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SPACECRAFT DYNAMIC ENVIRONMENTS TESTING

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FOREWORD

This Handbook is published by the National Aeronautics and Space Administration (NASA) as a guidance document to provide engineering information; lessons learned; possible options to address technical issues; classification of similar items, materials, or processes; interpretative direction and techniques; and any other type of guidance information that may help the Government or its contractors in the design, construction, selection, management, support, or operation of systems, products, processes, or services.

This Handbook is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Handbook establishes recommended practices across NASA programs, addressing dynamic environments testing of flight spacecraft, large instruments, associated dynamic test models (DTMs), and flight structure subsystems for the mission dynamics environments and loads. The emphasis of this Handbook is on vibration, acoustic, and shock environmental testing. Static and modal testing are discussed only in regard to the role each plays in complementing the dynamic testing in a complete structural qualification program.

Recent advances in the areas of structural dynamics, vibrations, and vibroacoustics, in both methodology and capability, have the potential to make spacecraft system testing more effective from technical, cost, schedule, and hardware safety points of view. However, application of these advanced test methods varies widely among the NASA Centers and their contractors. Identification and refinement of the best of these test methodologies and implementation approaches has been an objective of efforts by the Jet Propulsion Laboratory (JPL) on behalf of the NASA Office of the Chief Engineer (OCE). To develop the most appropriate overall test program for a flight project from the selection of advanced methodologies, as well as from conventional test methods, spacecraft project managers and their technical staff need overall guidance and technical rationale. Thus, the OCE has tasked JPL to prepare a NASA Handbook for Spacecraft Dynamic Environments Testing. The Goddard Space Flight Center (GSFC) has agreed to co-author this Handbook.

Requests for information, corrections, or additions to this Handbook should be submitted via "Feedback" in the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov.

Original Signed By: | ***06/12/2014***
Ralph R. Roe, Jr. | Approval Date
NASA Chief Engineer

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SPACECRAFT DYNAMIC ENVIRONMENTS TESTING

1. SCOPE

1.1 Purpose

The purpose of this Handbook is to provide guidance for dynamic environments testing of flight spacecraft, large instruments, associated dynamic test models (DTMs), and flight structure subsystems for the mission dynamics environments and loads. The emphasis of this Handbook is on vibration, acoustic, and shock environmental testing. Static and modal testing are discussed only in regard to the role each plays in complementing the dynamic testing in a complete structural qualification program. This Handbook concentrates on new dynamics testing methodologies but summarizes and provides key references for older dynamic test methodologies.

The recommendations in this Handbook are thought to be appropriate in the majority of cases. As this Handbook is not a Standard, exceptions can be considered on a case-by-case basis. The numerical values cited are believed to be typical, but they are not binding.

1.2 Applicability

This Handbook is applicable to all dynamic environments testing of National Aeronautics and Space Administration (NASA) flight spacecraft, large instruments, associated DTMs, and flight structure subsystems for the mission dynamic environments and loads. Although the dynamics testing of launch vehicles is not the object of this Handbook, much of the technical information herein may be applicable to the dynamics testing of some launch vehicle subsystems, e.g., upper stages, fairings, crew capsules. The Handbook is applicable to both manned and unmanned missions; however, in the case of manned missions, there may be safety and ergonomic considerations that are not covered herein.

This Handbook is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers. This Handbook may also apply to the Jet Propulsion Laboratory (JPL) or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

This Handbook, or portions thereof, may be referenced in contract, program, and other Agency documents for guidance. When this Handbook contains procedural or process requirements, they may be cited in contract, program, and other Agency documents for guidance.

1.3 Rationale

Currently, a diversity of testing cultures and approaches exists in NASA and industry. New testing technologies need to be disseminated. This Handbook summarizes the state of the art in dynamics testing for spacecraft and large instruments, discusses NASA baseline verification program guidelines and requirements, and describes and compares the advantages and disadvantages of the various test methodology options. Case histories of several spacecraft dynamic environments test programs are presented in the appendices.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section are applicable to the guidance in this Handbook.

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov or may be obtained directly from the Standards Developing Organizations or other document distributors.

2.2 Government Documents

Goddard Space Flight Center (GSFC)

GSFC-STD-1000	Goddard Open Learning Design (GOLD) Rules for Design, Development, Verification, and Operation of Flight Systems
GSFC-STD-7000	General Environment Verification Standard

Jet Propulsion Laboratory

JPL Publication 83-76	NASA Flight Electronics Environmental Stress Screening Survey

Marshall Space Flight Center (MSFC)

MSFC-STD-3676	Development of Vibroacoustic and Shock Design and Test Criteria

NASA

NASA-CR-116019	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 7 - Investigation of Mass Loading Effects Final Report

NASA-CR-116401	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 3 - Data Final Report
NASA-CR-116402	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 4 - Lockheed Data and Analyses Final Report
NASA-CR-116403	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 5 - Lockheed Data and Analyses Final Report
NASA-CR-116406	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 6 - Pyrotechnic Shock Design Guidelines Manual
NASA-CR-116437	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 1 - Summary and Analysis Final Report
NASA-CR-116450	Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight. Volume 2 - Data Final Report
NASA-HDBK-7004	Force Limited Vibration Testing
NASA-HDBK-7005	Dynamic Environmental Criteria
NASA-STD-5001	Structural Design and Test Factors of Safety for Space Flight Hardware
NASA-STD-5002	Load Analyses of Spacecraft and Payloads
NASA-STD-7001	Payload Vibroacoustic Test Criteria
NASA-STD-7002	Payload Test Requirements
NASA-STD-7003	Pyroshock Test Criteria
NASA-TM-106313	Design for Reliability: NASA Reliability Preferred Practices for Design and Test, (Practice No. PT-TE-1420, Sine Burst Load Test)
NASA/TM-2011-217000	The Development of the Acoustic Design of NASA Glenn Research Center's New Reverberant Acoustic Test Facility
NESC-RP-06-071	Flight Force Measurements (FFMs) of the Gamma-Ray Large Area Space Telescope (GLAST)/Delta II Flight, September 2009[1]

[1] Distribution of this document is limited to U.S. Government Agencies and U.S. Government Agency contractors only. The executive summary is available at http://www.nasa.gov/offices/nesc/reports/GLAST_prt.htm. Retrieved June 7, 2013. A Microsoft® PowerPoint™ presentation is accessible at

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2.4 Order of Precedence

This Handbook provides guidance for spacecraft dynamic environments testing but does not supersede nor waive established Agency requirements/guidance found in other documentation.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

μ	micro(n)
σ	sigma
ζ	zeta; percent of critical damping
~	approximately
@	at
=	equals

<	less than
#	number
™	trademark
ADEOS	Advanced Earth Orbiting Satellite
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
ASC	Aeronautical Systems Center
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ATS	Aerospace Testing Seminar
AVUG	Atlas V User’s Guide
BAT	Burst Alert Telescope
BATC	Ball Aerospace Technology Corporation
BATSE	Burst and Transience Source Experiment
BEM	boundary element model
C	constant
C/L	center line
CA	California
CG	center of gravity
CLA	coupled loads analysis
cm	centimeter(s)
CO	Colorado
CPT	comprehensive performance test
CR	contractor report
CT	Connecticut
dB	decibel(s)
dBm	power ratio in dB of the measured power referenced to 1 milliwatt
DDAS	dynamic data acquisition system
deg	degree(s)
DFAT	direct field acoustic test
DOF	degree of freedom
DTE	design, test, and evaluation
DTM	dynamic test model
EOS	Earth Observing System
ESA	European Space Agency
ESD	electrostatic discharge
ETU	engineering test unit(s)
EU	engineering unit(s)
FA	flight acceptance
FE	finite element
FEA	finite element analysis
FEM	finite element method
FFM	flight force measurement
FFM	flight force measurement

FPCA	Focal Plane Camera Assembly
FRF	frequency response function
ft	foot (feet)
g	acceleration of gravity
g_{rms}	acceleration root mean square
GLAST	Gamma-ray Large Array Space Telescope
GOLD	Goddard Open Learning Design
G_{pk}	peak acceleration
GRB	gamma-ray burst
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HDBK	handbook
HESSI	High Energy Solar Spectroscopic Imager
HLV	heavy launch vehicle
hr	hour(s)
Hz	hertz
I/F	interface
IEST	Institute of Environmental Sciences and Technology
IL	Illinois
IMAC	International Modal Analysis Conference
in	inch(es)
IPA	isopropyl alcohol
ISO	International Organization for Standardization
JPL	Jet Propulsion Laboratory
kg	kilogram(s)
L/V	launch vehicle
Lb	pound(s)
LM	Lockheed Martin
LTM	loads transformation matrix
LVA	launch vehicle adapter
LVDT	linear variable differential transformer
m	meter(s)
MA	Massachusetts
MD	Maryland
MAC	mass acceleration curve
MECO	main engine cutoff
MEFL	maximum expected flight level
MIDEX	medium explorer
MER	Mars Exploration Rover
MIMO	multiple-input multiple-output
min	minute(s)
mo	month(s)
MPE	mission-peculiar equipment
msec	millisecond(s)
MSFC	Marshall Space Flight Center

N	newton(s)
N/A	not applicable
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis
OA	overall
OASPL	overall sound pressure level
OCE	Office of the Chief Engineer
OCO	Orbiting Carbon Observatory
Pa	Pascal(s)
PAF	payload attach fitting
PF	protoflight
PSD	power spectral density
Q	amplification (quality) factor equal to $1/(2\zeta)$, where ζ is the percent of critical damping
QuikSCAT	Quick Scatterometer
RMS	root mean square
RP	recommended practice
RSS	root sum square
RTG	radioisotope thermoelectric generator
SAE	SAE International, formerly Society of Automotive Engineers
SEA	statistical energy analysis
sec	second(s)
SI	International System of Units (Le Système international d'unités)
SISO	single-input single-output
SPL	sound pressure level
SRS	shock response spectra
STD	Standard
STM	structural test model
TAC	test access connector
TDOF	two degree of freedom
THD	total harmonic distortion
TM	technical memorandum
UMB	umbilical mounting bracket
US	United States
UV	ultraviolet
UVOT	Ultraviolet/Optical Telescope
VAPEPS	Vibroacoustic Payload Environmental Prediction System
VCLA	Verification Coupled Loads Analysis
W	watt(s)
WG	working group
wk	week(s)
XRT	X-ray Telescope
yr	year(s)

3.2 Definitions

Definitions are provided for key terms that are not uniformly interpreted, such as limit load, protoflight test, and primary structure.

Acceptance Test: A test performed to demonstrate that the hardware is acceptable for its intended use. It also serves as a quality control screen to detect manufacturing, material, or workmanship defects in the flight build and demonstrate compliance with specified requirements.

Coupled Loads Analysis: Dynamic analysis of a coupled model of the spacecraft and launch vehicle, usually conducted by the launch vehicle provider.

Decibels: dB = 20 log (amplitude) = 10 log (square of amplitude), where the amplitude quantity may be voltage, pressure, acceleration, etc. (Note: the amplitude must be normalized to a reference, which, for pressure, is usually 0.0002 dyne/cm^2 (20 μPa).)

Diffuse Field: Waves distributed equally over all solid angles.

Direct Field: Waves arriving from source without having been reflected.

Extremal Control: A shaker controller algorithm based on control, in each narrow frequency band, of the maximum (extreme) of several inputs.

Flight Limits: Definition of accelerations or forces that are predicted to be the maximum flight environment. (See limit load.)

Force Limiting: Reduction of the base reaction forces in a vibration test to specified values, usually to the interface forces predicted for flight, plus a desired margin.

Level: Primarily, the test input or response value, particularly when expressed in dB; secondarily, a step in the assembly, e.g., component, subsystem, spacecraft.

Limit Load: The maximum anticipated load experienced by a structure during a loading event, load regime, or mission. Uncertainty factors associated with model uncertainty or forcing function uncertainty shall be incorporated into the limit load as reported. The factors of safety are not included in the limit load.

Margin: Factor to be multiplied times, or decibels to be added to, the flight limit (usually expressed as an acceleration) to obtain the design or test specification.

Maximax Spectrum: Envelope of the highest environment in each one-third octave frequency band, at any time during the flight.

Modal Overlap: The number of modal resonance frequencies within a resonance half-power bandwidth.

Notching: Reduction of acceleration input spectrum in narrow frequency bands, usually where test item has resonances.

Observatory: A specific type of spacecraft that carries subsystems (instruments or telescopes) for viewing terrestrial or celestial events.

Power Spectral Density: Measure of the distribution of the energy (squared amplitude) of the signal as a function of frequency.

Primary Structure: The structure that is the principal load path for all subsystems, components, and other structures.

Protoflight Test: A test performed on the flight hardware to verify workmanship and material quality and that the design meets structural and performance requirements; typically does not demonstrate life margin.

Prototype Test: A test performed on a separate flight-like structural test article to verify that the design meets structural and performance requirements.

Qualification Test: A test performed to demonstrate qualification of the design for flight. The test may be either a prototype or protoflight test.

Quasi-Static Acceleration: Combination of static and low-frequency loads into an equivalent load, usually specified for design purposes as the center of gravity (CG) acceleration.

Response Limiting: Reduction of input acceleration to maintain measured response at or below specified (limit) value.

Reverberant Field: Waves that have been reflected many times since leaving source.

Spacecraft: An integrated assemblage of modules, subsystems, instruments, components, and similar hardware designed to perform a specified mission in space.

Vibroacoustic: Random vibration induced by acoustic excitation.

4. TEST PURPOSE

4.1 Reasons to Conduct Dynamics Tests

There are generally four reasons for conducting dynamics tests of spacecraft: qualification, acceptance, workmanship, and verification. The overarching purpose of these tests is to ensure that the spacecraft will properly perform its intended mission. In the case of manned spacecraft or vehicles, the preservation of human life is, of course, of paramount concern. The dynamics tests are intended to demonstrate the structural and functional integrity of the spacecraft when exposed to flight dynamic environments with margin. (The margin is the ratio, sometimes expressed in dB, of the test level to the predicted flight level.) These tests are conducted to provide assurance that the delivered hardware meets the dynamic environmental requirements, to reveal latent workmanship defects in the assembled flight spacecraft, and to provide data for verifying analytical models used to simulate conditions that cannot be practically replicated in a test. Each type of dynamic test performed on a spacecraft satisfies one or more of these purposes.

4.1.1 Qualification for Flight Environments

The primary purpose of most dynamic tests of spacecraft is the simulation of the flight dynamic environments, which are typically so severe as to cause failure of electronic components, mechanisms, optics, and structures that were not specifically designed to survive these environments (NASA-HDBK-7005, Dynamic Environmental Criteria). These high levels of vibration and sound are generated by the launch vehicle and other sources, such as the firing of pyrotechnic devices or the impact of a spacecraft landing, as in the case of the Mars Exploration Rover (MER) spacecraft (Coleman and Davis, 2004). In the case of flight microphonics, which are vibrations caused by the operation of on-board equipment, the vibration test levels are usually not so high as to cause failure but rather degradation in the performance of sensitive instruments. The most straightforward way of testing for these dynamic environments would be to exactly simulate the flight environment, but this is not appropriate in most cases. Rather, the tests typically represent a simulation of the dynamic environments defined from a statistical analysis of many missions and many different operational conditions. It is also common practice to define the flight environments using descriptors that can be reasonably specified and controlled, e.g., random vibration power spectral densities (PSDs), one-third octave band acoustic levels, or shock response spectra (SRSs) (NASA-HDBK-7005).

Spacecraft dynamic qualification tests fall into two types: prototype and protoflight. In a prototype test, a dedicated flight-like test article is exposed to test levels that have margin over both maximum expected flight level (MEFL) and duration. A protoflight test is performed on flight hardware and has margin only on the test level. The protoflight test has the benefit that it does not require a dedicated test article in addition to the flight unit, but, unlike the prototype test, it does not demonstrate margin against cumulative damage type failures that may occur over the life of the hardware.

Spacecraft designers often complain that they must design to pass a test, rather than to survive the flight environment. This problem is exacerbated by the fact that the test levels are typically more severe and of longer duration than the flight environment, both intentionally (test margin) and unintentionally (test artifacts). The overtesting resulting from artifacts (frequency enveloping, shaker impedance, fixture resonances, tolerances, overshoot, etc.) are often justified by the environmental engineer as being conservative. However, from the designer's point of view, overtesting is unconservative. Therefore, it is good practice to periodically compare the test simulations with actual flight data to ensure that the "conservatisms" that invariably creep into test specifications do not become excessive.

