Max Launch Abort System (MLAS) Pad Abort Test Vehicle (PATV) II Attitude Control System (ACS) Integration and Pressurization Subsystem Dynamic Random Vibration Analysis

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In order to mitigate catastrophic failures on future generation space vehicles, engineers at the National Aeronautics and Space Administration have begun to integrate a novel crew abort systems that could pull a crew module away in case of an emergency at the launch pad or during ascent. The Max Launch Abort System (MLAS) is a recent test vehicle that was designed as an alternative to the baseline Orion Launch Abort System (LAS) to demonstrate the performance of a "tower-less" LAS configuration under abort conditions. The MLAS II test vehicle will execute a propulsive coast stabilization maneuver during abort to control the vehicles trajectory and thrust. To accomplish this, the spacecraft will integrate an Attitude Control System (ACS) with eight hypergolic monomethyl hydrazine liquid propulsion engines that are capable of operating in a quick pulsing mode. Two main elements of the ACS include a propellant distribution subsystem and a pressurization subsystem to regulate the flow of pressurized gas to the propellant tanks and the engines. The CAD assembly of the Attitude Control System (ACS) was configured and integrated into the Launch Abort Vehicle (LAV) design. A dynamic random vibration analysis was conducted on the Main Propulsion System (MPS) helium pressurization panels to assess the response of the panel and its components under increased gravitational acceleration loads during flight. The results indicated that the panels fundamental and natural frequencies were farther from the maximum Acceleration Spectral Density (ASD) vibrations which were in the range of 150-300 Hz. These values will direct how the components will be packaged in the vehicle to reduce the effects high gravitational loads.

Nomenclature

ACS	=	Attitude Control System
ASD	=	Acceleration Spectral Density
COPV	=	Composite Overwrapped Pressure Vessels
FTA	=	Flight Test Article
MLAS	=	Max Launch Abort System
MMH	=	Monomethyl hydrazine
MPS	=	Main Propulsion Systems
NESC	=	NASA Engineering and Safety Center
NTO	=	Nitrogen tetroxide
PATV	=	Pad Abort Test Vehicle
TVC	=	Thrust Vector Control

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fn	=	natural frequency
E	=	Young's modulus
D	=	Simple rectangular plate bending constant
v	=	Poissons ratio
φ	=	Mode Vibration

I. Introduction

Since the beginning of human space exploration scientists and engineers have worked to increase mission quality and performance by mitigating risks associated with endangering the life of humans in space. The path to expanding human presence in space is undoubtedly not absent from any failures and many lives could be and have been lost in the pursuit of this endeavor. One way to mitigate catastrophic failures on future generation spacecrafts is to provide the crew with a Launch Abort System (LAS) that could propel the crew module safely away from the launch vehicle in an event of an emergency at the launch pad or a malfunctioning solid rocket booster during ascent. The first crew abort system was the "Aerial Capsule Emergency Separation Device" or Launch Escape System (LES) designed by Maximum Faget in 1961. The system was prevalently used during the Mercury and Apollo programs, which were the first series of manned space missions. The LES was equipped with solid rocket motors that provided the space vehicle with quick thrust during ascent and supplied fuel to the attitude control motors for vehicle stabilization and reorientation. Several iterations of the LAS have been designed and demonstrated since the Apollo Program with the most recent being the Max Launch Abort System (MLAS) named after Max Faget. The MLAS Pad Abort Test Vehicle II will be designed to demonstrate propulsive coast attitude control and to reduce the risk associated with thrust vector control abort motors.

II. Baseline Orion Launch Abort System Design

The Orion Crew exploration vehicle was the first future generation American space vehicle to integrate a LAS system since the age of Apollo. The test vehicle was to demonstrate the escape capability of the LAS by utilizing solid rocket motors during ascent as well as attitude control to stabilize and reorient the vehicle during the abort phase. The spacecraft was also equipped with jettison motors to propel the LAS away from the crew module and allow the module to deploy its parachutes in its final stage of abort (Figure 1).

