COMBINED LOADS, VIBRATION, AND MODAL TESTING OF THE QUIKSCAT SPACECRAFT

Terry Scharton,
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA
terry.d.scharton@jpl.nasa.gov

and

Michael Vujcich
Ball Aerospace Technology Corporation
Boulder, CO
mvujcich@ball.com

ABSTRACT

Combining the quasi-static loads, workmanship verification, and model validation tests of aerospace hardware into a single vibration test sequence can considerably reduce schedule and cost. The enabling factor in the implementation of the combined dynamic testing approach is the measurement of the dynamic forces exerted on the test item by the shaker. The dynamic testing of the QuikSCAT spacecraft is discussed as an example of a successful combined loads, workmanship, and model validation test program.

KEYWORDS

Vibration Testing, Force, QuikSCAT

INTRODUCTION

The maximum expected acceleration of the center-of-gravity (CG), which is also called the quasi-static or net CG load factor, is a key parameter in the design, analysis, and testing of aerospace structures. The typical spacecraft structural design approach includes an initial sizing of primary structural members based on conservative quasi-static design load factors followed by more detailed coupled loads analysis to determine component accelerations. The net CG load factors, which are simply the interface forces divided by the weight of the payload, are typically provided to the spacecraft contractor by the launch vehicle contractor. The load factors are usually based on flight test data if available and previous analyses of similar payloads. The loads specified at this stage are intended as a conservative design envelope with sufficient margin to account for design changes. In a schedule critical program with a limited opportunity for coupled loads and design iterations, the quasi-static loads approach becomes more important as there are less opportunities to change the design.

Unfortunately, it is practically impossible to measure, with accelerometers, the acceleration of the CG of a flexible structure in a vibration test. One approach, used in the past, is to conduct a sine dwell vibration test at a frequency well below the first resonance of the test structure, so that the structure might be assumed to move as a rigid body. In this case, the input acceleration is approximately equal to the CG acceleration. However, the displacement limitations of the shaker often frustrate this approach, particularly in the case of large structures with low frequency resonances and high load requirements. Another approach is to use an accelerometer located at the static CG of the structure. However, once a body

