Vibration and Acoustic Testing of Spacecraft

Terry D. Scharton, Jet Propulsion Laboratory, Pasadena, California

Spacecraft are subjected to a variety of dynamics environments, which may include: quasi-static, vibration and acoustic loads at launch; pyrotechnic shocks generated by separation mechanisms; on-orbit jitter; and sometimes, planetary landing loads. There is a trend in the aerospace industry to rely more on structural analyses and less on testing to simulate these environments, because dynamics testing of spacecraft is time consuming, risky and expensive. However, as Dr. Edward Stone, the previous director of the Jet Propulsion Laboratory (JPL) told some students in the wake of the failures of two Mars spacecraft in 1999, "The key thing is to test. Build it, test it and test it some more. Because once it's gone, it's too late." Recognizing the essential role of testing, NASA is devoting considerable resources to the development of innovative and more efficient approaches to dynamics testing.

Figure 1 shows the launch of a space shuttle from NASA's Kennedy Space Center (KSC). Given the extent of the jet plume, one can only imagine the severe noise and vibration environment which a spacecraft, launched by the shuttle or by an Expendable Launch Vehicle (ELV), must survive. In the early days of the space program, it was common practice to build spacecraft Development Test Models (DTM), which were dedicated to testing. Also, most spacecraft hardware was very conservatively designed with respect to the dynamics loads. By contrast, in today's "faster, better, cheaper" culture, often there is only one build of spacecraft hardware and this 'protoflight' unit is subjected to all of the ground testing and then it is launched. Furthermore, as the aerospace industry has matured, the structural design margins have been reduced and there is increased emphasis on analysis and less on testing. All of this points to a need for innovation to increase the efficiency of dynamics testing, so that flight failures are avoided, while still maximizing performance and minimizing cost. This article describes some new dynamics testing techniques, which are being implemented in the spacecraft programs managed by the Jet Propulsion Laboratory (JPL) and by other NASA centers.

Figure 1. Launch of STS-96 on June 29, 1999.

Figure 2. Rendering of Cassini Huygens probe arriving at Saturn's moon Titan in 2004.

Force Limited Vibration Testing

Figure 2 shows an artist's rendering of the Cassini Huygens probe arriving at Saturn's moon Titan in 2004, and Figure 3 shows the magnificent, two story tall, Cassini spacecraft configured for the random vibration test at JPL in 1997. The test item was the actual flight spacecraft, which was launched for Saturn later that year. In the spacecraft vibration test, eight piezoelectric, tri-axial force gages were sandwiched between the shaker and the spacecraft in order to measure the shaker reaction forces and moments.[1] Limiting the shaker force simulates the mechanical impedance of the flight-mounting configuration and minimizes overtesting at test item resonances. This problem has plagued aerospace vibration tests for years. Figure 4 shows the shaker acceleration power spectral density (PSD) in the Cassini test. The notches shown in Figure 4 at frequencies of 17, 30 and 38 Hz correspond to the fundamental resonance frequencies of the Huygens probe, the cantilevered Radioisotope Thermoelectric Generators (RTG) and the rocket fuel tanks, respectively. At these frequencies, these items act like dynamic absorbers that will greatly reduce the vibration input when the spacecraft is mounted on the launch vehicle which has a finite mechanical impedance. Without force limiting, there would be a high risk of over testing and artificial failure of these items during the vibration test.

The force limit for vibration testing may be calculated by considering two coupled oscillators as shown in Figure 5.[2] For distributed systems, the equivalent of the oscillator masses is the modal effective mass which is the mass term in the modal expansion of the apparent mass frequency response function. The maximum response of the load oscillator and therefore the maximum force acting between the oscillators occur for the case where the uncoupled resonance frequencies of the two oscillators are equal and it occurs at the lower of the two resonance frequencies of the coupled system. The maximum normalized force PSD calculated for this case is plotted in Figure 5 against the ratio of payload to source oscillator masses for three values of the load quality factor Q_2 which is one over

Figure 3. Cassini spacecraft vibration test.