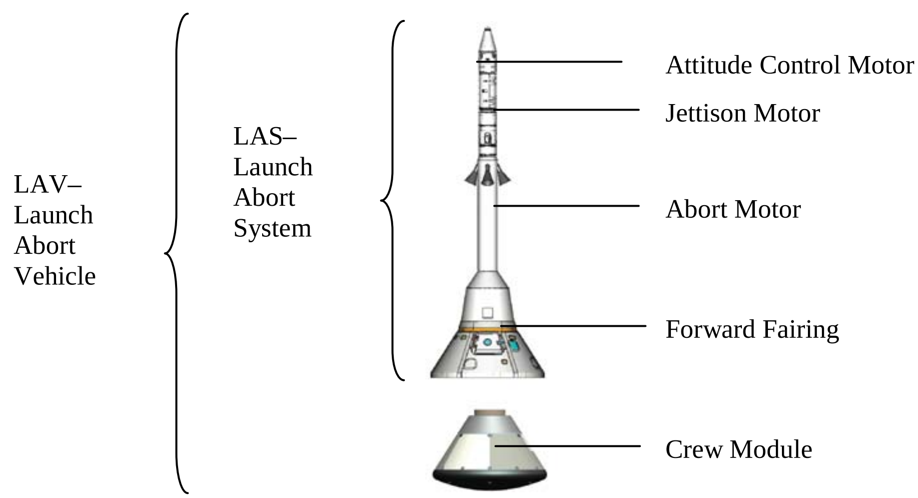

Figure 1 Orion Launch Abort System Pad Abort-1 Test Vehicle equipped with solid rocket abort, attitude control and jettison motors

In year 2007, the NASA Associate Administrator for Exploration (NAAE) acknowledged and identified potential risks associated with the vertical assembly design of the solid rocket abort motor. Such concerns involved the height of the abort motor potentially initiating severe bending moments and contributing to the Attitude Control Motor (ACM) plume asymmetry; thereby, affecting the overall stabilization phase of the vehicle [1]. In addition, the vehicle utilizes solid propellants for coast stabilization, which prevents control over varying the flow of thrust from the motors. As a result, the NAAE had asked the NASA Engineering and Safety Center (NESC), an organization established in July 2003 in response to the Columbia accident, to develop and demonstrate an alternate Launch Abort System (LAS) as risk mitigation for the baseline Orion LAS.

III. Max Launch Abort System (MLAS) Pad Abort Test Vehicle I

Upon the NAAE's request, the NESC proposed the concept of the Max Launch Abort System (MLAS) which unlike the baseline design, eliminated the vertical assembly structure of the abort motors and integrated side-mounted abort motors to reduce undesirable bending moments during flight. Since the main objective of the MLAS Flight Test Vehicle I was to demonstrate the innovative LAS configuration under abort conditions (Figure 2), the system eliminated a propulsive attitude control system. The test vehicle rather utilized a coast ring with mounted fins to passively stabilize the vehicle during the abort phase and a boost skirt to encase the solid rocket motors needed to propel the vehicle during ascent.

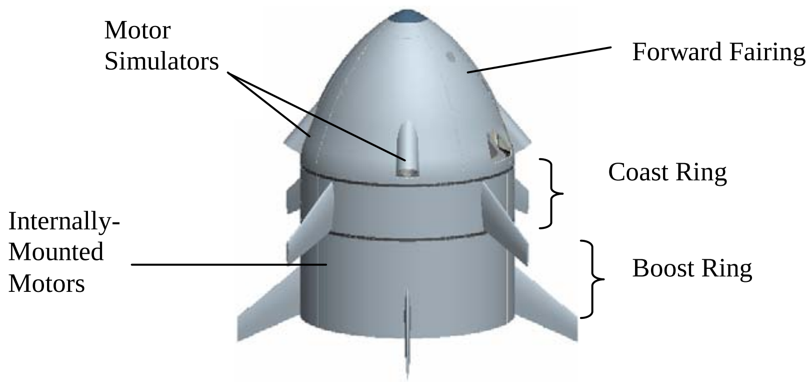

Figure 2 Max Launch Abort System (MLAS) Pad Abort Test Vehicle I

Given the project cost and schedule, a passive flight control test was advantageous where it demonstrated the flight response of the new vehicle configuration and reduced complicated flight control systems [2]. Upon the successful passive attitude control test of the novel LAS configuration, the MLAS Pad Abort Test Vehicle II design was being developed to demonstrate the use of liquid propellants for controlled propulsive coast stabilization.

IV. Max Launch Abort Objective System-1 Propulsive Coast Stabilization Pad Abort Test Vehicle II

MLAS II was an objective system concept that was generated prior to the testing of MLAS I. The key objectives of MLAS II are to demonstrate a flight system with thrust vector control equipped with solid motors, and use of conventional technology liquid Attitude Control System (ACS) for coast flight stabilization and reorientation. The objective system design will integrate 6 solid rocket abort motors with thrust vector control to propel the vehicle during ascent and 8 hypergolic liquid rocket control motors to provide for propulsive coast stabilization during abort (Figure 3).

