VIBRATION AND ACOUSTIC TESTING FOR MARS MICROMISSION SPACECRAFT

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***ABSTRACT** - Unique spacecraft dynamics qualification methodologies have been developed at the Jet Propulsion Laboratory in recent years in response to NASA's faster/better/cheaper initiative. This paper discusses the implementation and extension of these methodologies to the Mars Micromission program, which consists of a series of common spacecrafts with various payloads for Mars exploration and telecommunications planned to be launched on the Ariane 5 as Twin auxiliary payloads.*

1 - INTRODUCTION

The objective of the Mars Micromission program being managed by the Jet Propulsion Laboratory (JPL) for NASA is to develop a common spacecraft that can carry telecommunications equipment and a variety of science payloads for exploration of Mars [1]. The spacecraft will be capable of carrying robot landers and rovers, cameras, probes, balloons, gliders or aircraft, and telecommunications equipment to Mars at much lower cost than recent NASA Mars missions. The lightweight spacecraft (about 220 Kg mass) will be launched in a cooperative venture with CNES as a TWIN Auxiliary Payload on the Ariane 5 launch vehicle. The Mars launch window for the first mission is February 1 through May 1, 2003, which is currently planned to be the first communications/navigation orbiter. Several subsequent launches will create a telecommunications network orbiting Mars, which will provide for continuous communication with landers and rovers on the Martian surface. Beginning in 2005, at least two Mars Micromission launches (consisting of some combination of probe carriers, science orbiters, or communications orbiters) are planned for each Mars launch opportunity, which occur every 26 months.

This new cheaper and faster approach to Mars exploration calls for innovative approaches to the qualification of the Mars Micromission spacecraft for the Ariane 5 launch vibration and acoustic environments. JPL has in recent years implemented new approaches to spacecraft testing that may be effectively applied to the Mars Micromission. These include 1) force limited vibration testing, 2) combined loads, vibration and modal testing, and 3) direct field acoustic testing. In addition, it is proposed to adapt a transient vibration test method developed for spacecraft components and instruments to the qualification of the spacecraft structure. This paper discusses the rationale behind and advantages of the above test approaches and provides examples of their actual implementation. The applicability of the test approaches to Mars Micromission spacecraft qualification is discussed.

2 - SPACECRAFT STRUCTURAL DESIGN

The common Mars Micromission spacecraft will be designed and built by a system contractor who has yet to be selected. In order to establish the feasibility of meeting frequency and strength requirements established for Ariane TWIN Auxiliary Payloads [2] and to verify the applicability of Mass Acceleration Curve (MAC) loads [3] for preliminary design, a study of potential Mars Micromission spacecraft structural design concepts was undertaken at JPL. Figure 1 illustrates the conceptual configuration for the spacecraft. The unusual shape results from having to fit in one quarter of the ARIANE Structure for Auxiliary Payload 5 (ASAP5) ring. The probe carrier located on the center of the base panel must accommodate one large probe of about 80 cm diameter, two smaller probes of about 65 cm diameter, or 3 to 4 probes of 40 cm diameter. The probe carrier is flanked by the oxidizer and fuel tanks to place as much spacecraft mass as possible directly over the dual ASAP5 attachments. The curved solar panel forms the back surface of the spacecraft and helps stiffen the structure.