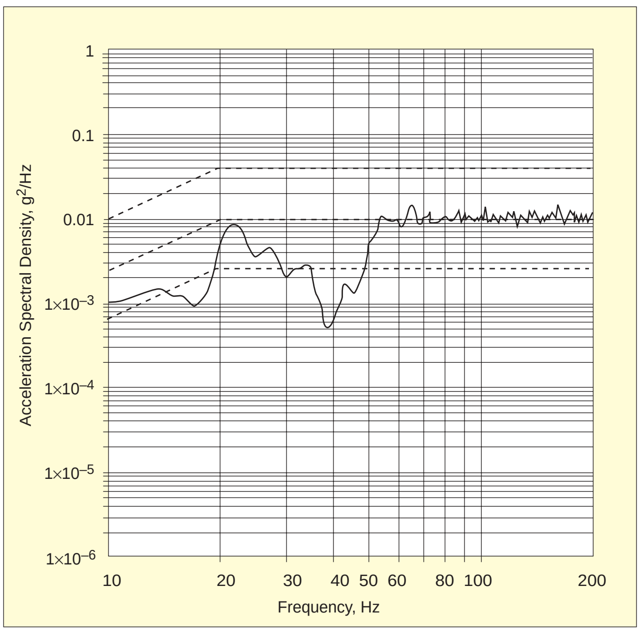

Figure 4. Acceleration input in vibration test.

twice the critical damping ratio. Notice from the curves in Figure 5 that when the load and source impedances are approximately equal, as is often the case in aerospace structures, the ratio of the force to the mass times input acceleration is only the square root of two or three. This lack of high amplification between subsystems in *built-up*, field structural configurations was observed many years ago.[3] Single-degree-of-freedom mechanical systems, with their associated high Q amplifications, occur primarily in textbooks and, unfortunately, in conventional vibration tests.

Flight Vibratory Force Measurements

Figure 6 shows the Shuttle Vibration Forces (SVF) Experiment, which was one of the payloads flown on the STS-96 mission shown at launch in Figure 1.[4] The objective of the SVF experiment was to obtain flight force measurements to validate theoretical methods of deriving force limits, such as that in

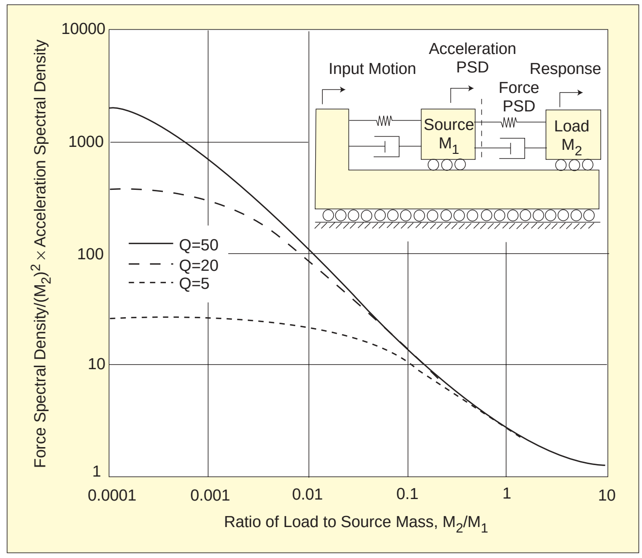

Figure 5. Force limit for TDFS model.

Figure 6. SVF experiment on STS-96.