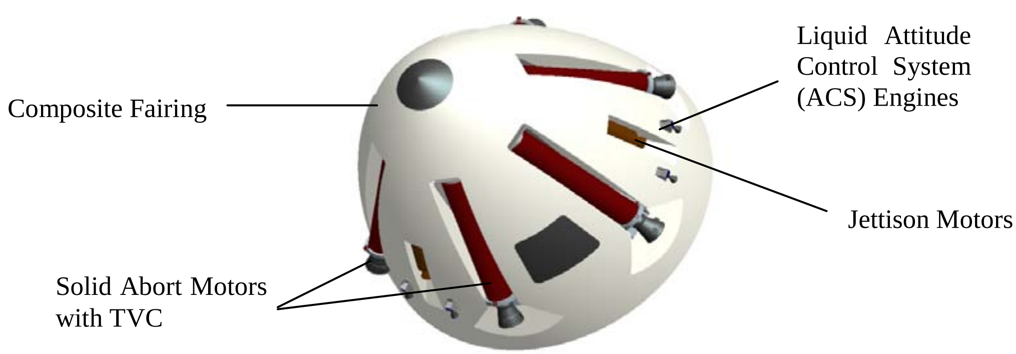

Figure 3 Max Launch Abort System (MLAS) Pad Abort Test Vehicle II

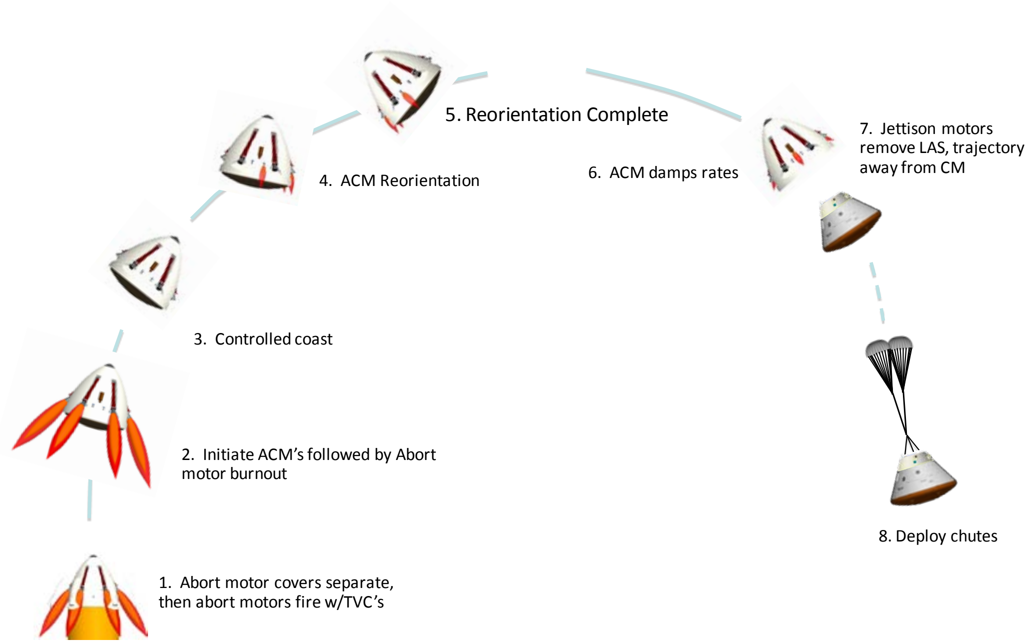

Figure 4 MLAS Pad Abort II Concept of Operations

The MLAS II propulsion system consists of 3 main elements: the solid abort motors, attitude control motors, and the jettison motors. The solid abort motors provide quick thrust and are equipped with thrust vector control to stabilize the launch abort vehicle during ascent. Upon the solid motor burn out stage, the vehicle passively coasts and the liquid Attitude Control Motors (ACM) will actuate to reorient and stabilize the vehicle by means of constraining the engine pulsing profiles. Once the reorientation phase is complete, the jettison motors are then fired to remove the LAS and propel the composite fairing away from the crew module.

V. MLAS II Attitude Control System (ACS) Design and Subsystems Integration

The Attitude Control System will consist of a liquid propellant distribution sub-system and a pressurization sub-system to provide for controlled propulsive stabilization. The ACS assembly was modeled and integrated onto the LAS using 3D Computer Aided Design software. During the design process, considerations such as structure geometry, attachment details, and arrangement of the ACS components were addressed for packaging and ease of manufacturing purposes. This also prevents critical hardware from detaching under ACS hydraulic loads and high gravitational acceleration loads during launch.