4.1.2 Acceptance Dynamic Tests

Acceptance testing is performed to demonstrate that the hardware is acceptable for flight. It provides both a workmanship screen of the as-built hardware and also demonstrates that the flight unit has been built to the same standard as the qualified design. Acceptance dynamic testing is performed to the MEFL and does not require any additional margin over the flight dynamic environment for the test. If the flight acceptance test level for the dynamic test falls below established guidelines for minimum workmanship, the acceptance test levels may be increased as discussed in section 4.3 in this Handbook. Acceptance dynamic testing requires that the spacecraft design be previously qualified through testing of a non-flight prototype or based on protoflight testing of an identical flight spacecraft. Acceptance testing of complete spacecraft is unusual in that most NASA spacecraft are one of a kind and typically without a prototype unit so that the design is qualified through protoflight testing of the flight spacecraft. Acceptance testing would be used in cases in which a single or multiple follow-on spacecraft of identical design are planned so that the first spacecraft would be qualified to the flight environment with test margin and the follow-on spacecraft would be acceptance tested to MEFL to verify the flight build.

4.1.3 Workmanship Dynamics Tests

A secondary reason for conducting dynamic tests of spacecraft is to identify workmanship defects, that, if undetected, would cause problems or failures in flight. Most workmanship defects are associated with electronic circuit boards, which are tested and remedied at lower levels of assembly where there are clear guidelines for minimum random vibration test levels that should be used as a workmanship screen. However, there are some interface and interconnection problems that can be and have been only detected in the system-level tests. When the flight dynamic environments for a particular mission are very low, as is the random vibration environment for a few launch vehicles, the definition of the appropriate test level for workmanship testing is somewhat controversial. Some argue that the workmanship test levels should be below the flight levels so that they do not cause any problems that would not occur in flight. NASA-STD-7001, Payload Vibroacoustic Test Criteria, defines the minimum workmanship test level for acoustic testing at 138-dB overall sound pressure level (OASPL), with guidance on how to derive the input spectrum if the test environment falls below those levels. There are no stated minimum workmanship levels for spacecraft-level vibration testing (sine, random, or transient), although Appendix B of NASA-STD-7001 recommends a minimum mass attenuated workmanship random vibration test level of 0.01 g^2/Hz flat from 20 to 2,000 Hz for components whose weight is greater than 200 kg (440 lb). The most common approach for vibration testing of complete spacecraft is to use the flight environment as a workmanship screen for the as-built spacecraft, although some organizations have defined minimum vibration test levels that have been found to uncover workmanship issues based on previous test history with spacecraft of similar design.

4.1.4 Model Verification

Verification dynamics testing is conducted to verify or update an analytical model or to check that the design indeed meets the requirements specified in the relevant project documents. An example might be to verify that a spacecraft meets the launch vehicle provider's requirement that the spacecraft have a fundamental lateral fixed-base resonance above 15 Hz. Another example would be the case of a modal test in which the test data may be used to improve the finite element (FE) model so that it may be used with confidence to predict the response of the test item to another dynamic environment for which a test will not be conducted.

Stinger-excitation vibration tests with the base of the test item fixed to a seismic mass are conducted expressly for the purpose of obtaining data for tuning the analytical model, which is usually based on the fixed-base modes of the system. Base-drive vibration tests can provide identification of the fundamental frequencies and, if force gages are used, also the effective modal masses. (The fixed-base modal characteristics of the test item may be estimated from base-drive vibration tests, but it is necessary to assess the effects of the finite stiffness and mass of the fixture, shaker, and inertial block in the interpretation of the data.) In any of these cases, it is strongly recommended that a model correlation effort be performed concurrently with the tests in which the modal data are obtained, because resolution of the differences between the measured and predicted behavior invariably requires collaboration between the test and the analysis engineers.

Validation is more fundamental than verification testing. Validation tests usually involve more of an end-to-end check of the whole design, fabrication, testing, examination, and inspection process.

4.2 Flight and Test Failures

Since dynamic tests of spacecraft are both expensive and risky, it is reasonable to ask, "How many flight failures have there been related to the dynamic environments?" In the beginning of the space program, there were probably quite a few, although it is always difficult to ascertain the cause of a flight failure with certainty. It is suspected that the JPL Ranger 4 and 6 spacecraft failures were caused by launch vibration and that the Galileo Spacecraft high-gain antenna's failure to open was caused by the transportation vibration environment. Other Government laboratories and agencies and their contractors have experienced similar cases of vibration-induced problems. For example, the problematic jitter of the original solar panels on the Hubble Space Telescope was caused by vibration generated by thermal transients (Massachusetts Institute of Technology, 2001).

It is also appropriate to ask, "How many problems have been discovered in spacecraft dynamics tests that would, or may, have caused flight failures? And which types of dynamic tests are most effective in discovering these problems?" Most mission-threatening defects, whether workmanship or design related, are found in tests at lower levels of assembly, but many problems associated with system integration and subsystem interfaces have been found in system dynamics tests. For example, the vibration test of the Cassini spacecraft conducted at JPL identified an electrical grounding problem between the spacecraft bus and the radioisotope thermoelectric generators (RTGs), which could have been a serious problem in flight. (See Appendix A in this Handbook.) The Cassini RTGs were extensively vibration tested at the subsystem level of assembly, but since the interface to the spacecraft was not realistically replicated in the subsystem testing, the grounding problem was not discovered until the spacecraft vibration test.

Finally, the risks of unjustified test failures related to overtesting caused by unrealistic test specifications, test artifacts, operation mistakes, and equipment failures need to be weighed against the risks of undertesting, or waiving certain tests. (See sections 4.3, 6.8, 6.9, 8.5, and 9.3 in this Handbook.)

4.3 Comparison of Various Tests

The various types of dynamic tests have different purposes, equipment sensitivities, effective frequency ranges, and risks to hardware of overtests or test mishap, so it is important to tailor the test program to fit the needs, reliability, schedule, and cost of each program. Different organizations and even different programs within organizations have different approaches to defining dynamic test programs. All dynamic tests entail some risk, in that even handling a built-up spacecraft involves risk. In general, the risk of overtesting in a dynamic test increases in proportion to the test severity. Thus, diagnostic tests (sections 5.2.1.1 and 5.2.2.1 in this Handbook) are the most benign dynamic tests, workmanship tests usually have moderate risk, and qualification tests are the most risky. (Static loads tests have moderate to high risk, if conducted on flight structures.) Some tests, like sine burst tests, which are strength tests conducted on shakers with open-loop control, have proven to be particularly risky. The most benign dynamic tests are obviously those conducted at low-test levels. Some examples of low-level tests are: modal tests conducted with small shakers connected to the spacecraft with stingers, pre- and post-test signature surveys that are typically conducted at very low test levels, and the low-level tests conducted in preparation for the full-level tests. However, even with these low-level tests, it is important to analyze for the expected responses before initiating the test, particularly if the tests are to be conducted without limiting, which is usually the case. It is essential to ensure that all the test equipment is in calibration and operating properly.

For many structures, acoustic tests are the most benign dynamic qualification tests. One exception would be the acoustic testing of large reflectors, mirrors, solar panels, and other lightly loaded honeycomb panels, which may be strongly coupled to the acoustic field. Following acoustic tests, dynamic qualification tests of increasing severity are random vibration tests, sinusoidal sweep vibration tests, and, finally, sine burst sub-resonance transient loads tests. Except in the aforementioned exceptional cases, acoustic tests are basically limited to detecting workmanship and high-frequency problems. Overtesting at test item resonances is more readily eliminated in random vibration tests than in swept sine tests, because in random excitation tests, the notches can be implemented and verified by holding the test at low levels until the notch is satisfactorily developed. In a sine-sweep test, on the other hand, the control system has to put in the notch “on the fly” while at full level, and sometimes the resonance frequency is passed before the notch is fully implemented. Also, studies, at least for electronic assemblies, show that random vibration provides a better workmanship test than sine testing. (For example, see JPL Publication 83-76, NASA Flight Electronics Environmental Stress Screening Survey.) This is perhaps because of the simultaneous excitation of all frequencies and modes in a random test. However, as previously mentioned, the amplitude of the input and response in random vibration tests usually cannot be controlled precisely enough for qualifying the primary structure, and therefore, sine tests would be less risky for that purpose. Also, it may be more difficult to define the input acceleration specification for a spacecraft random vibration test, as launch vehicle mission planner's guides often use sine testing as a requirement. Therefore, random vibration test levels or force limits may need to be modified based on pre-test analysis and/or low-level test runs to ensure that lower frequency (typically below 80 to 100 Hz) response loads do not exceed structure limit loads times 1.2 as defined by criteria such as coupled loads analysis (CLA), mass acceleration curve (MAC), and Modal MAC. In higher frequencies, it may be necessary to ensure that vibration responses are compatible with the vibration test responses in prior tests of the components, assuming spacecraft input random vibration test levels are not rigorously defined. However, a limited amount of flight random vibration data is available for this purpose. (See figure 11, Comparison of the Acceleration Specification for the Cassini Spacecraft Base-Drive Random Vibraton Test with the Launch Vehicle Specifications and Flight Data, in Appendix A in this Handbook.)

Both random and sine sweep closed-loop tests are safer, i.e., less prone to accidental overtesting, than sine burst tests. Sine burst tests are the most risky because they are of very short duration and open loop, so that overtesting may occur before there is any chance of rectifying the situation. The shaker failure that occurred during the High Energy Solar Spectroscopic Imager (HESSI) spacecraft vibration test is an example of this (Fisher, 2001). The spacecraft was damaged during a quarter-level sine burst test. An undetected problem with the shaker slip table resulted in the control system's miscalculation of the drive signal necessary to achieve the desired input amplitude. Because of the short duration of the test, the control system could not correct the calculated input and prevent damage to the spacecraft. In spite of the increased risk, shaker transient tests are still popular because they are relatively inexpensive and save schedule, compared with the static test programs that they can replace.

Table 1, Comparison of Different Dynamic Tests of Spacecraft, compares the benefits, sensitive equipment, frequency ranges, and risks of different types of dynamics tests. The four basic benefits are qualification, acceptance, workmanship, and model verification. The different sensitive equipment includes primary structure, secondary structure, antennas, reflectors, solar panels, interfaces, buildup, e.g., wiring, blankets, and plumbing, electronics, and instruments. It is important to realize, as discussed further in section 5 in this Handbook, that the different types of dynamics tests of spacecraft are typically effective in different frequency ranges, i.e., vibration qualification tests below ~200 Hz, acoustic tests between approximately 50 and 1,000 Hz, and shock firings above ~500 Hz. In general, the risks of the various tests are in proportion to their severity or strength. However, transient vibration tests are riskier than other options of comparable severity. Since the risk of a given test increases with the severity of the test, the risk in a high-level random vibration test could be higher than that of a low-level sine vibration test. The risk of performing a particular type of test also depends on the experience of the organization and staff in performing similar tests in the past, the sophistication and safety features of the test equipment, the quality control system, and the amount of test preparation and pre-test analysis.

Table 1—Comparison of Different Dynamic Tests of Spacecraft

Type of Test	Primary Benefit(s)	Sensitive Equipment[(1)]	Typical Test Frequency Range for Spacecraft	Risk (of overtest or test mishap)
Acoustic	Qualification, Acceptance, and Workmanship	Antennas, Reflectors, Solar Panels, and Lightly Loaded Panels	31.5-10,000 Hz	Low to Moderate[(2)]
Random Vibration[(3)]	Qualification, Acceptance, and Workmanship	Interfaces, Buildup, Secondary Structure, and Instruments	20-200 Hz[(4)]	Moderate
Sine Vibration[(3)]	Qualification, Acceptance, and Workmanship	Interfaces, Buildup, Primary and Secondary Structure, and Instruments	5-100 Hz[(5)]	Moderate
Sine Burst	Qualification	Primary and Secondary Structure	10-50 Hz (below structural resonance frequencies)	High (unless conducted on DTM)
Shock (Firings)[(6)]	Verification of Actuation Systems and Component Shock Test Levels	Separation System(s) and Electronics	100-10,000 Hz (short duration, e.g., <20 msec)	Low
Modal Vibration Fixed Base	Model Verification	Primary and Secondary Structure	5-500 Hz	Low (assumes test article is DTM or flight primary structure with mass simulators)[(7)]
Modal Vibration Base Drive	Resonance Frequency Determination	Built-up Flight Spacecraft	5-500 Hz[(4)]	Low (if conducted at low test levels in conjunction with environmental vibration test)
Microphonic Vibration	Performance Degradation	Instruments	20-500 Hz	Low
Static[(8)]	Qualification	Primary and Secondary Structure	N/A	Moderate, if flight structure used

Notes:

(1) Assumes that subsystems, instruments, electronics, and components have been qualified at lower levels of assembly. Any instruments, components, etc., that have been disassembled or modified since testing are also targets of the spacecraft dynamics test.

(2) Acoustic tests are not immune to overtesting and facility problems. Equipment that is particularly responsive to acoustic excitation, such as large reflectors and antennas, may be damaged by overtesting related to operator error, large spatial and frequency variations in direct field acoustic tests (DFATs), or standing waves in small reverberant chambers.

(3) Random and sine vibration tests may be redundant, so that only one or the other is needed. The primary distinctions are the test levels and frequency ranges. Sine tests usually focus more on structural qualification and, consequently, have somewhat higher levels, and they are generally limited to lower frequencies, where

the limit loads are well defined. Random tests are not suited to structural qualification but are considered better workmanship tests and can provide overlap with the acoustic frequency regime.

(4) The high-frequency limit for random base-drive vibration tests may be 500 Hz for small spacecraft or subsystems and may be as high as 1,000 Hz for low-level, pre- and post-test signature surveys.

(5) The high-frequency limit for sine base-drive vibration tests is selected to be consistent with the frequency content of the launch vehicle CLA, which is typically 100 Hz or less.

(6) Shock (Firings) are not considered to be true qualification tests since they normally do not include margin over the flight environment. Multiple firings are used to cover variability of shock-producing devices.

(7) In cases where shakers with stingers are used to excite the flight spacecraft to locally achieve flight or higher levels, the risk is considerably higher.

(8) Some type of qualification test of primary structure is usually required. The options, in order of increasing risk, are static test, high-level sine test, or sine-burst test. Secondary structure may usually be qualified either by test or by an analysis based on a test-verified model using higher no-test factors of safety.

5. TEST DESCRIPTION

5.1 Vibration Tests

Two types of vibration testing will be discussed: base drive and stinger drive. Base-drive vibration tests are conducted with the test item sitting on a moving platform that is driven by a vibration generator, commonly called a shaker. The base-drive configuration is commonly employed to achieve test levels comparable to the launch environment. A vertical axis base-drive vibration test of the MER spacecraft is shown in figure 1, MER Flight #1 Spacecraft in Vertical Vibration Test (Scharton and Lee, 2003). Figure 2, MER DTM Rover in Lateral Vibration Test, shows a lateral base-drive vibration test of the MER DTM Rover.