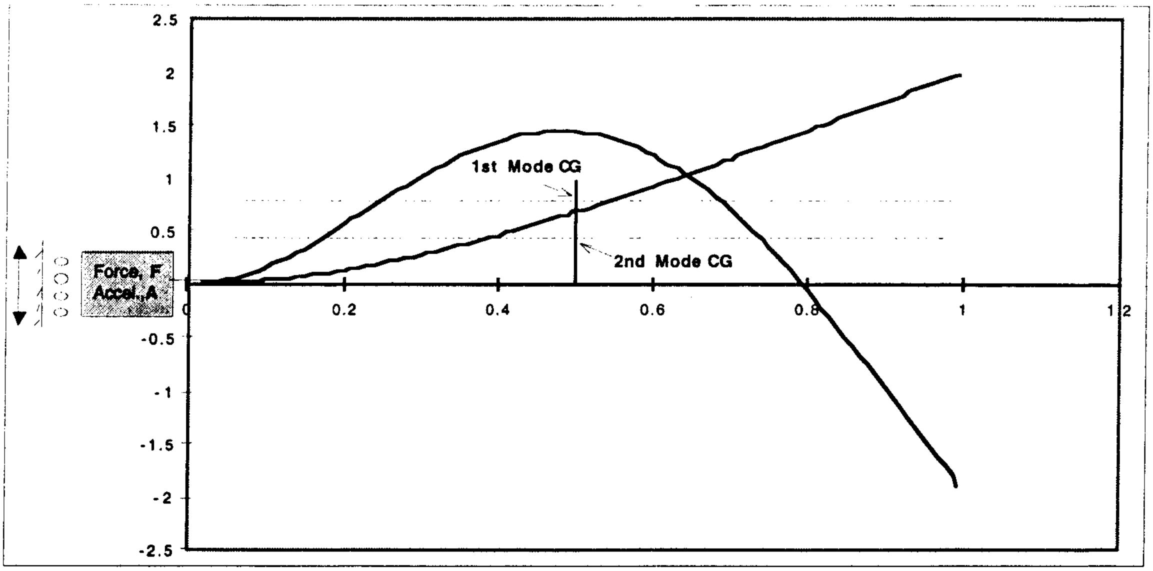

Figure.1 Where is the CG of the First and Second Modes of a Cantilevered Beam

begins to flex under vibration, the CG moves away from the static CG and becomes a virtual point, rather than a point fixed relative to the structure. This is illustrated in Figure 1, which shows the CG location of the first and second bending modes of a cantilevered beam. The CG location depends on the mode shape and therefore on frequency, and is generally not located on the structure. Clearly one could not locate an accelerometer there, at the CG.

Fortunately, the advent of piezoelectric force gages, sandwiched between the shaker and vibration test item, has made the measurement of CG acceleration in vibration tests very straightforward. By Newton's second law, the CG acceleration is simply equal to the measured external force divided by the total mass. In addition to providing a means for measuring CG acceleration in vibration loads tests, the measurement of shaker force has also proven very useful for limiting the response in environmental, sine-sweep and random, vibration tests used for qualification and workmanship verification of aerospace structures [1]. Finally, the measurement of shaker force also provides a means of measuring the effective mass in base-drive modal vibration tests conducted for model verification.

With NASA's increased emphasis on reducing costs and schedule, and consequently on reducing or in some cases even eliminating testing, it is very beneficial to combine the various types of dynamic tests. For the reasons previously discussed, the measurement of the input force vector in vibration tests has proven to be an enabling factor in combining vibration, loads, and modal tests of aerospace structures. The combined dynamic testing approach has recently been utilized in several spacecraft experiment and system test programs managed by the Jet Propulsion Laboratory (JPL). To illustrate the combined dynamic testing approach, this paper discusses the QuikSCAT spacecraft vibration testing which was conducted in October 1998 at the Ball Aerospace Technology Corporation (BATC) facility in Boulder, CO. The photograph in Figure 2 shows the QuikSCAT spacecraft configured for a lateral vibration test. Notice the eight piezoelectric, tri-axial force gages spaced at 45-degree intervals between the fixture plate and the mounting ring to which the spacecraft adapter is bolted.