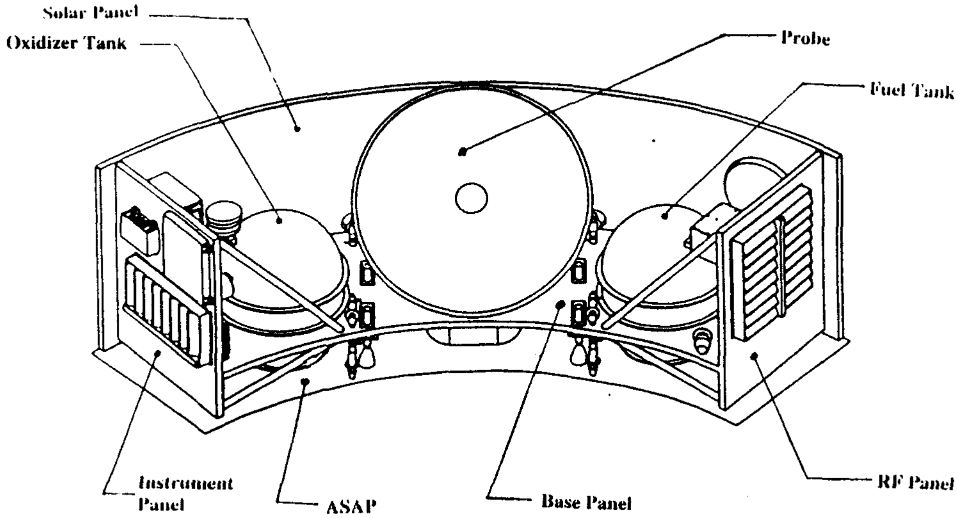

Figure 1. Mars Micromission Spacecraft Conceptual Configuration

The approach for the first part of the structural design study (frequency and strength requirements) started with a minimum structure NASTRAN finite element model (FEM) of the spacecraft. The structure was then incrementally stiffen as necessary to meet the frequency requirements, which are a minimum lateral frequency of 45 Hz and a minimum longitudinal frequency of 90 Hz. Some of the significant modeling assumptions were 1) an all aluminum structure to reduce cost, 2) honeycomb sandwich construction for base panel and solar array, 3) rigid probe with a mass of 45 Kg, 4) rigid propellant and oxidizer tanks, 5) tanks supported by aluminum cone structure with stiffeners, 6) honeycomb panels are interconnected by fasteners, 7) one inch stiffeners added to instrument and RF panels, 8) launch mass (less structure) of 189 Kg, and 9) structure designed for a total spacecraft mass of 222 Kg. A constraint was that the instrument and RF panel aluminum face sheet thickness be 2 mm or greater for thermal reasons. The spacecraft FEM is illustrated in Figure 2.

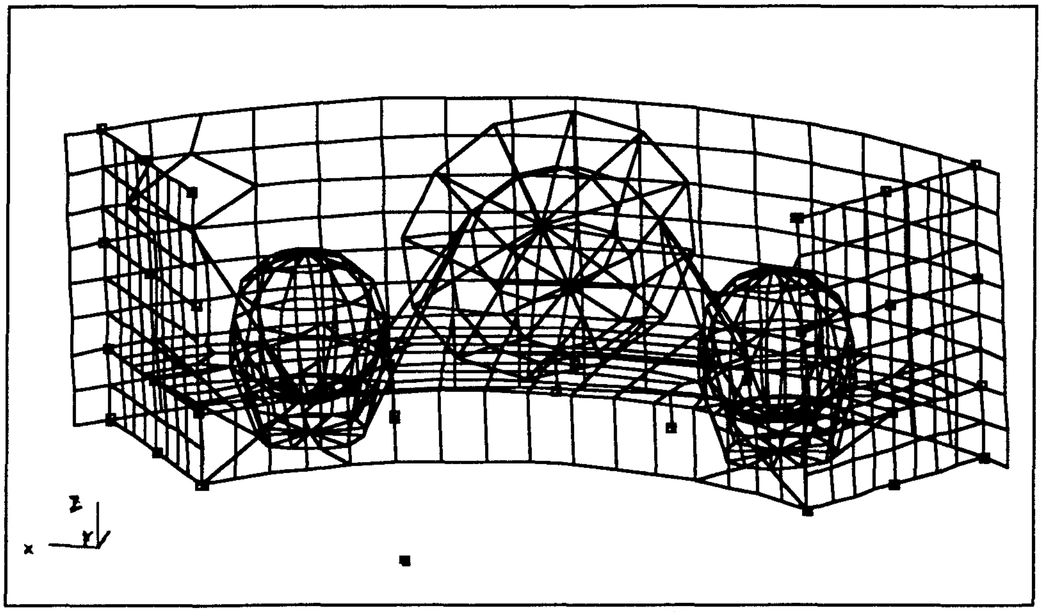

Figure 2. Mars Micromission Spacecraft Finite Element Model

Eight incremental changes were made to the model to stiffen it while staying within the initial modeling assumptions and constraint. The resulting design had a structural mass of 27.4 Kg and a longitudinal fundamental frequency of 105 Hz, but the lateral frequency was 40.6 Hz, compared to the lateral requirement of 45 Hz. It was concluded that the frequency criteria and mass allocation could not be met with an all aluminum structure. Composites were substituted for the aluminum honeycomb skins wherever feasible – the base panel, solar panel, instrument panel, RF panel, drop skirt, and tank support. In the final iteration, the lateral frequency increased to 49.7 Hz and the structural mass decreased to 19.6 Kg. It was concluded that both Ariane frequency and strength requirements can be met using a composite honeycomb structure.

The approach for the second part of the structural design study (MAC applicability) was to compare MAC loads to preliminary coupled loads analyses (CLA) performed by Arianespace on two dynamically reduced spacecraft loads FEM's representing a 220 Kg total mass Mars Micromission spacecraft and a 240 Kg spacecraft. The MAC provides an upper bound estimate of the structural loads, is used for preliminary sizing of spacecraft structure, and allows quick design cycle iterations. The MAC recognizes that the acceleration of physical masses of a spacecraft usually vary inversely with mass. The MAC is based on a combination of prior flight and test data, analysis, and experience. A single curve is typically developed for a given launch vehicle configuration that applies to a broad class of payloads.

Arianespace provided JPL with the modal response accelerations from the CLA for both spacecraft configurations. The critical Ariane 5 events analyzed were liftoff (0 ms and 50 ms), end of solid rocket booster flight, solid rocket booster jettisoning, stage 1 burnout, transonic, and max alpha Q. JPL then recovered the spacecraft member loads and accelerations for both configurations. The results for the 220 Kg configuration are shown in Table 1. It is concluded that the MAC is <u>conservative</u> for masses that are not close to the Ariane interface, but it is <u>not conservative</u> for members close to the interface. Interface distortion due to the payload dual attachment configuration is a significant contributor to the stresses in structure close to the interface and has to be accounted for in calculating stresses.