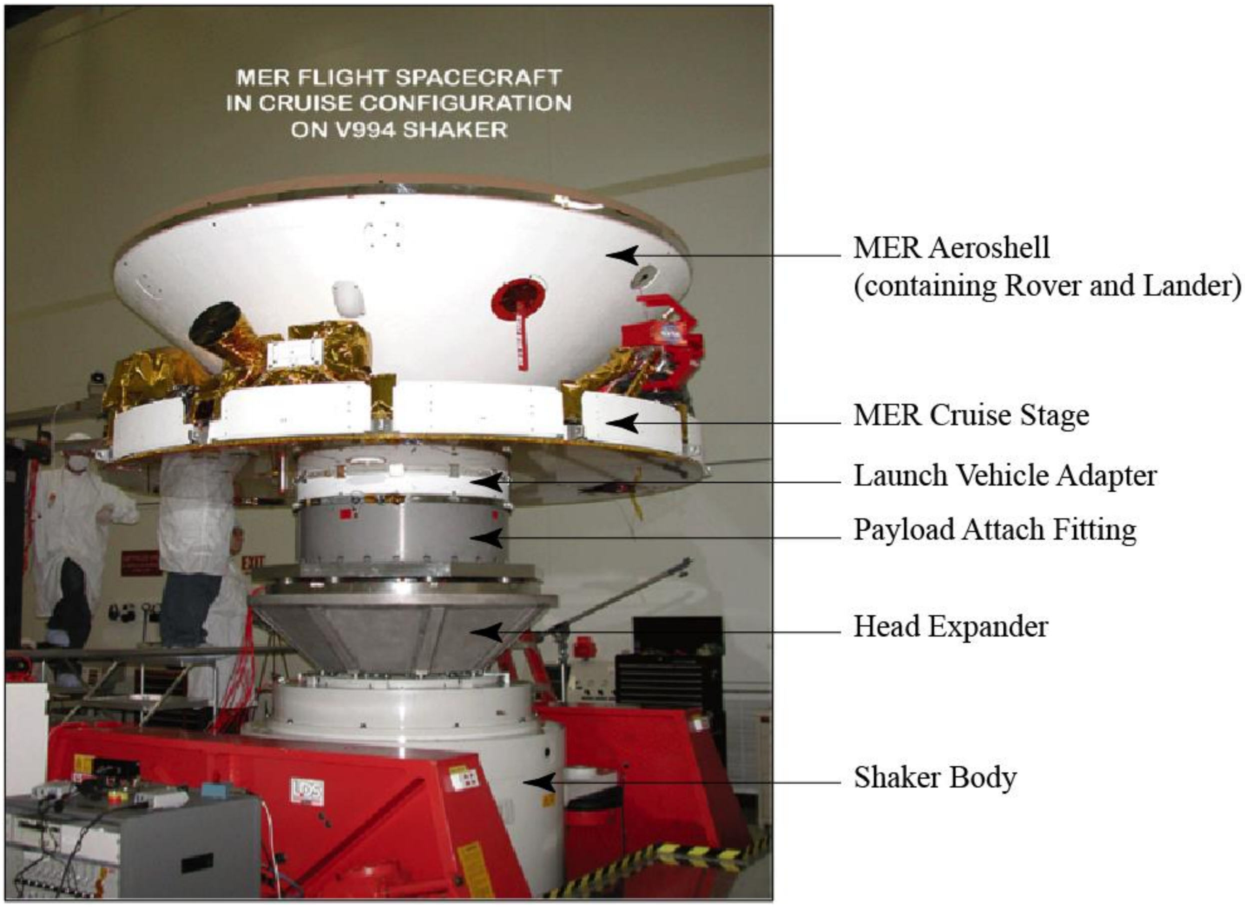

Figure 1—MER Flight #1 Spacecraft in Vertical Vibration Test

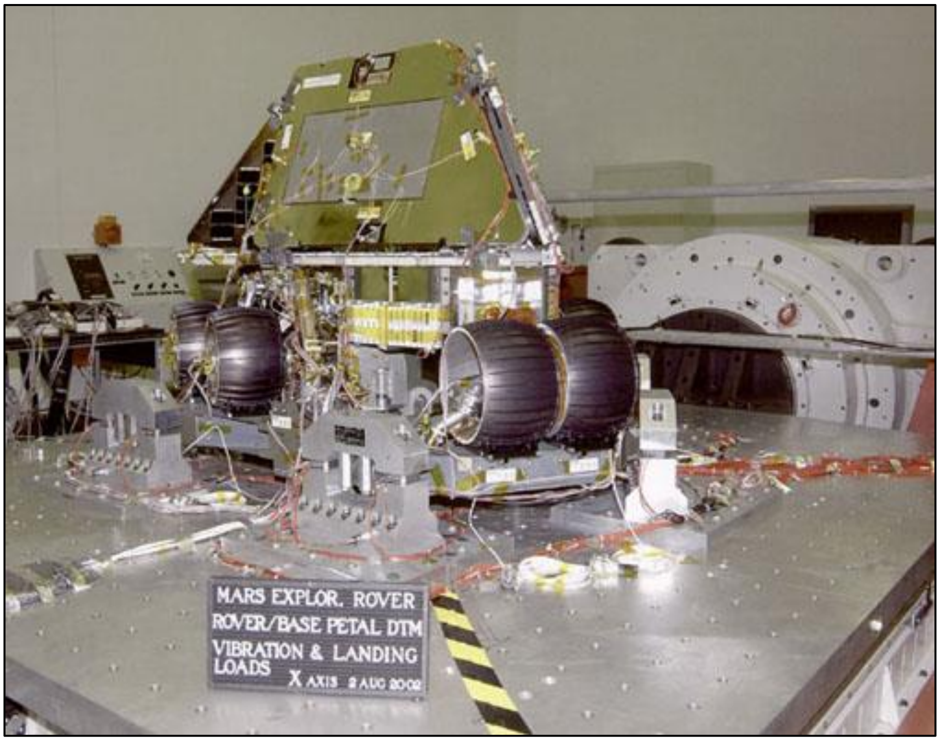

Figure 2—MER DTM Rover in Lateral Vibration Test

Stinger-drive vibration tests, on the other hand, are conducted with the test item either fixed or free, i.e., with the test item attached to a massive, nominally immobile platform so that it is fixed at the base or, alternately, with the test item suspended from a soft suspension system so that it is relatively free to move. In the latter case, ideally, the suspension modes of the system are well outside the frequency range of interest. If the suspension modes are close in frequency to the structural modes of interest, then the dynamic characteristics of the suspension system may need to be included in the FE model of the test article if model correlation is to be successfully achieved (Napolitano et al., 2013). One or more small shakers are then connected to the test item with long, thin rods, commonly called stingers, which are designed to minimize side loading. The stingers may incorporate force transducers to measure the in-axis, and ideally off-axis as well, force applied to the test item. Stinger-drive vibration tests are commonly used for modal vibration testing in which the object of the test is to generate low-amplitude data for verifying a mathematical model, which has assumed either fixed or free boundary conditions for the test item. Stinger (or local) excitation is also sometimes used for microphonic vibration testing, the objective of which is to simulate the in-flight vibration environment generated by on-board vibration sources such as reaction wheels, pumps, and mechanical drive mechanisms to assess the microphonic environment for potentially susceptible instruments before full integration of spacecraft hardware.

Of course, there are exceptions to the common roles of these two types of vibration tests in that base-drive tests can be used to generate modal data and stinger-drive tests can be used to generate relatively high amplitudes. One of the distinguishing features of the different types of dynamic tests is the frequency range over which they are effective. For large test items such as spacecraft, the useful range of both base-drive and stinger-drive vibration tests for high-amplitude testing is in the range of a few hertz to hundreds of hertz, above which frequency it is difficult to simulate flight-like vibration levels throughout a large test item without creating excessive motion at the drive location.

5.2 Acoustic Tests

A typical acoustic test specification includes frequencies from ~25 to 8,000 Hz. However, for a large spacecraft, the vibroacoustic response dominates the flight dynamic environment in only the mid-frequency range, ~100 to 1,000 Hz. (For lightweight antennas and reflectors, however, the response to acoustic excitation can be significant below 100 Hz.) At lower frequencies, below ~100 Hz, vibration testing is usually required to generate the dominant flight dynamic environment, and at higher frequencies, above ~1,000 Hz, shock loads are usually dominant. The dominant type of load in any particular case is usually dependent on the details of the launch vehicle and spacecraft configuration and test objectives. For example for manned missions, frequencies above 1,000 Hz may be critical for human factors considerations. The spacecraft acoustic test specification is usually designed to envelope the fairing interior acoustic levels generated by aerodynamic loading, e.g., turbulent boundary layer, oscillating shocks, separated flow, and the lift-off acoustic environment.

The frequency spectra and the amplitude of the acoustic and aerodynamic environments vary with time. The maximum acoustic environment normally occurs within a few seconds after liftoff, whereas the maximum aerodynamic environment normally occurs later during the transonic or maximum dynamic pressure segments of the flight. The acoustic test specification is usually an envelope of the highest environment, in each one-third octave frequency band, at any time during the flight, sometimes called the maximax spectrum (NASA-HDBK-7005, p. 12). As with all dynamic environments, the specification for acoustic tests should be based on a statistical evaluation of data from similar flights, not on only one particular flight measurement.

Acoustic excitation is most effective in exciting large, low-surface-density hardware, such as honeycomb panels, dish antennas, and solar panels. For example, if the surface density of the unloaded structure, i.e., without considering the mass of any equipment mounted on the structure, is less than 10 kg/m^2 (2.0 lb/ft^2) and the area of the structure is more than 0.1 m^2 (1.1 ft^2), then acoustic excitation may be an important load. If in doubt, an acoustic analysis of the system or major subsystem should be performed using statistical energy analysis (SEA), which provides space- and frequency-average estimates of the response of structures to sound, and/or the Boundary Element Method (BEM) and Finite Element Method (FEM) approaches, which employ the test article FE model to calculate accelerations, forces, and stresses at specific FE model elements. Acoustic loads can cause paint flaking, debonding and cracking of built-up structures, and electronic failures in equipment mounted on honeycomb panels. Acoustic tests are often viewed as good candidates for workmanship tests of flight spacecraft, because acoustic tests seldom result in failures of primary structure and, in comparison to vibration tests, are relatively immune to overtesting caused by input spectra enveloping and test equipment failure. In programs with a DTM spacecraft, acoustic tests may be conducted on the DTM early in the program to refine the random vibration test environments for flight instruments and components mounted on the spacecraft (Chang and Scharton, 1996). (For a description of the Cassini Spacecraft Test Program, see Appendix A in this Handbook.) However, it should be noted that, although the primary structure is normally flight-like for DTMs used for mechanical testing, components are sometimes represented only as mass mockups. Accelerometer measurements at the base of the mass mockups generally will not provide vibration data representative of inputs to flight hardware.

Spacecraft acoustic tests have traditionally been conducted with the test items located in large reverberant chambers, which are excited with one or more electro-pneumatic modulators fitted with horns mounted into the walls of the chambers. (The new NASA Glenn Research Center (GRC) 101,000-ft^3 volume reverberant chamber uses 36 modulators fitted with horns and achieves an empty chamber acoustic level of 163 dB OASPL (NASA/TM-2011-217000, The Development of the Acoustic Design of NASA Glenn Research Center's New Reverberant Acoustic Test Facility).) The preponderance of the sound waves in an acoustic test conducted in a large reverberant chamber bounce off the chamber walls many times before striking the test item, and this results in a diffuse field that is relatively uniform in frequency and space, at least in the mid- and high-frequencies. A reverberant chamber used for spacecraft acoustic tests should be sufficiently large so that the modal overlap is one at a frequency of 100 Hz or less. (The modal overlap is the number of modes within the 3-dB bandwidth of a mode (Schroeder and Kuttruff, 1962).) It would be preferable if the Schroeder frequency, i.e., the frequency at which the modal overlap is equal to three, were 100 Hz or less. However, the latter criterion is difficult to realize in large chambers with long reverberation times. If there are items on the spacecraft that are sensitive to acoustic excitation at frequencies below that at which the modal overlap is unity, then a modal analysis or modal survey of the chamber should be conducted. When conducting an acoustic test in a reverberant chamber, it is recommended not to mount the test item so that any of its large surfaces are near or parallel to the chamber walls, and the test item should not occupy more than 10 percent of the chamber volume (IEST-RP-DTE040.1, High Intensity Acoustics Testing). Additionally, chamber standing waves that could adversely couple with the test article should be identified beforehand and, if necessary, the test article position in the chamber adjusted to mitigate coupling. The sound pressure level (SPL) in a reverberant chamber acoustic test is typically controlled by averaging the signals from four or more microphones located in the free field, away from localized disturbances caused by the chamber walls and the test item. Nitrogen gas is usually used to power the acoustic drivers to reduce the high-frequency acoustic absorption associated with air, and liquid nitrogen is often used as a source of the high-pressure nitrogen gas. (After the testing is complete, the chamber has to be completely purged with air before admission to the chamber is permitted.)

DFAT, an alternative acoustic test method, employs a large number of electro-dynamic speakers arranged in close proximity to the test item, which may be located in a vibration or acoustic test chamber, a clean room, or a large open space, such as a high bay or loading area. DFATs are increasing in popularity because they do not require a permanent, relatively expensive test facility, such as a reverberant chamber. (A contractor typically provides, sets up, and operates the DFAT speakers, amplifiers, microphones, and control system for only as long as the test requires.) Figure 3, DFAT Setup, shows an example.I In this case, the DFAT setup has over 1,000 drivers in over 192 speaker cabinets, some of which will be added once the spacecraft is positioned inside the speaker circle (Larkin, 2012). In DFATs, the test item is in the direct acoustic field of the speakers, which means that most of the sound waves travel directly from the speakers to the test item without first striking another surface. However, some standing waves will be generated inside the volume within the speaker circle by reflections off the spacecraft and speakers. DFATs may have relatively large frequency and spatial variations caused by sound waves from different speakers constructively or destructively interfering at the various positions on the test item. However, the spatial and frequency variations in DFATs have been considerably reduced by the use of sophisticated multiple-input multiple-output (MIMO) control techniques. (See section 8.4.1 in this Handbook.) It is recommended that comprehensive analyses of the acoustic field and structural response be conducted before performing DFAT, but it is difficult to analyze DFAT with MIMO control strategies. Another complication in the application of DFATs is that the efficiency of acoustic waves in exciting the vibration of structures depends on the angle of incidence of the sound wave and the coherence of the various waves and is, therefore, somewhat different in reverberant and direct field tests (Kolaini and Kern, 2011). These and other problems are discussed further in Appendix D in this Handbook, which describes the first known DFAT test of a spacecraft.

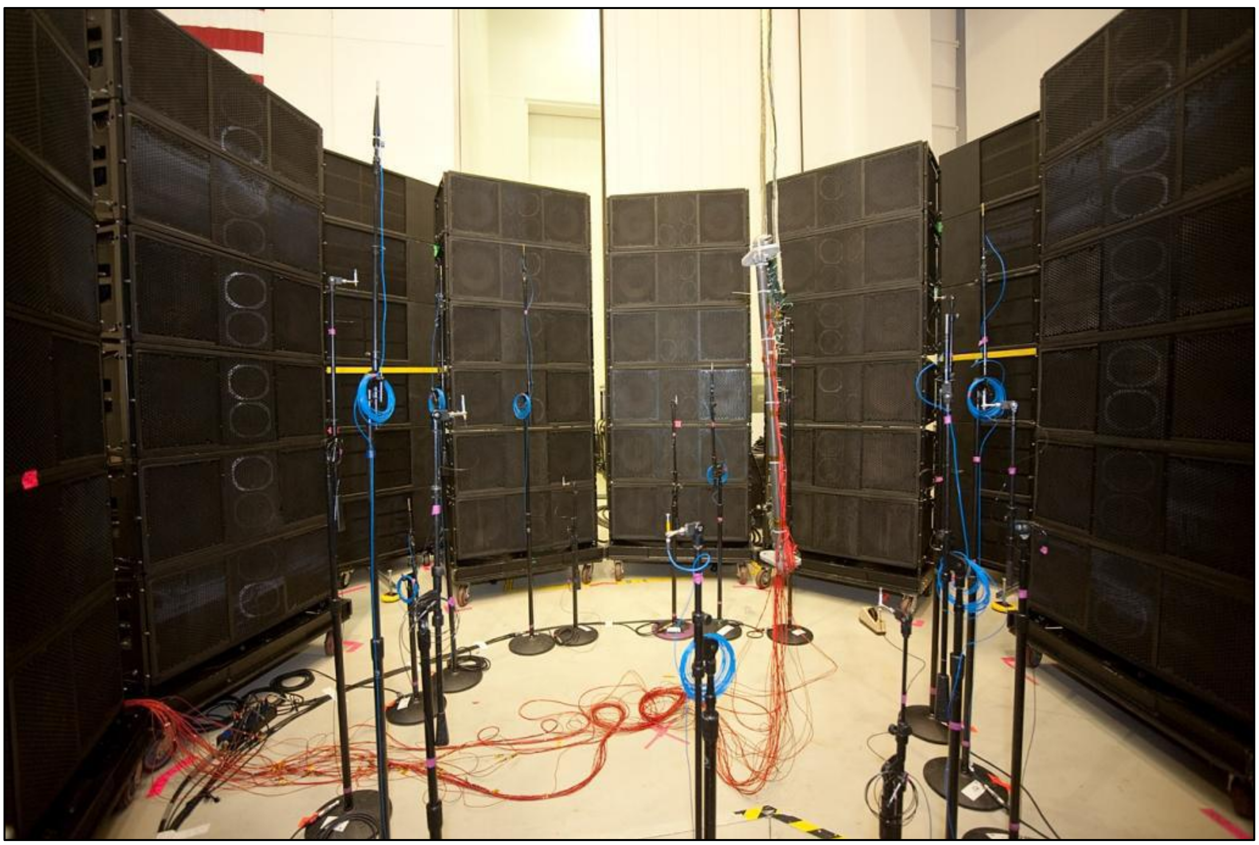

Figure 3—DFAT Setup
(Speaker ring is completed after spacecraft is installed in center.)

Acoustic tests can be conducted in the open-loop mode because, unlike vibration tests, the feedback between the test item vibration and the acoustic pressure is typically rather small, but it is usually convenient and safer to use a commercial closed-loop control system for equalization and control. An exception is the case of large reflectors tested in small reverberant acoustic test chambers where strong, narrow-band coupling has been observed. The acoustics of the reverberant chamber and/or free field are relatively linear at acoustic levels below ~150 dB, but the acoustic drivers and associated amplifier systems can be quite nonlinear, which can complicate the equalization process as one steps up to higher levels.