A. Propellant Distribution Subsystem Design

The ACS for the MLAS II flight test vehicle will integrate 8 hypergolic liquid rocket control motors to provide for propulsive coast stabilization during abort. Liquid propellants monomethyl-hydrazine and nitrogen-tetroxide will be used to control the engine pulsing modes during attitude control. The ACS engines are to be located towards the end of the vehicle on the outer circumference of the vehicle kick frame (Figure 5). Prior to launch, the ACS engines will be protected by blow-off covers and jettisoned upon actuating the solid rocket motors. The thrusters and propellant tanks were also designed to be symmetrical around the spacecrafts center of mass in order to prevent the vehicle from shifting during abort as propellant is consumed.

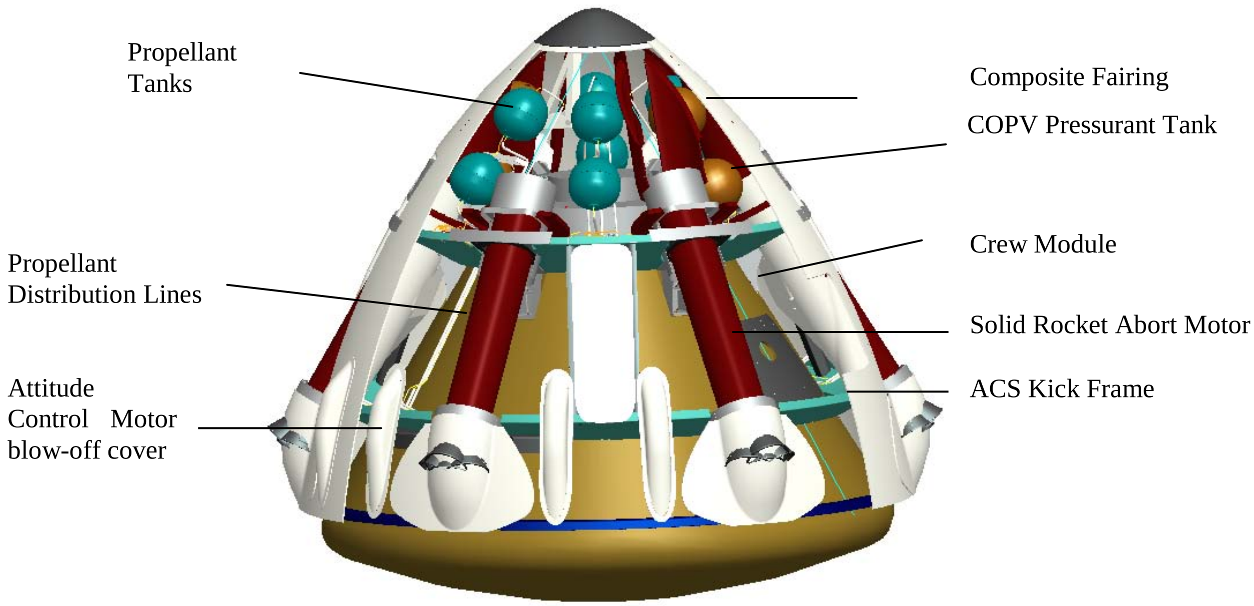

Figure 5 Front view of the Launch Abort Vehicle (LAV) and its respective Attitude Control System (ACS)

The modeled propellant lines were routed from the thruster valve ports to the propellant tanks symmetrically to maintain balanced pressure flow to each ACS engine. The final tubing dimensions were based on a line diameter trade study conducted by the MLAS II fluids analysis team to identify the optimum engine performance and mitigate severe pressure drop and water hammer effects that can potentially occur during the pulsing phase of the engines. The final configuration of the propellant pneumatic assembly would allow the analysis team to perform critical simulations and to predict the performance of the engines under the vehicles hydraulic loads.

B. Helium Pressurization Subsystem Design

The pressurization subsystem is used to maintain the pressure inside the helium tank, equalize the pressures between the propellant tanks, and force propellant to the attitude control engines. Due to demand from multiple ACS engines firing, a helium pressurization panel is to be integrated for each ACS engine pair in order to maintain the propellant tank pressures and increase combustion stability. The pressure in the helium tanks therefore must be higher than the pressure in the chamber engines. In order to accommodate this, helium regulator panels will be supplied from the Orbiter Main Propulsion System (MPS) as a means to benefit from existing Shuttle hardware and decrease the cost of the project. The main components of the helium regulator panel include a 750 psig helium pressure regulator, 850 psig relief valve, a helium check valve, distribution lines and control values (Figure 5).

