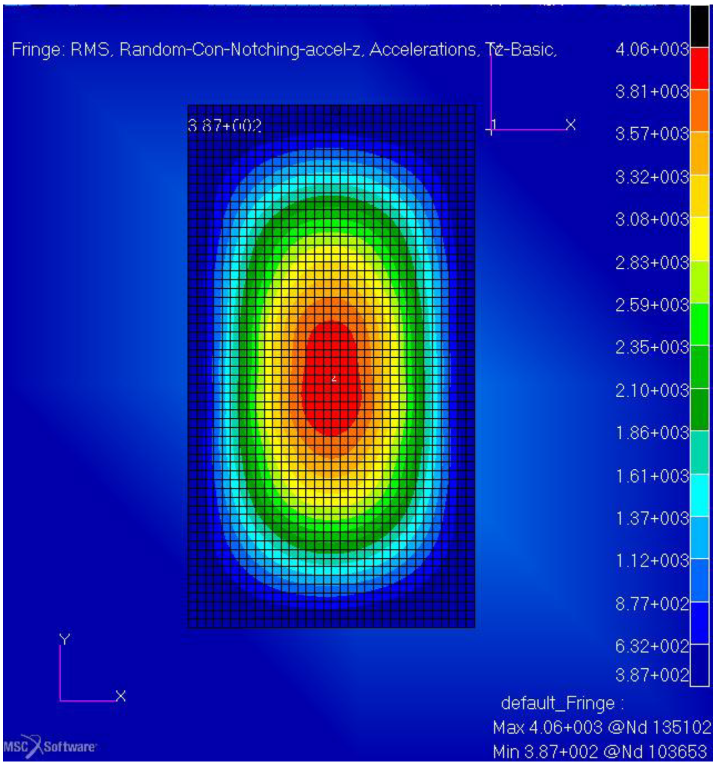

Figure 6-31: 3xRMS Tz component acceleration - Bottom Plate

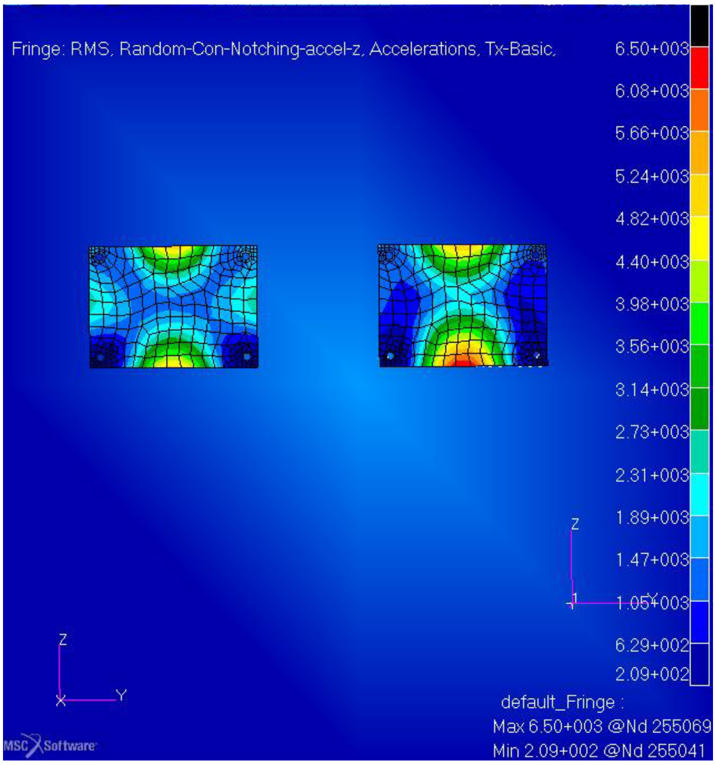

Figure 6-32: 3xRMS Tx component acceleration - idefx carriers

6.3.3 Acceleration PSD curves

The units of the following curves are $\mathbf{g^2/Hz}$. These curves show centre node responses of each PCB (the acceleration direction is perpendicular to each PCB), and nodes responses at the accelerometers locations.

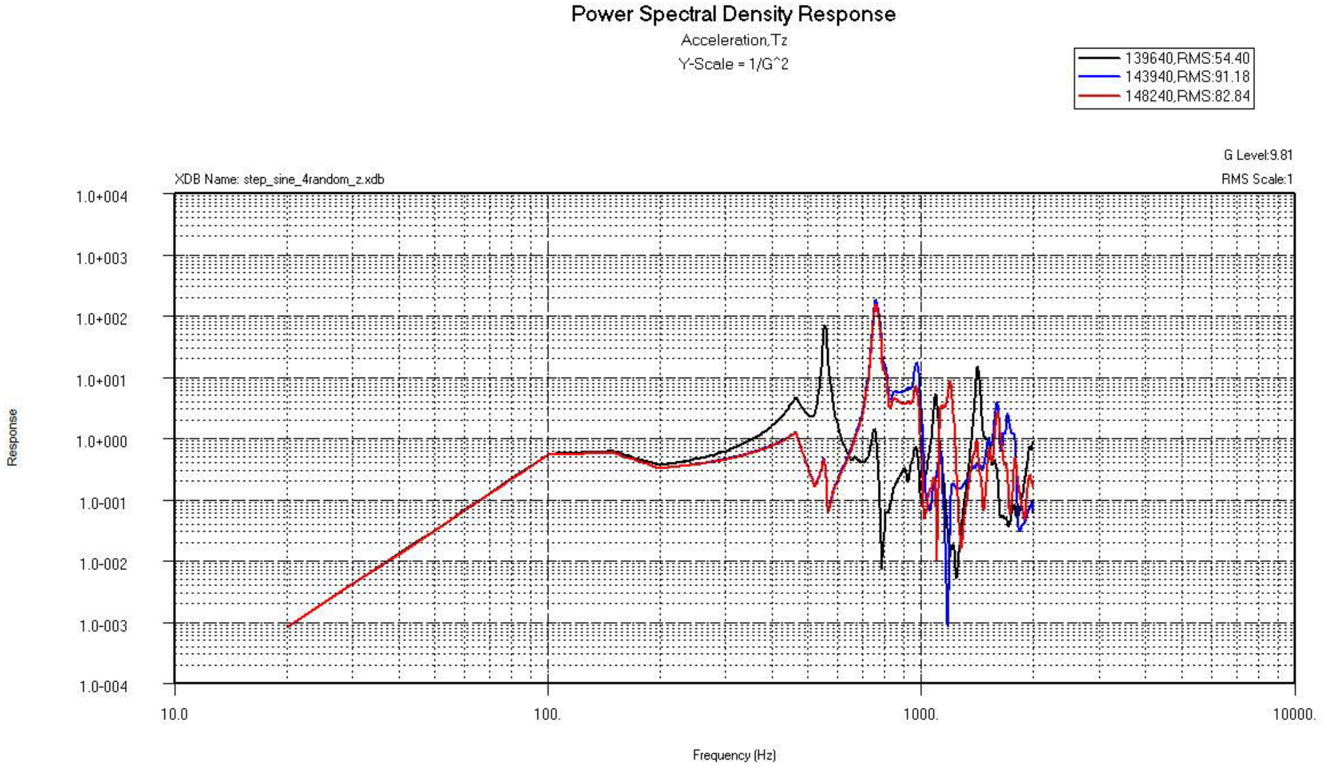

Figure 6-33: Acceleration PSD – LVPS Board (black), Digital Board (blue) and Analogic Board (red)

