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Vibration Lab

April 4th, 2018

Objectives➔

The main target of this lab is to execute a couple series of vibration tests on a chip called PCB (printed circuit board). The scientific experience commences with analyzing a PCB assembly to determine the normal modes. Based on the PCB analysis we will be able to determine the location of the monitoring accelerometer and the most accurate location on the board. Our next step is to fix the fasteners in the board to be able to determine the stresses and the loads. Upon determining the normal modes, NX analysis, stresses and loads, the margin of safety will be determined. The final step is to perform a vibration test on the PCS and observe the outputs of the PCB's vibrations characteristics and match with the NX prediction (stress and margins of safety).

Purpose➔

The target of the experiment is to test the board in different vibrations, pressures and stresses to ensure the durability during the space shuttle's launch to reach outer space and return to Earth's surface. The board passes through two stages of a pre-departure (static mode) and during the launch towards the desired orbit (dynamic mode). So various loads for various modes. These loads catalyzed during the launch which caused by gusts, transonic velocity stage. Other induces like, fairing jettison, liftoff, the shock of separation, thrusters, pressure loading. For vibration lab, we have a specific requirement in which testing data is gathered for is resonance survey test, sinusoidal vibration test and random vibration test (qualification and acceptance testing requirements for launch).

Table 1 states the characteristics of the resonance survey test and indicates whether it is required or not. Vibration resonance occurs when our board is exposed to an external forced vibration. This vibration resonances can cause a lot of damages to the board and decrease the life-time of the board. As we see in (QB50-SYS-2.2.1) the lowest natural of the board shall be > 90 Hz. At this frequency the system of the board will fluctuate after facing an external force (natural frequency at which the system is under vibration mode). During the test, the board shall be attached to a fixed rigid structure. After that we will be able to run a resonance survey test before and after running the test at full level. Comparing the results of the test before and after. We will be able to find the fatigue of the material or the damage. Depending on the test equipment higher value could be required to properly identify the natural frequencies of the board. On our lab we will apply a test only on a sinusoidal vibration and random vibration.

	Qualification		Acceptance	
Resonance survey test	Required		Required	
Reference Frame	{BRF}		{BRF}	
Direction	X, Y, Z		X, Y, Z	
Type	Harmonic		Harmonic	
Sweep rate	2 oct/min		2 oct/min	
Profile	**Frequency**, $[Hz]$	**Amplitude**, $[g]$	**Frequency**, $[Hz]$	**Amplitude**, $[g]$
	5	0.15*	5	0.15*
	100	0.15*	100	0.15*

Sinusoidal vibrations occur during flight because of launch, ascent transients and oscillatory flight events. The vibrations include low-frequency flight dynamic events such as liftoff transients, transonic/maximum Q oscillations, pre-MECO (Main Engine Cut-Off) sinusoidal oscillations, MECO transients and second/third stage events. A sinusoidal vibration resonance survey is occurring before and after the test on each axis. Based on the data, any significant change in the values means a sign of damage.

	Qualification		**Acceptance**	
Sine vibration test	Required		Required	
Reference Frame	{BRF}		{BRF}	
Direction	X, Y, Z		X, Y, Z	
Sweep rate	2 oct/min		4 oct/min	
Profile	**Frequency**, *[Hz]*	**Amplitude**, *[g]*	**Frequency**, *[Hz]*	**Amplitude**, *[g]*
	5	1.3	5	1
	8	2.5	8	2
	100	2.5	100	2

Random vibrations are mainly generated by acoustic noise field under the payload fairing. These vibrations can however be neglected when designing a spacecraft. Random vibrations depend on specific payload configuration; hence, the definition of a generic random vibration environment is inapplicable.

	Qualification		**Acceptance**	
Random vibration test	Required		Required	
Reference Frame	{BRF}		{BRF}	
Direction	X, Y, Z		X, Y, Z	
RMS acceleration	8.03 g		6.5 g	
Duration	120 s		60 s	
Profile	**Frequency**, *[Hz]*	**Amplitude**, $[g^2/Hz]$	**Frequency**, *[Hz]*	**Amplitude**, $[g^2/Hz]$
	20	0.009	20	0.007
	130	0.046	50	0.007
	800	0.046	200	0.035
	2000	0.015	640	0.035
			2000	0.010

Acoustic noise is generated throughout the boost phase of the flight until the vehicle is out of the atmosphere. Acoustic noise is generated by engine noise, buffeting (The launch vehicle's components being struck repeatedly) and boundary layer noise. Thus, it is crucial to determine the magnitude of each of these vibrations and infer whether a PCB can handle the variety of loads, to ensure that it will reach its orbit and function at its maximum potential. The incident acoustic wave generates various modes of vibration in a structure, causing the stress concentrations which lead to eventual failure.

Prelab Activities➔

As we see in figure 1, the part created in by using NX. Note that all the bolt locations were included but only the specified ones will be constrained. A part file was created using the given dimensions in figure 2.