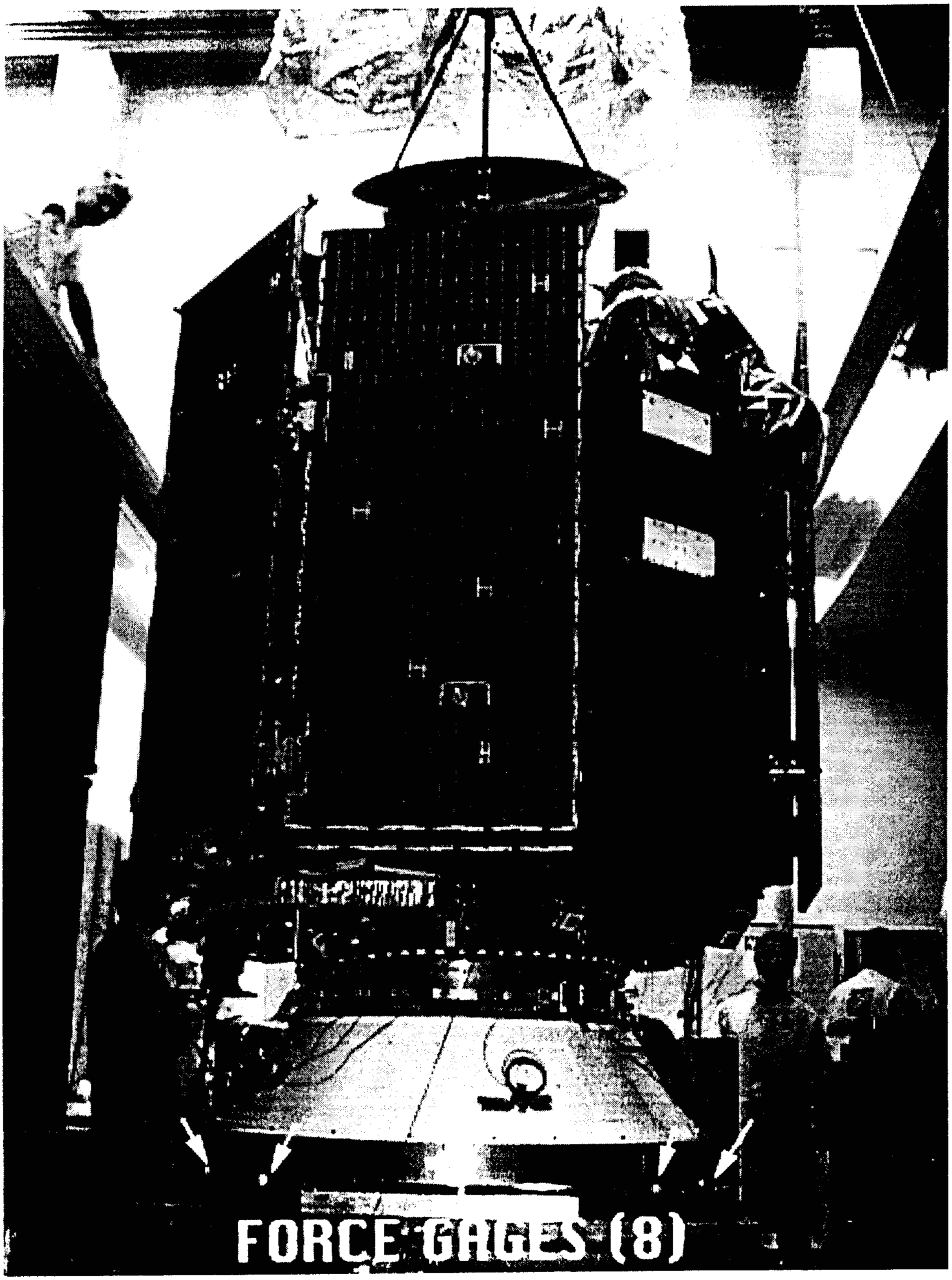

Figure 2. QuikSCAT Spacecraft Configured for Lateral Axis Vibration Test

DESCRIPTION OF QUICKSCAT SPACECRAFT

The Quick Scatterometer (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 Launch Vehicle is a Lockheed Martin Astronautics Titan II. The QuikSCAT mission is a replacement for the JPL NASA Scatterometer (NSCAT) which was lost when the ADEOS I spacecraft failed on 6/30/97.

The QuikSCAT spacecraft was the first contract awarded under the NASA Rapid Spacecraft Acquisition (RSA) program. The spacecraft contract was awarded in December 1997 with a scheduled launch in November 1998 resulting in a short design cycle time and a real application of the NASA "faster, better, cheaper" design philosophy.

HISTORY OF QUICKSCAT LOADS DEFINITION

The maximum predicted quasi-static limit load factors (intended as a conservative envelope of flight events) were specified as +10.0 G (Stage II Shutdown) in the thrust direction and +/- 2.5 G (Stage I Fuel Depletion) in the lateral direction. The spacecraft primary structure was subsequently designed to +11.0 G in the thrust direction and +/- 3.6 G in the lateral direction resulting in a base shear load of 7506 lb. limit and a base bending moment of 377476 in-lb. limit.

An MSC/NASTRAN model of the Scatterometer payload was provided by JPL and coupled to a model of the Ball Aerospace RS2000 Bus. The predicted first lateral bending frequency of the spacecraft was 20 Hz vs. a minimum required frequency of 10 Hz. A transient response analysis (coupled loads analysis) was performed by Lockheed Martin Astronautics to compute design internal loads in the spacecraft primary structure. The Stage I Fuel Depletion event was determined to be critical resulting in interface loads significantly in excess of the spacecraft structural capability. The predicted base shear was 9690 lb. limit and the predicted base bending moment was 660612 in-lb. limit.