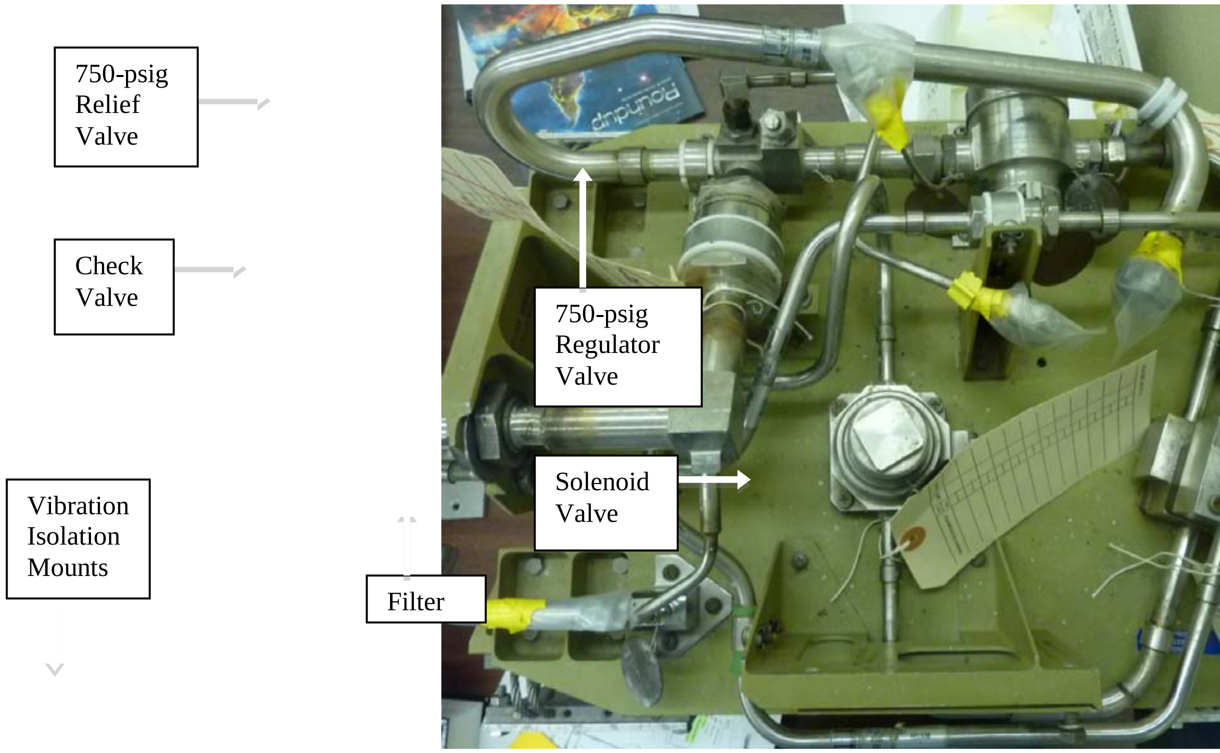

Figure 5 Orbiter helium regulator pneumatic panel

When the pressurization system is actuated, helium gas flows from a 4500 psig COPV pressurant tank towards the pressurization panel prior to entering the propellant distribution subsystem. The helium is then passed through a filter to clear the pressurant from any contaminants prior to entering the propellant tanks. The filtered helium gas then enters a 750-psig helium pressure regulator that regulates the engine helium supply from 4,500 psig down to 750 psig. In an event when the pressure regulator fails and the pressure exceeds the preset relieving pressure, an 850-psig helium pressure relief valve is included to prevent downstream overpressurization. The relief valve also provides pressurization to expel propellants from the feed systems and provide engine purge gas. Located at the corners of each panel are helical vibration isolators of aluminum 2024 alloy material whose main function is to prevent the pneumatic assembly from reaching its natural frequency by dampening out the vibration. The significance of these pressurization panel components in maintaining the pressure along the propellant lines and effecting the overall performance of the attitude control engines was the motivation to analyze the dynamic response of the panel under MLAS loads and environments.