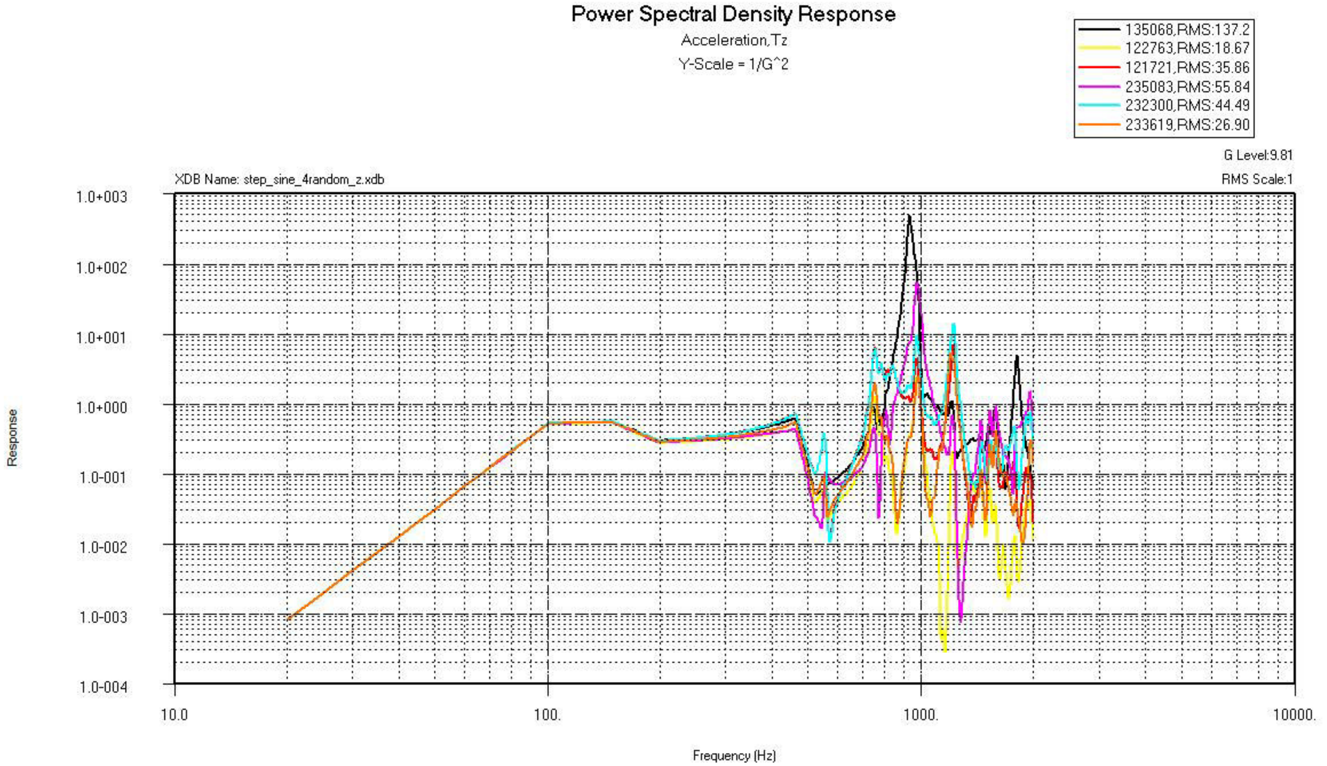

Figure 6-34: Acceleration PSD – A1z (black), A5z (yellow), A6z (red), A8z (pink), A9z (green) and A10z (orange)

6.4 Random IF forces

The forces and the moments at the interfaces have been recovered with CBUSH elements. The values, with a model factor (K_M) of 1.2, have been gathered from Table 6-5 to Table 6-7.

IF	**Random X**		
	CBUSH ID	Axial force (N)	Shear force (N)
STEP IF	10001	271.71	260.51
	10002	200.35	197.42
	10003	280.81	266.28
	10004	236.64	266.71
	10005	228.02	217.31
	10006	297.30	267.58
Ebox housing – Ebox cover IF	51031	165.06	114.07
	51032	112.18	133.47
	51033	128.71	100.74
	51034	202.40	150.60
	51035	165.09	235.70
	51036	118.69	172.04
	51037	91.92	305.56
	51038	182.75	111.50
Ebox cover – Senhousing basis	51121	149.10	122.61
	51122	150.09	164.69
	51123	106.99	135.97
	51124	90.70	109.29
	51125	95.82	99.43
	51126	121.26	91.63
	51127	154.01	88.33
	51128	120.73	105.45
Senhousing basis – Unit p support	91001	38.28	46.49
	91002	46.89	54.73
	91003	38.68	46.40
	91004	43.33	53.17
Senhousing basis – Unit i support	92001	15.21	19.04
	92002	15.77	19.25
	92003	13.64	16.30
	92004	14.17	16.39

Table 6-5: Random X (with notching) resultant loads - IF Forces

IF	Random Y		
	CBUSH ID	Axial force (N)	Shear force (N)
STEP IF	10001	176.28	180.11
	10002	106.93	158.79
	10003	238.08	172.92
	10004	202.44	157.47
	10005	105.97	150.04
	10006	227.84	157.80
Ebox housing – Ebox cover IF	51031	196.73	70.76
	51032	65.63	102.27
	51033	70.26	96.99
	51034	240.20	110.74
	51035	249.56	107.62
	51036	59.97	107.56
	51037	55.01	122.35
	51038	157.87	69.44
Ebox cover – Senhousing basis	51121	116.79	55.11
	51122	115.03	93.16
	51123	92.68	84.66
	51124	83.28	90.82
	51125	104.62	109.38
	51126	74.90	88.04
	51127	138.03	50.90
	51128	187.76	89.57
Senhousing basis – Unit p support	91001	81.55	49.73
	91002	131.47	72.42
	91003	63.55	44.29
	91004	69.36	50.42
Senhousing basis – Unit i support	92001	40.39	24.79
	92002	46.82	25.11
	92003	25.47	13.37
	92004	21.18	13.92

Table 6-6: Random Y (with notching) resultant loads - IF Forces

IF	Random Z		
	CBUSH ID	Axial force (N)	Shear force (N)
STEP IF	10001	151.76	99.23
	10002	235.50	103.06
	10003	223.48	104.47
	10004	156.96	109.17
	10005	250.77	109.36
	10006	210.93	116.08
Ebox housing – Ebox cover IF	51031	181.52	68.00
	51032	122.50	62.88
	51033	118.60	58.84
	51034	249.98	71.76
	51035	238.48	51.26
	51036	88.03	40.99
	51037	92.55	45.97
	51038	151.87	41.50
Ebox cover – Senhousing basis	51121	118.76	65.75
	51122	120.42	47.41
	51123	126.68	50.14
	51124	77.38	42.17
	51125	120.42	44.95
	51126	119.91	30.79
	51127	143.47	70.00
	51128	177.41	55.65
Senhousing basis – Unit p support	91001	61.14	31.03
	91002	82.08	39.32
	91003	64.29	34.29
	91004	94.79	50.13
Senhousing basis – Unit i support	92001	42.32	21.04
	92002	46.01	20.21
	92003	25.95	11.65
	92004	22.94	12.28

Table 6-7: Random Z (with notching) resultant loads - IF Forces

7 QUASI-STATIC LOAD

Quasi-static load equivalent to original random specification (see Table 5-1) and to random specification with notching (see Table 6-1) has been calculated directly from random vibration analysis of the FEM by the recovery of the total IF force with CELAS elements. The QSL levels are shown in Table 7-1.

Random Specification	QSL in X (g)	QSL in Y (g)	QSL in Z (g)
Original	152.43	93.46	96.03
With notching	61.29	46.35	54.71

Table 7-1: QSL levels

The results summary is shown in Table 7-2 and Table 7-3.