The base bending moment was reduced to 534758 in-lb. limit (3.26 sigma) by performing an oxidizer depletion shutdown as opposed to fuel depletion. The CLA was repeated for a set of 14 forcing functions based on nozzle pressure measurements from previous flight data.

Initial investigation revealed that the high lateral loads were due to a differential thrust generated during Stage I depletion. Upon fuel/oxidizer depletion, a differential thrust shown in Figure 3 results as "sputtering" occurs in one of the nozzles. The differential thrust causes a bending moment applied to the launch vehicle and a subsequent high lateral acceleration on the payload.

Furthermore, the QuikSCAT spacecraft was determined to be the lightest/stiffest payload flown to date on Titan II. The QuikSCAT spacecraft has a weight of 2100 lb., and a first lateral bending frequency of 20 Hz compared with previous Titan II payloads in the 4000 lb. range with lateral bending frequencies around 10 Hz. The coupled spacecraft/booster primary bending frequency was predicted to be 13.3 Hz, directly in line with the peak response shown in Figure 3.

Preliminary analysis of a 10 Hz isolation system resulted in a technically feasible design producing loads within the original design envelope. This option was not pursued due to program schedule constraints and potential risk. A program decision was made to fly at higher loads with reduced margins of safety. The protoflight test factor was also lowered from 1.25 to 1.10.

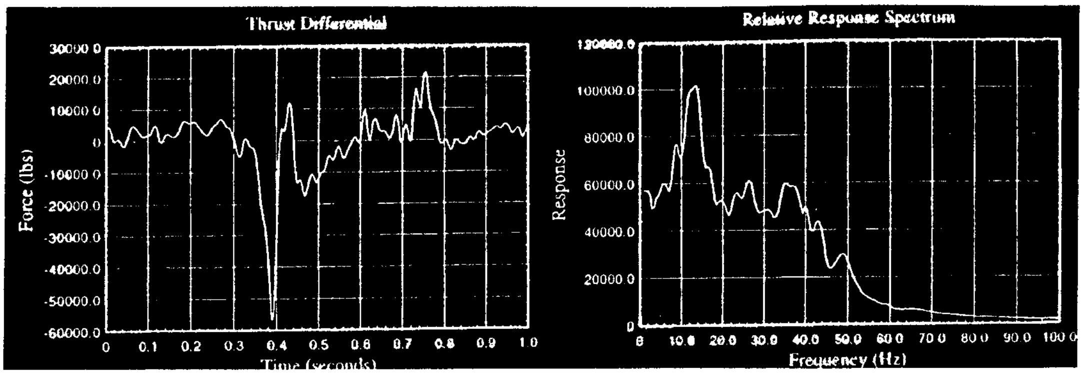

Figure 3. Stage I Oxidizer Depletion Thrust Differential and Relative Response Spectrum

QUASI-STATIC LOADS TEST

A quasi-static sine burst test was performed along 2 axes, one lateral and one vertical, to demonstrate the structural integrity of the QuikSCAT spacecraft under maximum loading conditions. The lateral axis test was conducted along the Z 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 introducing "static" loads onto 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 increases the level in steps and makes adjustments between the steps. The 12 Hz input frequency was chosen lower than the primary natural frequency of the test article, approximately 17 Hz, in order to limit the transmissibility of the test article response at resonance. After preliminary runs at 25%, 50%, and 72% of full level, a full level test was performed.

Data for the full level sine burst is shown in Figures 4 to 6. 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 numerical values were read with a digital cursor.) 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:

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

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:

$$
\begin{aligned}
M\text{ base} &= 634000 - (279\text{ lb.} * 3.53\text{ G} * 2.25\text{ in.}) - (9802\text{ lb.} * 4.50\text{ in.})\\
&= 587675\text{ in-lb.},
\end{aligned}
$$

which represents 99.9 % of the required protoflight base bending moment of 588233 in-lb. The center-of-shear in the test was located at:

X shear = 587675 in-lb. /9802 lb. = 60 in.