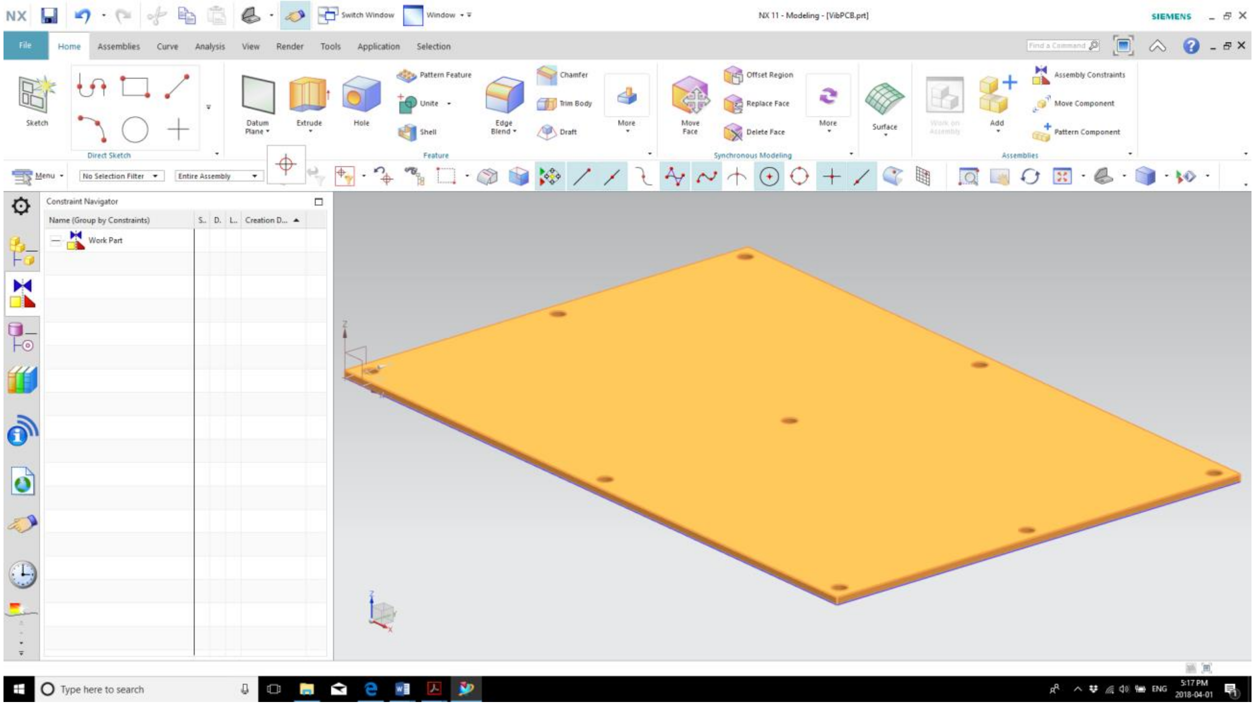


Figure 1, NX part file

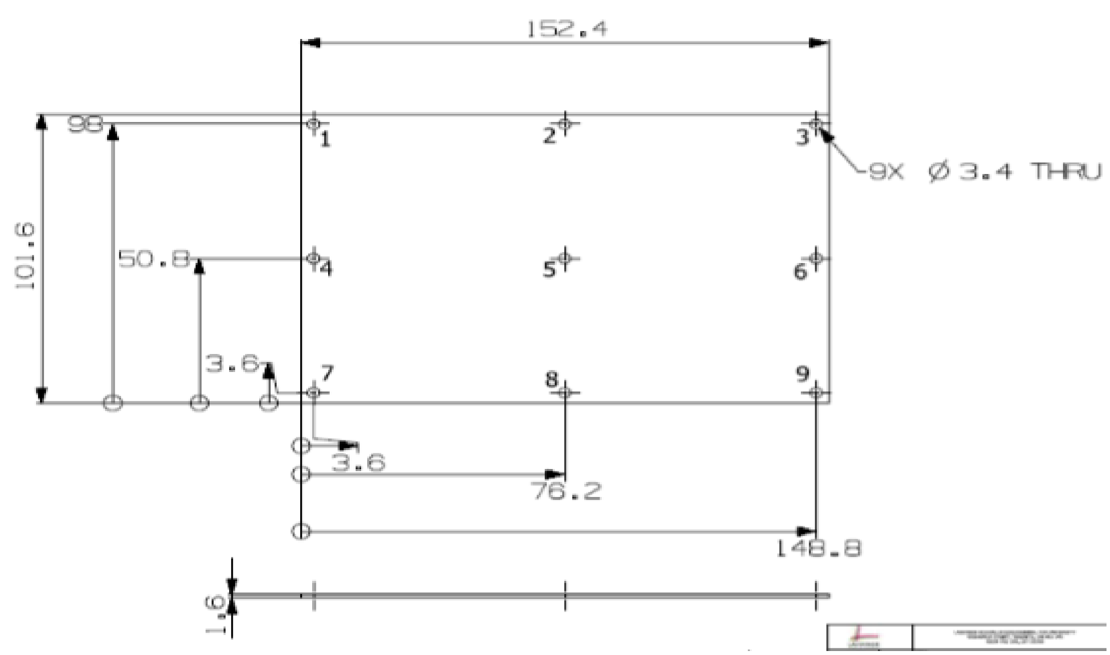


Figure 2, PCB dimensions and fasteners positions

Following the part file, a FEM was created and meshed using 5mm element size. Note that only the top side was meshed. As we can see here in figure 3 shows the meshed part.

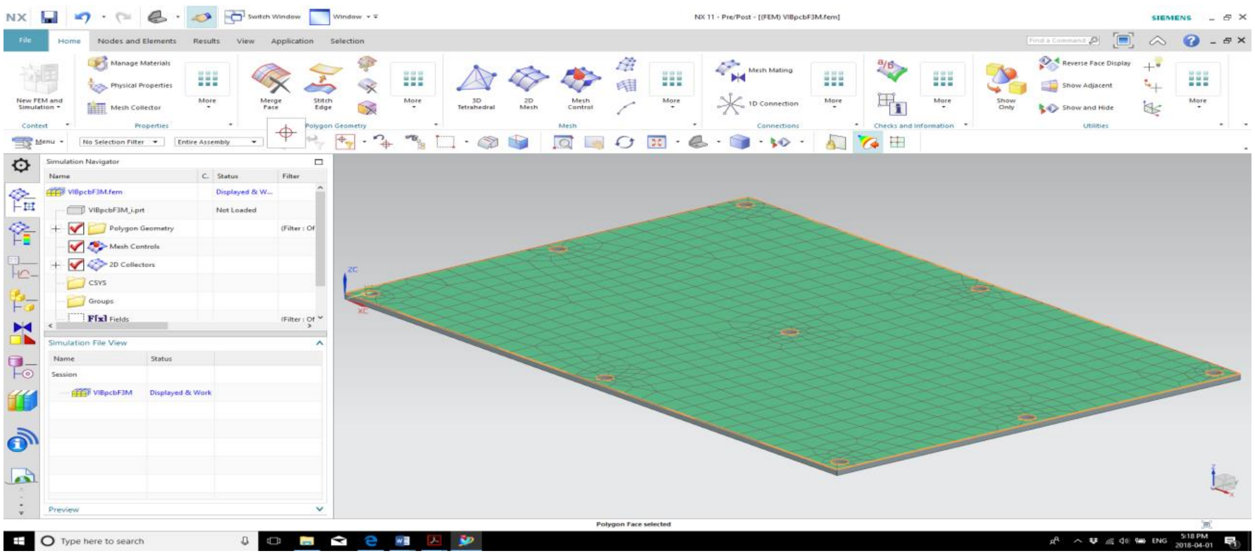


Figure 3: NX FEM file using a 2D mesh and 5mm element size

The material used was 370HR. the material properties are listed in figure 4.

Peel Strength	A. Low profile copper foil and very low profile copper foil all copper foil >17 µm [0.669 mil] B. Standard profile copper 1. After thermal stress 2. At 125°C (257°F) 3. After process solutions	1.14 (6.5) 1.25 (7.0) 1.25 (7.0) 1.14 (6.5)	N/mm (lb/inch)	2.4.8C 2.4.8.2A 2.4.8.3 2.4.8.3
Flexural Strength	A. Length direction B. Cross direction	90,000 77,000	ksi	2.4.4B
Tensile Strength	A. Length direction B. Cross direction	55,900 35,620	ksi	ASTM D3039
Young's Modulus	A. Length direction B. Cross direction	3744 3178	ksi	ASTM D790-15e2
Poisson's Ratio	A. Length direction B. Cross direction	0.177 0.171	–	ASTM D3039
Moisture Absorption		0.15	%	2.6.2.1A
Flammability (Laminate & laminated prepreg)		V-0	Rating	UL 94
Max Operating Temperature		130	°C	UL 796

Figure 4: Appendix B material data.

Following the FEM, a SIM file was created to perform dynamic structural analysis to find the normal modes of the PCB. Figure 5 shows the options chosen in the solution window.

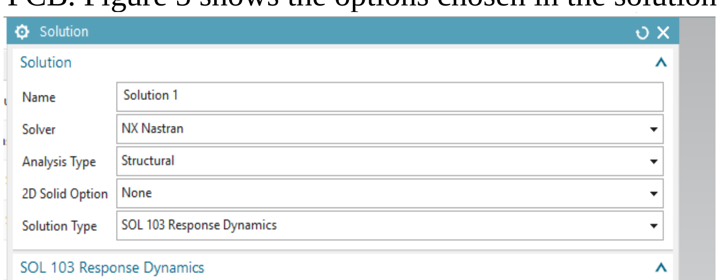


Figure 5: Solution window details

Following the solution window, a new user defined constraint was added. Refer to figure 6 for the constraint's location (2, 4, 6, 8 and 9).

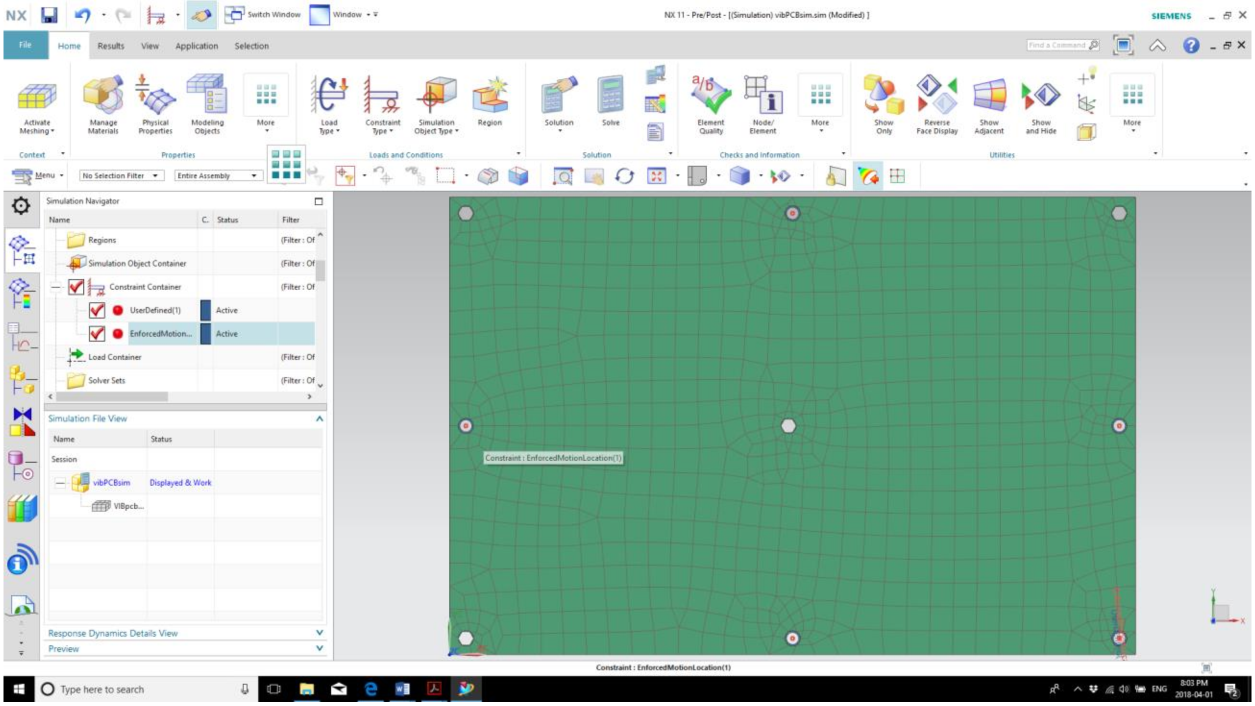


Figure 6: Constrains were added on the same locations as the fasteners.