Part	Material	Maximum Von Mises stress (MPa)		
		QSL X	QSL Y	QSL Z
Al6061-T6 Structure	Al6061-T6	149.0	37.0	36.6
Ebox cover	Ti 6Al4V	135.0	43.8	47.4
Stand Offs	Ultem	23.3	9.4	6.4
Idefx covers	Copper	17.9	27.8	12.3
Power Board	FR4	17.6	2.8	27.9
Digital Board	FR4	26.5	2.1	16.9
Analogic Board	FR4	18.9	3.1	17.0
idefx unit P	FR4	20.1	1.9	0.7
idefx unit i	FR4	19.8	1.3	0.6

Table 7-2: Maximum Von Mises stress – QSL (Original random specification)

Part	Material	Maximum Von Mises stress (MPa)		
		QSL X	QSL Y	QSL Z
Al6061-T6 Structure	Al6061-T6	59.8	18.4	20.8
Ebox cover	Ti 6Al4V	54.4	21.7	27.0
Stand Offs	Ultem	9.4	4.7	3.7
Idefx covers	Copper	7.2	13.8	7.0
Power Board	FR4	7.1	1.4	15.9
Digital Board	FR4	10.6	1.0	9.7
Analogic Board	FR4	7.6	1.5	9.7
idefx unit P	FR4	8.1	1.0	0.4
idefx unit i	FR4	8.0	0.7	0.3

Table 7-3: Maximum Von Mises stress – QSL (Random specification with notching)

7.1 Quasi-static load – X axis

7.1.1 Stress plots

The units of the following plots are **Pa**.

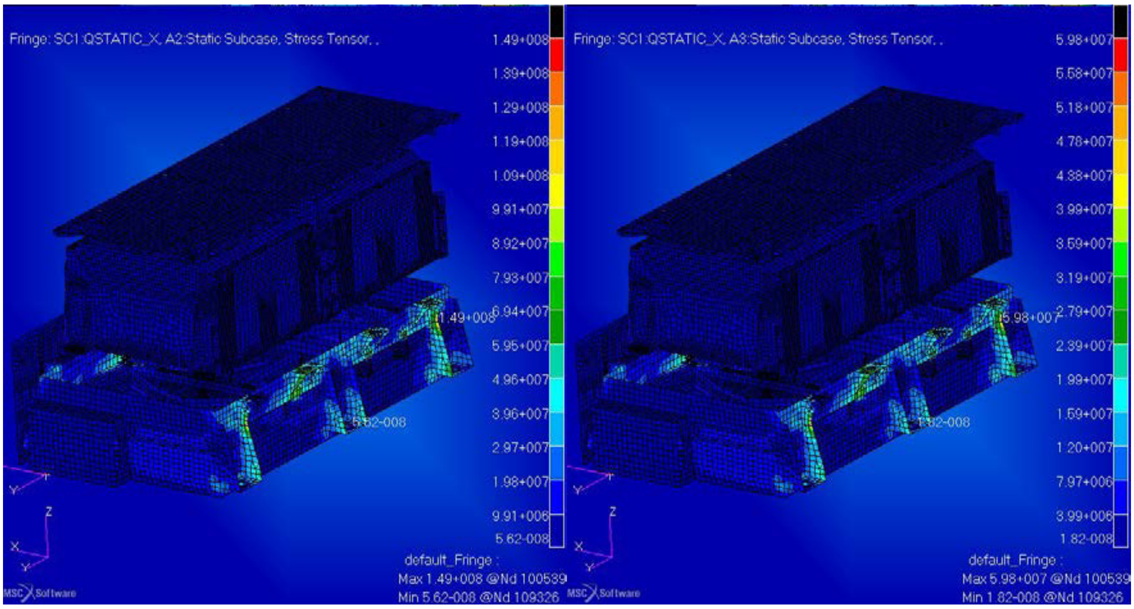

Figure 7-1: Von Mises Stress - Al6061 Structure - QSL X: Original RV (left) and RV with notching (right)

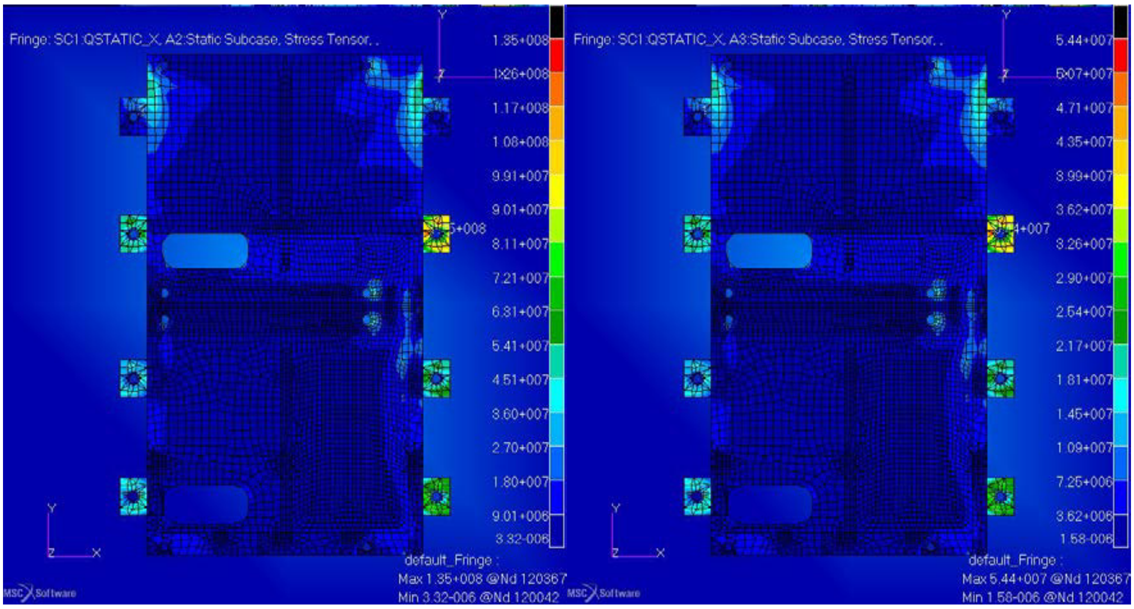

Figure 7-2: Von Mises Stress – Ti Cover - QSL X: Original RV (left) and RV with notching (right)

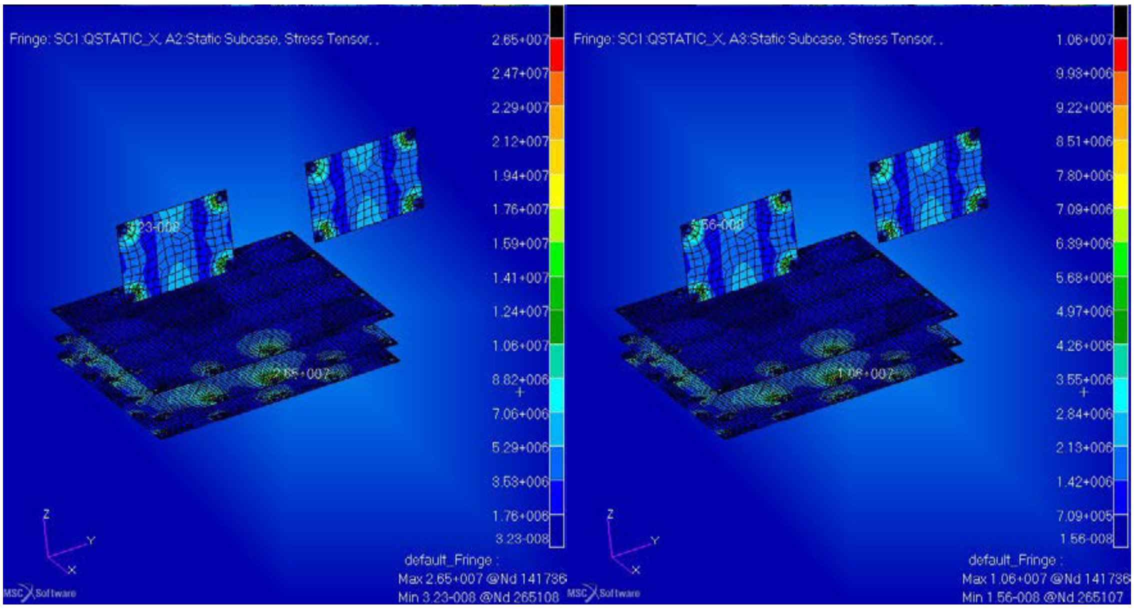

Figure 7-3: Von Mises Stress – PCBs - QSL X: Original RV (left) and RV with notching (right)