	Accelerations, g		Ratio
Location	CLA	MAC	MAC/CLA
Spacecraft Base Panel	4.5	11.5	2.6
Spacecraft Solar Panel	5.8	12.1	2.1
Probe CG	3.4	10.8	3.2
Oxidizer Tank	3.4	10.5	3.1
Fuel Tank	3.8	10.7	2.8
Electronic Boxes	5.0	11.5	2.3
	Maximum Stress, ksi		Ratio
	CLA	MAC	MAC/CLA
Spacecraft Interface	29.2	5.5	0.19

Table 1. CLA vs. MAC for Accelerations and for Interface Stresses

3 – SPACECRAFT VERIFICATION TESTING

The dynamics qualification tests specified for Ariane TWIN Auxiliary Payloads are random and low frequency sine vibration testing [2]. These tests are intended to provide environmental and structural loads qualification and modal frequency identification for the spacecraft. The vibration test input is typically notched at resonance frequencies such that structural loads do not exceed design limit loads. Although acoustic testing is not required for TWIN Auxiliary Payloads, the large solar panel on the Mars Micromission spacecraft makes an acoustic test of at least the first spacecraft prudent. The Ariane approach of combining the typically separate environmental, structural loads, and modal tests into a combined test performed sequentially in a single test setup is consistent with cheaper and faster test approaches in use at JPL, but the following enhancements are proposed for the Mars Micromission spacecraft: a) force measurement and limiting for environmental vibration tests, quasi-static loads tests, and model validation tests, b) a transient vibration alternative to the sine-sweep, and c) a direct field acoustic test. Examples of the application of these improvements employed in the Quick Scatterometer (QuikSCAT) spacecraft dynamics qualification program and the benefits to the Mars Micromission program are discussed below. The QuikSCAT spacecraft program managed by NASA's Goddard Space Flight Center (GSFC) and JPL consists of a Honeywell microwave radar instrument that measures the near surface wind velocity over the oceans integrated on a Ball Aerospace RS2000 Commercial Spacecraft Bus. The QuikSCAT spacecraft configured for a lateral axis vibration test is shown in Figure 3.