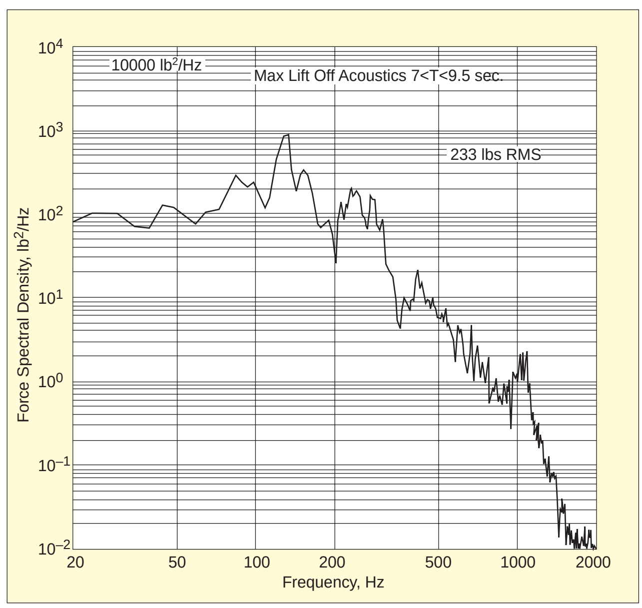

Figure 7. Flight force measurements.

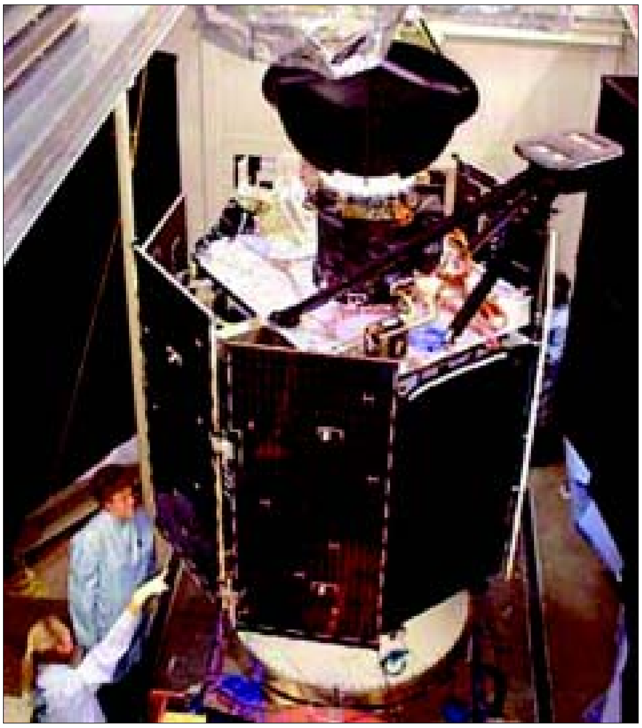

Figure 8. Direct acoustic test of QuikSCAT.

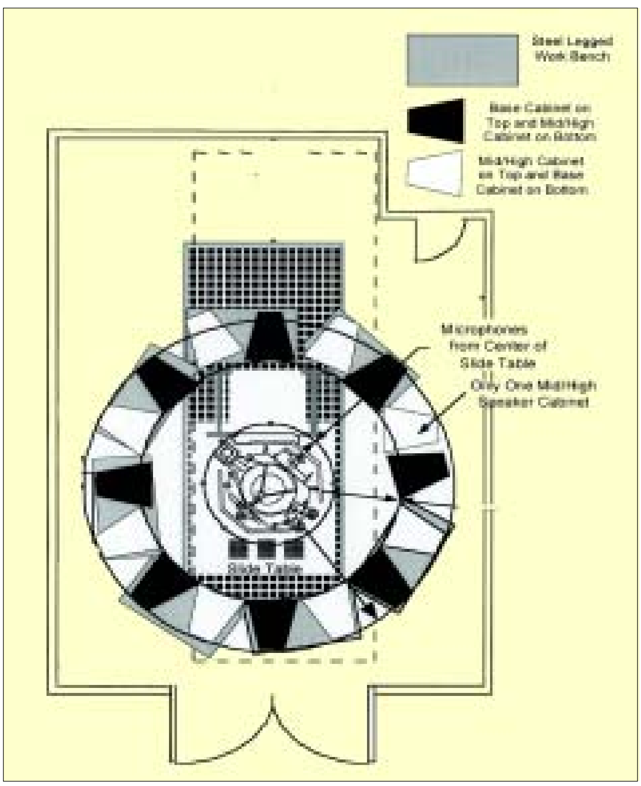

Figure 9. Setup for QuikSCAT test.