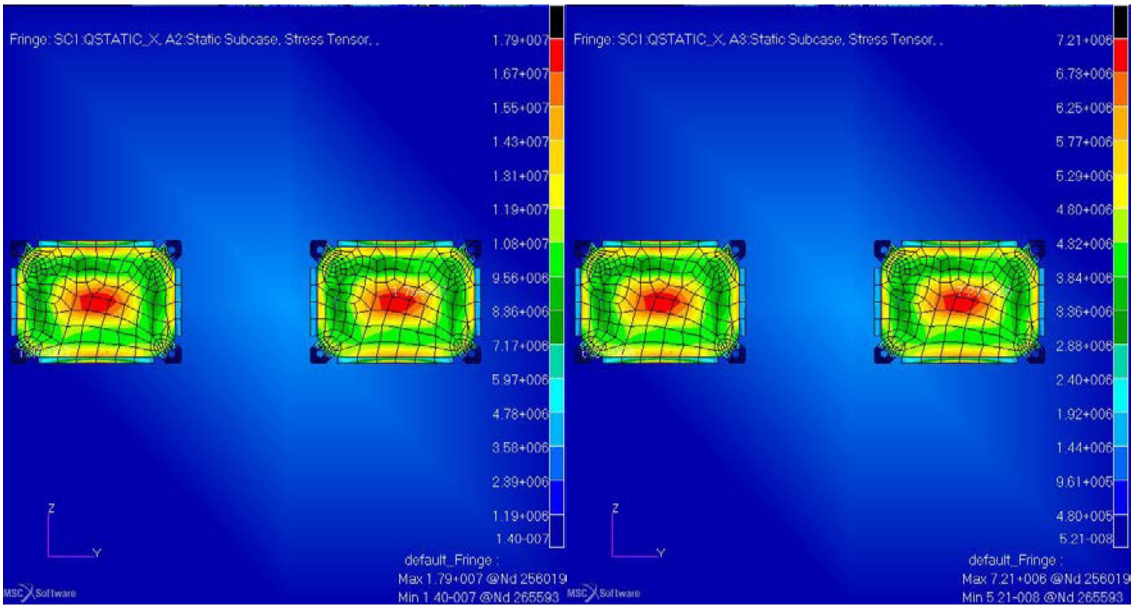

Figure 7-4: Von Mises Stress – Copper parts - QSL X: Original RV (left) and RV with notching (right)

7.2 Quasi-static load – Y axis

7.2.1 Stress plots

The units of the following plots are **Pa**.

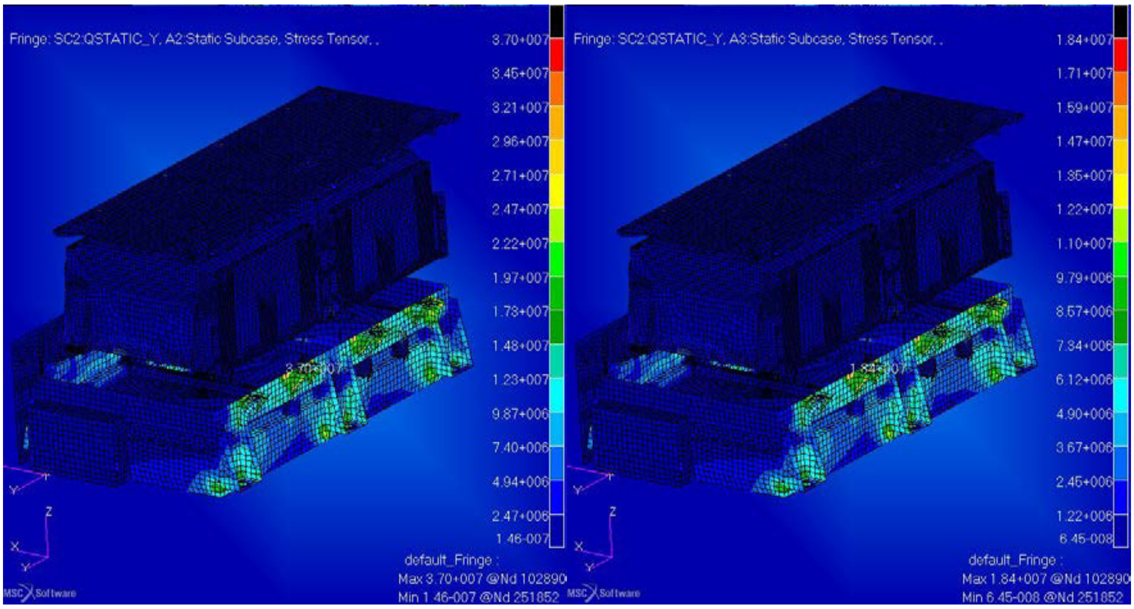

Figure 7-5: Von Mises Stress - Al6061 Structure - QSL Y: Original RV (left) and RV with notching (right)

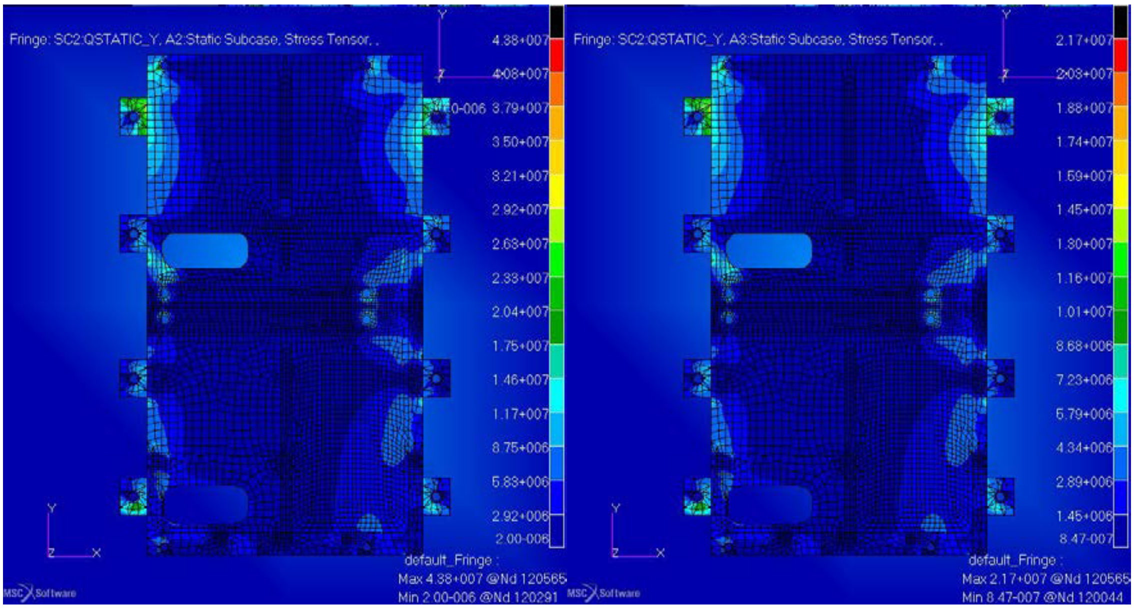

Figure 7-6: Von Mises Stress – Ti Cover - QSL Y: Original RV (left) and RV with notching (right)