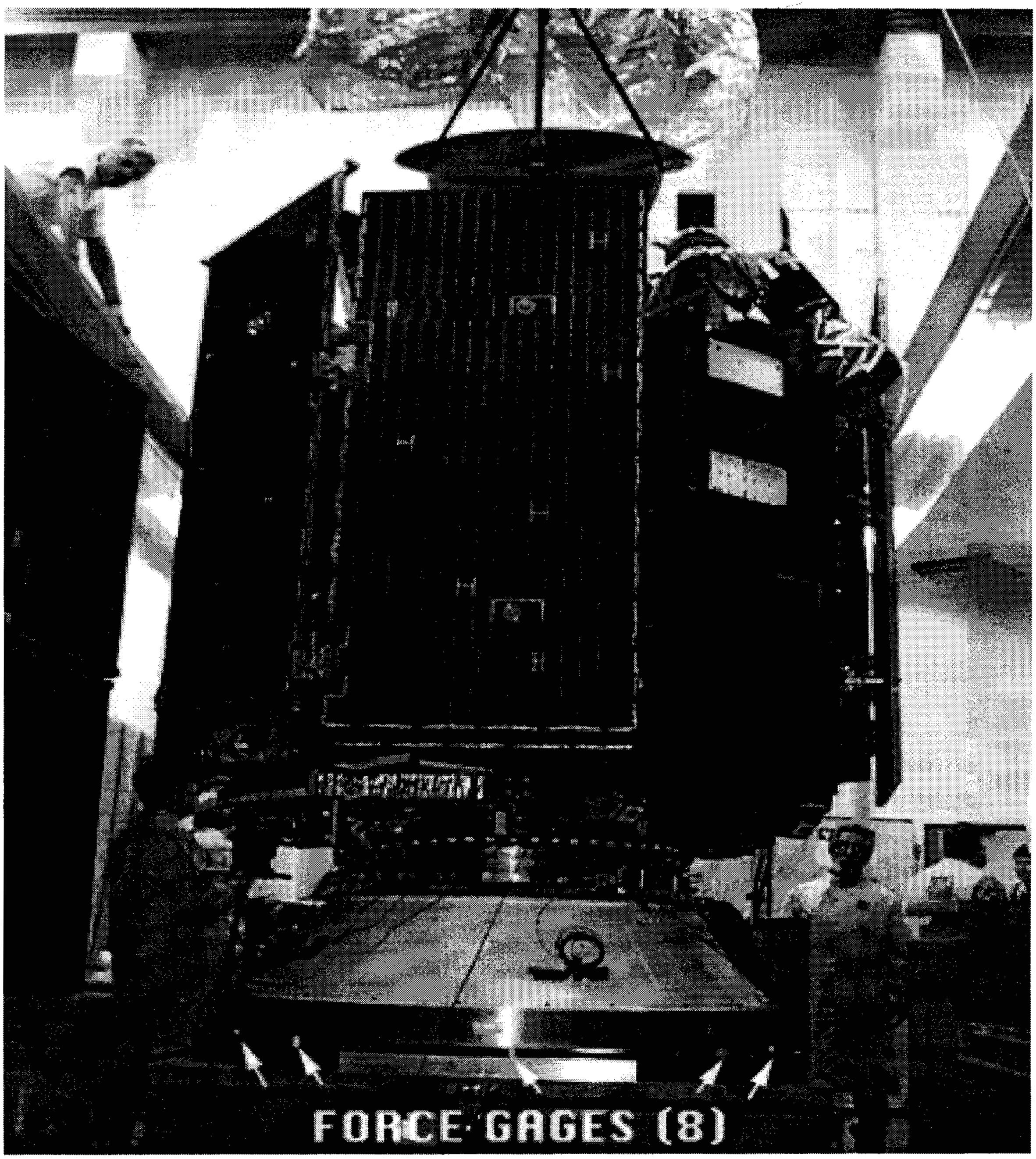

Figure 3. QuikSCAT Spacecraft Configured for Lateral Axis Vibration Test

3a - Force Measurement and Limiting

Environmental Vibration Tests

The purpose of force limiting is to reduce the response of the test item at its resonances on the shaker in order to replicate the response at the combined system resonances in the flight mounting configuration. In force limited vibration tests, both the shaker motion and reaction force are controlled to values predicted for flight. The reaction forces are measured and controlled using triaxial piezo-electric force gages sandwiched between the test item and the shaker adapter fixture. Reference [4] describes the force limited vibration testing technique and methods to develop force limit specifications. When a coupled loads analysis is available for the test item and its flight support structure, such as in the case of a spacecraft and its launch vehicle, the spacecraft structure limit loads are also considered in the development of the force limit specification and additional response limits may also be required.

The QuikSCAT random vibration test acceleration specification in the lateral and vertical axes consisted of a flat input acceleration spectrum of 0.02 G^2/Hz from 20 to 200 Hz with a 3 dB/octave roll-off from 20 to 10 Hz and from 200 to 500 Hz [5]. The lateral axis test involved limiting the overturning moment, in-axis shear force, and two critical responses. The force and moment limits were derived using the semi-empirical method [4]. Figure 4 shows the notched input acceleration in the lateral random vibration test. The notch at approximately 17 Hz is due to the limit of 2.5 x 10^8 in-lb^2/Hz in the overturning moment shown in Figure 5, and the notch at approximately 33 Hz is due to the limit of 0.1 G^2/Hz on the propulsion tank response.

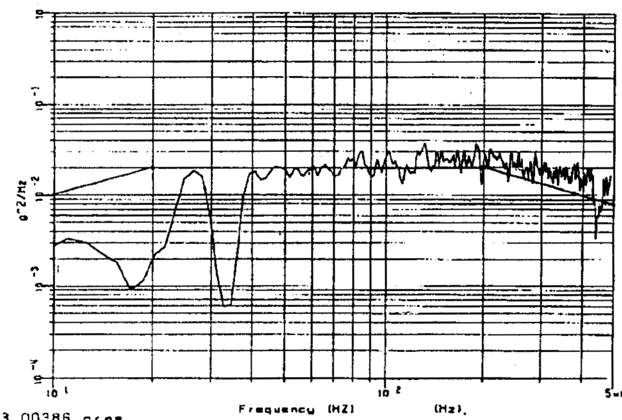

Figure 4. Notched Input Acceleration in Lateral Random Vibration Test

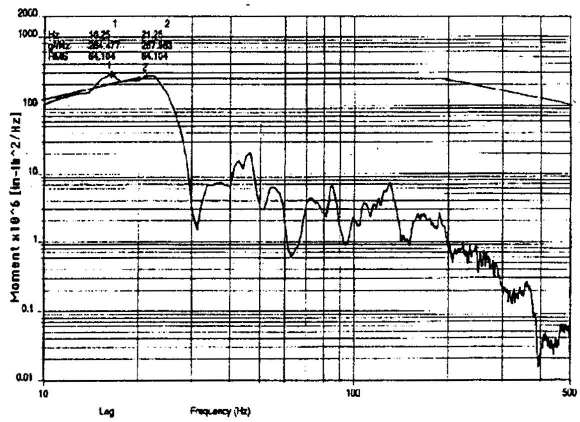

Figure 5. Limited Overturning Moment in Lateral Random Vibration Test

Quasi-static Loads Tests

A quasi-static sine burst test was performed along two axes, one lateral and one vertical, to demonstrate the structural integrity of the QuikSCAT spacecraft under maximum loading conditions [5]. The lateral axis test was conducted along launch vehicle axis which corresponded to the maximum lateral load condition, the overturning moment. This involved clocking the spacecraft at an angle of 50.25 degrees relative to the spacecraft principal lateral axes. This test was performed in place of a static test for structural qualification and provides an efficient means of applying the flight-limit loads to a structure using a vibration shaker instead of a potentially complicated static test setup.