The same procedure was followed for the enforced motion. However, all the DOF where set to free except DOF3 was set to enforced. Figure 7 shows the frequency limits and desired number of nodes.

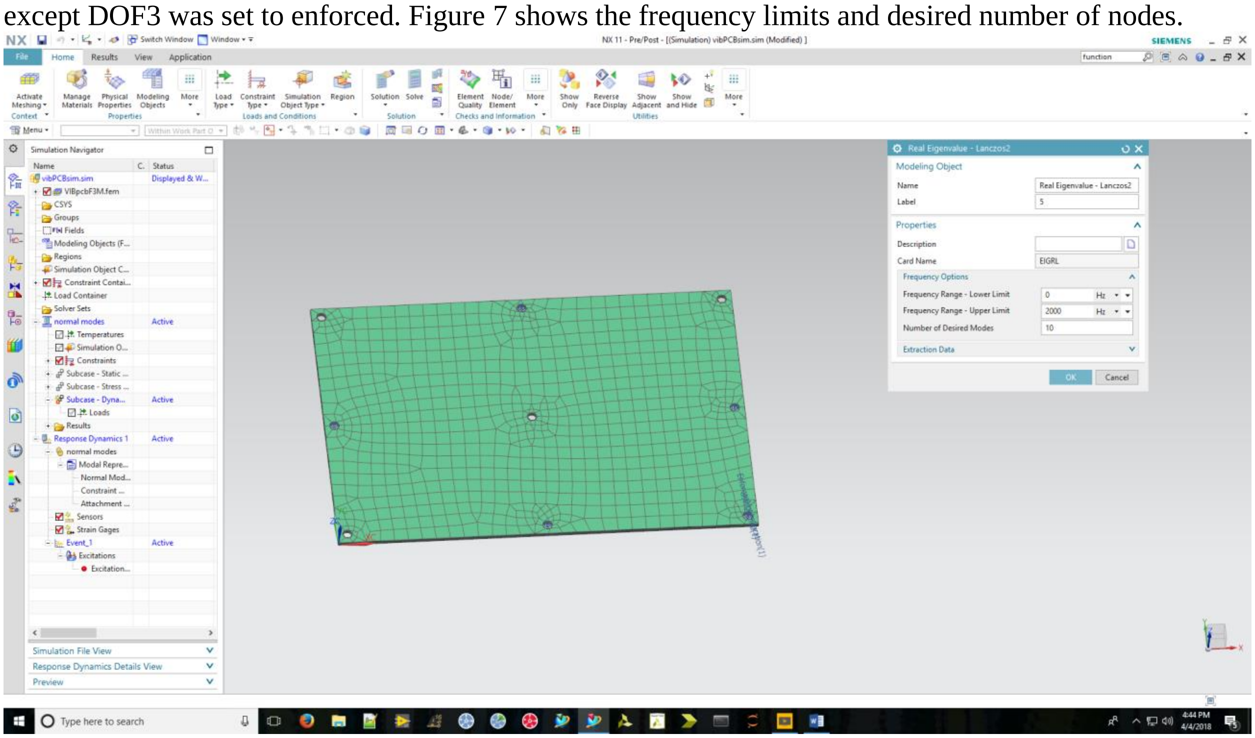
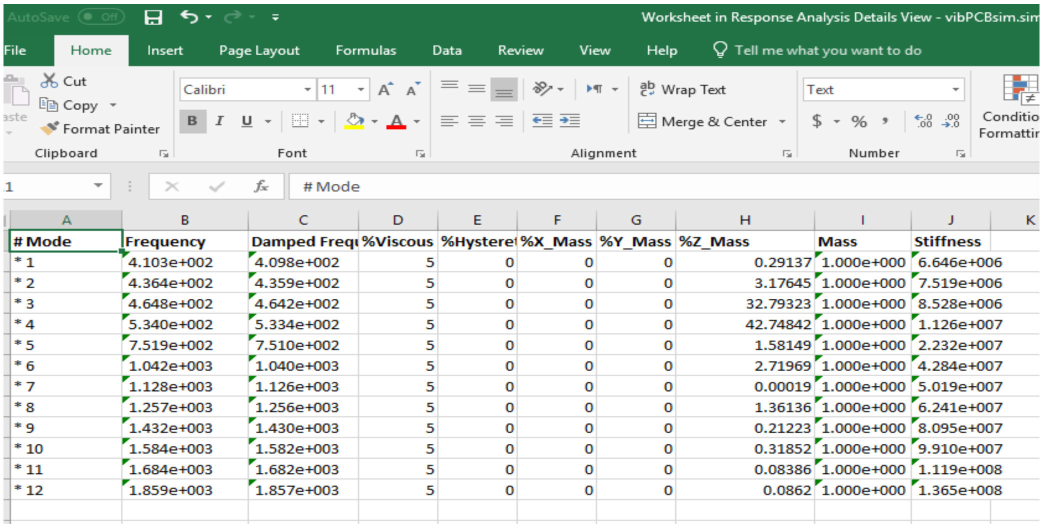


Figure 7: Setting frequency limits

Note that the normal modes are the modes with a high displacement percentage in the Z-direction.



# Mode	Frequency	Damped Frequ	%Viscous	%Hystere	%X_Mass	%Y_Mass	%Z_Mass	Mass	Stiffness
* 1	4.103e+002	4.098e+002	5	0	0	0	0.29137	1.000e+000	6.646e+006
* 2	4.364e+002	4.359e+002	5	0	0	0	3.17645	1.000e+000	7.519e+006
* 3	4.648e+002	4.642e+002	5	0	0	0	32.79323	1.000e+000	8.528e+006
* 4	5.340e+002	5.334e+002	5	0	0	0	42.74842	1.000e+000	1.126e+007
* 5	7.519e+002	7.510e+002	5	0	0	0	1.58149	1.000e+000	2.232e+007
* 6	1.042e+003	1.040e+003	5	0	0	0	2.71969	1.000e+000	4.284e+007
* 7	1.128e+003	1.126e+003	5	0	0	0	0.00019	1.000e+000	5.019e+007
* 8	1.257e+003	1.256e+003	5	0	0	0	1.36136	1.000e+000	6.241e+007
* 9	1.432e+003	1.430e+003	5	0	0	0	0.21223	1.000e+000	8.095e+007
* 10	1.584e+003	1.582e+003	5	0	0	0	0.31852	1.000e+000	9.910e+007
* 11	1.684e+003	1.682e+003	5	0	0	0	0.08386	1.000e+000	1.119e+008
* 12	1.859e+003	1.857e+003	5	0	0	0	0.0862	1.000e+000	1.365e+008

Figure 8, the normal modes.

Note that the maximum displacement is at the bottom left or top left. Hence, the accelerometer can be placed at either location.

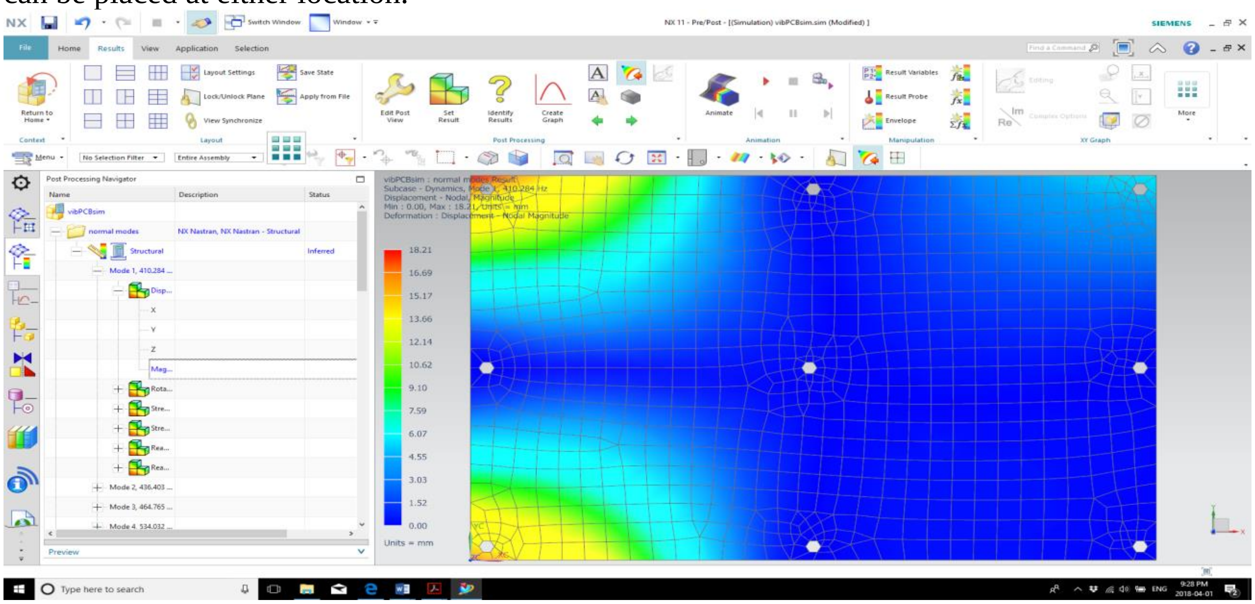


Figure 9, shows the displacement for one of the normal modes

After finding the normal modes, new response dynamics was created to perform the sequence of tests on the PCB. two functions were created using the function tools for Response Dynamics tab. One function was created using random PSD and the other using frequency with the following values for Sine and random vibration➔

