Force Limited Vibration Testing on NPSCuL – What to Expect When You’re Expecting To Fly

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What is NPSCuL?

- ESPA-compatible payload with a capacity of 24 1U CubeSats using P-PODs and 6U dispensers
- Flew on the Atlas V launch vehicle on the Aft Bulkhead Carrier (ABC) in September 2012
- Carried 8 P-PODs and 11 CubeSats
- Scheduled to fly on an Atlas V in December 2013

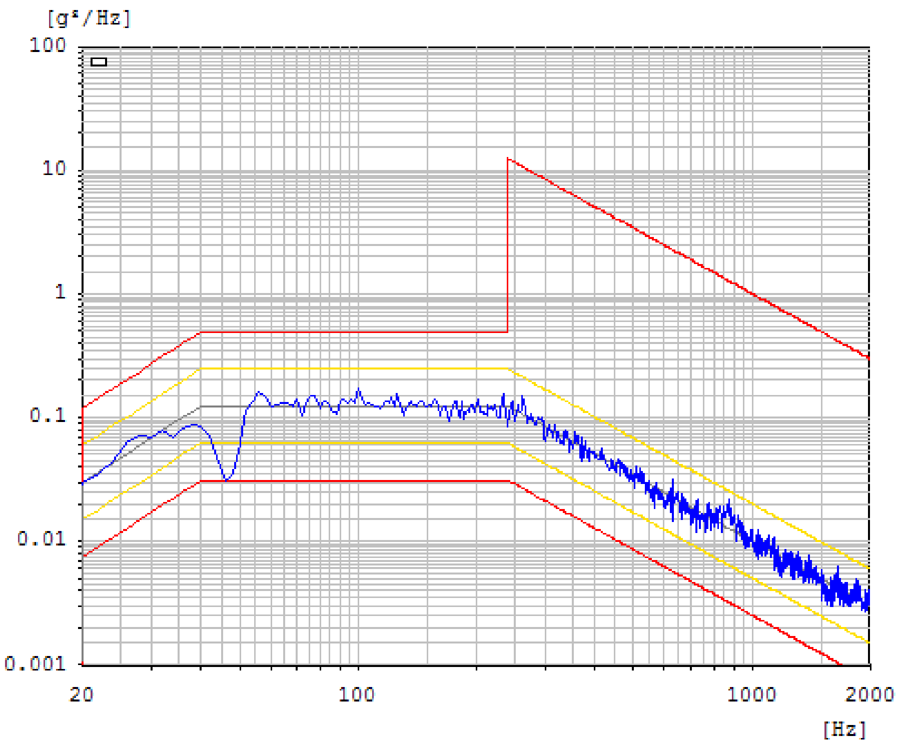
Test Like You Fly

- Goals of auxiliary payload vibration tests are to identify problems that would result in flight failures and to "do no harm" to the primary spacecraft
  - Requires implementation of flight-like test
- Acceleration controlled vibration tests are generally performed to test aerospace hardware
  - May result in over-test of hardware
    - Shaker can input more force than the actual launch vehicle at a system resonance
    - Controlling acceleration alone, results in artificially high shaker forces and responses at the resonance frequencies of the test item
- Vibration test should be representative of flight environment

References: NASA-HDBK-7004B, Force Limited Vibration Testing, 2003.
Force Limited Vibration Testing, Aerospace Testing Seminar, 2011.

What is Force Limited Vibration Testing?

- Results in a notch at resonant frequency that is closer to actual flight input
- Notch is valid due to vibration absorber effect
- Various methods exist to derive force limit, including
  - Response limiting
  - Apparent mass approximation
  - Semi-empirical method
  - Flight and ground test data referencing