5.3 Shock Tests

In tests of spacecraft, the shock testing is typically conducted by initiating the device that causes the shock environment in flight (NASA-STD-7003, Pyroshock Test Criteria). The system that separates the spacecraft from the launch vehicle usually involves a pyrotechnic charge and is, therefore, an important shock source for the spacecraft. This system is commonly tested by suspending the spacecraft, firing the separation charge, and allowing the payload attach fitting (PAF) section below the separation plane to drop a few centimeters (inches) onto a soft cushion. (Alternately, the spacecraft and mated PAF may be placed on the floor with the spacecraft spring loaded to offset gravity. The spacecraft can be lifted free of the PAF to verify separation.)

While other pyrotechnic devices on the spacecraft should also be fired, in the sequence and ideally in the environment (thermal and/or vacuum) in which they are fired in flight, this is often not practical. The dominant frequency range of spacecraft shock tests is typically from hundreds to thousands of hertz, with much of the energy concentrated above 1,000 Hz.

5.4 Types of Excitation in Vibration Tests

Three types of excitation are used in spacecraft vibration tests: sinusoidal, random noise, and transients. Each of these three classes of time history has many variations; the most commonly used will be discussed herein.

5.4.1 Sinusoidal Excitation

A frequently used form of excitation in vibration testing of spacecraft is sinusoidal input. For spacecraft testing, sinusoidal input is typically used for three types of tests: signature (low-level) sine, qualification (high-level) sine, and sine dwell or burst. While all three types of tests involve input that is sinusoidal in nature, each of these types of tests has a different role in spacecraft qualification. Each type of test is discussed in detail in the following sections. The low-level signature and high-level qualification sine tests are usually swept sine tests. In swept sine tests, the input is a sinusoidal waveform that varies in frequency from a lower starting frequency to an upper frequency limit. The rate of change in the frequency is usually done logarithmically and specified in octave/min so that the number of cycles at each resonant frequency of the test article is approximately the same. Linear sweep rates are supported by most vibration control systems, but they are typically not used for testing of spaceflight hardware. In addition to specifying the sweep rate, the amplitude of the sinusoidal input is also specified as a function of frequency. A typical specification for a high-level sine sweep test might be an input amplitude of 1 g (one times the acceleration of gravity) from 5 to 50 Hz with a sweep rate of 4 octave/min. The sine dwell and burst tests involve subjecting the hardware to a sinusoidal input that is fixed in frequency; these tests are conducted for a fixed duration or number of cycles. Sine dwell tests typically involve a rather large number of cycles of fixed amplitude. Sine burst tests typically involve only a few cycles (5 to 10 at peak amplitude), which ramp up to full amplitude and then down again. Sine dwell and burst tests are usually conducted at a frequency below the fundamental resonance frequency of the test article to generate quasi-static loads in the hardware. In most cases, sine testing of spacecraft involves base-driven excitation, although sinusoidal input can also be applied to the test hardware through the use of stingers.

5.4.1.1 Signature or Low-Level Sine Testing

Sine-sweep signature testing is a base-driven test that subjects the test article to a swept sine input to characterize the behavior of the structure and derive a transfer function that relates input at the base of the spacecraft to instrumented responses at various locations on the test article. This test is typically run in conjunction with higher level dynamic testing as a diagnostic tool to evaluate the status of the hardware before and after it has been exposed to the high-level input. In addition, the data gathered from a signature sweep can also be used to predict the response of the spacecraft to higher level sine input. The signature sine sweep is a very important data-gathering step in performing flight-level sine testing as discussed in section 5.4.1.2 in this Handbook. The signature sine sweep is typically done at very low levels so that the risk of damaging the hardware is minimal. The signature sine test is not intended as a qualification test or as a replication of a known flight environment. Typical input levels for signature sine tests of spacecraft are in the 0.05- to 0.1-g range. Signature sweeps are typically performed at 4 octave/min; slower sweeps rates, such as 2 octave/min, may be used, especially if there is difficulty in controlling the test with a higher sweep rate. If modal parameters are to be extracted, 1 octave/min is even better. The input amplitude of the sine signature is usually constant over the frequency range. The frequency range for signature testing of spacecraft varies, depending on the type of high-level dynamic testing being performed and the hardware being tested, but typically does not go higher than 500 Hz.

Response data from sine tests are typically plotted as acceleration (g) versus frequency. These data are processed by the controller or data acquisition system to calculate the peak g response (plus or minus) at a specific frequency as the control system sweeps through the frequency range. The data are sometimes processed using a tracking filter, which is a band-pass filter with the center frequency of the band following the frequency of the input. One must give some thought to the question of whether a tracking filter is to be used. A tracking filter offers the advantage of reducing noise related to rattles but reduces the measured response related to nonlinear behavior.

The most common use of the signature sine is to run this test before and after high-level dynamic tests and then to compare the responses at various locations on the spacecraft to verify that the signature or characteristic response has not changed. Significant shifts in resonant frequency or changes in amplitude can indicate that an item has been damaged and is responding differently after exposure to a dynamic test environment. Typically, frequency shifts of greater than 5 percent on primary mass modes and 10 percent on secondary modes indicate a significant change in structural behavior and should be investigated. Amplitude changes, as well as a change in overall response characteristics, can also indicate that a problem has occurred. An example of pre- and post-test signature runs from a test of the Swift Observatory indicating response differences is shown in figure 4, Pre-/Post-Sine Signature Overlay. (Also, see Appendix C in this Handbook.) The differences in the pre-/post-sine plots were traced to a loose cover mechanism that had not been properly preloaded.

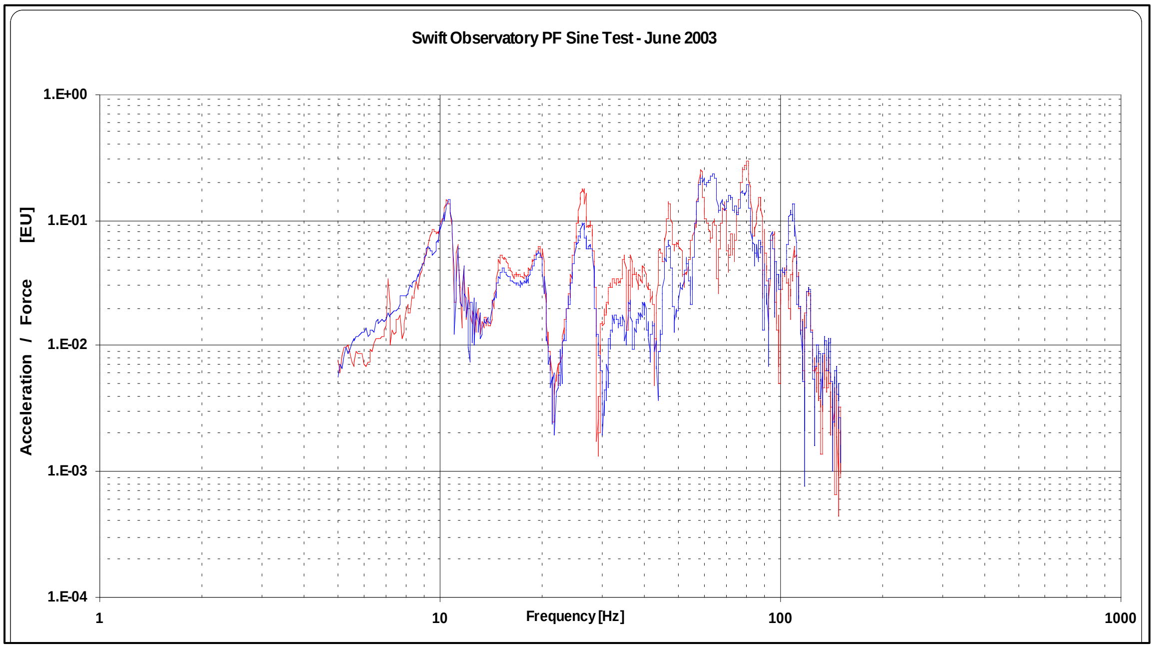

Figure 4—Pre-/Post-Sine Signature Overlay

5.4.1.2 Flight-Level Sine Test

The basic purpose of the sine test is to qualify spacecraft hardware for the low-frequency launch environment and to provide a workmanship screen for hardware that does not respond significantly to the vibroacoustic environment but may respond significantly to mechanical vibration transmitted through the spacecraft interface to the launch vehicle. Examples of such types of hardware include wiring harnesses, stowed appendages, blankets and supports, flex-hoses, plumbing bracketry, and mechanisms with clearances and/or bearings (Conley, 1997). In many cases, the above items are not tested at lower levels of assembly and are typically difficult to model and analyze. Three-axis sine vibration testing is required under NASA-STD-7002, Payload Test Requirements, when sinusoidal transients or sustained sinusoidal environments are present in flight.

The sine test is an alternative test method to verify the behavior of the as-built flight spacecraft under the simulated dynamic inputs from the launch environment while on the ground. While components and subsystems are typically tested at lower levels of assembly, it can be difficult to accurately replicate the actual flight boundary conditions in a subsystem-level test. This is especially true for components or subsystems such as deployables, which can have redundant interfaces with the spacecraft so that these interfaces may be subjected to loads and deflections caused by the excitation of the low-frequency modes of the spacecraft bus. An analytical model that does not accurately capture the interaction between the subsystem and the spacecraft mounting interface can lead to unexpected behavior, possibly resulting in damage that would not be predicted by analysis or uncovered during subsystem-level testing.

Note that the system-level sine vibration test is usually not intended to be a strength qualification test but rather is intended to verify that the system performs as expected after being exposed to flight-like low-frequency vibration input. However, some spacecraft organizations that perform little or no static loads testing on their structures do use the flight or DTM spacecraft sine test for structural verification. This approach may result in both undertest and overtest of the structure relative to design loads because of differences in resulting loads distribution between flight and rigid shaker excitations and can raise safety issues. The input in a system-level sine vibration test may be notched to ensure that the response of the hardware does not exceed the predicted flight response with the appropriate test factor applied. This ensures that the test can be performed safely without exceeding the strength capability of the hardware and preventing unrealistic failure related to over test.

The flight-level sine test is intended to replicate the low-frequency dynamic environment that the spacecraft will experience during launch. Most launch vehicle planner's guides provide a sine specification to be used for testing of spacecraft. Figure 5, Payload Sine Vibration Levels for the Atlas V Launch Vehicle, shows the sinusoidal specification from the Atlas V Launch Services User's Guide (United Launch Alliance, 2010). The sine test levels shown in payload planner's guides tend to be generic test levels that envelope a wide range of launch vehicle and spacecraft combinations. Mission-specific sine test levels may also be derived based on coupled loads results for a particular spacecraft. Equivalent sine sweep test input levels can be developed using SRS techniques for transient flight events and then dividing the resulting SRS by the assumed amplification (quality) factor ($Q = 1/(2\zeta)$, where ζ is the percent of critical damping) for the system to derive equivalent sine input. Note that, in developing equivalent sine inputs, the assumption of a lower Q is more conservative in that it will tend to overestimate the equivalent sine amplitude required to achieve the same response of a single degree-of-freedom (DOF) system. Ideally, the estimation of flight-level damping used in the derivation of equivalent sine specs for testing is developed from flight data. However, in the absence of flight data, a value of Q=20 is commonly used for deriving sine test inputs for spacecraft tests. In addition, some launch vehicles can experience periods of sustained sinusoidal vibrations because of pogo, resonant burn, or thrust oscillation events during flight, which may induce sinusoidal responses in spacecraft. These inputs, which do not require use of SRS techniques, should also be included in the test specification derivation by enveloping the magnitude of the input at the spacecraft interface over the frequency range of the event.

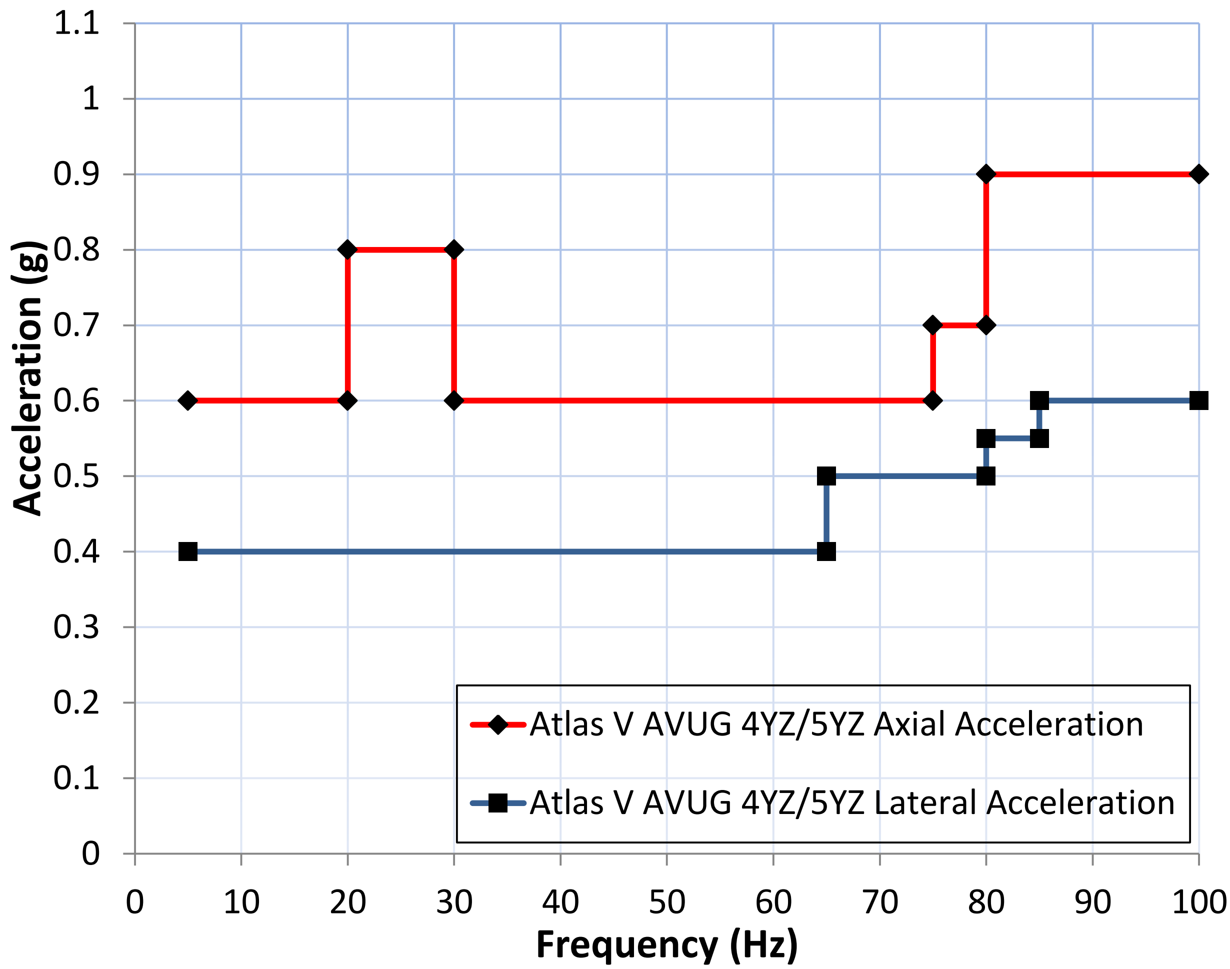

Figure 5—Payload Sine Vibration Levels for the Atlas V Launch Vehicle

The test factors for sine testing are typically 1.25 times the flight level for protoflight and qualification testing. Acceptance sine testing would be performed at 1.0 times the flight environment. The sweep rate for qualification testing is typically one-half the sweep rate for protoflight/acceptance testing; therefore, if a protoflight test were performed at 4 octave/min, the corresponding qualification test would be performed at the same input amplitudes but with a sweep rate of 2 octave/min. Other sweep rates may be used as necessary to more accurately simulate the duration of specific flight events. In this case, the acceptance/protoflight sweep rate is defined based on the flight duration, and the qualification sweep rate will be one-half that defined for the flight duration.

Sine testing of spacecraft is performed in all three spacecraft axes. In most cases, the typical test flow for an axis of vibration consists of a constant amplitude signature sweep at low levels of input, followed by low-level runs of the shaped sine spectrum (one-quarter level and one-half level) in which the data are evaluated and changes to the input spectrum are made before proceeding with the full-level test. Additional intermediate-level runs may be performed, and signature sweeps may be repeated based on the discretion of the test director. The full-level sine test is then followed by a post-test signature run, which is then compared with the pre-test signature to verify that the structural characteristics have not changed; changes might indicate damage or degradation of the hardware.