Frequency (Hz)	Amplitude (g)
5 - 100	2.5
100 - 125	1.25

Frequency (Hz)	Amplitude (g^2/Hz)
20	0.01124
130	0.05625
800	0.05625
2000	0.015

Following the two functions, two new events were created, each event using its specified function (Random PSD even uses function with Random PSD values and Frequency even uses function with Frequency values). After creating the events, a sensor was placed at approximately the same location the accelerometer was placed in (Figure 10).

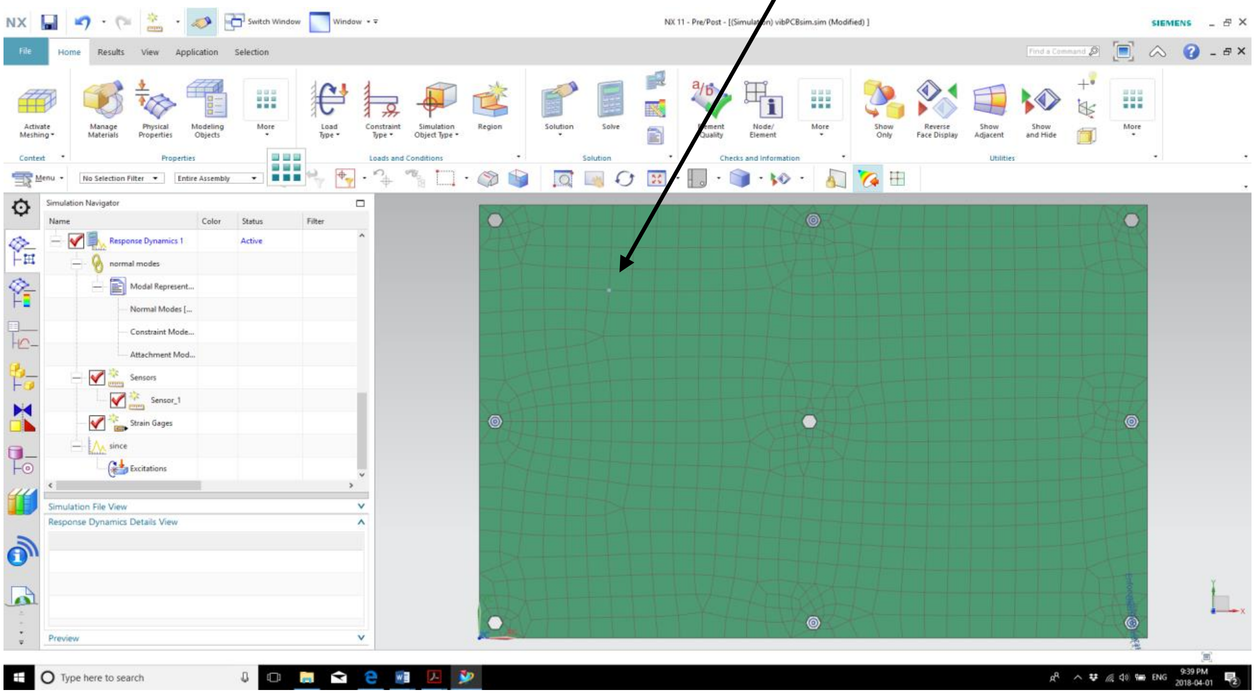


Figure 10, Sensor placement at relatively the same location of the accelerometer in the vibration test

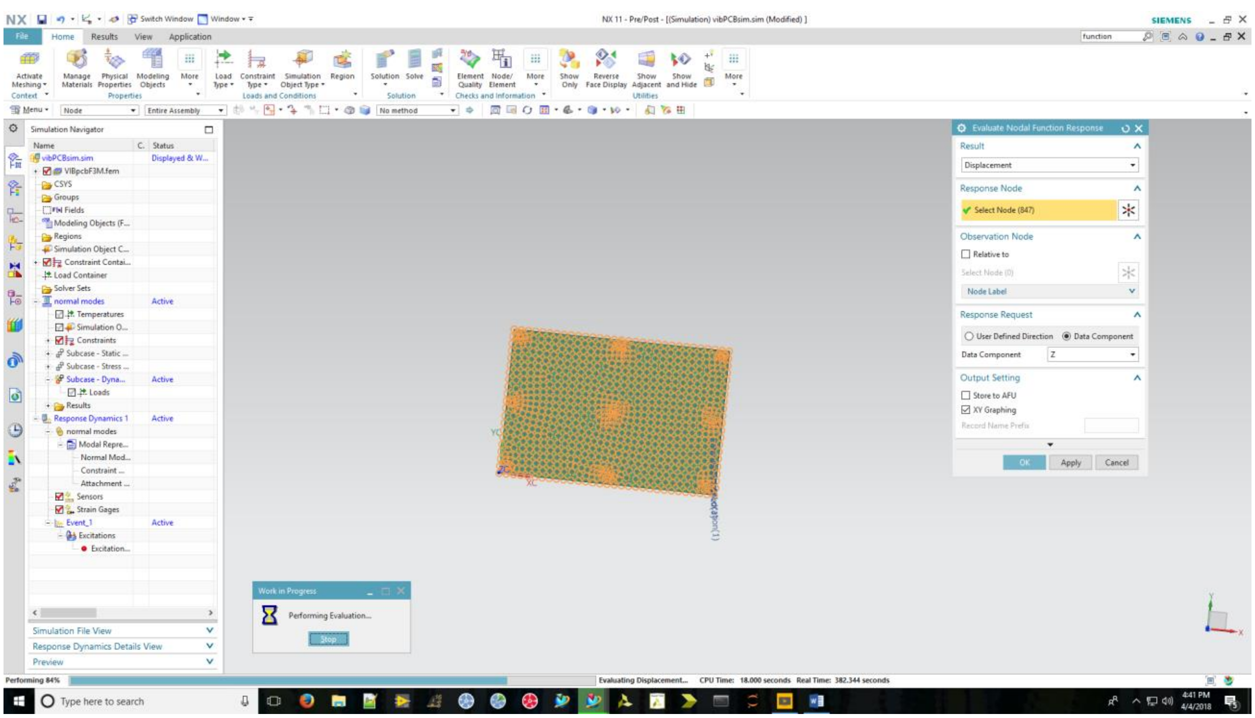


Figure 11, Evaluate Nodal function response.