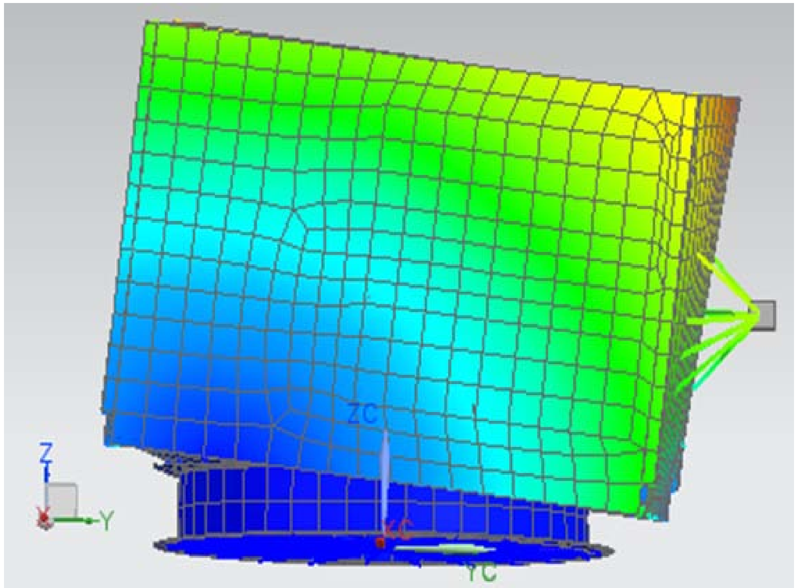


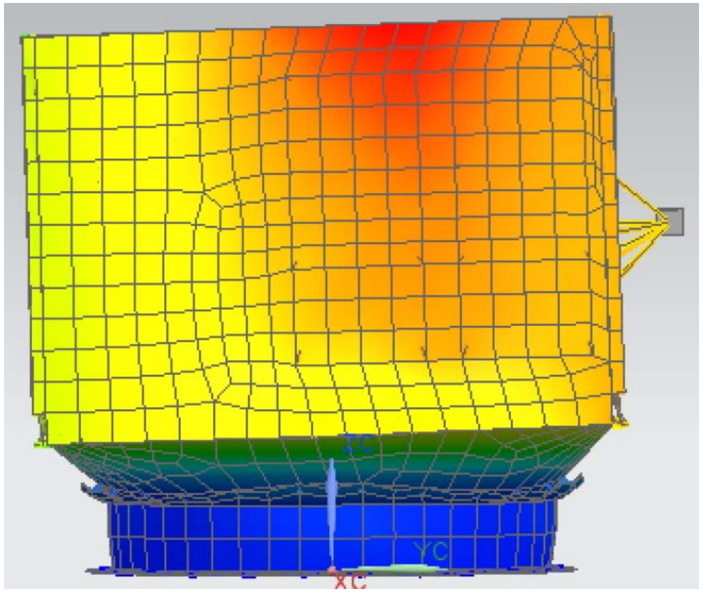
X-Axis Random Vibration Test Control Profile, OUTSat Acceptance Test

References: NASA-HDBK-7004B, Force Limited Vibration Testing, 2003.
Force Limited Vibration Testing, Aerospace Testing Seminar, 2011.

Why FLVT for NPSCuL?

- “Harsh environment” is due to the test set-up and the nature of a fixed-base test configuration
- Large response at resonant frequencies below 100 Hz (bandwidth of concern for structural damage) with high modal effective mass fractions