It is typical to perform aliveness checks between axes of sine testing. Aliveness checks verify the ability of the hardware to power on and include only very limited functional testing. This allows the check to be performed quickly after completion of an axis of test to identify any gross hardware issues without significantly impacting the test flow. Electronic hardware that is required to operate during launch should be operating and functionally monitored during the tests. After completion of all axes of test, a full functional test is performed to verify that all spacecraft systems will function as required after exposure to the low-frequency launch environment.

It is recommended that two or more in-axis control accelerometers be used to control the sine input into the test article. (In spacecraft-level tests, one or more additional accelerometers are often placed on the fixture to monitor the input acceleration and to check the uniformity of the input.) Most vibration controllers have the ability to adjust the sine input based on either the average or the maximum of the control accelerometer signals. The common control method for sine testing is to use maximum control for sine testing of spacecraft as a precaution to limit overtest. (Average control is often used for smaller test items.)

In addition to the control accelerometers, several response accelerometers may also be patched into the control loop. At these locations, response limits will be specified so that as the response limit is approached during the test, the controller will reduce the input so that the response limit is not exceeded. Abort limits can also be specified for the control and response accelerometers in the control loop. Abort limits are typically defined based on the design capability of the hardware so that the controller will shut down the test before the hardware experiences loads that will result in permanent damage. Low-level runs with proportional response and abort limits can be used to determine how well the controller is able to control the test and adjust the limits accordingly.

One of the critical areas to be monitored during spacecraft-level sine sweep testing is the forces and moments at the spacecraft interface. While these loads may be inferred from the measured acceleration response, it is much more straightforward to measure these interface forces directly; therefore, it is very common for spacecraft-level sine vibration tests to include force transducers at the base of the test article. A stiff plate or ring is used to make the transition between the bottom of the test article, typically the payload adapter, and the interface to the shaker head or slip table. The translational forces at the interface are then simply calculated as the sum of the individual force gages, and the overturning moments can be calculated based on the measured forces and the layout of the gages around the interface. Not all control systems have the ability to support dual control (acceleration and force) for swept sine testing; therefore, the input may need to be adjusted manually based on the measured forces from the results of the signature and lower test level sine runs.

As with all base-driven shaker tests, the input level for the sine test should be monitored very closely and tailored during testing to prevent overtest. Because the sine test simulates the dynamic launch environment with equivalent sinusoidal input, the sine test may produce unrealistic responses as locations on the spacecraft are swept through resonance. This, combined with the ability of an infinite impedance shaker to overdrive the hardware through major structural resonances, requires that the response of the test article be monitored very closely during test. Typically, sine testing requires that the input test levels be notched based on a combination of monitoring interface forces at critical interfaces and also limiting responses at spacecraft subsystems to not exceed coupled loads predictions or design capability of the hardware. Typically, instrumentation (force gages, accelerometers, strain gages, and displacement sensors) is selected to limit the response of the hardware based on predictions from coupled loads as to how the spacecraft will respond to the launch environment.

There is agreement within the NASA community that low-frequency vibration testing of the as-built spacecraft is required as a final dynamic qualification and workmanship screen. Both base-driven sine and random vibration testing can be used to meet this goal. Both techniques are a conversion of the actual flight environment (typically short-duration transient inputs) into the frequency domain for the convenience of testing. The reasons for sine testing are that it is a straightforward test with much history within the aerospace community and that it accurately replicates periods of sustained sinusoidal vibration experienced by many launch vehicles; because measured responses can be compared directly to CLA results, it is much more straightforward to protect the hardware with input notching and response limiting based on flight predictions. The downside to sine testing is that, by replicating the low-frequency launch environment with equivalent sinusoidal input, the test will only excite one frequency at a time as it sweeps through the frequency range of the test. This is different from the actual dynamic environment during launch in which the spacecraft is responding to multiple input frequencies at a given time of flight. The sine test also has the ability to cause more damage, since it will excite the hardware one resonance at a time, which can result in higher resonant response than equivalent levels of random energy, which induce multimodal responses. Therefore, care should be taken in the selection of the instrumentation, and the responses of the test article should be monitored very closely to prevent overtest.

5.4.1.3 Sine Burst Testing

The sine burst test is a base-driven test in which the test article is subjected to a few cycles (typically 2 to 10 at peak amplitude) of sinusoidal input. This is usually done below the first resonant frequency of the test article to expose the hardware to a quasi-static loading. This test is primarily intended as a strength qualification test and does not usually represent a specific flight event. The sine burst test is an alternative method for strength qualification and is used to generate specific loads in primary structure. This test may be used in place of static pull or centrifuge tests.

Typically, strength testing should not be performed on complete spacecraft, as it is overly risky to subject the full spacecraft build with expensive science hardware to strength testing at this level of assembly (Fisher, 2010). Sine burst testing is better suited to testing at lower levels of assembly and at the primary structure level with mass mockups to limit the damage and recovery effort, should a failure occur. However, in some cases, because of schedule constraints and other limitations, it may be elected to strength qualify the spacecraft primary structure after it has been fully integrated. Sine burst testing is attractive in this case, because the strength testing can be performed as part of the planned dynamic testing while the spacecraft is on the shaker table. If sine burst testing is performed as part of the spacecraft dynamic test sequence, it is important that all parties involved fully understand the risks and limitations of this approach.

While the sine burst test is intended to subject the test article to loads as a rigid body, limitations of the test facility do not make this possible, in many cases. A typical profile for a sine burst test consists of 2 to 10 cycles at peak amplitude, with approximately the same number of cycles for ramp up and ramp down. An example of this profile is shown in figure 6, Example Sine Burst Profile for Strength Qualification. NASA-TM-106313, Design for Reliability: NASA Reliability Preferred Practices for Design and Test, recommends that the input frequency of the test be less than one-third of the first resonant frequency of the test article. However, because the frequency at which a certain acceleration level can be achieved is limited by the stroke of the shaker, in many cases it may not be possible to achieve the above recommendation, especially as the size of the test article increases and the fundamental resonance of the system becomes lower in frequency. If the sine burst test is run closer to the resonant frequency of the test article than recommended, the test article will start to respond dynamically. This means that the response of the test article will have some amount of dynamic amplification that must be accounted for when calculating the input amplitude of the test to achieve the proper loading in the structure. In many cases, it is not possible to accurately predict the amount of dynamic amplification before the test, as it is very dependent on the resonant frequency of the hardware and level of damping. Therefore, the input amplitude should be adjusted based on the response measured during runs performed at lower levels of input. It is strongly recommended that force gages be used at the interface between the test article and the shaker head or slip table to directly measure the reactive load generated during a test run, as this is the most accurate means to verify that the proper loading is achieved.

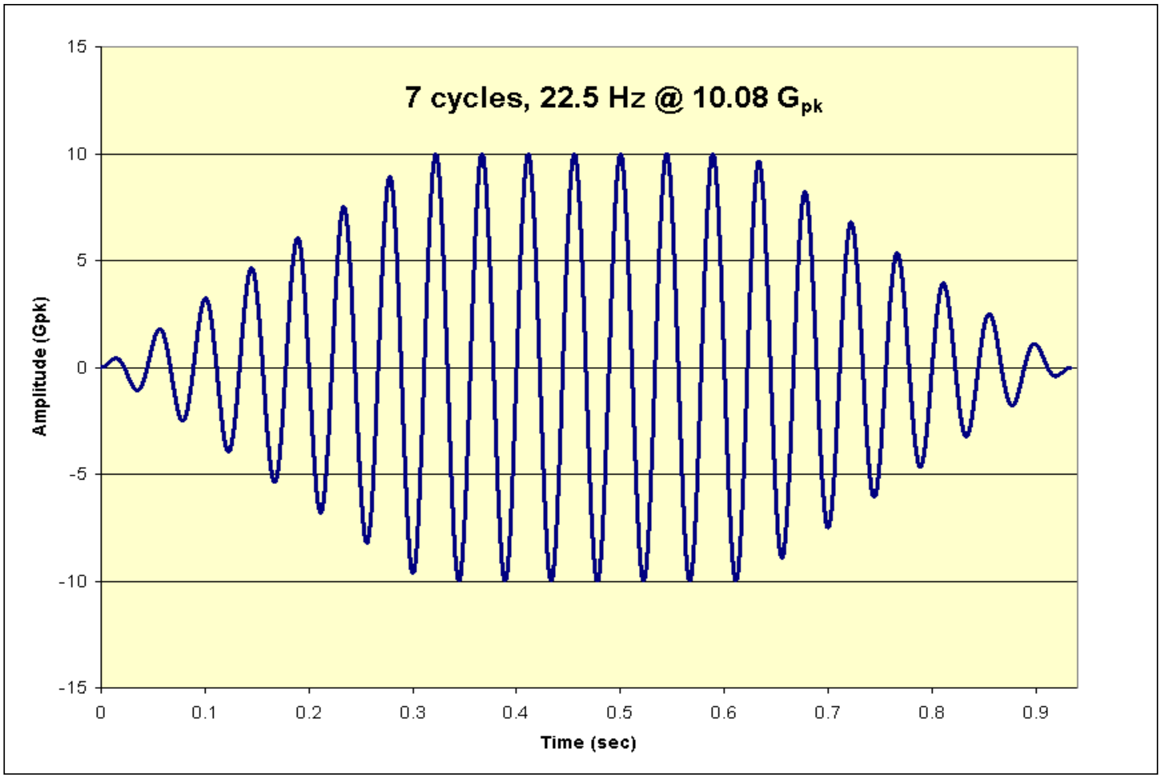

Figure 6—Example Sine Burst Profile for Strength Qualification

Also, because the duration of the test is very short (on the order of 0.3 to 0.5 sec), it is not possible for the shaker control system to run this as a closed-loop test. Therefore, the test is run open loop with the control system adjusting the input waveform for the next run based on the measured waveform from the previous run as the controller steps up in level. If the test article is responding dynamically, it can make it more difficult for the control system to accurately predict the input based on the results of the previous run. Therefore, it is critical that the response data be reviewed after each low-level run to ensure that the system is behaving in a predictable (and, hopefully, linear) manner as the input level is increased and also to monitor any dynamic behavior so that the input waveform can be adjusted to account for the amount of dynamic amplification exhibited by the test article. Significant nonlinearities or testing too close to the resonant frequency of the test article can result in a situation in which the controller cannot accurately predict the behavior of the test article from one run to the next and also can result in overtesting of the hardware at the full-level input. Some test laboratories have implemented a real-time shutdown system if the time history exceeds a predetermined level during the profile ramp up. The ability of a shutdown system needs to be thoroughly verified to prevent damage to hardware.

5.4.2 Random Excitation

5.4.2.1 Signature or Low-Level Random

Broadband random excitation is often used instead of swept sine for the pre- and post-test low-level signature tests. This is particularly advantageous when the flight-level vibration test uses random vibration excitation instead of sine excitation, because then the data analyses of the signature and flight-level tests are similar, and the data can be directly compared. Sometimes, a burst of random noise is used instead of continuous random noise to avoid the potential issues of windowing, which distorts the resonance peaks of extremely lightly damped modes and thus artificially inflates their modal damping estimate and the deterioration of the spectral lines at or near resonance that are indicated by the coherence dipping at resonance peak frequencies in the frequency response functions (FRFs). To get high resolution, obtain at least 30 frames (not overlapping) of data. For continuous random excitation, typically 75 percent overlapping and Hanning windowing are used to calculate PSDs, FRF, and coherences from the time histories. Comparison of FRFs is preferred to that of PSDs or linear spectra, as the FRFs are relatively insensitive to small changes in the input excitation levels, while these changes in the input excitation levels will be manifested in the PSDs and linear spectra. Overlaying the pre- and post-low-level signature test FRFs is a very quick and easy way to determine if the health of the test article has changed during testing. To further quantify the health of the test article, modal parameters can be extracted from the pre- and post-FRF and easily compared.

5.4.2.2 Flight-Level Random

In flight, random vibrations are generated by the rocket engines and by acoustic and aerodynamic excitation of the launch vehicle and spacecraft fairing. Random excitation may be used in both base-drive and stinger-drive flight-level vibration tests. For large spacecraft, the practical frequency range for high-amplitude random vibration tests is ~ 20 to 200 Hz. (For smaller spacecraft, e.g., below 454 kg (1,000 lb), the upper frequency may be up to 500 Hz.) Random vibration tests are sometimes difficult to control below 20 Hz, because of occasional large displacements. At frequencies above ~ 200 Hz, it is usually difficult to transmit vibration through a large spacecraft. Conventional wide-band random excitation offers the advantage that, as in flight, many frequencies and modes can be excited simultaneously. Infrequently, to attain higher levels, a narrow-band random input may be swept through some frequency range (swept random), or a band of frequencies may be excited for a short time (burst random).

Base-drive random vibration tests of spacecraft are useful for exciting instruments and appendages, which typically have fundamental resonance frequencies in the 20- to 200-Hz range, and for exciting structural and electrical interfaces and items which are difficult to test at the assembly level, e.g., cables, plumbing, blankets. Random vibration tests are also used for low-frequency workmanship vibration testing of assembled spacecraft. Stinger-drive random vibration tests of spacecraft are useful for measuring modal frequencies and damping and occasionally for locally enhancing the response levels in acoustic tests. Random vibration tests are not generally used for strength testing of the spacecraft primary structure, because of the amplitude variations and uncertainties, which are inherent in random processes.

Random vibration tests are defined by specifying the PSD of the input acceleration as a function of frequency. The PSD of a signal is a measure of the distribution of the energy (squared amplitude) of the signal over frequency (Crandall and Mark, 1973, pp. 29-30). (As in sine input tests, it is recommended that the input in random vibration tests of spacecraft and other large test items be defined as the average or the maximum of two or more control accelerometers mounted at different locations on the test item and fixture interface and that additional accelerometers be used to monitor the in-axis and cross-axis vibration of the interface.) The test PSD specification usually comprises connected straight line segments when viewed on a log-log plot of the excitation versus frequency. The specification should be based on the envelope or average of data measured on similar structures on similar flights and not on a particular flight measurement or FEM analysis, and, therefore, the specification should be a relatively smooth function of frequency.

In the case of base-drive vibration tests, it is recommended that the input acceleration profile be notched in real time at the resonance frequencies of the mounted spacecraft to compensate for the artificially large impedance of the shaker and fixture and sometimes other response constraints. (See section 8.5 in this Handbook.) The notching can be defined by limits on the responses, such as the base reaction force, the spacecraft acceleration responses, or both. (These notches introduced in the input by real-time response limiting will mirror the shape of the system resonances, and, therefore, they may be quite sharp.)

The most appropriate measure of the severity of the input in a random vibration test is the maximum PSD value of the input, or better yet, the PSD value at the frequency of the major resonances of the test item (Crandall and Mark, 1973, p. 71). It is a common misconception to think of the root mean square (RMS) of the signal as a good measure of the severity of the input in random vibration tests. The problem with the RMS is that, since it is defined as the square root of the integral of the acceleration PSD over frequency, it depends strongly on the values of the PSD of the input at high frequencies, which are usually of secondary importance for defining the input. However, for responses**,** the RMS (or, specifically, three to five times the RMS value of the response) is the appropriate descriptor of severity (Crandall and Mark, 1973, p. 52).

Random vibration test control and data acquisition requires multi-channel random data analysis and control software, with the capability of computing and displaying the PSDs of a limited number of control and response accelerometers in real time and, preferably, also the capability to record and later display the time histories of all the data.

As with sine-sweep testing, the validity of random vibration tests is influenced by the impedance and resonances of the fixture and shaker configuration, the enveloping of flight data, the location and combination of control accelerometers, and the use of mass simulators to replace flight hardware on the test item.

5.4.3 Transient Excitation

All the inputs in vibration tests are transient in the sense that they are of limited duration, but here the term transient refers to inputs that last only a fraction of a second or so. Many different types of transient waveforms may be used for vibration tests of spacecraft, and transient excitation may be characterized in many ways, including waveform, duration, frequency content, and test level. Except for high-frequency shock tests, which are seldom conducted with a spacecraft mounted on a shaker, transient vibration tests of spacecraft are usually conducted for the purpose of structural qualification, and therefore, involve low frequencies and high test levels. Transient waveform frequency content is often concentrated at frequencies an octave or more below the first resonance of the test article to minimize resonant responses. Transient waveforms may include a classical half-sine or a modification thereof, a bundle of sinusoidal cycles of a single frequency (a sine burst), or, less frequently, a wavelet with many frequencies or a complex time history. Ideally, transient inputs might be representations of actual in-flight events, but this approach has proven problematic. One of the problems has been that of developing a control system fast enough to provide closed-loop control of short-duration inputs. A more fundamental difficulty concerns the question of how to define representative transient inputs.