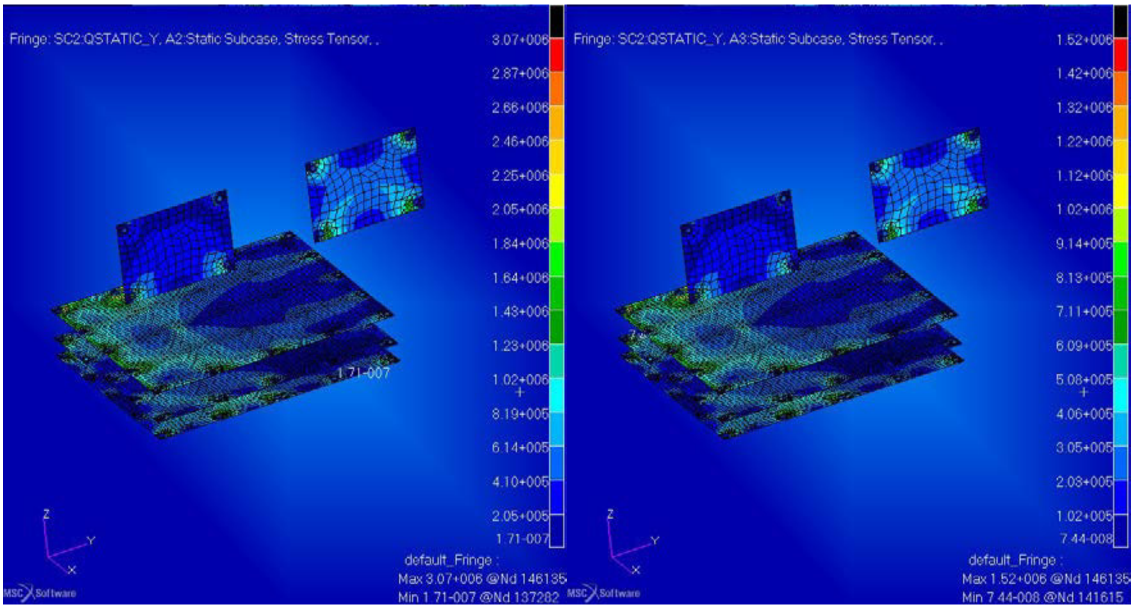

Figure 7-7: Von Mises Stress – PCBs - QSL Y: Original RV (left) and RV with notching (right)

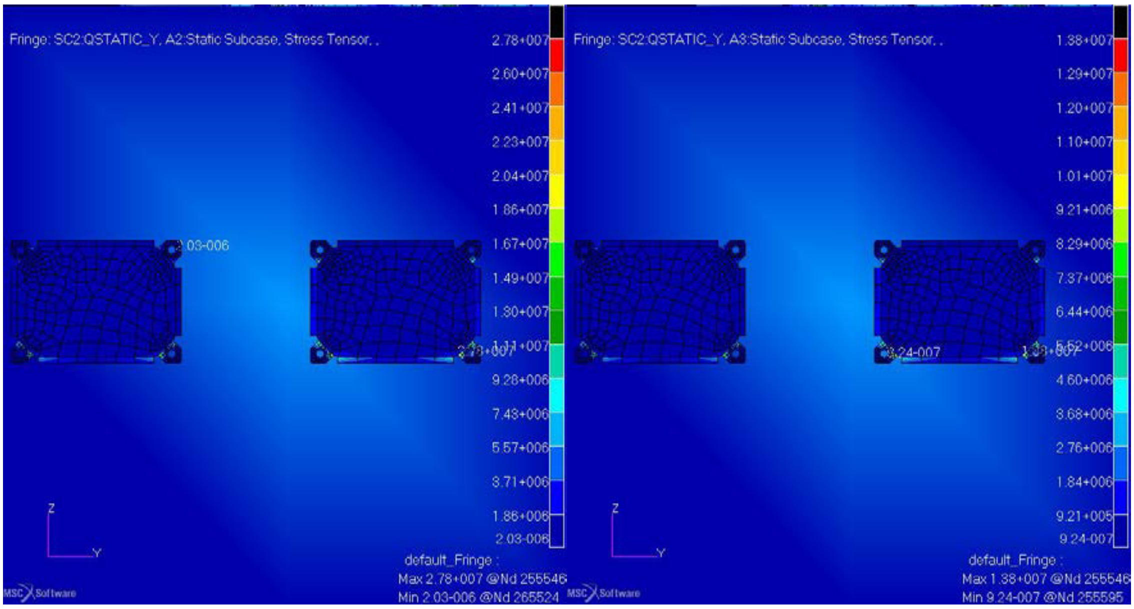

Figure 7-8: Von Mises Stress – Copper parts - QSL Y: Original RV (left) and RV with notching (right)

7.3 Quasi-static load – Z axis

7.3.1 Stress plots

The units of the following plots are **Pa**.

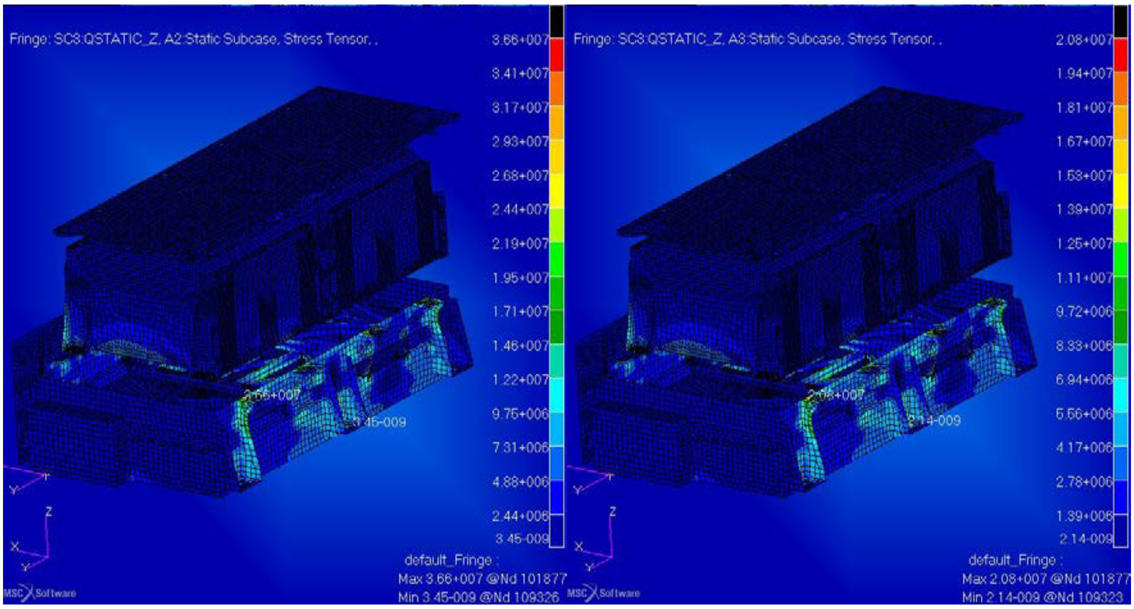

Figure 7-9: Von Mises Stress - Al6061 Structure - QSL Z: Original RV (left) and RV with notching (right)