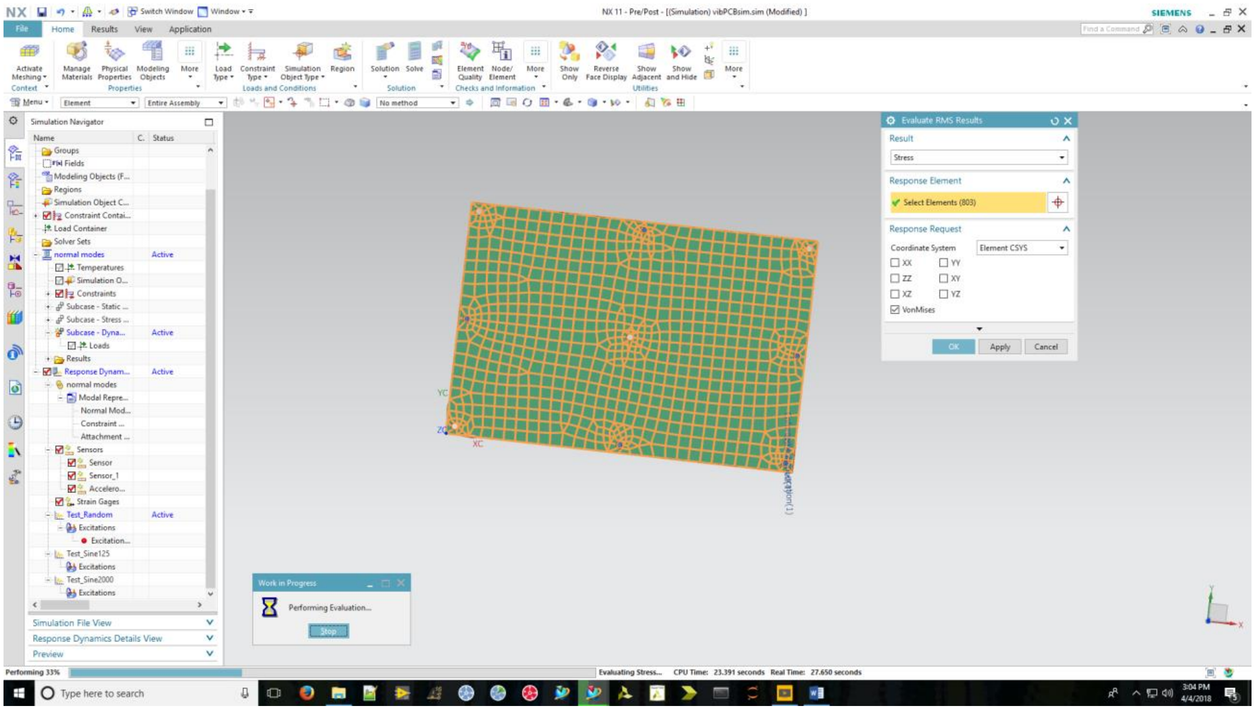


Figure 12: Select the entire PCB and choose the response request as Von-Mises

And now let's discuss the Pre-Lab questions ➔

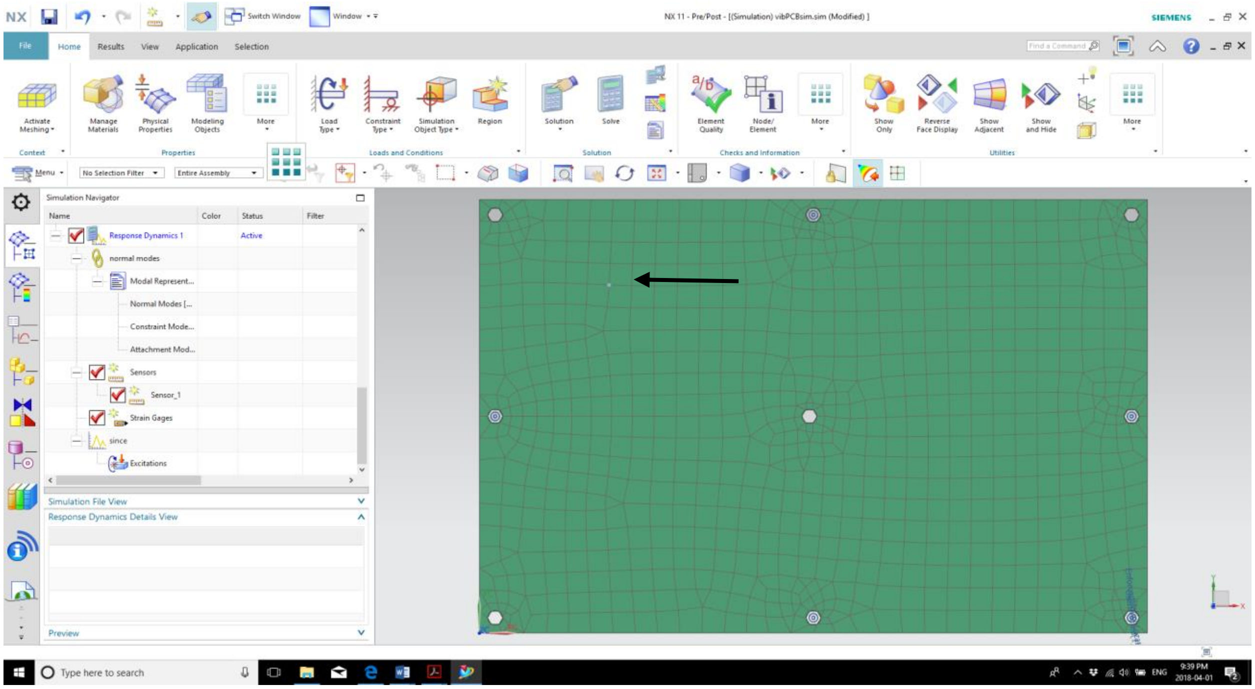
1) *Determine the normal modes of the PCB in Appendix A (see the tutorials for how to do this using NX). Note – you will be told which of the 9 fastener locations that your group will be using to test the PCB.*

A	B	C	D	E	F	G	H	I	J	K
# Mode	Frequency	Damped Freq	%Viscous	%Hysteret	%X_Mass	%Y_Mass	%Z_Mass	Mass	Stiffness	
* 1	4.103e+002	4.098e+002	5	0	0	0	0.29137	1.000e+000	6.646e+006	
* 2	4.364e+002	4.359e+002	5	0	0	0	3.17645	1.000e+000	7.519e+006	
* 3	4.648e+002	4.642e+002	5	0	0	0	32.79323	1.000e+000	8.528e+006	
* 4	5.340e+002	5.334e+002	5	0	0	0	42.74842	1.000e+000	1.126e+007	
* 5	7.519e+002	7.510e+002	5	0	0	0	1.58149	1.000e+000	2.232e+007	
* 6	1.042e+003	1.040e+003	5	0	0	0	2.71969	1.000e+000	4.284e+007	
* 7	1.128e+003	1.126e+003	5	0	0	0	0.00019	1.000e+000	5.019e+007	
* 8	1.257e+003	1.256e+003	5	0	0	0	1.36136	1.000e+000	6.241e+007	
* 9	1.432e+003	1.430e+003	5	0	0	0	0.21223	1.000e+000	8.095e+007	
* 10	1.584e+003	1.582e+003	5	0	0	0	0.31852	1.000e+000	9.910e+007	
* 11	1.684e+003	1.682e+003	5	0	0	0	0.08386	1.000e+000	1.119e+008	
* 12	1.859e+003	1.857e+003	5	0	0	0	0.0862	1.000e+000	1.365e+008	

Figure 13, the normal modes

The normal modes are at numbers 3, 4 and 2. This is because these modes have the highest percentage of mass that moved in the Z-direction.

2) *Based on the modes, recommend an accelerometer location to be monitored during the test.*



As seen in figure 14 above, the accelerometer should be placed in the top left of the PCB. this is because at that location, the PCB experiences the largest displacement.

3) *Using your NX model, predict the acceleration of a selected chip accelerometer during the low-level sine test. Select the chip location that will give the largest acceleration (see Appendix for details).*

Based on the modes, given that we only have one accelerometer, the best placement for the accelerometer is closer to one of the 4 corners. Because the motion in the Z direction is the greatest at these locations. This means that the greatest translational stress and the largest acceleration are applied at the corners. The two figures below demonstrate this effect.

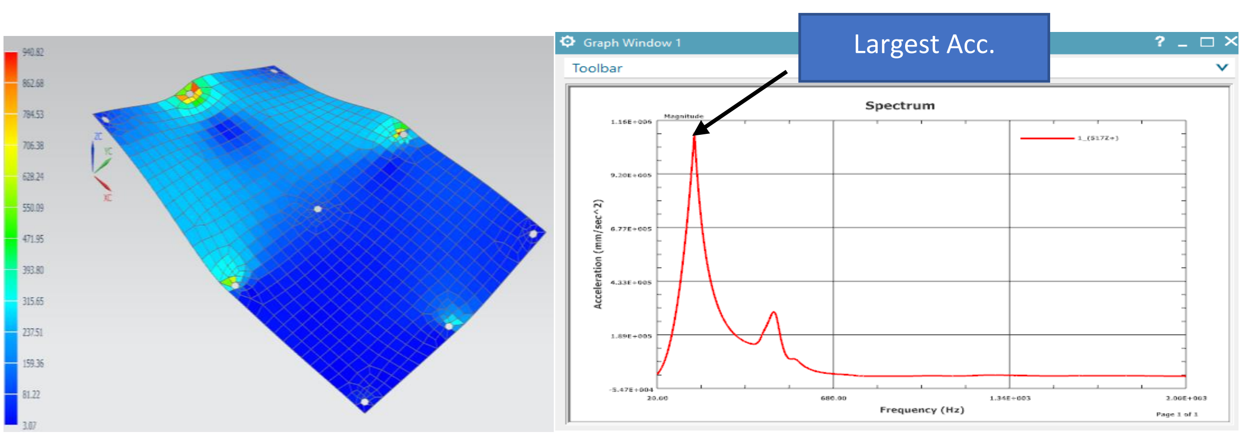


Figure 13, Showing the Von Mises and the largest Acceleration.