5.5 Overview of Control and Limiting of Vibration and Acoustic Tests

The details of the control in vibration tests are closely related to the type of input being used; however, there are some common features of the control and limiting. First, most of the control is closed loop, which means that the input is adjusted in real time to coincide with what is desired. Transient testing is the exception, because there is generally not enough time to adjust the input in a transient test. Sometimes, the control system may be configured to terminate a transient test if the input is not as desired, but sudden termination of a high-level test is, in itself, problematic. Acoustic tests are commonly conducted with a closed-loop control system because such a system speeds up the process of equalization to the test specification as the test level is increased. Sinusoidal tests are generally controlled to a peak or RMS value (0.707 times the peak), and random tests to a PSD value specified as a function of frequency. In both vibration and acoustic tests, there is some preset tolerance and a threshold for automatic shutdown. Sections 8.4 and 8.5 in this Handbook contain more specific information on control and limiting of vibration and acoustic tests.

It is common practice in spacecraft vibration tests to have some response limit channels, which are used to modify the input if the signals in these limit channels start to exceed their specified limits. (See section 8.5 in this Handbook.) In either sinusoidal or random vibration tests, these limits may be a function of frequency and the input may be reduced (notched) at frequencies where the limit is exceeded. Notching is often needed at the fixed-base resonance frequencies of the test item because these resonances are much more pronounced on the shaker than in flight, where the compliance of typical flight mounting structures will not support strong resonances of the test item. Traditionally, acceleration responses measured at various positions on the test item have constituted the basis for limiting and notching. The development of force gages suitable for measurement of the interface forces between the shaker and test item in vibration tests has made the measurement and limiting of the shaker forces in vibration tests an attractive alternative or complement to acceleration response limiting (NASA-HDBK-7004, Force Limited Vibration Testing).

6. TEST PROGRAM

Here, the term test program refers to the strategy for testing all of the hardware associated with a given spaceflight program, whereas the term test plan, discussed in section 7 in this Handbook, refers to the plan for testing a specific hardware item, such as the flight spacecraft. The term test procedure, which refers to the detailed steps of conducting the test, is discussed in section 8 in this Handbook.

6.1 Test Requirements

The first step in putting together a dynamics test program for a new spaceflight project is to assemble the requirements, some of which may flow down from external organizations. For example, there may be requirements imposed by the NASA Center responsible for the launch, from the launch vehicle contractor, or from the spacecraft provider. For NASA programs, general payload test requirements are specified in NASA-STD-7002. More specific requirements for vibroacoustic testing and for pyroshock testing are specified in NASA-STD-7001 and NASA-STD-7003, respectively. Requirements for structural qualification are specified in NASA-STD-5001, Structural Design and Test Factors of Safety for Space Flight Hardware, and requirements for modal survey testing and mathematical model verification are specified in NASA-STD-5002, Load Analysis of Spacecraft and Payloads. Some of these requirements may be difficult to change, but most of them may be negotiated, and they should always be scrutinized to make sure that they are applicable and the best approach for the subject system. Often, each organization has its own institutional test requirements; MSFC-STD-3676, Development of Vibroacoustic and Shock Design and Test Criteria, is one example of such. These particular test requirements may depend on the risk category of the mission or ultimately on the customer. In the past, these requirements were often contained in various standards, and compliance with the standards was mandatory. Now, there tends to be more flexibility and a willingness to let projects tailor the testing requirements to the needs of the specific mission. In the case of commercial spacecraft, the insurers often set the test requirements; however, NASA is self-insured.

6.2 Requirements Flowdown

In addition to external and institutional requirements, there is the logical requirement that subsequent tests should be more benign than the ones that preceded it, so that the early tests are a proof or masking test. For example, tests conducted on the flight structure are usually at lower test levels than those conducted earlier on a qualification structure. Similarly, the tests at higher levels of assembly are usually at lower test levels than those conducted on the units/components.

Finding problems through testing at lower levels of assembly is usually more cost and schedule effective than finding them later. Additionally, testing at the assembly or subsystem build level is generally more effective at finding some types of failures than is testing at the spacecraft build level. For instance, workmanship failures in electronics boxes are most effectively found at the component build level, whereas failures in interconnections, i.e., cabling, plumbing, can be found only in subsystem- or system-level testing. Pre-test and post-test functional checks and inspections can usually be performed much more thoroughly at lower levels of assembly. The verification flow should ensure that testing is conducted at levels of assembly at which specific failure modes can be checked. Testing typically starts with screening tests by the piece part vendor and then proceeds to component-level (electronics boxes) qualification and workmanship testing; this is sometimes followed by subsystem qualification/workmanship testing before system-level testing. The system-level test program may be influenced by the thoroughness of the test program at the lower levels of assembly.

6.3 Roles of Test and Analysis

In dynamic environments, the roles of testing and analysis are complementary. The most important role of testing is to find the unexpected, new things that were not considered or that cannot be predicted accurately by analysis; whereas, the role of analysis usually involves quantifying phenomena that are already known, investigating conditions that are difficult to simulate in a ground test, or running trade studies. The ideal situation is the cradle-to-grave approach in which the same personnel are involved in the design, analysis, and testing of the hardware. Then, the iteration between these three functions happens naturally and automatically. This interplay between test and analysis is illustrated nicely in a study of the flight forces measured on the Gamma-ray Large Area Space Telescope (GLAST) spacecraft (Gordon and Kaufman, 2009) (NESC-RP-06-071, Flight Force Measurements (FFMs) of the Gamma-Ray Large Area Space Telescope (GLAST)/Delta II Flight).

The analysis of a new design necessarily will involve some assumptions, the validity of which is best checked by test. Conversely, a good test usually produces some surprises, which need to be analyzed and explained. Unfortunately, in large organizations, the testing and the analysis functions are sometimes carried out by different personnel, who are often in different parts of the organization. The complexity of FEM codes, of laboratory equipment, and of software has also contributed greatly to this specialization. This division of labor places a burden on the project to develop a plan with integrated design, test, and analysis efforts. Fortunately, some of the new software packages now available to spacecraft providers address these three disciplines, as well as data management. If feasible, dynamic environments meetings for a project should involve people with experience and responsibility in each of these disciplines.

Analysis is generally more suited to the design phase of a program, and testing more suited to the integration phase. With the increasing emphases on reducing cost and schedule and on moving the engineering effort forward in the design and build process, one is often forced to rely completely on analysis in the early stages of a project. For new technology, however, the project should strive to increase the amount of developmental testing early in the program. A skilled analyst can usually predict the dynamic response of conventional designs with reasonable accuracy, but the prediction of the response of a new configuration should always be questioned and compared with test data, and dynamics-related failures are still very difficult to predict. The airbag drop tests conducted by JPL in the MER program are an example of a case in which the high loads, low margins, and many unknowns dictated that a comprehensive test program be conducted to define the appropriate structural loads for subsequent system testing (Coleman and Davis, 2004). Once the flight hardware is available, testing is generally accepted as being more appropriate for verification and validation, although even then there is a tendency to push for more verification by analysis, because testing can be very expensive and ties up the hardware. One cannot overstate the value of pre-test and post-test analysis. Since testing tends to be expensive, it is important to use analysis to plan the tests carefully so that they may be conducted intelligently and efficiently. After the tests, analysis should be used to explain the test results and then, if possible, to extend the results to other loading configurations.

6.4 Baseline Test Requirements

A set of baseline dynamic tests should be defined at the beginning of each program. The system-level dynamics test program should be integrated with the design and analysis work, the static test plan, and the plan for dynamics testing at lower levels of assembly, so that the complete package minimizes the risk of flight failure. One seeks to avoid having to expand the dynamics testing program later as a result of increased loads or questions raised in reviews or, alternately, having to descope the testing program later because of funding, schedule, or facility availability problems. The baseline program should include sufficient testing to satisfy the requirements for qualification (validation) of the ability of the system to withstand the flight dynamic loads, workmanship tests with levels sufficient to identify manufacturing and assembly problems, and verification of models used to predict responses to loads and environments that cannot be adequately or reasonably simulated in a test. (The dynamics of a large inflatable boom in a 0-gravity environment is an example of the latter.) The number and type of system dynamic environments tests included in the baseline program will depend on the culture of the institution, the risk category of the mission, the heritage of the spacecraft, the severity and nature of the flight environment, the amount and credibility of the dynamics analyses, facility and hardware availability, and of course, cost and schedule constraints.

The baseline dynamic test requirements for a spacecraft should include an acoustic test, because acoustic tests are relatively safe for the hardware and low cost, while providing some degree of qualification and workmanship testing of the assembled flight spacecraft. (See section 5.2 in this Handbook.) Shock tests of the assembled spacecraft should be performed, i.e., activation of the device that separates the launch vehicle from the spacecraft and other pyrotechnically activated devices to verify that these devices function properly and do not cause shock-induced failure in any other flight systems. Some type of modal test is required to tune and verify the accuracy of the analytical models used to predict the response of the spacecraft to the low-frequency flight loads. A vibration test with the spacecraft mounted on a shaker is required to qualify the spacecraft for the low- to mid-frequency dynamic loads and to complete the workmanship dynamic testing. Sometimes, the flight environment involves special loads and operations, which should also be addressed in the baseline test plan. Some examples of these are:

- Microphonics, i.e., in-flight vibration of sensitive instruments excited by spacecraft rotating machinery, such as reaction wheels and pumps, articulating optical devices, etc.

- Landing loads, such as those that dominated the structural loading of the Mars Landers (Coleman and Davis, 2004).

- Thermal snap of large structures, such as the Hubble Space Telescope solar panels (Massachusetts Institute of Technology, 2001).

Ideally, the dynamics test program would include a complete set of system build-level tests of each of the aforementioned types, as well as a comprehensive dynamics analysis and test program at lower levels of assembly to minimize the risk of flight failures. However, budget constraints often force the project to make some compromises in the test program, and those compromises may involve downsizing or even elimination of one or more of these types of dynamics tests. Hopefully the compromises are limited to only tailoring of the test details and options or possibly combining one or more of these tests, as discussed in sections 6.5 and 6.6 in this Handbook.

6.5 Test Options and Trades

The test options and trades discussed here are those that will have a significant impact on the scope (the cost and schedule) of the testing program and, of course, on the degree of risk that the project is willing to assume. Other sections of this Handbook discuss details of the individual tests, such as the test levels, frequency range, test item configuration, fixturing, limiting, and pre- and post-test analysis, which are also important considerations in mitigating the risk of test and flight failures but generally are secondary to defining the overall scope of the dynamics test program.

6.5.1 Qualification by Analysis

Since the primary reason for dynamics testing at the system build level is usually to check for workmanship and interface problems, both of which are very difficult to predict, it is seldom justified to substitute analysis for a system-level dynamics test. However, since extensive analysis is often cited as one of the factors in a decision to not conduct a system-level vibration test, some of the considerations involved in the decision to qualify a structure by analysis are reviewed here. If the structure is qualified by analysis, a higher margin of safety is required, but a higher margin alone generally is not sufficient justification for qualification by analysis (NASA-STD-5002). The following are some other considerations:

- Is the structure simple to analyze?

- Has the analytical model been validated?

- Has the structure (or have the substructures) been previously tested to the current specification?

6.5.2 Dynamics Testing at Lower Levels of Assembly

A comprehensive dynamics test program often involves testing at least three levels of assembly: components, subsystems, and system. However, the amount of testing at each level of assembly varies from organization to organization, program to program, and subsystem to subsystem.

Advantages of testing at lower levels of assembly are as follows:

- It is prudent to test before accepting delivery from a supplier.

- A more thorough workmanship screen can generally be performed at lower levels of assembly.

- Post-test inspections are easier and more thorough than at higher levels of assembly.

- Most importantly, there is more time to diagnose and fix problems found in tests at lower levels of assembly.

On the other hand, system-level tests are usually more realistic and less prone to overtesting and provide the confidence that can be attained only by end-to-end testing. Sometimes, however, the complete system, e.g., a spacecraft bus and a telescope, is too big to be dynamically tested at any available facility, and it is necessary to test subsystems separately before they are mated. Whenever possible, subsystem testing in lieu of system testing should be reserved for cases in which the subsystem mechanical and electrical interfaces are simple and relatively easy to analyze.

Typically, all components are tested using a random vibration and sometimes a sine vibration excitation, unless this is not practical, such as for electrical cables, propulsion lines, waveguides, and blankets. Often times, a sample section of these types of assemblies is vibration tested at qualification test levels to provide confidence in its survivability. Structural verification may be performed on larger components, particularly those with resonances below ~100 Hz, if the component random or sine vibration test does not achieve specified test loads. Testing may be by sine burst, sine dwell or sweep, or static load.

Acoustic and shock testing at the component build level is performed selectively. Acoustic testing is usually reserved for large, low-surface-density components and subsystems, such as solar arrays, antennas, and reflectors. Pyroshock simulation testing is usually reserved for components containing known shock-sensitive parts or for cases in which particularly severe pyroshocks are predicted for the assembly (NASA-STD-7003). Some aerospace organizations routinely defer assembly shock testing to the spacecraft build-level pyrotechnic device firings if the predicted shock levels are considered moderate. This is often because of the lack of in-house shock simulation facilities and the concern that simulated shock tests may induce unrealistic failures. Multiple firings at the spacecraft build level are used to cover variability of the shock-producing devices. However, since spacecraft pyrotechnic firings do not provide qualification-level margin, the shock sensitivity and test heritage of component parts should be assessed before making the decision to omit component build-level shock testing (NASA-STD-7003).

6.5.3 Static Testing

Another reason sometimes cited for not doing a system-level dynamics test is that the primary structure has been previously qualified with static testing. The qualification of primary structure should not be left until the system-level dynamics test. Sometimes, however, in the interest of cost or because of a last-minute increase in loads, it is decided to use a sine burst vibration test of the flight spacecraft to supplement or replace static testing conducted on a DTM structure or on the primary flight structure before the equipment is added; this is not recommended. (See section 5.2.1.3 in this Handbook.) System-level sine and random vibration tests generally provide a more realistic dynamics test of secondary structures, such as booms, struts, telescopes, and interfaces, which are not tested or do not have the right boundary conditions and mode shapes in a static test. Thus, the system-level dynamics test provides some level of structural qualification, particularly in the case of secondary structure and interfaces, in addition to workmanship verification.

6.5.4 Development Test Model

One important decision is whether to build a mechanical DTM, sometimes called a structural test model (STM). Related to this decision is the fidelity that should be required of the model. A DTM consists of some or all of the primary spacecraft structure with components and subsystems replicated with mass mockups, high-fidelity simulators, or an engineering test unit (ETU). The DTM may be built using the flight structure, or a dedicated flight-like structure may be fabricated. The DTM is then exposed to the same dynamic tests as the flight spacecraft to provide additional data on the dynamic behavior of the flight hardware. It is very advantageous to have a DTM available early in the program for static, modal, vibration, and acoustic testing to identify problems and to help refine the test levels for the subsequent instrument and flight spacecraft dynamics tests. (See Appendix A in this Handbook.) However, it should be noted that, although an STM consisting of flight or flight-like primary structure and mass mockups for electromechanical hardware may be highly beneficial for static and modal testing and useful as a vibration test precursor, it may give misleading results for higher frequency acoustic and pyroshock testing (Hughes and McNelis, 1998).

6.5.5 Facility Selection

Often, the choices regarding which system dynamics tests to conduct and how to conduct them are limited by the availability and suitability of the spacecraft manufacturer’s facilities, as it is often difficult, cost and schedule prohibitive, and potentially risky to transport a flight spacecraft. Some obvious facility requirements are availability, cleanliness, access, size, weight, handling, and test level capability. In the case of stinger modal testing, it is desirable to fix the test item to a large inertial mass or, in other cases, to freely suspend the test item. Often, however, such facilities are not available, and some compromises must be made, such as locking down the slip table of a large shaker to approximately fix the base of the spacecraft. Almost every spacecraft test program includes an acoustic test, but an important decision is whether the acoustic test is conducted in a fixed reverberant chamber or with portable electronic speakers in a convenient location. (See section 5.1.2 in this Handbook.) Often, this decision hinges on the availability of a reverberant chamber, but cost, the risks of moving the spacecraft, and the advantages of combining tests (discussed section 6.7 in this Handbook) are also important considerations.

6.5.6 Shock Tests

Some of the important options in system shock testing include the following:

- Should the thermal and/or vacuum environment be simulated? The impact of temperature and vacuum on the pyroshock levels generated has not been extensively studied; however, air versus vacuum and extreme temperature can affect separations and deployments, and their impacts need to be considered.