The lateral axis test consisted of a sinusoidal input at 12 Hz with 5 cycles to ramp up to full level, 6 cycles at full level, and 5 cycles to ramp down from full level. Originally, it was planned to use closed loop control of the measured overturning moment. However, tests with a mass simulator revealed that the controller loop time was too long (~1-2 seconds) to reliably control the level with a limited number of cycles (<30). Therefore the test was run using a shock test algorithm, which is essentially an open loop test. Manual adjustments, to account for non-linearity, are made between runs of increasing level. The 12 Hz input frequency was chosen lower than the primary natural frequency of the test article, approximately 17 Hz, in order to avoid any possible instability in the response of the test article at resonance. After preliminary runs at 25%, 50%, and 72% of full level, a full level test was performed.

The utilization of force gages was essential to avoid overtest since it is practically impossible to measure, with accelerometers, the acceleration of the CG of a flexible structure in a vibration test. The maximum slip table input acceleration, shown in Figure 4, was 3.53 G. The maximum shear, shown in Figure 5, measured at the force gages was 10787 lb. The maximum bending moment, shown in Figure 6, measured at the force gages was 634000 in-lb. Using these numbers, the mass of the spacecraft (2080 lb.), and the mass (279 lb.) and height (4.5 in.) of the mounting ring located above the force gages, the acceleration of the spacecraft CG is:

$$A = (10787 \text{ lb.} - 279 \text{ lb.} * 3.53 \text{ G})\ 2080 \text{ lb.}$$
$$= 9802 \text{ lb.}/2080 \text{ lb.} = 4.71 \text{ G.}$$

The amplification of the input acceleration is: 4.71 G / 3.53 G = 1.33, which corresponds to the overtest factor that would have resulted if the input had been assumed to be identical to the CG acceleration, i.e. rigid body motion. The bending moment at the base of the spacecraft is:

$$M \text{ base} = 634000 - (279 \text{ lb.} * 3.53 \text{ G} * 2.25 \text{ in.}) - (9802 \text{ lb.} * 4.50 \text{ in.})$$

$$= 587675 \text{ in-lb.,}$$

which represents 99.9 % of the required protoflight base bending moment of 588233 in-lb.

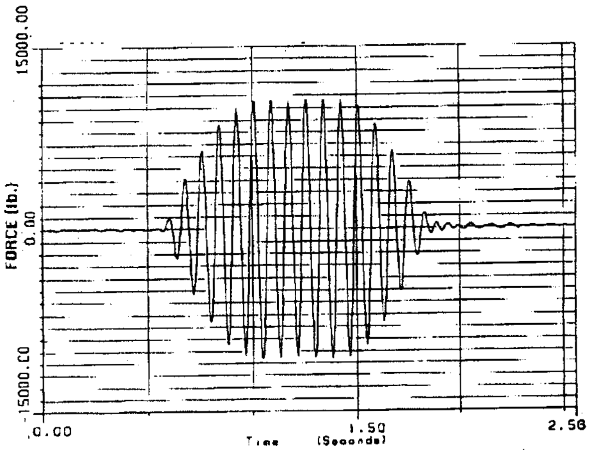

Figure 5. Base Shear Force in Sine Burst Test

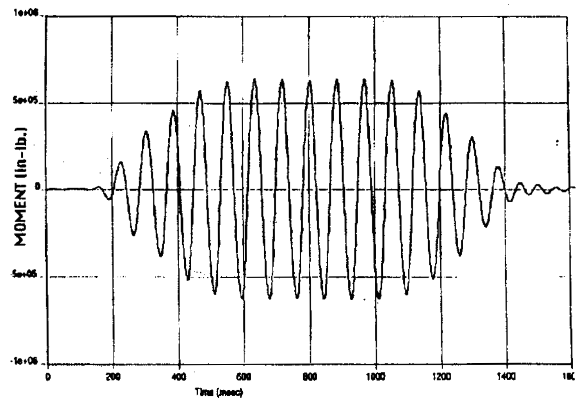

Figure 6. Base Moment in Sine Burst Test

Model Validation Tests

Low level (0.1 G input) sine-sweep tests were conducted at the beginning and the end of each axis of testing of the QuikSCAT spacecraft [5]. (Other 0.1 G sine-sweep tests were also conducted at various stages of the sine-burst testing, and low-level flat random tests were conducted at the beginning of workmanship verification sequence of random tests.) The purpose of the sine-sweep tests was threefold. First, they provide data to determine the fixed-base mode shapes, natural frequencies, and modal masses of the spacecraft in order to validate the analytical model used to predict the spacecraft loads. There was no separate modal test of the QuikSCAT spacecraft. Second, the sine-sweep tests provide a measure of the structural integrity of the spacecraft at various stages of the quasi-static and workmanship vibration testing. Third, they provide a good end-to-end check of the calibration and set-up of the force gage instrumentation.