4) *Perform a forced-vibration analysis (see the tutorials for how to do this using NX) to determine the stresses in the PCB considering the random vibration spectrum input.*

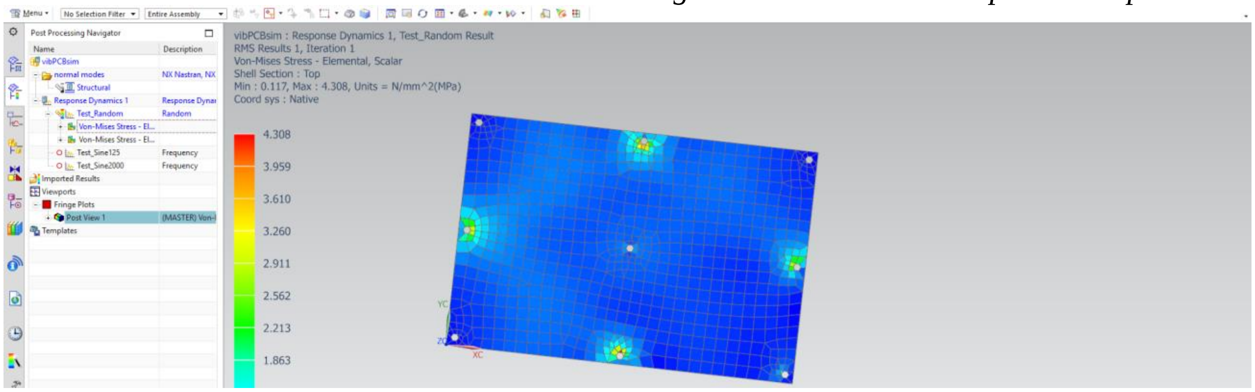


Figure 14, Showing the Von Mises (different angle)

The stresses above are shown as a RMS Von Mises contour plot using the response simulation. The max stress is 4.3 which will be used to find the Margin of safety.

Procedure and observations➔

We first mounted the PCB to the top surface of the fixture using the bolts that were used in the Pre-Lab analysis. Then we mounted a small accelerometer in the location that was chosen from the Pre-Lab work, see figure 15 and 16. In figure 17, the blue wire is the accelerometer channel (the measurement channel) and the white wire is channel one. After insuring the correctness of the setup, the following sequence of tests was performed using the control PC:

Low-level sine
Sine
Low-level sine
Random
Low-level sine

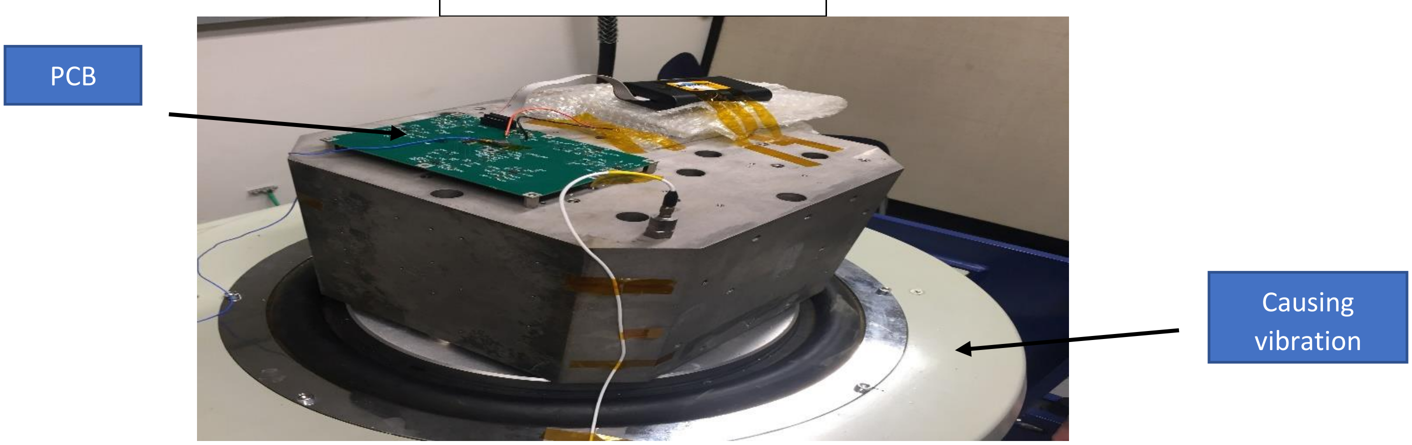


Figure 15, main fixture mounted on the shaker

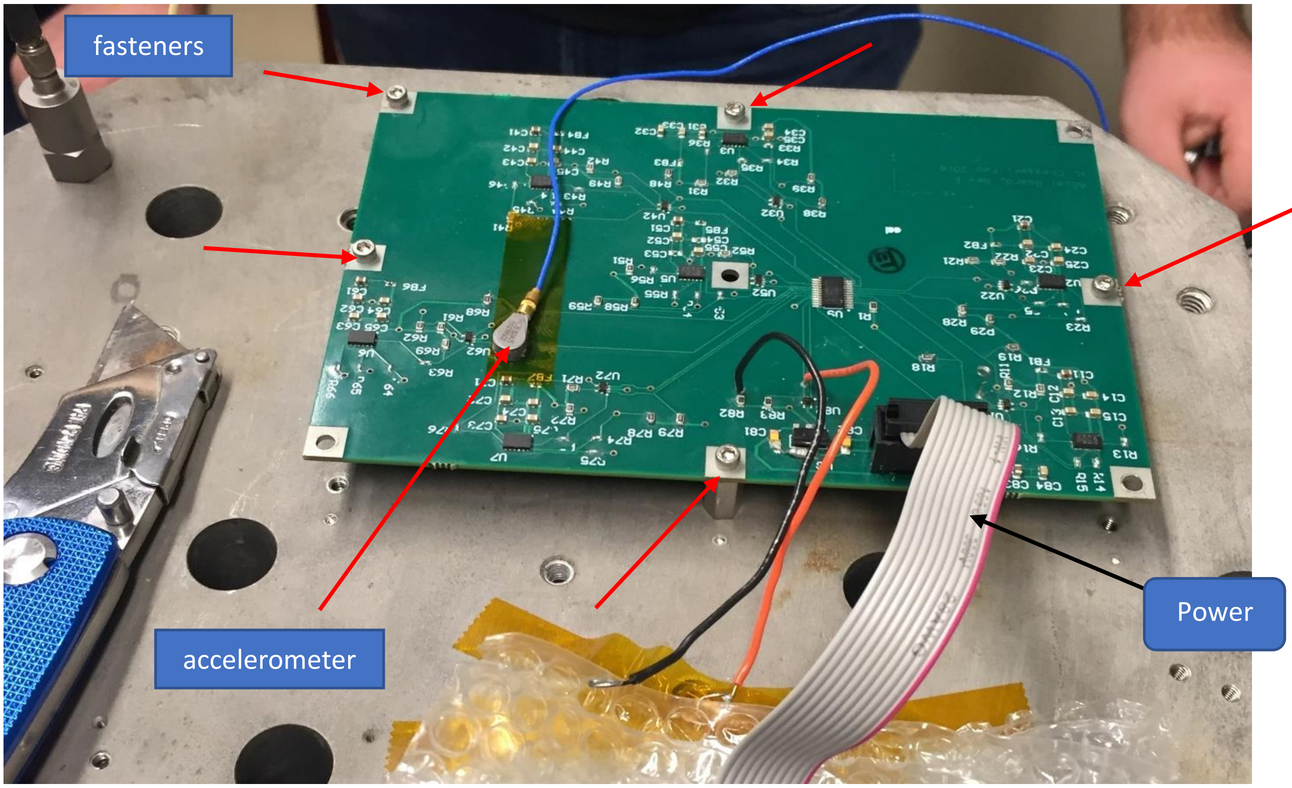


Figure 16, PCB set-up in the vibration lab, the fasteners are places on the board and the accelerometer as well

The accelerometer was placed in a position of maximum displacement, which was inferred from the prelab work done using NX.

Figure 17, CPU of the control PC connecting the accelerometer with the PCB

For the computer simulation observations and procedures, we used NX Nastran. We used the PCB listed in Appendix A to model the part in NX and created a NX Nastran FEM file with a 2D mesh. We then created a NX Nastran Simulation file and ran a dynamic structural analysis to find the normal modes solution. In the Solutions window, we selected the “103 Response dynamics” and in the dynamics subcase we edited the solution parameters specifically we entered the frequency limits from 0 to 2000 kHz. From there we were able to create some constraints to match the real test that is done in the vibration lab (all these steps mentioned with pictures in the pre-lab part).