- Should the flight electronics be used to initiate firings? System-level test firings provide an opportunity to verify the operation of the pyrotechnic subsystem, including the flight firing circuitry (NASA-STD-7003). Wiring errors in flight firing circuitry have been found as a result of system-level test firings.

- How many times should each device be fired? It is recommended to fire pyrotechnic devices more than once to obtain some flight firing-to-firing magnitude variation data for statistical verification of component shock requirements (NASA-STD-7003).

- Should the spacecraft electronics be powered on or off during the test? It is recommended that spacecraft electronics be in the operational mode applicable to the flight pyrotechnic event and that powered-on electronics be monitored to detect intermittents (NASA-STD-7003).

6.5.7 Number of Axes of Vibration Test

Ideally, a base-drive vibration test should be conducted in three mutually perpendicular axes. Only a few vibration test facilities are capable of simultaneous vibration in three axes, so the tests in different axes are usually performed sequentially. Therefore, the decision regarding how many axes to test can have a significant impact on the schedule, since testing in each axis can take anywhere from a couple of days to a week or more to complete. Testing almost always includes the vertical axis, since the spacecraft is usually relatively stiff in the vertical direction, so that more high-frequency response can be generated by excitation in this axis. Occasionally, however, it is decided to do only one lateral axis, in addition to the vertical one. This is sometimes justified by performing the lateral axis test at a 45-deg angle to the two principal lateral axes to induce excitation in both axes with one test. The decision to limit the number of axes of test should be evaluated based on pre-test analysis to demonstrate that the goals of the vibration test can be achieved by testing in less than three axes. In addition, the schedule and cost savings of doing an abbreviated vibration test should be weighed against the risk of failing to uncover a hardware problem in ground test. Some experimentation has been conducted with simultaneous multi-axis testing, but there is not sufficient information in the literature to indicate that this technology has advanced to the state where it can be used on flight spacecraft.

6.6 Force Gages

In the 1980s, the advent of compact, stiff, triaxial piezoelectric force gages, which can be conveniently sandwiched between the shaker and vibration test item and which use essentially the same signal processing as piezoelectric accelerometers, has made the measurement of the force between the shaker and test item relatively easy to implement. The capability to measure and limit the shaker force is a powerful tool for reducing the complexity of vibration tests and for minimizing the risk of overtesting. The decision as to whether to use force gages in a system vibration test might be left to the detailed planning, but it is mentioned here because the decision to use force limiting necessitates some early planning related to securing the gages and designing the fixturing to accommodate the gages, as discussed in section 7.4 in this Handbook. The possible configurations, installation, and calibration of force gages in vibration tests are discussed in detail in NASA-HDBK-7004. As described in NASA-HDBK-7004, it is recommended that the force gage installation be calibrated in situ during the low-level vibration tests by comparing the frequency spectrum of total force measured by the gages to the product of the total mass of the test item times the input acceleration spectrum at a frequency well below that of the fundamental resonance frequency of the test item. Without in-situ calibration, there is a risk of overtesting by as much as 20 percent, since the force gages may be reading as little as 80 percent of the load (NASA-HDBK-7004).

In addition to facilitating force limiting, the use of force gages between the shaker and test item also provides means for measuring the quasi-static loads, i.e., the acceleration of the CG of the test item, which is an important design parameter for spacecraft. It is very difficult to use accelerometers to measure the acceleration of the CG in a vibration test, because, when the structure flexes, the CG moves away from the static CG and is at a different location for every vibration mode. However, the acceleration of the CG of the test item may be obtained by dividing the external force by the total mass of the test item. The CG acceleration may also be approximated by weighting the responses of an array of accelerometers by an appropriate mass, which must be determined with an FE model (Gregory et al., 1986) (Blelloch et al., 2012.)

The measurement of the base reaction forces is also the key to the combining of dynamics tests discussed in section 6.7 in this Handbook. Finally, the measurement of shaker force also provides means of measuring the effective modal mass in base-drive modal vibration tests. The effective modal mass is a very important parameter in the reconciliation of modal models and test data, as discussed in section 9.4 in this Handbook (Wada et al., 1972). It is difficult, if not impossible, to measure the effective modal masses without the measurement of forces. The use of force gages and force limiting in vibration tests is discussed in detail in NASA-HDBK-7004.

6.7 Combining Tests

Sometimes, various types of dynamics tests may be combined with considerable savings of schedule, cost, and handling risk. For example, in the Quick Scatterometer (QuikSCAT) project described in Appendix B in this Handbook, the quasi-static loads test, modal frequency identification test, random vibration test, and an acoustic test were all conducted in the space of approximately 1 week with the spacecraft mounted on a shaker in the vibration test cell (Vujcich and Scharton, 1999) (Scharton et al., October 1999). This saved at least a month of schedule compared to a test campaign involving separate static, modal, vibration, and acoustic tests. The short schedule of the QuikSCAT project, 1 year from contract initiation to launch readiness, would not accommodate the schedule for conducting four separate tests, and combining these tests provided an acceptable baseline dynamics test program.

The enabling factor in combining the three vibration tests in the QuikSCAT project was the measurement of the dynamic forces exerted on the test item by the shaker. The force gages provided the quasi-static loads achieved in a transient vibration test, the effective modal masses in a base-drive modal test, and the force limiting in a random vibration test. In addition, with the spacecraft still on the shaker, a DFAT was conducted using portable speakers and electronics provided by a concert sound system contractor.

There is no question that combining the dynamics tests somewhat compromises the accuracy and utility of the individualized tests. A comprehensive stinger-drive, fixed-base vibration test program will provide higher quality modal data for verifying the analytical model than a base-drive vibration test, since the sole objective of the former is to obtain modal data. Similarly, a complete static loads test campaign conducted on an STM or on the primary structure of a spacecraft before the equipment is added will provide better verification of the strength capability of the spacecraft than will a transient vibration test of the built-up spacecraft. However, technical compromises are sometimes necessary to meet the program budget and/or schedule, as was the case in the 1-year duration QuikSCAT project.

6.8 Test Specifications, Margins, Test Levels

The starting point for the test engineer is often a test specification, which may have been provided by someone else responsible for planning the complete design and test program for the system and its constituent parts. The design specifications for most systems include a specification based on the dynamics tests that are planned. The level of the dynamic loads in the test specification is generally lower than that of the design specification but higher than that for the loads predicted for the flight environment. (Exceptions are acceptance, workmanship, and re-work tests; see sections 4.1 and 9.3 of this Handbook.) The flight environment predictions are generally developed using statistical approaches. The Flight Acceptance (FA) acceleration and/or SPL levels are an envelope of the MEFL. The ratios of the design and test levels to the FA level, often expressed in dB, are called margins. For example, for random vibration or acoustic tests, a typical value of the protoflight test margin might be 1.4, i.e., 3 dB, while the test margin for swept sine or sine burst testing is typically 1.2 to 1.25 over the FA level. The amount of margin depends on many factors, such as the institution, the purpose of the test, the consequences of failing the test, and the degree of confidence in the flight predictions.

The duration of the test is dependent on whether the test is intended to demonstrate acceptance or qualification of the hardware. While the duration of an acceptance test is intended to reflect the duration of the flight event being simulated, the duration of a qualification test is typically increased by a factor of 2 over an acceptance test, as the purpose of the qualification test is to demonstrate fatigue-life capability against planned ground testing and exposure to the flight environment. A 60-sec random acceptance test is increased to 120 sec for qualification. In the case of swept sine testing, the sweep rate is reduced by half for qualification, i.e., from 4 octave/min to 2 octave/min. It should be noted that protoflight testing, which is used to qualify hardware that will eventually fly, uses qualification test margins but maintains test durations associated with acceptance testing to limit the impact on hardware life.

Structural design and test factors of safety are discussed in NASA-STD-5001; vibroacoustic test criteria and margins are discussed in NASA-STD-7001; and pyroshock test criteria and margins are discussed in NASA-STD-7003. State-of-the-art methodologies for developing design and test criteria are summarized in NASA-HDBK-7005. Note that the 1-min acceptance test duration discussed in the previous paragraph envelopes the test duration that would be derived for most current launch vehicles in accordance with the methods of NASA-HDBK-7005, which uses a factor of 4 times the maximum equivalent flight duration for fatigue considerations.

Test specifications for random and swept sine vibration tests and for acoustic tests should generally be relatively smooth functions of frequency. Avoid the temptation to follow a complex frequency pattern, e.g., one associated with a time history recorded for a particular flight or a complex FRF predicted by a FEM code. A study of force and acceleration data measured in flight on the GLAST spacecraft showed that, for the purpose of defining vibration test specifications, smoothed averaged specifications of both the interface acceleration and force are basically equivalent to a detailed frequency description of the acceleration for a particular configuration and event (Gordon et al., 2009). It is also good to be open to negotiation in the case of flow-down specifications, so that the specification may be adjusted if pre-test analyses or preliminary tests with a mass simulator or with low-level inputs show that the project would be better served by modifying the test inputs. While it is not good to be excessively conservative in setting the specification at the beginning of a program, it is usually better (less disruptive) to reduce the test levels later than it is to increase them.

6.9 Risks: Test Safety, Flight Failure, and Cost/Schedule

The three greatest safety risks to the flight hardware during dynamic testing are damage resulting from overtesting associated with the unrealistic impedance or shakers, damage caused by the facility malfunction or operation error, and handling damage. (Of course, there is also the risk that the hardware will fail the vibration test because it is not adequately designed or fabricated to pass the test. This risk can be minimized by testing at lower levels of assembly and by pre-test analysis.) Overrunning of the program cost and schedule are, of course, also risks that are very important to the program, since a project may be descoped or even canceled because of a cost and/or schedule overrun. The risks of damaging the hardware during the test and then perhaps overrunning the cost and schedule have to be balanced against the risk of a flight failure related to the dynamic environment or to a workmanship problem.

7. TEST PLANNING

The first step in preparing the test plan for a dynamics test is to ask some questions, such as:

- Why are we doing this test?
- How does it fit into the overall structural qualification plan?
- What do we expect to learn from this specific test?
- How will the test data be used and reported?
- What are the types of test failures that one might anticipate, and what would be the consequences of these failures?

Since dynamics tests usually involve some risks, one of the first aspects of test planning is to address the subjects related to test safety.

- Are the test levels in the specification appropriate? How do they compare with the design limits of the hardware to be tested?
- Are facility conditions, test equipment, instrumentation, and test configuration in compliance with the approved project Quality Assurance Plan?
- What test methods, test levels, examinations, and inspections are appropriate for qualifying the test facility, test support equipment, test fixturing, and instrumentation before the test?
- Are there temperature or temperature gradient, humidity,electrostatic discharge (ESD), or unusual cleanliness constraints on the test item during the test?
- Is the hardware configuration complete, or are some items missing or represented by simulators?
- Have all the required inspections, examinations, and other testing specified in the project Quality Assurance Plan been conducted before conducting the dynamics testing?
- Does the test plan include the required inspection, examination, and functional testing of the test item during and after the dynamics testing program?

Some other important test planning considerations for a dynamics test are test margins, schedule, pre-test analysis, personnel qualification, fixtures, verifiable instrumentation configuration, force limiting, and the facility capability, e.g., shaker force, displacement, and velocity limits, size, access, crane capacity, cleanliness, security, and availability. The content and order of the test plan will vary somewhat with the individual and organization preparing it, but one option is to use an outline based on the following subsections.

7.1 Hardware Definition

The first item discussed in the test plan is usually the test item(s). The extent and configuration of the system test hardware have to be defined. The details of the system test configuration will depend on the availability of the subsystems and their schedule for integration into the system.

- Will the system to be tested consist entirely of flight hardware, some engineering models, mass simulators, or a combination of these? (See DTM in section 6.5 in this Handbook.)
- Will any items be missing?
- Will flight-like boundary conditions be simulated?
- Will the launch vehicle PAF be used?
- Will the propellant tanks be empty, filled, or mass simulated?
- Will the spacecraft be powered in the launch configuration?

Usually, the test plan will include drawings, solid model pictures, or photos of the test hardware showing the major components and interfaces. All of the coordinate system(s) and relationships between them should also be defined in the test plan.

7.1.1 Wet versus Dry Vibration Testing

One of the major configuration questions regarding spacecraft vibration testing is whether the mass of the propellant needs to be represented for the test. The decision to perform spacecraft-level vibration testing with empty, filled, or mass-simulated tanks has to be evaluated against the goals of the test. The purpose of most spacecraft-level vibration testing is to expose the flight hardware to the most accurate representation of the flight environment with appropriate test factors to verify that the system will function as expected after exposure. To get the most flight-like dynamic response from the spacecraft, the hardware should be in the most flight-like configuration possible. This would lead to the conclusion that the mass of the propellant should be present during spacecraft vibration testing. However, there are many issues that would prevent spacecraft testing from being performed with mass-loaded tanks. The safety risks associated with using actual propellant are far too great so that this is very rarely if ever done.

One option for mass loading of the propulsion tanks for vibration testing is to use a referee fluid that simulates the behavior of the tanks with a flight-like propellant load. When selecting a referee fluid, consideration should be given to the impact on the test flow and compatibility with the spacecraft propulsion system. For example, distilled water and isopropyl alcohol (IPA) are two commonly used referee fluids for simulating propellant during vibration testing. IPA can pose significant safety risks as a flammable liquid, should the system develop a leak, so using IPA as a referee fluid can significantly increase the complexity and cost associated with the test to address these risks. Water does not have the safety issues associated with IPA but can be a problem because of the time and effort involved with drying out tanks and piping after completion of the test. Also, depending on the design of the propulsion system, it may not be possible to get the system fully dry if water is used to mass load the tanks. Bolt-on mass dummies that simulate the weight of the propellant are another option that can be used for vibration testing, but these have to be considered early in the design phase to provide the necessary mounting interfaces. In some cases, it may be impossible to locate mass simulators to adequately simulate the propellant loading once the spacecraft has been fully configured.

The decision to test without the mass of the propellant or with reduced propellant or simulated mass during a spacecraft vibration test should be based on assessment of the impact that the missing propellant mass has on the dynamic behavior of the spacecraft. Typically, this is only an issue for base-drive vibration testing, which simulates the low-frequency launch environment and drives the bigger mass modes of the spacecraft. Acoustic and shock testing, which cover the high-frequency launch environment and cause more localized hardware responses, can usually be performed in the dry configuration. However, it needs to be verified that components mounted nearby will not experience excessive acoustic test-induced random vibration environments related to the lesser mass loading provided by empty tanks. Analysis, which simulates the planned vibration test and compares the responses at various locations on the spacecraft with and without propellant mass, should be used to determine how the missing mass affects the dynamic response of the test article. One of the primary issues to be addressed is whether critical areas of the spacecraft will see sufficient excitation in a dry configuration to demonstrate qualification for the low-frequency launch environment. Another issue to address is how the empty propellant tank responds in the test. The loaded propellant tank may have modes in the test range and dynamically respond to the test input, whereas that same tank without the fuel mass may not respond at all during the test. Of critical importance is verification that the propellant lines that run between the tank and the spacecraft will see sufficient dynamic deflection to screen for design and workmanshiphenp defects under flight-like loading conditions. Finally, the tank itself should be evaluated to ensure that it can handle the dynamic test environments in a dry configuration without damage.

Once the limitations associated with vibration testing of the spacecraft in a dry configuration have been identified, they can be weighed against the test and program risks associated with performing the test with a simulated propellant mass to determine the appropriate test configuration. In some cases, it may be possible to augment the dry vibration test with additional testing at lower levels of assembly, to perform targeted stinger-drive testing on the spacecraft, or to increase the vibration input in certain frequency bands to achieve more flight-like dynamic responses in critical areas of the hardware.

7.1.2 Test Boundary Conditions

Another consideration regarding the configuration of the spacecraft during dynamic testing relates to the boundary conditions and the interface hardware that should be used during the test. A base-drive vibration test requires that the spacecraft be supported at the launch vehicle interface during the test. Acoustic testing is typically performed with the spacecraft attached to a dolly or support structure at the flight interface, although in some cases the test article may also be hung in the test chamber. Separation shock testing is usually performed by lifting the spacecraft, firing the separation system, and allowing the launch vehicle PAF to drop a short distance onto foam, although the shock test may also be performed while the spacecraft is attached to the same test support structure used for acoustic testing by counterbalancing the weight of the spacecraft with a crane or pulley system attached to the top of the spacecraft.