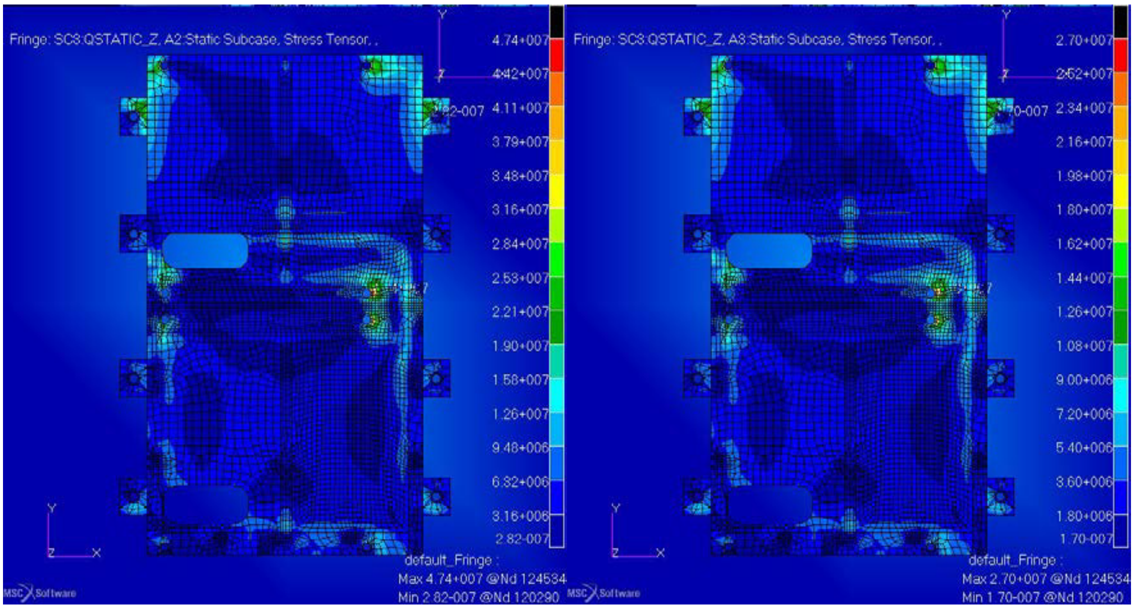

Figure 7-10: Von Mises Stress – Ti Cover - QSL Z: Original RV (left) and RV with notching (right)

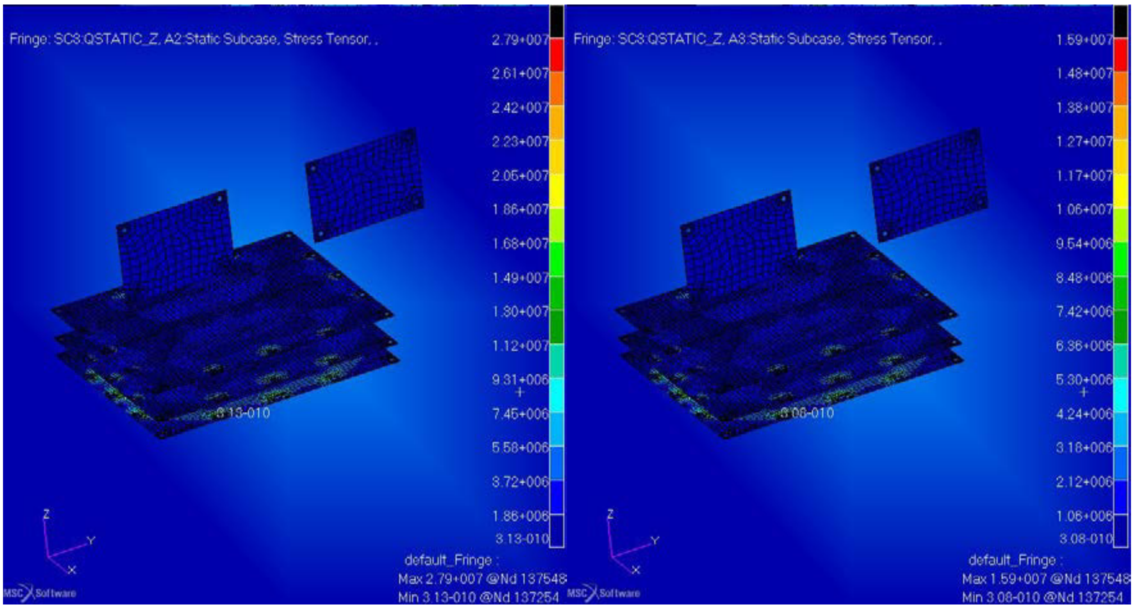

Figure 7-11: Von Mises Stress – PCBs - QSL Z: Original RV (left) and RV with notching (right)

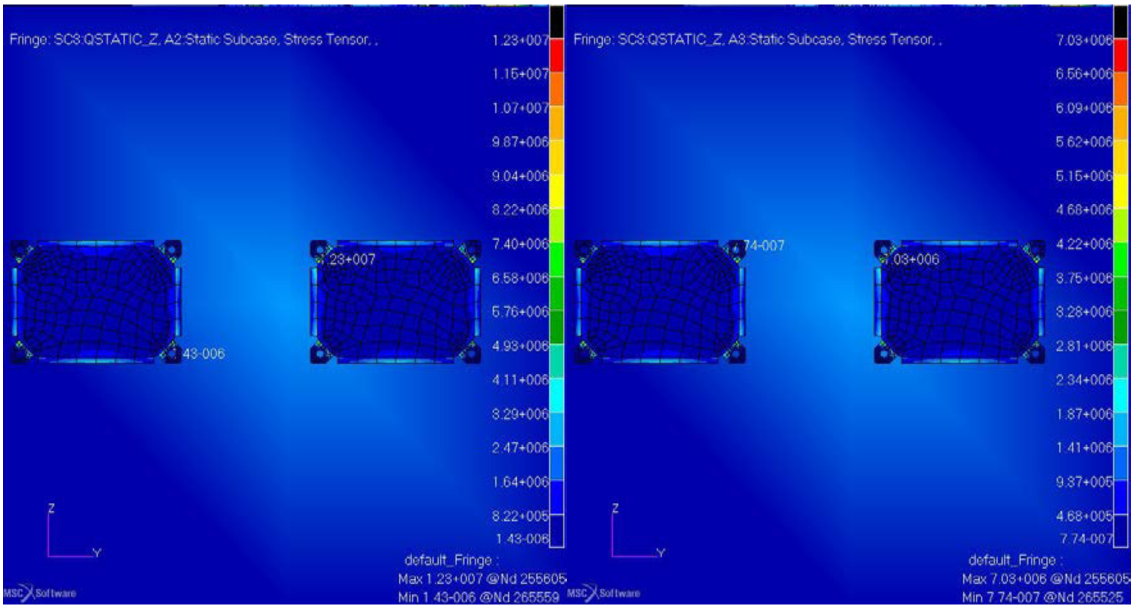

Figure 7-12: Von Mises Stress – Copper parts - QSL Z: Original RV (left) and RV with notching (right)

8 BOLT ANALYSIS

For this analysis, the most severe loads from random vibration analyses have been used.