The constraints included adding a user defined constraint where the X and Y directions are fixed, and the Z and the angle directions are free to move. The Z direction was then enforced to simulate the effects of launch where the screws were secured. The simulation was then solved and processed using the Response dynamics menu to view details about the Normal modes of the PCB. Thereafter, we were about to add dynamic loading to the simulation from the function tools menu. From the menu we select the Random PSD option and enter the parameters in the lab instructions. We then created a loading event and excitation in the Z direction. And to avoid running the simulation forever, we will add a damping factor about 5%. The Response can be viewed from the “Evaluate Function Response” menu of the event.

Discussion and Interpretation➔

Answering the post-lab questions➔

1) *Provide all vibration plots and from the low-level sine plots extract the measured natural frequencies of the structure*

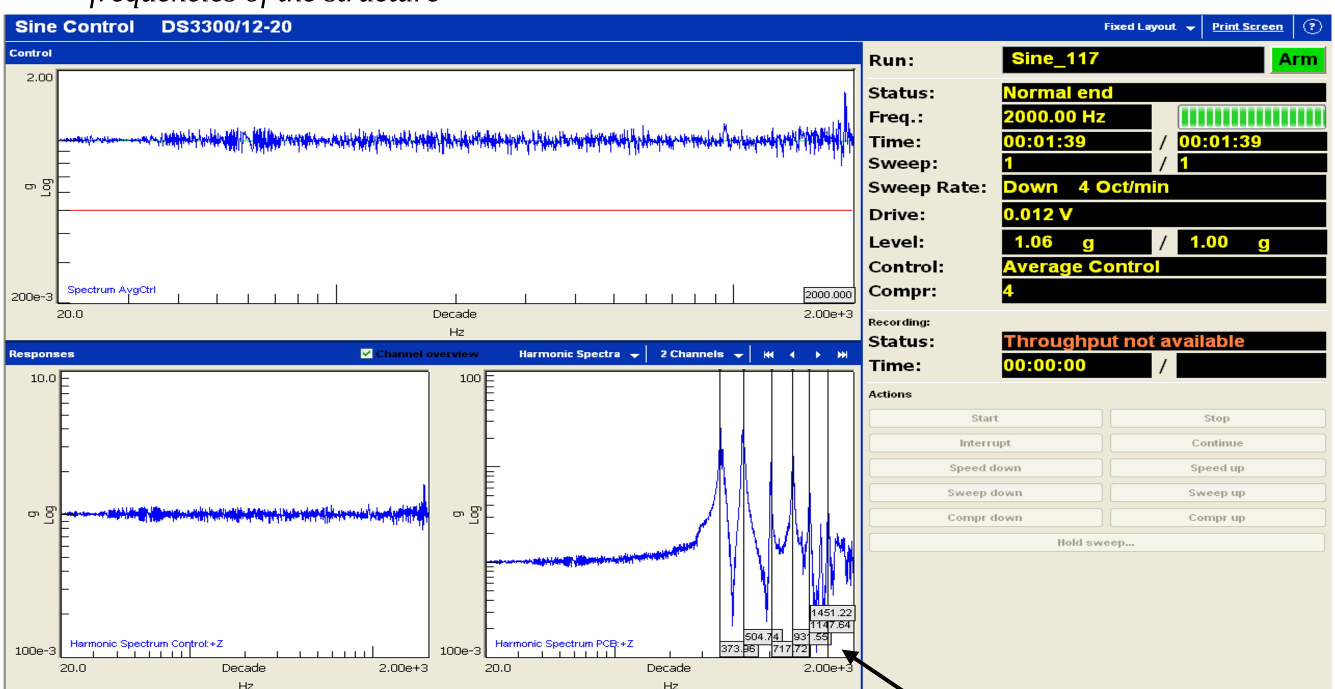


Figure 18: Low-level sine test (Normal modes)

Using these values for Q2.

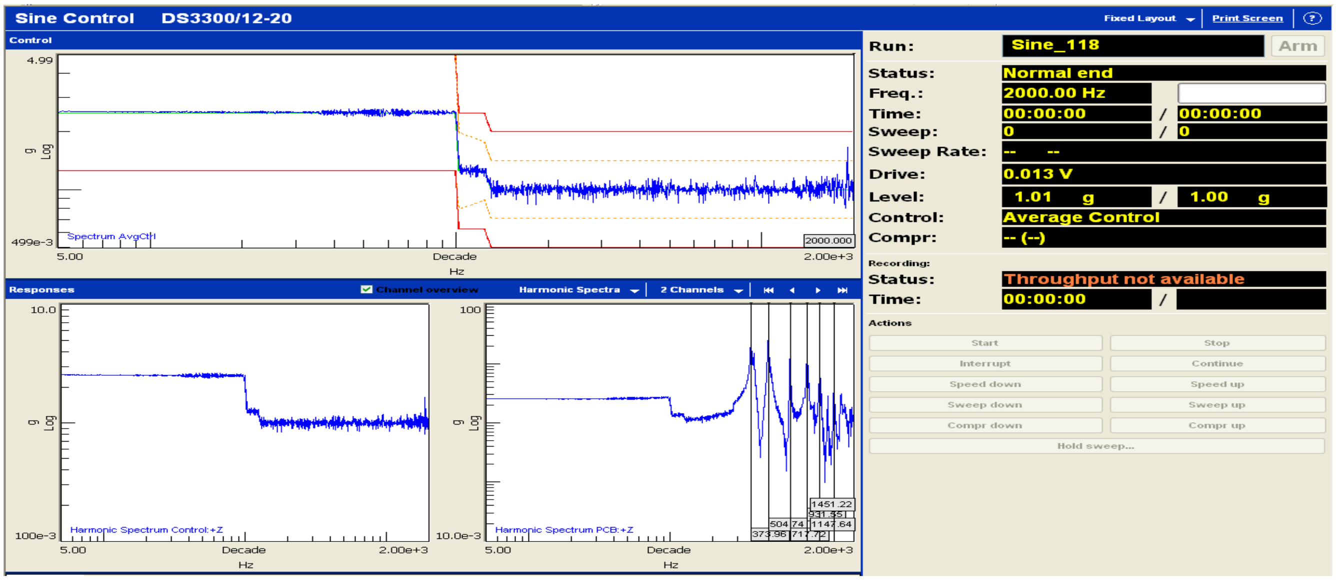


Figure 19: Sine test

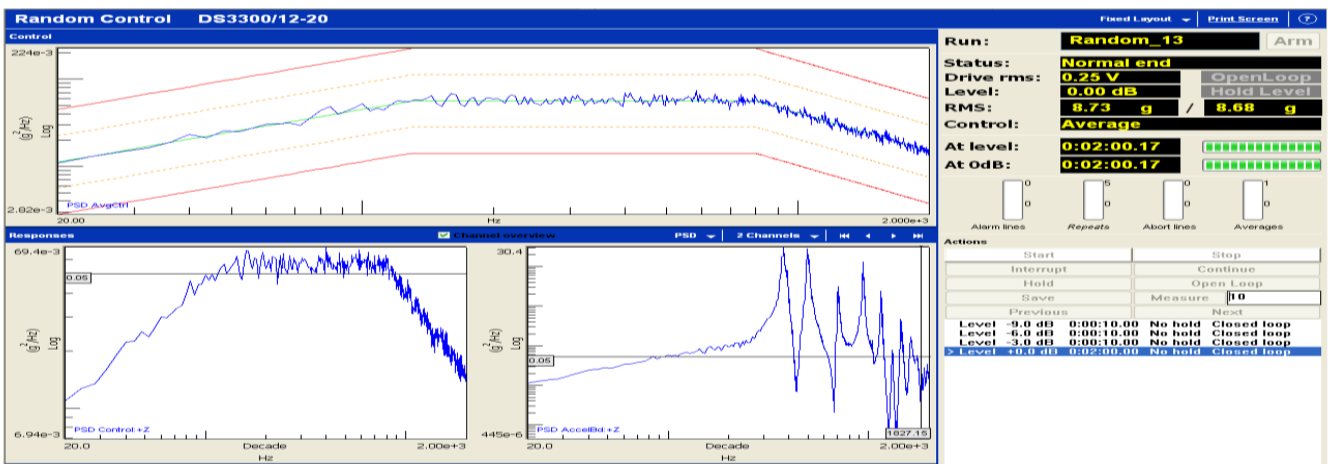
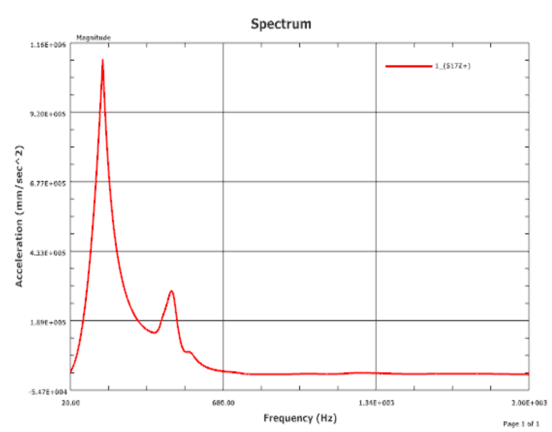