Benefits to Mars Micromission

Force limited vibration testing is routinely employed on all flight projects at JPL. Over 200 force limited vibration tests have been performed in the past 10 years. Force limiting alleviates the severe overtest at hardware resonances inherent in conventional vibration tests, with the associated risk of unnecessary hardware failures. It is preferred over other means of reducing the overtest because it is less dependent on the hardware dynamic analysis, it automatically applies the acceleration input notch at exactly the right frequency and depth regardless of structural nonlinearities, the rationale for the methodology is soundly based in physics, and the force limit adds additional protection against accidental overtest.

The sine burst test provides structural loads qualification of the core spacecraft structure without the disadvantages of the sine-sweep test. The force gages provide a direct measurement of the acceleration of the CG of the spacecraft, avoiding the possible overtest in attempting to use accelerometers to measure CG accelerations. The force measurements also add to the modal data obtained in the 0.1 G sine-sweeps, providing a direct measure of modal masses.

3b - Transient Vibration Tests

Although the above described quasi-static loads test is a good substitute for a static test or a sine-sweep test to qualify the core spacecraft structure for the structural loads, it does not qualify structural appendages and their associated hardware, which will experience higher accelerations than will the spacecraft CG. A transient vibration test is proposed to qualify appendages on the Mars Micromission spacecraft. The test would consist of a series of individually applied, discrete frequency, limited cycle, modulated sine pulses in each axis. The pulses are similar to the sine burst pulses used for the quasi-static loads test, but would be applied at frequencies corresponding to flight frequencies generating significant loading on the spacecraft to simulate the flight environment without excessive margins. Since the coupled loads analyses for TWIN Auxiliary Payloads extend to 90 Hz, the CLA results can be employed directly to define pulse frequencies and magnitudes. Perhaps two to five pulses would be applied per axis. The shape of the waveform is the acceleration versus time response of the mass of a one degree of freedom system when it is base-excited by an exponentially decayed sine wave transient. The normalized waveform, shown in Figure 7, can be approximated by the following equation:

$$G_p\,(f_i,t) = Bte^{-\zeta\omega_i t}\,\mathrm{Sin}\,(\omega_i t) \quad \text{for } t \geq 0 \quad \text{(Peak Gs)} \tag{1}$$

where

$$t = \text{time} \quad \text{(seconds)} \tag{2}$$

$$f_i = \text{frequency of the } i^{th} \text{ pulse} \quad \text{(Hz)} \tag{3}$$

$$\omega_i = 2\pi f_i \quad \text{(radians/sec)} \tag{4}$$

$$B = \omega_i e\,\zeta G_i \quad \text{(Peak Gs/sec)} \tag{5}$$

$$\zeta = \text{damping ratio} = 0.04897 \tag{6}$$

$$G_i = \text{Peak Gs input at the } i^{th} \text{ frequency} \tag{7}$$

The modulated sine pulse waveform was chosen to simulate the transient environment because it is the basic waveform observed, for widely separated modes, from spacecraft loads analysis responses. Figure 8 shows the response waveform of a spacecraft component in the vertical axis, resulting from the spacecraft loads analysis, which can be compared to the normalized test pulse in Figure 7. The Figure 8 waveform is for a spacecraft element with two dominant modes. The corresponding filtered waveform for each mode would be similar to that of Figure 7.

Analytically, this waveform can be approximately derived by making simplifying assumptions regarding the source pulse and the launch vehicle / spacecraft coupled dynamic model. This is illustrated in Figure 9. The transient source waveform is assumed to be a delta function. Assuming the launch vehicle lower stage can be represented as a single degree of freedom system, the response at the interface with the upper stage is an exponentially decayed sine wave transient. Assuming that the upper stage can be represented as a single degree of freedom system, the response at the interface with the spacecraft is the modulated sine wave shown in the bottom of Figure 9. The same approximate waveforms will also result for more complex systems and for more realistic transient waveforms than the delta function if the modes are widely separated.

The benefit of implementing the modulated sine pulse test for the Mars Micromission is to avoid possible unrealistic test failures in the sine-sweep test. The responses of spacecraft to sine-sweep tests are frequently considerably greater than to the actual flight transient environment due to resonance buildup. The resonance buildup can be compensated for by reducing the sine test level to provide the same spacecraft response as predicted in flight, however this requires knowledge of the Q for the critical resonance and may result in overtest or undertest for other resonances with different Q values. Also, the sine-sweep test produces many more peak response cycles than does the actual flight transient environment. The modulated sine pulse has been successfully employed on several JPL projects, such as Galileo [6] and Cassini, to eliminate the sine-sweep overtest for hardware sensitive to low frequencies.