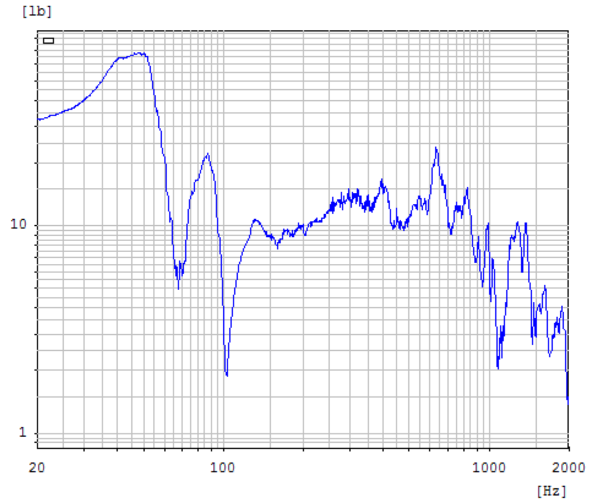


Force Limited Vibration Testing on OUTSat

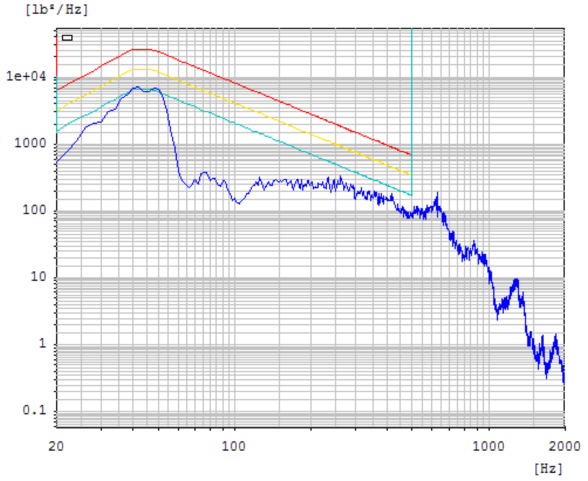
- Force-limited vibration testing was implemented on the OUTSat mission to reduce over-test
- Semi-empirical method was used to derive force-roll off out to 500 Hz
- The force spectral density (S_{FF}) is calculated as follows:

$$S_{FF} = C^2 M_o^2 S_{AA}, \quad f < f_o$$
$$S_{FF} = C^2 M_o^2 S_{AA}(f_o/f)^2, \quad f \geq f_o$$

- M_o is the total mass of the test item
- S_{AA} is the acceleration spectral density
- f_o is the frequency with the greatest effective mass
- f is the frequency
- C is a dimensionless constant which depends on the configuration ($C=\sqrt{2}$ for NPSCuL test configuration)



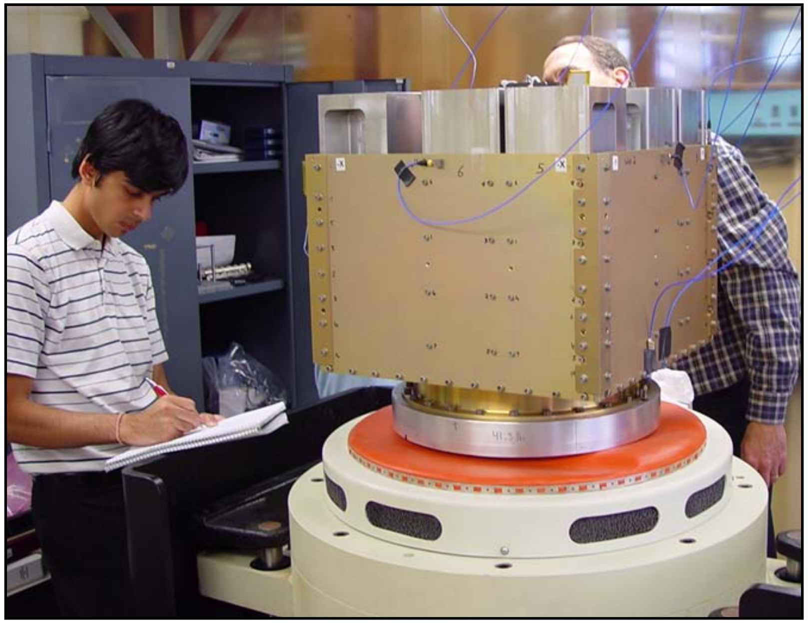
X-Axis Force Sine Sweep, OUTSat Acceptance Test