VI. Dynamic Response Analysis of Helium Pressurization Panels

Space vehicles typically encounter dynamic random vibrations and high gravitational loads as a result of tremendous forces required to propel the spacecraft from the launch pad. Such environments represent base criteria for space-vehicle design and must be considered prior to design verification through ground testing. Critical pressurization subsystem components that will likely be impacted by such loads are the MPS helium regulator panels, which control the pressure flow to the ACS engines. A dynamic random vibration analysis must be conducted to obtain the primary structure’s modes of vibration and its associated natural frequencies in order to predict potential failures. The modes of vibration for any component would be of concern due to maximum displacement amplitudes that the structure typically experiences at its natural frequencies. Such displacements can impose high stresses on the spacecraft structure. In order to conduct this analysis, a simplified model of the panel was created and a modal and dynamic analysis was conducted to verify the response from the MLAS II panel configuration. This approach had allowed the team to predict the behavior of the MPS panels at its natural frequencies and under high gravitational loads.

A. Pressurization Panel Natural Frequencies and Mode Shapes of Vibration

A solid 14'' x 20'' rectangular plate model was generated to simplify the pressurization panel geometry to a single degree of freedom system (Figure 6). Basic structural dynamics equations were used to determine the pressurization panel modes, natural frequencies, and mode shapes of vibration. Equation (1)[3] represents the natural frequency equation of a simple rectangular plate where the fundamental and the natural frequencies are calculated as:

$$f_n(c,d) = \frac{\Pi}{2}\left[(\frac{c}{a})^2 + (\frac{d}{b})^2\right]\sqrt{\frac{D}{\gamma}} \tag{1}$$

where f_n is the natural frequency of a simple rectangular plate, *a* and *b* correspond to the plates length and width, *c* and *d* are positive whole numbers that correspond to different modes of vibration, γ is the mass per unit area, and *D* is the plate bending constant, defined for a solid plate as:

$$D = \frac{Et^3}{12(1-v^2)} \tag{2}$$

where *E* is the Young's modulus, *t* is the thickness, and *v* is Poisson's ration. Each mode of vibration of a structure has an associated natural frequency and mode shape which is the deformed shape of a vibrating structure. Equation (3) is used to predict how the object deforms at its corresponding natural frequencies:

$$\phi = (c,d,x,y) = \sin\frac{c\Pi x}{a}\sin\frac{d\Pi y}{b} \tag{3}$$

To find the fundamental frequency, c=d=1 in equation (1) and for higher modes of vibration, any combination of positive integers can correspond to the natural frequency at those combinations. Table 1 was generated to obtain and extract the first 6 natural frequencies and mode shapes of vibration (Table 2) for the simplified panel.

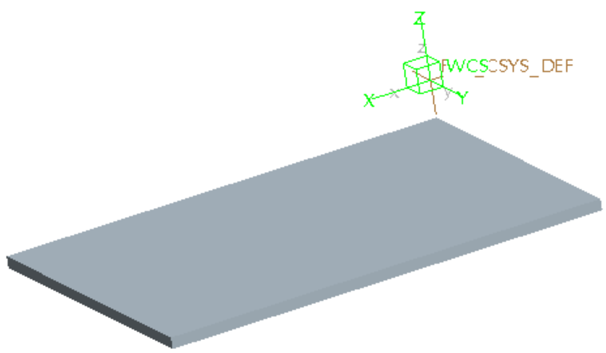

Figure 6 Simplified 14''x 20'' rectangular model of the pressurization panel

Table 1 Generating the natural frequencies and mode shapes of vibration for the simplified panel model

Modes	**d**					
c	**0**	**1**	**2**	**3**	**4**	**5**
0	0.00E+00	3.32E+02	1.33E+03	2.99E+03	5.32E+03	8.31E+03
1	6.78E+02	1.01E+03	2.01E+03	3.67E+03	6.00E+03	8.99E+03
2	2.71E+03	3.05E+03	4.04E+03	5.70E+03	8.03E+03	1.10E+04
3	6.10E+03	6.44E+03	7.43E+03	9.09E+03	1.14E+04	1.44E+04
4	1.09E+04	1.12E+04	1.22E+04	1.38E+04	1.62E+04	1.92E+04
5	1.70E+04	1.73E+04	1.83E+04	1.99E+04	2.23E+04	2.53E+04

Table 2 First 6 natural frequencies and modes of vibration for the simplified rectangular model of the panel

Mode	Natural Frequency (Hz)	Mode Shapes (c,d)	
1	1010.5	1	1
2	2010	1	2
3	3050	2	1
4	3670	1	3
5	4040	2	2
6	5700	2	3

B. Finite Element Modeling (FEM) and Model Verification

Upon predicting the fundamental and natural frequencies for the simplified plate model, a modal analysis was simulated on the actual panel to observe how the object deforms at its natural frequencies and to validate the integer combinations that signify the mode shapes of vibration. A finite element model was generated in Pro/MECHANICA Wildfire 4.0, and a modal analysis predicted the mode shapes of vibration and areas of maximum deformation (Figure 7). The results yield a minimum natural frequency of 1055 Hz, which is also the fundamental frequency for the MLAS pressurization panel.