8.1 Margin of safety on tensile failure

$$MoS_{tot,y} = \frac{A_s \sigma_y}{F_{V,\max} + \Phi_n F_A sf_y} - 1$$

$$MoS_{tot,ult} = \frac{A_s \sigma_{ult}}{F_{V,\max} + \Phi_n F_A sf_{ult}} - 1$$

In the above expressions, the following parameters were used:

- Stress area for the fastener (M5) $\equiv A_S = 1.42 \cdot 10^{-5}$ m^2
- Stress area for the fastener (M3) $\equiv A_S = 5.03 \cdot 10^{-6}$ m^2
- Maximal guaranteed screw preload (M5) $\equiv F_{V,max} = 8550$ N
- Maximal guaranteed screw preload (M3) $\equiv F_{V,max} = 3236$ N
- Yield stress for Ti6Al4V $\equiv \sigma_y = 1030$ MPa
- Ultimate stress for Ti6Al4V$\equiv \sigma_{ult} = 1100$ MPa
- Force ratio (M5) $\equiv \Phi_n = 0.362$
- Force ratio (M3) $\equiv \Phi_n = 0.058$
- Yield safety factor $\equiv sf_y = 1$
- Ultimate safety factor $\equiv sf_{ult} = 1.4$
- Axial load (K_M included) $\equiv F_A$

IF	CBUSH ID	Most severe load case					
		Original random	$MoS_{tot,y}$	$MoS_{tot,u}$	Random with notching	$MoS_{tot,y}$	$MoS_{tot,u}$
STEP IF	10001	Random X	0.65	0.74	Random X	0.69	0.80
	10002	Random X	0.67	0.77	Random Z	0.69	0.80
	10003	Random X	0.66	0.75	Random X	0.69	0.79
	10004	Random X	0.66	0.76	Random X	0.69	0.80
	10005	Random X	0.67	0.76	Random Z	0.69	0.80
	10006	Random X	0.65	0.74	Random X	0.69	0.79
Ebox housing – Ebox cover IF	51031	Random Y	0.59	0.69	Random Y	0.60	0.70
	51032	Random X	0.59	0.70	Random Z	0.60	0.70
	51033	Random X	0.59	0.70	Random X	0.60	0.70
	51034	Random X	0.59	0.69	Random Z	0.59	0.70
	51035	Random X	0.59	0.69	Random Y	0.59	0.70
	51036	Random X	0.59	0.70	Random X	0.60	0.70
	51037	Random X	0.59	0.70	Random X	0.60	0.71
	51038	Random X	0.59	0.69	Random X	0.60	0.70
Ebox cover – Senhousing basis IF	51121	Random X	0.59	0.69	Random X	0.60	0.70
	51122	Random X	0.59	0.69	Random X	0.60	0.70

	51123	Random X	0.59	0.70	Random Z	0.60	0.70
	51124	Random X	0.59	0.70	Random X	0.60	0.71
	51125	Random Y	0.59	0.70	Random Z	0.60	0.70
	51126	Random X	0.59	0.70	Random X	0.60	0.70
	51127	Random X	0.59	0.69	Random X	0.60	0.70
	51128	Random X	0.59	0.70	Random Y	0.60	0.70
Senhousing basis – Unit p support IF	91001	Random Y	0.60	0.70	Random Y	0.60	0.71
	91002	Random Y	0.60	0.70	Random Y	0.60	0.70
	91003	Random Z	0.60	0.70	Random Z	0.60	0.71
	91004	Random Z	0.60	0.70	Random Z	0.60	0.71
Senhousing basis – Unit i support IF	92001	Random Z	0.60	0.71	Random Z	0.60	0.71
	92002	Random Z	0.60	0.71	Random Y	0.60	0.71
	92003	Random X	0.60	0.71	Random Z	0.60	0.71
	92004	Random X	0.60	0.71	Random Z	0.60	0.71

Table 8-1: Margins of safety on bolt tensile failure

8.2 No gapping criteria

$$MoS_g = \frac{F_{V,\min}}{(1-\Phi_n)F_A sf_g} - 1$$

For this last expression for the margin of safety, the following parameters are defined additionally to those from previous subsection:

- Minimum guaranteed screw preload (M5) $\equiv F_{V,min} = 6449$ N
- Minimum guaranteed screw preload (M3) $\equiv F_{V,min} = 1398$ N
- Gapping safety factor $\equiv sf_g = 1.4$

IF	CBUSH ID	Most severe load case			
		Original random	MoS_g	Random with notching	MoS_g
STEP IF	10001	Random X	8.27	Random X	25.56
	10002	Random X	12.42	Random Z	29.64
	10003	Random X	8.62	Random X	24.70
	10004	Random X	10.62	Random X	29.49
	10005	Random X	11.01	Random Z	27.78
	10006	Random X	7.61	Random X	23.27
Ebox housing – Ebox cover IF	51031	Random Y	1.35	Random Y	4.39
	51032	Random X	2.85	Random Z	7.65
	51033	Random X	2.17	Random X	7.24
	51034	Random X	1.01	Random Z	3.24
	51035	Random X	1.51	Random Y	3.25
	51036	Random X	2.24	Random X	7.93
	51037	Random X	3.21	Random X	10.53
	51038	Random X	1.06	Random X	4.80
Ebox cover – Senhousing basis IF	51121	Random X	1.76	Random X	6.11
	51122	Random X	1.53	Random X	6.06
	51123	Random X	3.15	Random Z	7.37

	51124	Random X	3.27	Random X	10.69
	51125	Random Y	3.74	Random Z	7.80
	51126	Random X	3.10	Random X	7.74
	51127	Random X	1.87	Random X	5.88
	51128	Random X	2.74	Random Y	4.65
Senhousing basis – Unit p support IF	91001	Random Y	7.76	Random Y	12.00
	91002	Random Y	4.70	Random Y	7.06
	91003	Random Z	7.71	Random Z	15.49
	91004	Random Z	4.34	Random Z	10.19
Senhousing basis – Unit i support IF	92001	Random Z	22.02	Random Z	24.05
	92002	Random Z	19.81	Random Y	21.64
	92003	Random X	32.74	Random Z	39.86
	92004	Random X	37.69	Random Z	45.22

Table 8-2: Margins of safety on gapping

8.3 No sliding criteria

$$MoS_{slip} = \frac{(F_{V,\min} - (1-\Phi_n)F_A)N\mu_s}{F_S sf_{ult}} - 1$$

For this last expression for the margin of safety, the following parameters are defined additionally to those from previous subsections:

- Number of bolts of each joint $\equiv N = 1$
- Friction coefficient (STEP IF) $\equiv \mu_S = 0.15$
- Friction coefficient (Other IFs) $\equiv \mu_S = 0.21$
- Total in plane load of the foot (K_M included) $\equiv F_S$
- Axial load (K_M included) $\equiv F_A$
- Ultimate safety factor $\equiv sf_{ult} = 1.4$

IF	CBUSH ID	Most severe load case			
		Original random	MoS_{Slip}	Random with notching	MoS_{Slip}
STEP IF	10001	Random X	-0.03	Random X	1.58
	10002	Random X	0.37	Random X	2.43
	10003	Random X	0.06	Random X	1.52
	10004	Random X	-0.07	Random X	1.53
	10005	Random X	0.18	Random X	2.11
	10006	Random X	0.00	Random X	1.51
Ebox housing – Ebox cover IF	51031	Random X	-0.53	Random X	0.63
	51032	Random X	-0.54	Random X	0.45
	51033	Random X	-0.43	Random X	0.90
	51034	Random X	-0.66	Random X	0.20
	51035	Random X	-0.77	Random X	-0.21
	51036	Random X	-0.65	Random X	0.12
	51037	Random X	-0.80	Random X	-0.36