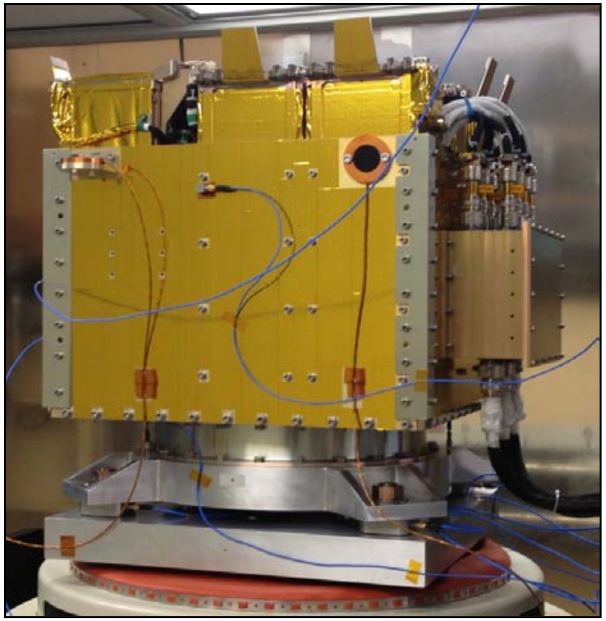


X-Axis Force Limit, OUTSat Acceptance Test

OUTSat Test Setup

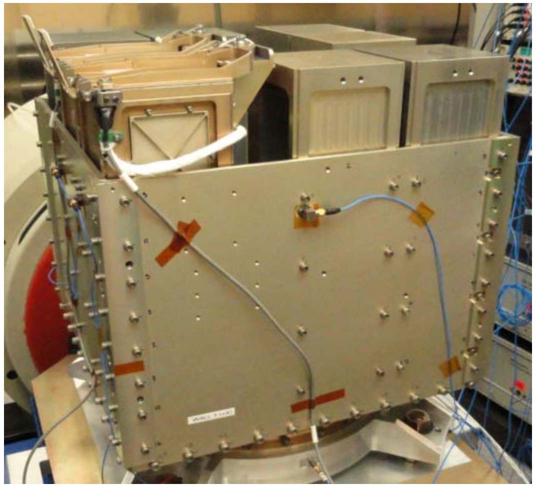
- Forces at ABC interface measured using force gauges sandwiched between two plates
  - Measured forces used as “watchdog” channel for input control channel

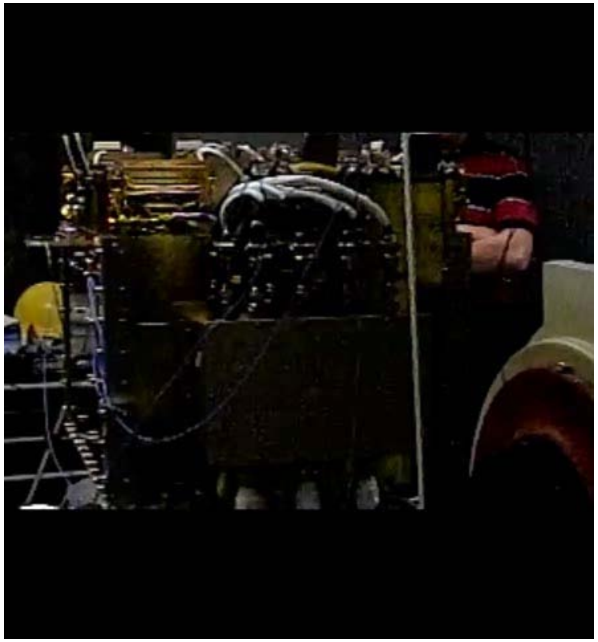


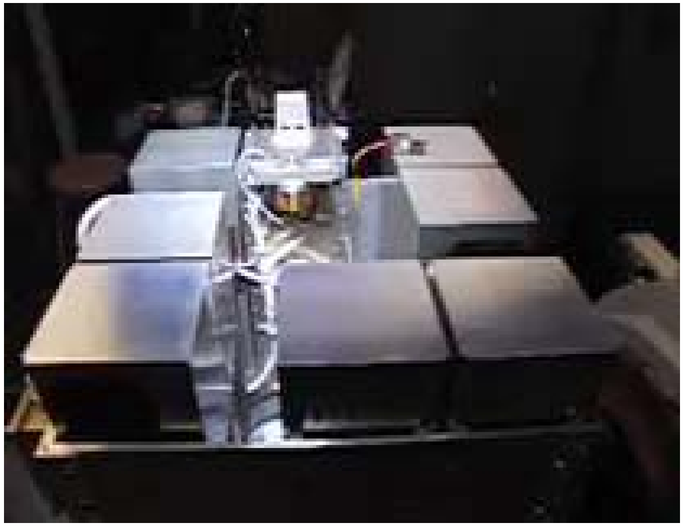


We Have Data – Now What?

- Responses measured at P-POD to NPSCuL interface are used to derive CubeSat test environments
  - CubeSats must be vibe-tested in a TestPOD before the integrated acceptance test
- Environment is still harsh despite the use of FLVT