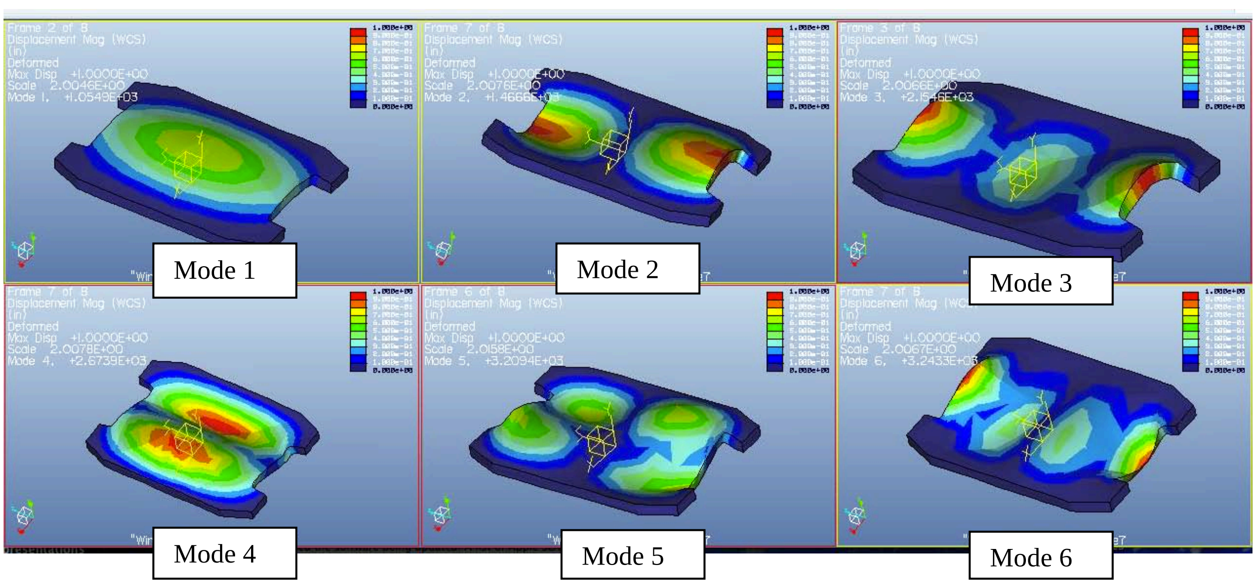

Figure 7 First 6 modes of vibration for the simplified model. *The scale represents the translation of the structure.*

The natural frequencies for the second and third modes of vibration were 1466.6 Hz and 2154.6 Hz respectively. The fourth mode of vibration had a natural frequency of 2674 Hz and a maximum deformation occurring at the center of the plate where the helium check valve and regulator are located. The range of MLAS random vibrations occur between 20 Hz to 2000 Hz. The maximum critical vibrations occur between 150-300 Hz which correspond to an acceleration spectral density of 1.0 g^2/Hz. Therefore, one can predict that the panel's fundamental frequency and natural frequencies are safe from undesirable MLAS vibrations.

C. Dynamic Random Vibration Analysis

The objective of generating a dynamic random analysis was to provide data confirming that the valves and regulators on the panel could survive and operate at increased gravitational acceleration loads expected for MLAS PATV II. This type of analysis is often used for acoustic environments where the loads are continuous, long duration and random. Since a force-time history for random-vibration environments is unpredictable and the gravitational loads are applied to all frequencies simultaneously, an Acceleration Spectral Density (ASD) curve is used to describe dynamic random vibration for spacecraft structures. ASD is a statistical measure of the response of a structure to random dynamic loading conditions and it is expressed in units of g^2/Hz, where g is the acceleration of Earths gravity at sea level. The square root of the area under the curve represents the mean square acceleration within a selected frequency band divided by the bandwidth. The Miles equation (4) can be used to solve for the expected maximum gravitational acceleration forces or Root Mean Square Acceleration (G_{rms}) that the panel experiences under MLAS loads and dynamics:

$$G_{RMS} = \sqrt{\frac{\Pi}{2} f_n Q[ASD_{input}]} \tag{4}$$

where f_n is the fundamental frequency, $[ASD_{input}]$ is the input acceleration spectral density at f_n in units of g^2/Hz, and Q represents the transmissibility at the natural frequency, equation (5) where ξ is the critical damping ratio. The root mean square acceleration values are represented in units of G's.