Comparing the center-of-shear location of 60 in. to the CG location, 52 in. above the bottom of the spacecraft adapter, indicates that the bending moment includes a significant contribution from the rotation of the spacecraft. Since the spacecraft is fixed at the base, this rotation results only from the flexibility of the spacecraft.

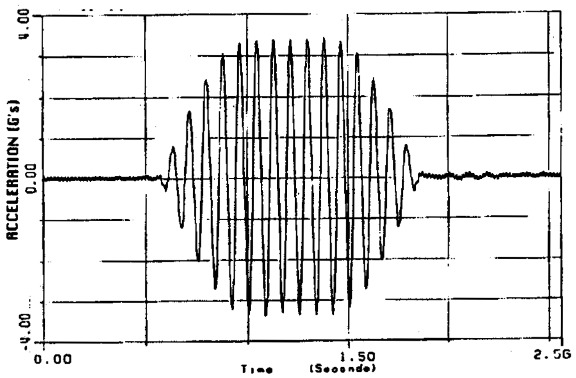

Figure 4. Input Acceleration in Sine-burst Test

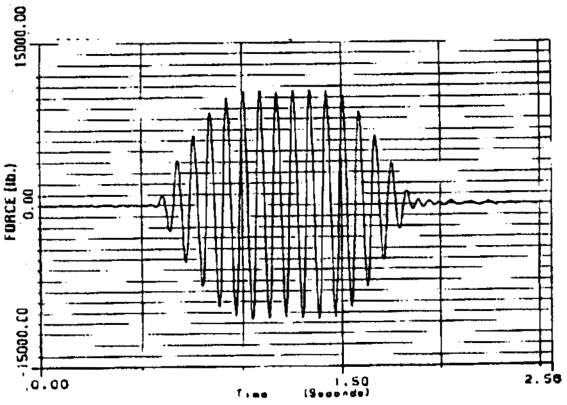

Figure 5. Base Shear Force in Sine-burst Test

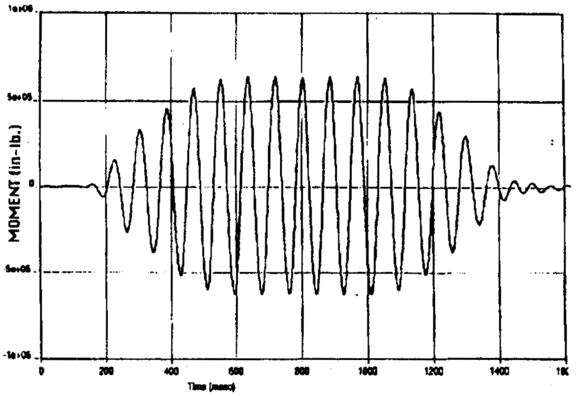

Figure 6. Base Moment in Sine-burst Test

ENVIRONMENTAL VIBRATION TESTS

After successful completion of the sine-burst quasi-static loads testing, the spacecraft was subjected to a force-limited random vibration test for workmanship verification. In workmanship tests, it is customary to notch the input acceleration to limit the response of the components to their flight-limit loads. It is recommended that this notching be implemented by limiting the input force as described in [1] if at all possible. Limiting the input force, and possibly the overturning moment in lateral tests, limits the critical responses over most of the spacecraft structure and components. In some cases, such as for the QuikSCAT spacecraft discussed here, it is still desirable to limit the responses of a few critical items using acceleration limits.

The QuikSCAT acceleration specification for both the lateral and vertical random vibration tests consisted of a flat input acceleration spectrum of 0.2 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. The lateral axis test involved limiting the overturning moment, in-axis shear force, and two critical responses. The axial test involved limiting the axial force and the nadir deck axial response. In addition, the axial test was stopped after a –3 dB run, because a number of components were at their flight-limit loads. The force and moment limits were derived using the semi-empirical method [2].To verify the structural integrity of the spacecraft, a 0.1G sine-sweep test was conducted both before and after the random vibration tests in each axis.