Figure 20: Random test



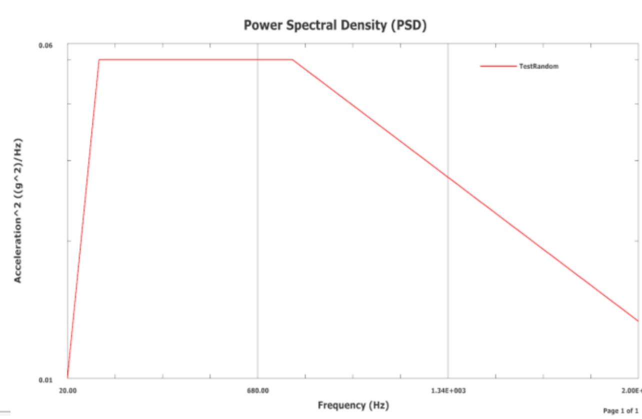


Figure 21: Sine test… Figure 22: Random test ➔ *these two plots from NX*

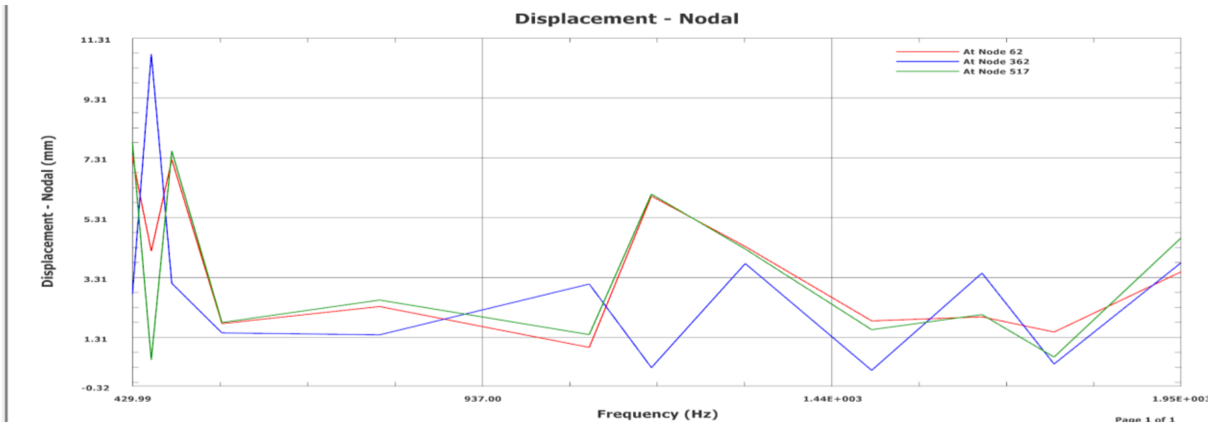
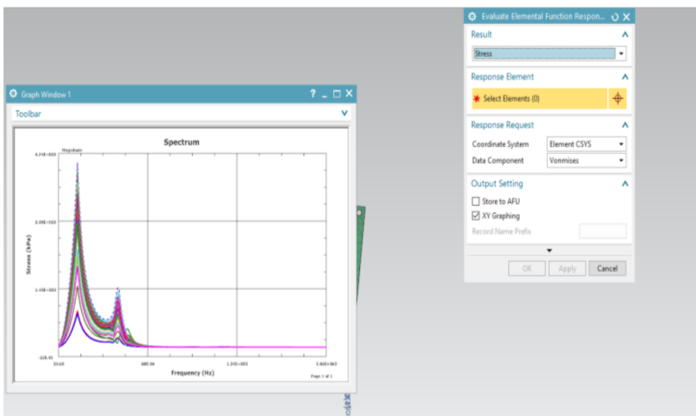


Figure 23, various locations of the sensor on the board will provide this graph (NX)



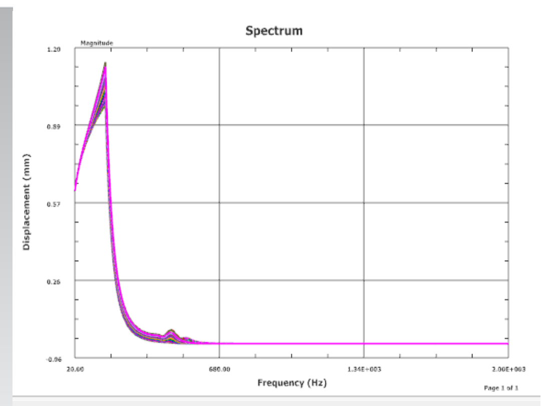


Figure 24, Stress Vs Frequency … Figure 25, Displacement vs Frequency (NX)

2) *Compare your vibration predictions from the Pre-Lab with the test results. Do the frequencies match? How well – provide a table listing the measured vs. predicted frequencies and the % difference*

Vibration Test Frequency Hz	NX Simulation Frequency Hz	Percentage Difference %
373.96	534	45
504.74	464.8	7.9
717.72	436.4	39
931.55	1042	11
1147.64	751.9	34
1451.22	1257	12.3

Some possible error sources are that the density used for the PCB in the computer simulation is not exact. Another source of error might be the meshing size. Using a larger meshing size can provide values that have larger error. Another possible error can be the way the calculations were performed. This means that the steps taken to calculate the normal modes are incorrect or some crucial steps were missing.

3) *Provide a table of stresses and Margins of Safety – provide a contour plot of the predicted stresses*

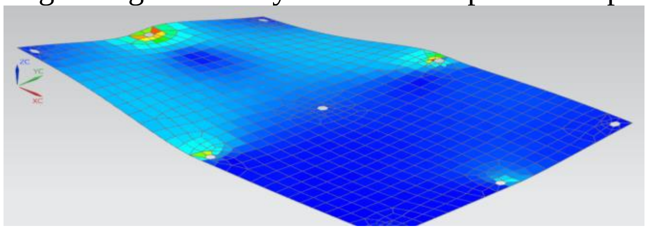
The equation used to calculate the Margin of Safety is:

$$MOS = \frac{FS}{SF*S*3} - 1$$

Where MOS is the Margin of Safety, upper case S is the maximum stress applied, and SF is the safety factor (Spacecraft ~ 1.1 – 2.0). Here the strength flexure(FS) 90,000 lb/in^2, which is 620.5 MPa, see figure 4. Max of Von-Mises is 4.3 MPa, see question (4 or 3) pre-lab activity.

SF	Max of Von-Mises	Safety Factor	MOS
650.5	4.3	1.1	45.8
650.5	4.3	1.2	42
650.5	4.3	1.3	38.7
650.5	4.3	1.4	36
650.5	4.3	1.5	33.6
650.5	4.3	1.6	31.5
650.0	4.3	1.7	29.66
650.0	4.3	1.8	28
650.5	4.3	2.0	25.2

The best choice for Factor of Safety is to 1.1 since we can save cost by saving weight and still manage to have a pretty high margin of safety. The contour plot of the predicted stresses ➔



Pre-lab activity, Question 4 or 3

Conclusions➔

Comparing figures 21 and 19, which are the results of the sine test from the vibration lab and computer simulation respectively, both graphs have a similar shape with the peaks.
Some possible reasons for the difference in magnitudes is that for the computer simulation, all the tests are performed according to the obtained normal modes, and since there was a 24% difference between the normal modes from the vibration lab and computer simulation, the results have deviated from each other due to the 24% difference acting as a systematic error.
To improve results, the material properties of the PCB should be revised to ensure that the PCB used in the vibration test is the same as the PCB used in the computer simulation. Another possible error source is that the calculations in NX are made for a specific element size. However, if the element size is too small, a normal PC might not be able to handle all the calculations. Thus, the results might not be as accurate. Also, the MOS is reasonable as we have

larger safety factor we will have smaller MOS. But we make sure that the MOS is larger than zero. In conclusion, aside from learning how to perform each vibration test using NX, the most important thing leaned is that a low-level sine test is performed after every test to ensure that the PCB is not damaged. Moreover, the placement of fasteners at various locations affects how much stress the PCB experiences and changes its normal modes as well. Thus, not only the material of the PCB changes the results, but the placement of fasteners influences how much a PCB can handle during various lift-off stages. I wished to work on NX and then doing the vibration lab and see the results in the same days with the professor.