$$Q = \frac{1}{2\xi} \tag{5}$$

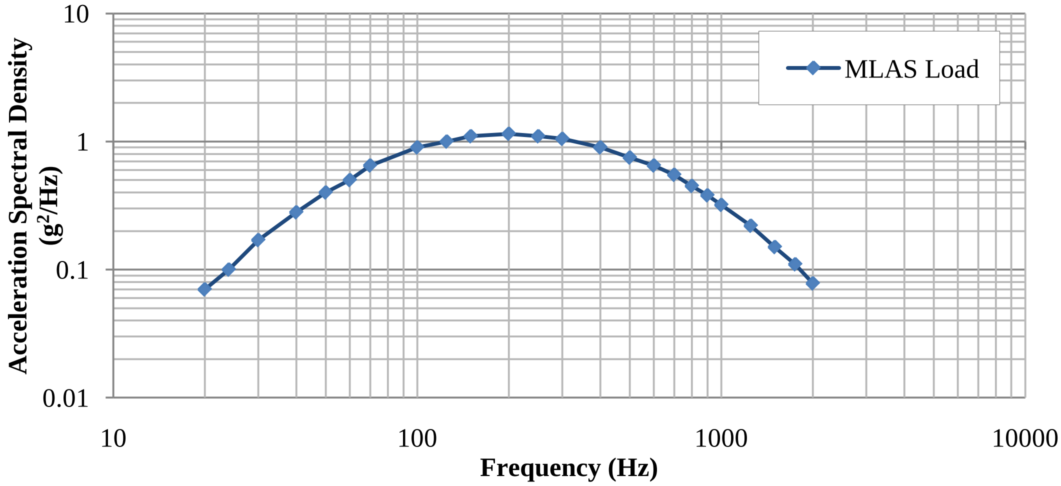

Figure 8 MLAS Random Vibration Magnitude Specification and Panel Fundamental Frequency. *The peak points on the ASD curve frequencies at which vibration is most intense.*

The ASD plot in Figure 8 was produced from the MLAS I vibro-acoustic kick-frame data in order to develop test specifications for the vehicle and predict the internal structural responses. This specification will be used to simulate the MLAS random vibration environments and obtain the computational root mean square acceleration values.

VII. Conclusion

The MLAS PATV II team is in the process of completing the design and analysis work to prepare the project for a preliminary design review. Upon maturing the ACS design, assembling techniques are to be considered to refine the design and prepare the vehicle for manufacturing. The final packaging of the vehicle will be done through numerous trade studies, which consist of static, dynamic, and thermal analysis. Further analysis tools such as FLUENT will be used to simulate the fluid flow through the thruster injector plate, and determine significant computational fluid flow values. This data will assist the ACS team to support the projects preliminary design review for a ground test flight

Appendix

Table 3 MLAS Random Vibration Magnitude Specification

Frequency (Hz)	ASD (g^2/Hz)	dB	OCT	dB/OCT	Area	G-rms
24	0.	1.55	0.26	5.89	0.34	0.58
30	0.17	2.30	0.32	7.16	1.14	1.07
40	0.28	2.17	0.42	5.22	3.37	1.84
50	0.4	1.55	0.32	4.81	6.75	2.60
60	0.5	0.97	0.26	3.68	11.25	3.35
70	0.65	1.14	0.22	5.12	16.99	4.12
100	0.9	1.41	0.51	2.75	40.26	6.34
125	1	0.46	0.32	1.42	64.03	8.00
150	1.1	0.41	0.26	1.57	90.30	9.50
200	1.15	0.19	0.42	0.47	146.60	12.11
250	1.1	-0.19	0.32	-0.60	202.80	14.24
300	1.05	-0.20	0.26	-0.77	256.50	16.02
400	0.9	-0.67	0.42	-1.61	353.45	18.80
500	0.75	-0.79	0.32	-2.46	435.44	20.87
600	0.65	-0.62	0.26	-2.36	505.17	22.48
700	0.55	-0.73	0.22	-3.26	564.90	23.77
800	0.45	-0.87	0.19	-4.52	614.62	24.79
900	0.38	-0.73	0.17	-4.32	655.96	25.61
1000	0.32	-0.75	0.15	-4.91	690.82	26.28
1250	0.22	-1.63	0.32	-5.05	757.08	27.52
1500	0.15	-1.66	0.26	-6.32	802.50	28.33
1750	0.11	-1.35	0.22	-6.06	834.62	28.89
2000	0.078	-1.49	0.19	-7.75	857.80	29.29

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