Figure 7 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 8, and the notch at approximately 33 Hz is due to the limit of 0.1 G^2/Hz on the propulsion tank response shown in Figure 9.

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. (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 and natural frequencies 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. The initial 0.1 G input sine–sweep tests preformed at the beginning of the lateral and vertical axis tests are shown in Figures 10 and 11, respectively.

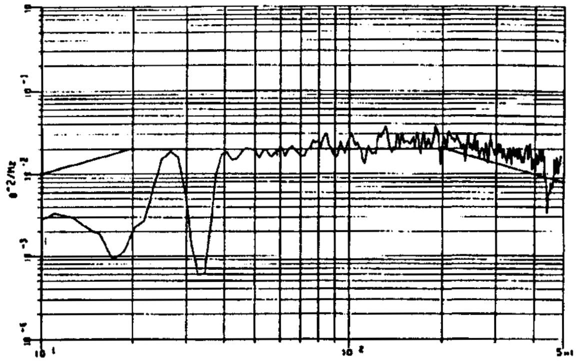

Figure 7. Notched Input Acceleration in Lateral Vibration Test

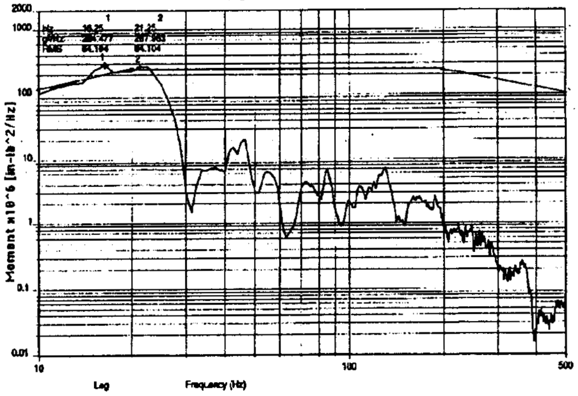

Figure 8. Limited Overturning Moment in Lateral Vibration Test

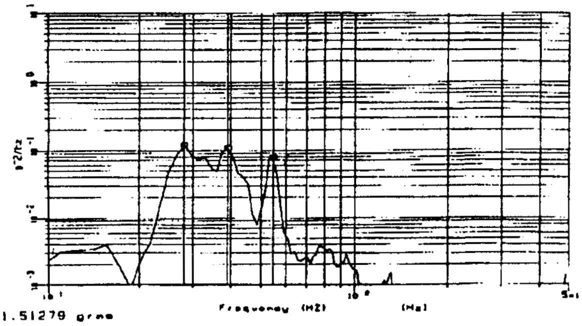