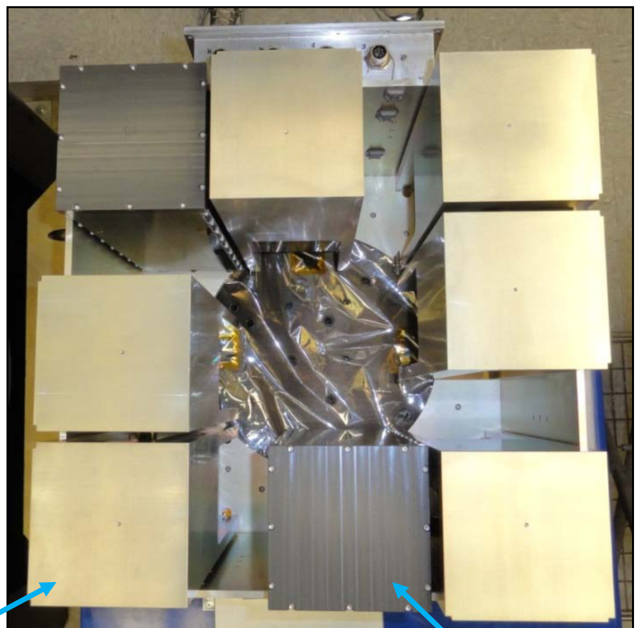


OUTSat Test Environments Evolution

- Several variables were examined to reduce over-test
  - Test configurations
    - Mass models vs. P-PODs
    - Fixed-base TestPOD vs. TestPOD in NPSCuL
  - Environment derivation techniques
    - Linearity and scaling effects of existing data
    - Providing position-dependent levels instead of one level for all P-POD positions
  - Damping techniques or structural modifications to NPSCuL

CubeSat Proto-Qual Testing for OUTSat

- Testing on NPSCuL in a TestPOD was the best option given the data at the time
- Position-dependent levels were provided to CubeSats to avoid including cross-axis responses
  - Alternative to testing on NPSCuL
  - Qual test data at MPE +3dB was enveloped to obtain levels



P-POD Mass Model

TestPOD

P-PODs 1 and 5

X-Axis		Y-Axis		Z-Axis	
Frequency	ASD	Frequency	ASD	Frequency	ASD

P-PODs 2 and 6

X-Axis		Y-Axis		Z-Axis	
Frequency	ASD	Frequency	ASD	Frequency	ASD

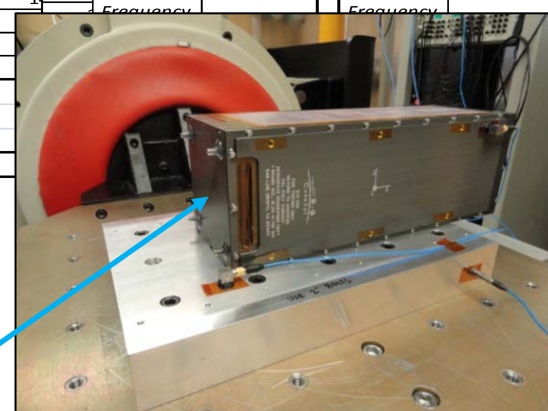
P-PODs 3 and 7

X-Axis		Y-Axis		Z-Axis	
Frequency	ASD	Frequency	ASD	Frequency	ASD

P-PODs 4 and 8

Z-Axis

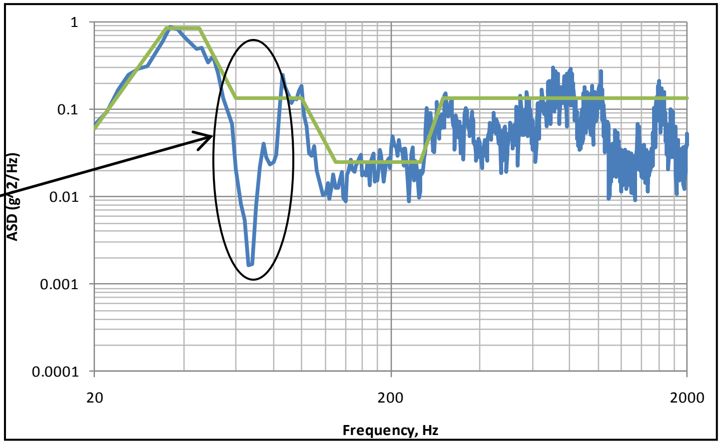
Frequency (Hz)	ASD (g^2/Hz)
20	0.06
70	0.44
140	0.44
220	0.05
400	0.05
600	0.01
800	0.01
1100	0.04
1600	0.04
2000	0.01
10.29 Grms	