	51038	Random X	-0.56	Random X	0.65
Ebox cover – Senhousing basis IF	51121	Random X	-0.54	Random X	0.54
	51122	Random X	-0.68	Random X	0.14
	51123	Random X	-0.54	Random X	0.43
	51124	Random X	-0.41	Random X	0.80
	51125	Random X	-0.35	Random X	0.97
	51126	Random X	-0.31	Random X	1.10
	51127	Random X	-0.34	Random X	1.13
	51128	Random X	-0.40	Random X	0.83
Senhousing basis – Unit p support IF	91001	Random X	0.60	Random Y	2.99
	91002	Random X	0.31	Random Y	1.64
	91003	Random X	0.58	Random X	3.40
	91004	Random X	0.42	Random X	2.83
Senhousing basis – Unit i support IF	92001	Random X	3.22	Random Y	7.23
	92002	Random X	3.35	Random Y	7.09
	92003	Random X	4.00	Random X	11.75
	92004	Random X	3.95	Random X	11.67

Table 8-3: Margins of safety on sliding

8.4 Margin on safety on fastener shear failure

The used expressions for the calculation have been the following:

- Pure shear

$$MoS_{S,y} = \frac{\tau_y \, A_s}{F_S \, sf_y} - 1$$

$$MoS_{S,ult} = \frac{\tau_{ult} \, A_s}{F_S \, sf_{ult}} - 1$$

- Combined shear and axial loads

$$MoS_{comb,y} = \frac{1}{\sqrt{\left(\frac{F_S \, sf_y}{\tau_y \, A_s}\right)^2 + \left(\frac{F_{V,max} + \Phi_n \, F_A \, sf_y}{A_s \, \sigma_y}\right)^2}} - 1$$

$$MoS_{comb,ult} = \frac{1}{\sqrt{\left(\frac{F_S \, sf_{ult}}{\tau_{ult} \, A_s}\right)^2 + \left(\frac{F_{V,max} + \Phi_n \, F_A \, sf_{ult}}{A_s \, \sigma_{ult}}\right)^2}} - 1$$

For the expressions for the margins of safety additionally to those from previous subsection, the following parameters are defined:

- Yield shear strength for Ti6Al4V ≡ $\tau_y = 510 \, MPa$
- Ultimate shear strength for Ti6Al4V ≡ $\tau_{ult} = 545 \, MPa$
- In plane load (K_M included) ≡ F_S
- Axial load (K_M included) ≡ F_A

IF	CBUSH ID	Most severe load case					
		Original random	$MoS_{S,y}$	$MoS_{S,u}$	$MoS_{Comb,y}$	$MoS_{Comb,u}$
STEP IF	10001	Random X	9.97	7.38	0.64	0.71
	10002	Random X	14.13	10.55	0.66	0.75
	10003	Random X	10.97	8.13	0.64	0.72
	10004	Random X	9.33	6.89	0.64	0.72
	10005	Random X	12.15	9.04	0.65	0.74
	10006	Random X	10.38	7.69	0.63	0.70
Ebox housing – Ebox cover IF	51031	Random X	6.93	5.05	0.56	0.63
	51032	Random X	5.88	4.25	0.55	0.62
	51033	Random X	8.08	5.93	0.57	0.65
	51034	Random X	5.44	3.91	0.54	0.60
	51035	Random X	2.96	2.03	0.48	0.48
	51036	Random X	4.45	3.16	0.53	0.57
	51037	Random X	1.99	1.28	0.41	0.36
	51038	Random X	7.32	5.35	0.56	0.63
Ebox cover – Senhousing basis IF	51121	Random X	6.55	4.77	0.56	0.63
	51122	Random X	4.44	3.15	0.53	0.57
	51123	Random X	5.79	4.18	0.55	0.61
	51124	Random X	7.64	5.60	0.57	0.65
	51125	Random X	8.27	6.08	0.57	0.65
	51126	Random X	9.18	6.77	0.57	0.66
	51127	Random X	9.77	7.22	0.57	0.66
	51128	Random X	8.04	5.90	0.57	0.65
Senhousing basis – Unit p support IF	91001	Random X	19.81	14.88	0.59	0.70
	91002	Random X	16.57	12.41	0.59	0.69
	91003	Random X	19.82	14.89	0.59	0.70
	91004	Random X	17.60	13.20	0.59	0.69
Senhousing basis – Unit i support IF	92001	Random X	51.81	39.31	0.60	0.71
	92002	Random X	53.27	40.43	0.60	0.71
	92003	Random X	61.45	46.67	0.60	0.71
	92004	Random X	60.70	46.10	0.60	0.71

Table 8-4: Margins on safety on bolt shear failure (original random)

IF	CBUSH ID	Most severe load case				
		Random with notching	$MoS_{S,y}$	$MoS_{S,u}$	$MoS_{Comb,y}$	$MoS_{Comb,u}$
STEP IF	10001	Random X	26.76	20.19	0.69	0.79
	10002	Random X	35.64	26.97	0.69	0.80
	10003	Random X	26.16	19.73	0.69	0.79
	10004	Random X	26.12	19.70	0.69	0.79
	10005	Random X	32.28	24.41	0.69	0.80
	10006	Random X	26.03	19.63	0.68	0.79
Ebox housing – Ebox cover IF	51031	Random X	21.49	16.17	0.59	0.69
	51032	Random X	18.22	13.67	0.59	0.69
	51033	Random X	24.47	18.44	0.59	0.70
	51034	Random X	16.04	12.00	0.59	0.69
	51035	Random X	9.89	7.31	0.58	0.67
	51036	Random X	13.91	10.38	0.59	0.69

	51037	Random X	7.40	5.41	0.57	0.65
	51038	Random X	22.01	16.56	0.59	0.69
Ebox cover – Senhousing basis IF	51121	Random X	19.93	14.97	0.59	0.69
	51122	Random X	14.58	10.89	0.59	0.69
	51123	Random X	17.87	13.40	0.59	0.69
	51124	Random X	22.48	16.92	0.59	0.70
	51125	Random X	24.80	18.70	0.60	0.70
	51126	Random X	27.00	20.37	0.60	0.70
	51127	Random X	28.05	21.17	0.59	0.70
	51128	Random X	23.33	17.57	0.59	0.70
Senhousing basis – Unit p support IF	91001	Random Y	50.59	38.38	0.60	0.70
	91002	Random Y	34.43	26.04	0.60	0.70
	91003	Random X	54.30	41.21	0.60	0.71
	91004	Random X	47.26	35.83	0.60	0.71
Senhousing basis – Unit i support IF	92001	Random Y	102.48	77.99	0.60	0.71
	92002	Random Y	101.19	77.00	0.60	0.71
	92003	Random X	156.41	119.15	0.60	0.71
	92004	Random X	155.51	118.47	0.60	0.71

Table 8-5: Margins on safety on bolt shear failure (random with notching)

8.5 Bolt analysis conclusions

This bolt analysis shows negative MOS for the following cases:

- Original random specification:
    - Sliding: Negative MOS on sliding for 2 STEP IF bolts, for all Ebox housing – Ebox cover IF bolts and for all Ebox cover – Senhousing basis IF bolts.
- Random with notching:
    - Sliding: Negative MOS on sliding for 2 Ebox housing – Ebox cover IF bolts.

The applied torque for M3 titanium screws is 2.1 Nm. If this torque is increased to **3.1 Nm**, all MOS are positive for all M3 bolts for the random with notching load case, but there are still negative MOS on sliding for the original random load case.

9 CONCLUSIONS

This technical note shows stress and acceleration results in according to original random specification [AD8] and random specification with notching [RD9].

The model analysed in this technical note has been previously correlated with the PQM STEP Low Level tests results [RD6].

This technical note also shows the bolt analysis with the resultant forces obtained from random analyses.