Figure 9. Propulsion Tank Response in Lateral Random Vibration Test

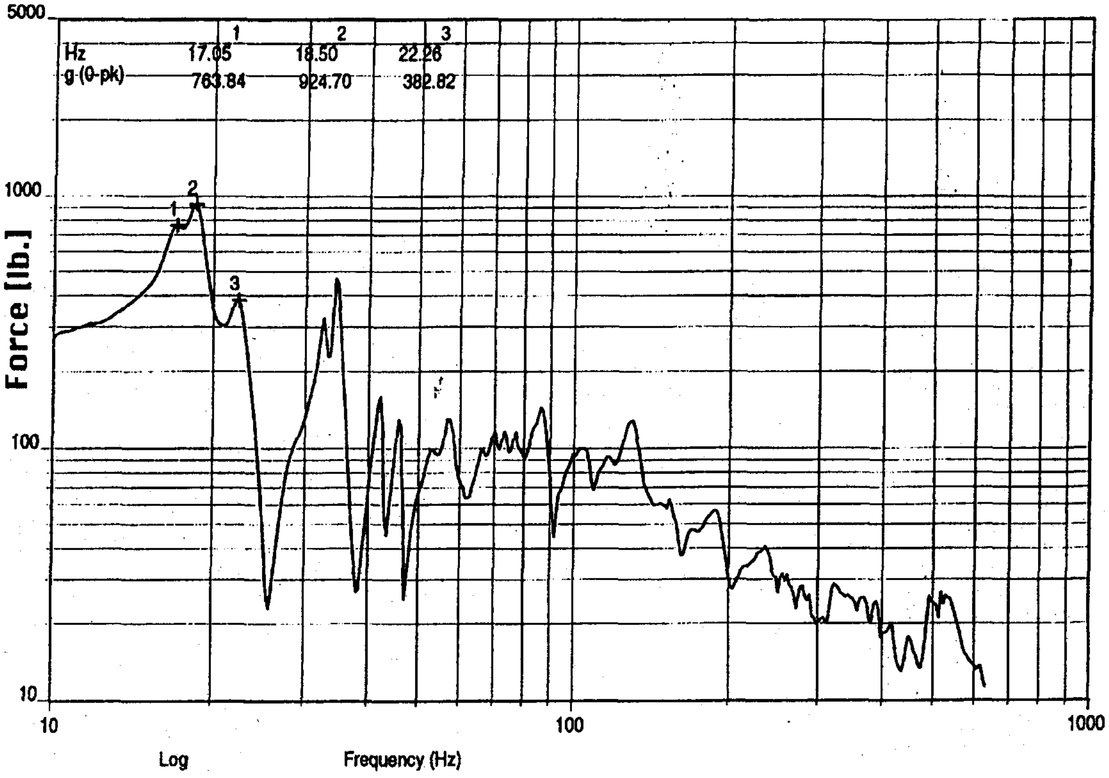

Figure 10. In-axis Force in 0.1 G Input Initial Lateral Sine-sweep Test

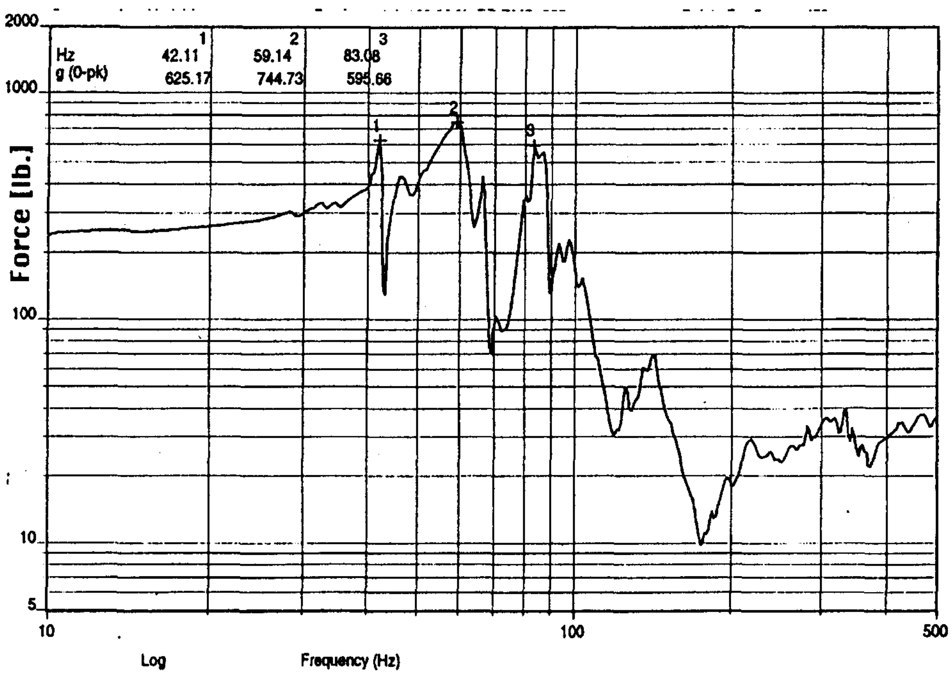

Figure 11. In-axis Force in 0.1 G Input Initial Vertical Sine-sweep Test

The value of the in-axis force at 10 Hz in the lateral sine-sweep test is approximately 271 lb., see Figure 10. This is somewhat above the expected rigid body value of 0.1 G * (2080 + 279) = 236 lb., because at 10 Hz there is already some resonant contribution to the CG acceleration from the first mode at approximately 17 Hz. In the axial test data shown in Figure 11, the value of the in-axis force at 10 Hz is very close to the 236 lb. rigid body value.