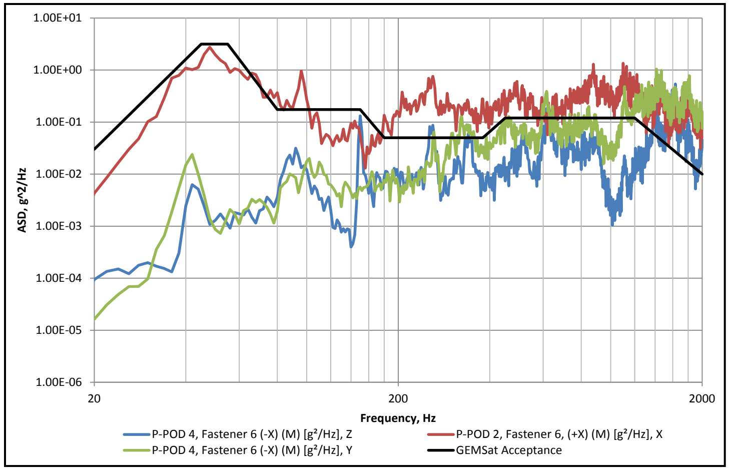


Lessons Learned from OUTSat Testing

- Testing on NPSCuL has its advantages
  - Able to test several CubeSats simultaneously in a flight-like configuration
  - Reduces over-test due to “white space” from enveloping data

- Testing on NPSCuL has its disadvantages
  - CubeSats have to test on specific dates
  - Dynamic coupling for the varying test configurations is hard to predict
    - CubeSat resonances inside the P-POD do not affect overall system resonances
    - TestPOD and P-POD mass model interactions increases over-test above 200 Hz (non-structural range)





CubeSat Proto-Qual Testing for GEMSat

- One set of test profiles for all P-POD positions
  - Allows for all CubeSat candidates to test before final GEMSat manifest is determined
  - Acceptance test profile is an envelope of OUTSat data
    - Includes cross-axis responses
  - Proto-qual and qual test profiles are +3dB and +6dB from OUTSat acceptance test envelope

X-Axis			
Freq, Hz	ASD, g^2/Hz		
	Acceptance	*Protoqual*	*Qual*
20	0.03	0.06	0.12
45	3.15	6.3	12.6
55	3.15	6.3	12.6
80	0.17	0.35	0.70
150	0.17	0.35	0.70
180	0.05	0.1	0.2
380	0.05	0.1	0.2
450	0.12	0.24	0.48
1200	0.12	0.24	0.48
2000	0.01	0.02	0.04
Overall Grms	**15.1**	**21.4**	**30.3**

Y-Axis			
Freq, Hz	ASD, g^2/Hz		
	GEMSat Acceptance	*GEMSat Protoqual*	*Qual*
20	0.05	0.10	0.20
45	1.80	3.60	7.20
55	1.80	3.60	7.20
80	0.23	0.46	0.92
120	0.23	0.46	0.92
130	0.10	0.20	0.40
200	0.10	0.20	0.40
300	0.19	0.37	0.75
400	0.19	0.37	0.75
600	0.09	0.18	0.36
2000	0.09	0.18	0.36
Overall Grms	**15.9**	**22.5**	**31.8**

Z-Axis			
Freq, Hz	ASD, g^2/Hz		
	Acceptance	*Protoqual*	*Qual*
20	0.04	0.08	0.16
45	0.30	0.60	1.20
130	0.30	0.60	1.20
155	0.09	0.18	0.36
220	0.09	0.18	0.36
240	0.14	0.28	0.56
300	0.14	0.28	0.56
400	0.05	0.10	0.20
1000	0.05	0.10	0.20
1100	0.02	0.04	0.08
2000	0.02	0.04	0.08
Overall Grms	**10.5**	**14.8**	**21.0**

Test Environments For A "Simple Structure" – Not So Simple

- Easy to envelope data
- Hard to reduce over-test
- Understanding responses for a new structure with differing test and flight configurations is a challenge
  - Dynamic properties of all sub-systems are not always known prior to testing
  - Difficult to come up with a single realistic solution for all possible configurations
    - Varying dynamic properties of CubeSats, P-POD, and TestPOD
    - Varying locations of P-POD, TestPOD, and P-POD mass models

Current and Future Work to Reduce Levels

- ULA instrumenting ABC plate with flight accelerometers to provide flight data for the current ABC configuration
- Algorithm-based environments derivation to reduce “white space”
- Derive less conservative force roll-off without compromising test requirements using other force limit techniques
- Re-design NPSCuL to reduce amplification at P-POD interface at resonant frequencies
- Design and implement vibration isolation or damping solution that is valid for a range of system properties