Figure 5. Figure 7 shows the PSD of the total force acting normal to the interface between the payload canister and the shuttle sidewall measured during a 2.5 sec interval corresponding to the maximum acoustic loading at lift-off. The ratio of the measured force PSD to previous measurements of the sidewall acceleration PSD (~0.01 g^2/Hz) divided by the canister mass (100 kg) squared is equal to two, which is consistent with the curve in Figure 5, for the case of approximately equal load and source oscillator masses.

Direct Acoustic Testing

Acoustic tests of spacecraft are normally conducted in large

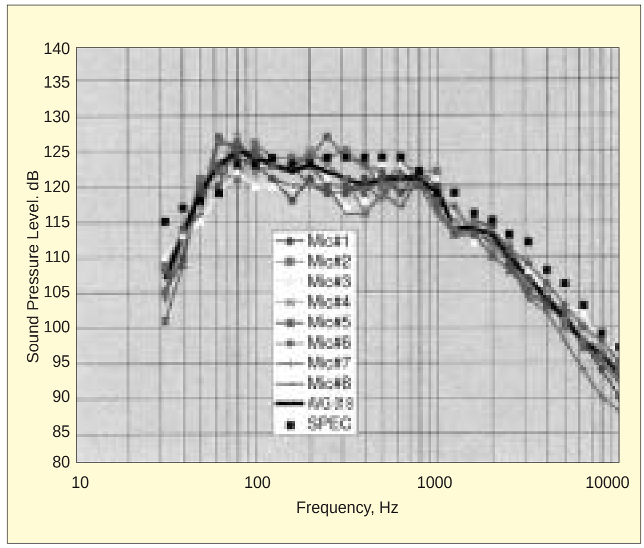

Figure 10. SPLs in QuikSCAT acoustic test.

Figure 11. COTE direct acoustic test.

(and expensive) reverberant test facilities excited with electro-pneumatic drivers. Many of the smaller aerospace contractors do not have a reverberant acoustic test facility and it is usually inconvenient to move the spacecraft to another facility for testing. Sometimes it is even inconvenient to move a spacecraft within a complex and it is desirable to conduct the acoustic test wherever the spacecraft is located. Figure 8 shows the setup for the QuikSCAT spacecraft direct acoustic test, which was conducted in October 1998 in the vibration test chamber at Ball Aerospace Corporation, using a portable electrodynamic sound system provided by a company that supplies sound systems for music concerts.[5]

Figure 9 is a diagram of the speaker setup for the QuikSCAT acoustic test and Figure 10 shows the third-octave band SPLs measured by 8 microphones spaced uniformly around a circle approximately 1 m in front of the speakers and 30 cm from the spacecraft. The overall SPL of the average (multiplex) of the signals from the 8 microphones was 134 dB. Obviously, the uniformity and directionality of the acoustic field in a direct acoustic test are considerably different from those in a reverberant chamber. Figure 11 shows the speaker configuration for the BSAT COTE direct acoustic test conducted in a high-bay at Orbital Science Corporation (OSC) in February 2000.[6] By surrounding the spacecraft with speakers, some of which were

Figure12. QuikSCAT combined vibration test.

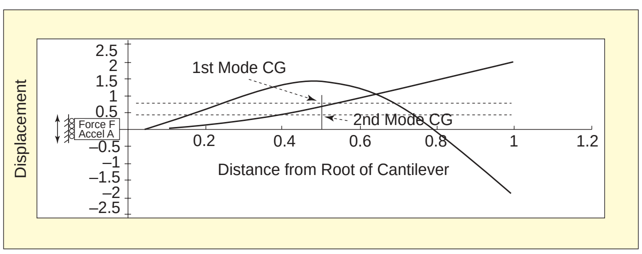

Figure 13. "There's no there there," at the CG of a vibrating cantilever.

specially designed for the purpose, an average overall SPL of 144 dB was obtained!