The model was correlated using data from both the low level sine-sweep tests as well as from the low-level flat-spectrum random vibration tests. Both mode shapes and natural frequencies were generated from the test data. Four low-frequency peaks are apparent in the lateral axis data shown in Figure 10. The three peaks at approximately 17, 18.5, and 22 Hz are complicated by participation of the shaker slip table and by the 55-degree clocking of the spacecraft relative to its principal axes. The 34 Hz lateral resonance shown in Figure 10 involves motion of the propulsion tank. Six modes were identified from the low-level axial vibration test data. A "best fit" of the analytical modes was obtained by changing parameters of both the spacecraft and fixture portions of the model. Once the model was correlated with the vibration test data, changes were made to the model used for the coupled-loads analysis.

The forces measured in a sine-sweep test may also be utilized to calculate the modal effective mass [3], a very important modeling parameter, which quantifies the relative participation of each mode. For example, the effective mass m_1 of the first mode shown at approximately 42 Hz in Figure 11, may be calculated as follows:

$$F_1 = A_0 * [M_1 + m_1 * Q_1]$$

$$625 \text{ lb.} = 0.1 \text{ G } [2359 \text{ lb.} + m_1 * 17]$$

$$m_1 = 229 \text{ lb.}$$

where F_1 is the peak force at the modal resonance frequency, A_0 is the acceleration input, M_1 is the residual mass [4] (which, for the first mode, is equal to the total mass), and Q_1 is the quality factor of the subject mode. (The quality factor may be determined from the half-power band-width, here 2.5 Hz, of the mode as follows: $Q_1 = 42 / 2.5 = 17$.) In the same manner, one may then calculate the effective mass of the second mode and so on, but the residual mass for the subject mode must be reduced by the sum of the effective masses of the lower frequency modes. An important property of the modal effective masses is that they must add up to the total mass.

Comparison of the forces and responses measured in the low-level sine-sweeps before and after each axis of vibration showed negligible changes in natural frequencies and amplitudes. The in-axis force provides an excellent overall "signature" for checking the structural integrity because it tends to integrate over the structure and thus is less sensitive to local effects and noise than individual response measurements. The frequency shifts of the low frequency modes were less than the 5% criterion and the amplitude changes were less than the 20% criterion. After the complete vibration testing sequence, the spacecraft performance met all of the test success criteria, and there were no visible signs of damage.

CONCLUSIONS

The QuikSCAT spacecraft was designed, fabricated, and tested in just one year and a week. The vibration testing sequence of the QuikSCAT spacecraft included: 1. sine-burst vibration tests to qualify the structure for quasi-static loads, 2. random vibration tests to verify workmanship, and 3. sine-sweep vibration tests to obtain modal data for validating the loads model. The technology, which enabled the combining of these dynamics tests, was the employment of tri-axial, piezo-electric force gages mounted between the shaker and spacecraft to measure the input forces and moments. The complete dynamics testing sequence, which included the aforementioned three types of vibration tests plus a novel in-situ acoustic test conducted while the spacecraft was mounted on the vibration test slip table [5], was completed in just one week! If these four dynamics tests had been conducted individually, i.e. separate static, vibration, modal, and acoustic tests, each of them, with the associated spacecraft handling and testing, might easily have consumed a week of schedule and commensurate costs. It is envisioned that the benefits of the combined dynamics testing approach demonstrated in the QuikSCAT program will make this approach attractive for many future spacecraft programs.

ACKNOWLEDGMENTS

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