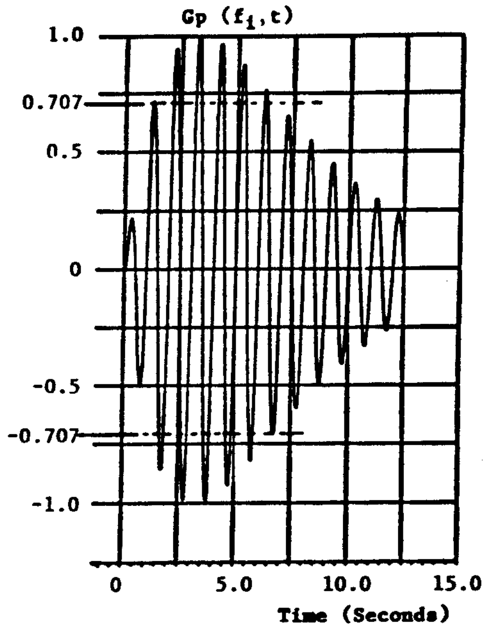

Figure 7. Normalized Modulated Sine Pulse

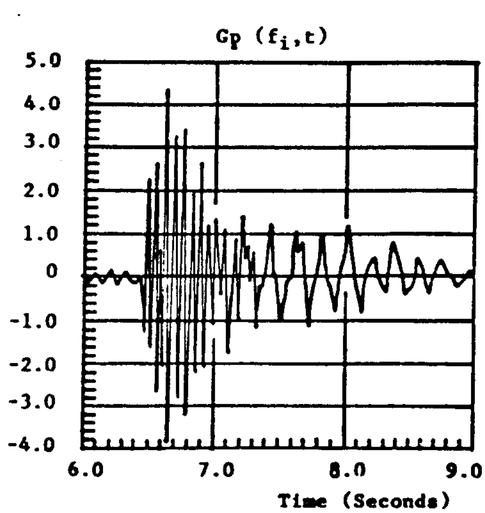

Figure 8. Typical Spacecraft Hardware Response from Loads Analysis

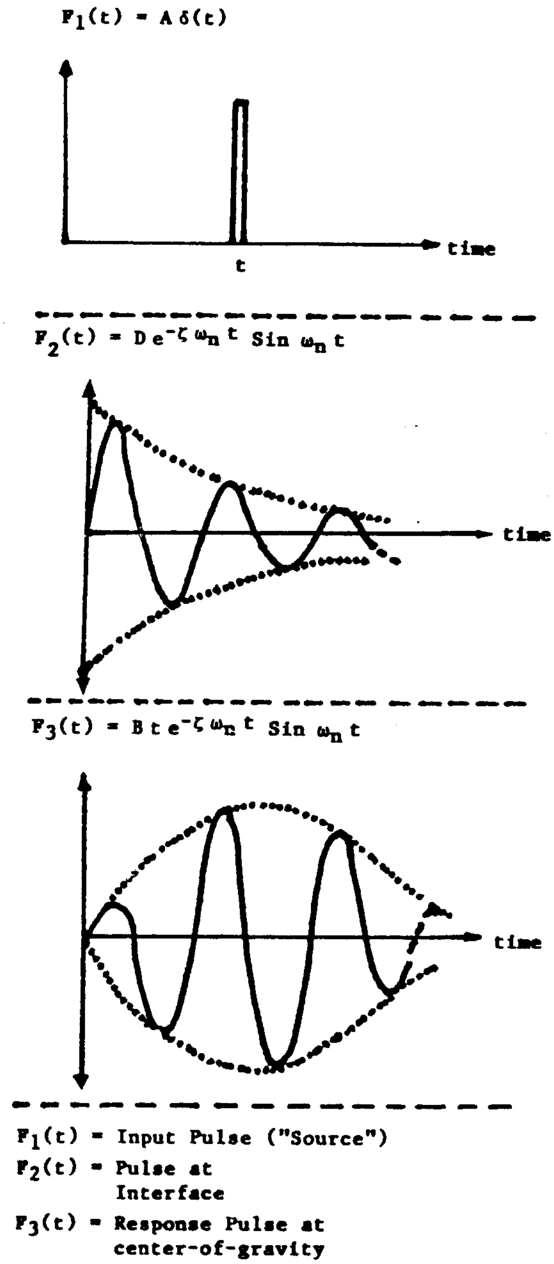

Figure 9. Input/Response History

3c - Direct Field Acoustics

A novel direct acoustic test was performed on the QuikSCAT spacecraft at Ball Aerospace Technology Corporation (BATC) in Boulder, Colorado, in October 1998 [7]. Instead of conducting the acoustic test with the spacecraft in a reverberant room, as is the usual practice, the test was conducted with the spacecraft mounted on a shaker slip-table in a nearly anechoic, vibration test cell. The spacecraft was surrounded with a three-meter high ring of large, electro-dynamic speakers, spaced approximately 1.3 meters away from the two-meter diameter, 900 kg. spacecraft. The thiry-one speaker cabinets were driven with 40,000 rms watts of audio amplifier power. The acoustic specification, with an overall sound pressure level of 135 dB, was achieved one meter in front of the speakers, Figure 10.