Combined Vibration Testing

A combined vibration test consists of: 1. random vibration, 2. base-drive modal and 3. quasi-static load tests – all conducted while the spacecraft is mounted on a shaker. Sometimes, an acoustic test is also conducted while the spacecraft is on the shaker, as was done in the case of QuikSCAT. In the QuikSCAT program, the schedule was one year from contract initiation to launch, this combined vibration and acoustic test approach saved approximately a factor of four in cost, schedule and handling risk! The key to success in conducting all three of these vibration tests on the shaker is to mount the spacecraft on force gages as shown for the QuikSCAT spacecraft in Figure 12.[7] The force gages in a combined vibration test serve several purposes. They are used to notch the random vibration test, as has been previously discussed. For the base-drive modal test, the force gages provide the force input and also the modal effective masses. JPL is also experimenting with measuring the base reaction forces and using "operational modal analysis" in acoustic tests. In the loads test, the base force measurement, divided by the total mass of the test item, provides the specified acceleration of the center-of-gravity (CG), which generally cannot be measured with an accelerometer. Gertrude Stein's quip about Oakland, CA, "There's no there, there," applies equally well to the CG in a vibration test, as illustrated in Figure 13.

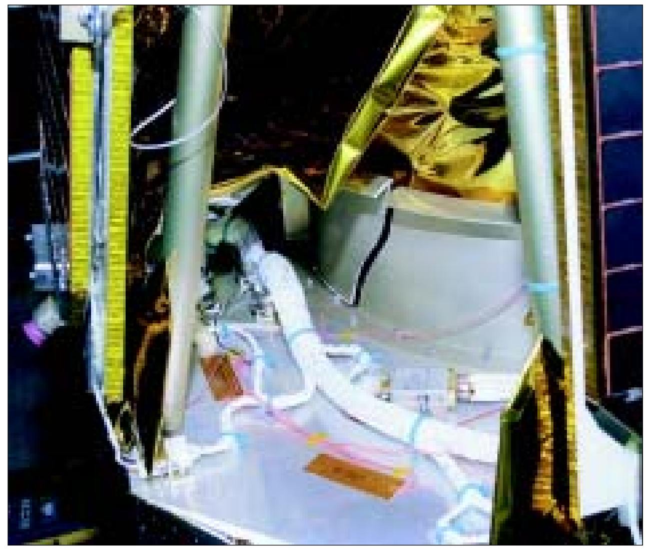

Figure 14. HESSI spacecraft ring fracture.

Figure 15. HESSI solar array damage.

For the loads test, some form of pulse (such as a half-sine, sine burst or sine ramp) is used to achieve the desired CG acceleration. These transient tests are usually conducted by operating the shaker in the open-loop mode, which is dangerous, as we learned the hard way when an accidental over-test occurred during the vibration test of the HESSI spacecraft. Figures 14 and 15 show some of the damage to the spacecraft as a result of the over-test. The cause of the HESSI over-test was stiction in the shaker slip table during the shaker self check. The self check is a low-level random pretest, which the shaker computer conducts before the pulse test in order to get a transfer function between the specified acceleration and the required input voltage. Needless to say, there are now many safety procedures in place at JPL to avoid a reoccurrence of the HESSI incident.

Conclusions

Today's challenge is to make spacecraft dynamics testing more efficient, so that testing will survive the pressure of faster, better, and cheaper. Without testing, the risk of flight failures is too great. Tomorrow's challenge is to find a way to merge dynamics testing and analysis, so that the results of dynamics tests which are necessarily conducted near the end of the program can be extrapolated and carried forward to help design spacecraft for future programs.

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The author may be contacted at: terry.d.scharton@jpl.nasa.gov.

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