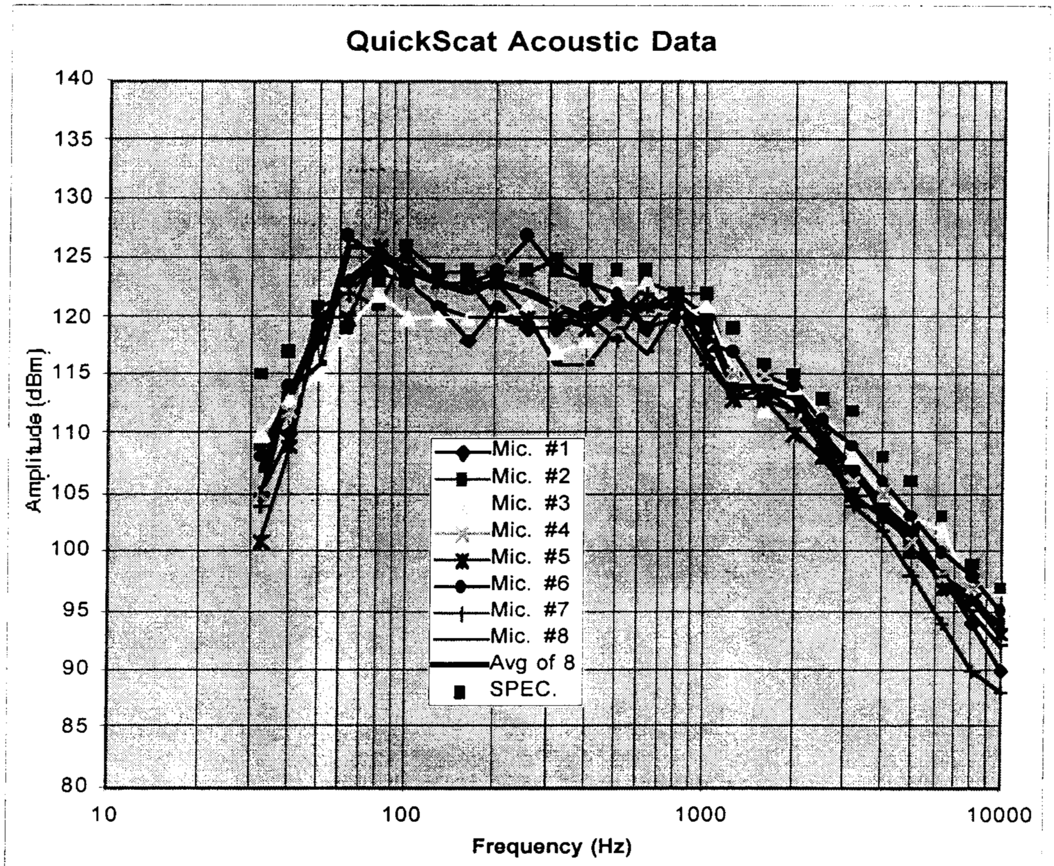

Figure 10. Comparison of Eight Microphones and Specification Acoustic Levels

As previously noted, the Mars Micromission spacecraft contractor has not yet been selected. Small spacecraft manufacturers often do not have convenient access to a reverberant acoustic facility. To perform an acoustic test, the manufacturer must pack up and transport the spacecraft to an outside facility, sometimes that of a larger competitor. In the case of the QuikSCAT spacecraft, this would have added over a week to the system test schedule and incurred additional handling risks. Many acoustical issues may be raised concerning such a test and how it compares with a conventional reverberant-field acoustic test, e.g., the maximum obtainable levels and spectrum, the spatial and frequency uniformity, the efficiency of a normal-incidence direct field vs. a reverberant field in the excitation of structures, and the importance of the spatial coherence of the acoustic field. However, it should be recognized that the conventional reverberant acoustic test is also an inexact representation of the actual flight acoustic environment, which consists largely of progressive waves coming from a select range of angles. The direct field acoustic test provides the option to qualify the spacecraft for the flight acoustic environment while avoiding significant schedule impacts and handling risks, at a small fraction of the cost of building and maintaining a reverberant acoustic facility.

4 - CONCLUSIONS

A viable structural design for the Mars Micromission spacecraft that will meet Ariane frequency and strength requirements has been demonstrated. It has been verified that the MAC provides a conservative estimate of structural loads for preliminary design, except close to the attachment, where interface distortion is a significant contributor to the loads and must be accounted for in calculating stresses. The utilization of force gages in the spacecraft vibration test is essential to simulate the flight environment without unnecessary overtest. The theory and application of force limiting is well established in environmental vibration tests. Force gages are the only practical method to measure the actual CG acceleration in quasi-static loads tests on shakers. Force measurements provide additional modal data in vibration tests for FEM validation. The utilization of sine pulses at selected frequencies for spacecraft structural qualification is a viable alternative to avoid the conservatisms inherent in sine-sweep vibration tests. Finally, direct field acoustic tests are an attractive alternative for spacecraft qualification when convenient access to a reverberant acoustic facility is not available.

5 - ACKNOWLEDGEMENTS

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