The general baseline for all dynamic tesing is to use, if at all possible, a flight-like PAF and flight-like separation system as the test boundary condition. A test version of the PAF and separation system is usually provided by the launch vehicle organization to serve as the test interface, although the actual flight systems may be used in some cases. The purpose of this approach is twofold: the first is to ensure that the flexibility of the separation system and PAF will be accurately represented in the test; the second is to expose the separation system to dynamic loading and verify that the system will separate without any issues. For this reason, it is typical to perform dynamic testing (vibration and acoustic) with a test PAF and separation system provided by the launch vehicle and then to perform shock testing by actuating the separation system after testing is complete. This not only provides a shock exposure to the spacecraft but also demonstrates that the separation system will operate as expected after dynamic exposure. It is difficult to expose the separation system and PAF to flight-like dynamic loading with the correct boundary conditions in an off-line test, so having this hardware present during spacecraft-level dynamic testing provides the final “test as you fly” opportunity. If a loads isolation system is being flown in line with the load path of the spacecraft, PAF, and separation system, this should also be included in the test configuration if possible.

While it may seem that the decision to use the PAF and separation system is relatively straightforward, some issues should be taken into consideration. The first is scheduling. The test schedule should be coordinated with the launch vehicle organization to ensure that the hardware and necessary personnel are available to support the test. Launch vehicle personnel are typically required to perform installation of the PAF and separation system before the start of testing. In some cases, they may also be present for the duration of the dynamic test campaign to periodically monitor the status of the hardware, e.g., check clamp-band tension. Launch vehicle personnel should also be available after dynamic testing is complete to support the actuation of the separation system and de-integrate the hardware. Another issue that should be considered is control of the test during a base-drive vibration test. Typically, vibration environments provided by the launch vehicle are defined at the spacecraft separation plane. Including additional hardware, such as the PAF and separation system between the drive location and the location where the test is controlled, can make the test more difficult to run and may require additional control strategies to achieve the correct test levels at the spacecraft interface. Regardless of the control strategy used for the test, it is always recommended to include in the test setup a force measurement system that can directly measure the interface loads develped during the test to prevent unrealistically high interface forces and to protect the hardware from damage. If, in the end after all factors have been weighed, it is not feasible to include a flight-like PAF and separation system as the interface for dynamic testing, then additional testing of the PAF and separation system with a spacecraft simulator should be considered to adequately qualify the hardware for the dynamic launch enviroment and to ensure that dynamic interactions between the PAF, separation system, and spacecaft have been adequately accounted for in spacecraft-level testing.

In some cases, it may be acceptable to perform vibration testing without a flight-like PAF and separation system. If the PAF, separation system, and spacecraft interface have flight heritage, i.e., that these systems have been tested and flown together on previous missions, and the expected dynamic loading conditions are consistent with previous environments, then it becomes less critical that a flight-like system be used during the test and actuated after vibration exposure. This allows hardware developed by the spacecraft organization to be used as the test interface during dynamic testing and removes the scheduling issues associated with using hardware supplied by the launch vehicle provider. Separation shock testing will still need to be performed with the flight or test separation system and PAF, but this can be accomplished independently from the spacecraft dynamic test flow. Even if a flight-like PAF and separation system is not used for dynamic testing, it is still desirable to have the interface hardware replicate the stiffness of the PAF and separation system to provide the proper boundary conditions for the spacecraft during vibration testing. In many cases, a dedicated test clamp band and structural ring that mimics the stiffness of the upper portion of the PAF is used.

7.2 Facility

The test facilities should be identified in the test program and specifically described in the test plan. Should the testing be conducted in house or at another facility? Usually, it does not make sense to move a spacecraft to an outside facility for a single test, given the handling risks, quality assurance issues, and the impact on schedule. The facility selected should have the capability to safely implement the test specification and meet the cleanliness, handling, and other test requirements. This is often a challenge. However, the safety of the hardware is the one thing that should not be compromised. It is a good idea to inquire about the recent use of the facility and the test equipment for conducting similar dynamics tests of similar hardware, i.e., similar type of test and excitation, and similar test item size and weight. Also, it is appropriate to inquire about the staffing and work schedule for the test and to ask about the experience of the specific operators in conducting similar tests.

It is also important and required that the test facility have in place a quality system that shows that the facility is capable of performing a specific type of dynamics test, that it is proficient at performing this type of test, and how it handles deviations and departures from specified and approved test plan configuration and tests nonconformances.

7.3 Instrumentation

Instrumentation is discussed briefly here, as well as in section 8 in this Handbook, because the instrumentation should be described in the test plan and also because it is often necessary to install some of the instrumentation well before the test. In addition, some lead time may be required to ensure that all the instrumentation and test equipment have been reserved or acquired, inspected, and calibrated in a timely manner. Accelerometers are the most common instrumentation for structural dynamic tests; these may be of a variety of sizes, sensitivities, frequency ranges, etc., depending on their application. For example, the accelerometers used for modal tests often have very high sensitivity and relatively low-frequency characteristics, whereas those used for shock testing may have low sensitivity and high-frequency response characteristics. Other common types of instrumentation include force gages, strain gages, and microphones for acoustic tests. Often the test item interior instrumentation locations are only accessible for the mounting of accelerometers and strain gages at specific times during the buildup of the test item. For these hard-to-access interior instrumentation locations, a consideration is to add redundant instrumentation in case the primary instrumentation fails during testing and is inaccessible for repair. This instrumentation may be removed after the test if the test item is partially disassembled, or sometimes the cables are cut and the instrumentation is left in place for the flight.

Control instrumentation should be of sufficient quantity and appropriately placed to ensure the integrity and safety of the test. For shaker testing, it should be decided if force gages are to be used to measure the interface force between the shaker and test item; the number and location of the accelerometers and perhaps other force gages to be used for response monitoring and limiting should also be defined. For acoustic tests, the number and location of the monitoring and control microphones will depend on whether it is a reverberant chamber test or a DFAT. Sufficient response instrumentation is required for all vibration, acoustic, and pyrotechnic firing tests to help in diagnosing post-test structural or functional failures and to assess the adequacy of the subsystem- and component-level test programs. Special considerations apply to the measurement of the high test levels and high frequencies associated with pyrotechnic shocks. For example, shock accelerometers located near the source should be attached with bolts rather than with adhesive, and care should be taken to avoid aliasing of the data (IEST-RD-DTE012.2, Handbook for Dynamic Data Acquisition and Analysis). The type and quantity of instrumentation used for modal verification testing varies greatly, depending on the spacecraft configuration, the number of modes of interest, and whether the purpose of the test is merely identification of fundamental frequencies, identification of general mode shapes, or a full modal correlation.

7.4 Fixtures

Base-drive vibration tests usually require one or more special fixtures to mate the test item to the shaker. For example, the test setup for the vertical vibration test of the MER spacecraft, shown in figure 1, had three fixture elements stacked between the white shaker and the grey cylindrical PAF: a conical head expander, a lower ring, and an upper ring, with force gages sandwiched between the two rings. The test setup for the lateral vibration test of the MER DTM Rover, shown in figure 2, had three complex fixtures designed to replicate the three attachments of the Rover to the MER Lander, which was not present in the test.

The fixture should mate with the test item in the same way as the flight interface does, so that the interface load distribution is similar to that in flight. However, the input for a vibration test is usually specified as the acceleration at a rigid interface, so it is also desirable that the fixture behave as a rigid body over the entire frequency range; this requires that the fixture be as light and stiff as practical so that the fundamental resonance of the fixture is above the upper frequency of the test (IEST-RP-DTE047, Design and Use of Shock and Vibration Fixtures). The requirements that the fixture simulate the flight-mounting configuration and also that it be rigid are obviously in conflict, since flight structures are anything but rigid at the higher frequencies. The rigidity of a test fixture may result in an unrealistic distribution of stresses at the fixture and test item interface; this disparity between mechanical impedances of the flight and test mounting structures typically results in a severe problem at the test item resonances as, discussed in section 8.5 in this Handbook. The primary objective of force limiting is to alleviate this source of overtesting.

The vibration fixture configuration and its interfaces to the test item and the vibration source, as well as other ground support equipment, should be defined, fabricated, inspected, fit checked, and proof tested well in advance of the scheduled system vibration test, so that any problems with the fixtures may be addressed and, if necessary, the fixture be redesigned or reworked. If a vibration test fixture has resonances within the test frequency range, in spite of the best efforts to prevent them, some remedial measures should be employed. Damping is sometimes incorporated into the fixture design to reduce the amplitude of fixture resonances. Test controllers notch the input at the fixture resonance frequencies to try to reduce the response of the test item. Also, several accelerometers at different locations on the fixture are often employed for control, and the average or maximum of these accelerations is controlled to the specified acceleration. However, none of these remedies will prevent some points on the fixture at the test item interface from being above or below the specification at the fixture resonance frequencies. Therefore, it may be necessary, in the case of severe fixture resonances, to restrict the test frequency range to frequencies below the fixture resonance rather than endanger the test article.

Acoustic test fixtures often consist of some sort of ground support or handling equipment. In addition to the requirements for adequate support and safe handling, some acoustic test fixture considerations include the following:

- Minimal shielding of the test item.

- Positioning of the test item some distance from the chamber surfaces, i.e., the walls, ceiling, and floor of the chamber, ideally a quarter of an acoustic wavelength away at the frequency of concern, but, in any case, no closer than 1.2 m (4 ft) away.

- Positioning of the test item so that any large planar surfaces are not parallel to the chamber surfaces.

- Provision of acoustic closeout (baffling) to prevent acoustic excitation of regions, e.g., the underside to the PAF, of the test article that are not exposed to high-level excitation in the flight configuration.

If the test item is a large lightweight structure, such as a solar panel or reflector, these acoustic considerations may often be most conveniently honored by suspending the test item, rather than mounting it on a platform. Moreover, the flight supporting structure typically adds damping and stiffness to large lightweight structures; thus, the acoustic test tends to be more conservative when these large lightweight items are suspended.

Shock testing at the spacecraft level may be limited to firing the spacecraft separation devices, and measuring the shock transmission into the spacecraft. For this type of test, the spacecraft attached to the PAF is typically suspended a few centimeters (inches) above a soft pad on the floor; after the devices are fired, the separated PAF falls onto the pad. Confidence that the spacecraft will separate properly in the 0-g environment of space can be gained by taking and studying high-speed videos of the separation. Alternately, in cases where it is desired to simulate the 0-g environment for validation of the flight separation as well as to simulate the shock loading, the spacecraft and PAF sit on the floor with the PAF held down with a fixture on the floor, and the spacecraft is loaded with a spring that counterbalances the spacecraft weight and allows the push-off springs to move the spacecraft up away from the PAF after the separation devices are fired.

In the case of stacked spacecraft, shock testing of the top interface may be conducted with the stack sitting on the PAF, then the top spacecraft lifted off with a crane, and the lower interface shock tested.

Pyrotechnic firing of devices on the spacecraft to actuate separations and deployments may be performed at the system build level or the subsystem build level. These tests are often limited to first motion of the separation or deployment when the primary purpose is for validation of pyrotechnic mechanism functionality and measurement of shock levels induced at nearby equipment. In this case, special fixturing is often not required. Full deployment of solar arrays and other mechanisms may require extensive fixturing to counterbalance the effects of gravity. Full deployments may involve mechanical releases rather than firing of the pyrotechnic devices.

7.5 Schedule

The test plan should include a master schedule of events leading up to the test, a detailed schedule for the conduct of the test, and the test report delivery date. The master schedule shows how the dynamics tests interface with the other integration and test activities. As the integration and test schedule often changes (it usually slips), it is important to keep all the test team members apprised of the schedule changes, so they can plan their activities accordingly. The detailed schedule for the tests should include time for test preparation, fixture qualification, setup, instrumentation installation, inspections, the actual testing, teardown, data analysis, post-test analysis, and reporting. Ideally, the detailed schedule should also include some contingencies for problems that may come up during the testing; these contingencies should also be reflected in the master schedule.

7.6 Test Personnel and Responsibilities

The single most important step in organizing a spacecraft dynamics test is to have one person identified as the test director. It is also very important that everyone understand that the test director is in control of the test and responsible for the spacecraft safety, for the instrumentation, for the test conduct, for data analysis, and often for writing the test report. Obviously, the dynamics test director should have knowledge and experience in structural and environmental dynamics and dynamics testing in particular. All information flow and important decisions have to flow through the test director, and the test director alone interfaces with the test facility personnel who actually run the test and data analysis equipment. The test director gives approval before an actual test run is commenced. The test director ensures that tests are in strict accordance with the approved test plan and verifiable by quality assurance. Also, it is the responsibility of the test director to present and defend the test plan at project and test-readiness reviews and to participate in facility safety surveys and other meetings related to the test.

It is also essential to identify the test structural analyst. (In some cases, but rarely for a spacecraft dynamics test, the test director may also be the cognizant structural analyst.) The structural analyst is responsible for conducting the pre-test analysis and for comparing the responses during the test with the predictions and with the design loads. The test director should obtain the approval of the structural analyst before instructing the test operators to proceed to the next test level or configuration. All of the other interrelationships and responsibilities for the test will depend on the organization of the institution(s) responsible for the spacecraft and for performing the test. The engineering organization responsible for planning the test may have separate groups responsible for structures, environments, hardware, safety, quality, etc. Generally, the test will be conducted in a test laboratory, which may be part of the organization that provides the spacecraft or may be an independent or outside organization. The responsibility of the test laboratory includes facility safety, which means that the shakers and other test systems operate properly and do not malfunction. The test laboratory will also provide personnel to operate the test equipment, to set up and run the instrumentation, and to conduct the data reduction. For example, one large testing organization uses the following staffing for vibration testing: at the console, one test operator, one data acquisition operator, and one test engineer; at the shaker, one test operator who has a shutdown switch and who watches and listens for problems. (Some test laboratories may not allow personnel at the shaker while the test is running.)

7.7 Pre-Test Analysis

Pre-test analysis is one of the most important aspects of test planning. Analysis should be used to define the configuration and boundaries of the test, as well as to provide insight into what to expect and how to deal with it in advance of the actual test. A comprehensive pre-test analysis enables the actual testing to go much faster and more safely, and allows attention during the test to focus on newly discovered problems that could not be anticipated. The most common type of pre-test analysis consists of a simulation of the actual test using numerical models, which may consist of FE models for static, modal and environmental vibration testing and SEA or BEM for acoustic testing. In addition, the pre-test analysis may include some strength of materials calculations of stress (Young and Budynas, 2001), analytical predictions of force limits (NASA-HDBK-7004), and semi-empirical predictions of shock transmission (Dalton et al., 1995).

The pre-test analysis is very important for planning the location of the accelerometers and other instrumentation. If feasible, the test plan should specify the grid points on the FE model where the instrumentation is to be located, so that the pre-test analysis and test data can be correlated. It is essential to have a complete set of predictions of the test item response before beginning a test. As the test proceeds, the measurements are compared with the predictions, and one gets a sense of whether the models and underlying assumptions are valid and whether the model-based predictions of the flight responses and limit loads are accurate or need to be modified. Since the prediction of dynamic response is sensitive to the resonance frequencies and damping values in the model, it is usually very informative to compare the measured and assumed parameter values. (Sometimes, a preliminary estimate of the frequencies and damping of the fundamental fixed-base vibration modes of the test item can be obtained from the tap testing conducted before the start of a base-drive vibration test as part of the data quality checks that are typically performed to verify the instrumentation, cabling, signal conditioners, and data acquisition system computer and software.) Since most analytical models of spacecraft dynamics are linear, it is also important to identify any nonlinearities as the test level is increased in the base-drive test.

7.7.1 Pre-Test Analysis for Low-Frequency Vibration Testing (Sine or Random)

Pre-test analysis for a system-level dynamic test to simulate the low-frequency vibration environment begins with the development of a model, which reflects the test being run and the test configuration. For vibration testing using either sine or random vibration input, a model is typically developed using software based on the FEM, the most common being NASA Structural Analysis (NASTRAN), but other FEM codes such as Abaqus or ANSYS may be used. By the time a spacecraft-level vibration test is run, the overall system model typically will have been through multiple CLA cycles and will most likely have very detailed representations of the spacecraft structure and subsystems. In many cases, the coupled loads model, which represents the flight configuration, will have to be modified to reflect the spacecraft-level test configuration if it is different from flight. For example, many spacecraft-level vibration tests are performed without the fuel present, so the model of the test configuration has to be updated. In a low-frequency sine vibration test, it is also important to ensure that the model has sufficient fidelity to cover the frequency range of the test being run. Typically, the FE model should include modes of the hardware at least up to 1.4 times the highest test frequency. For example, if a sine test is being run to 50 Hz, then, as a minimum, the model should reflect modes of the spacecraft up to 70 Hz to adequately capture any pre-resonant interactions and to account for subsystem modes dropping as they are attached to a flexible interface. This frequency range is consistent with most CLAs with frequency content out to 50 Hz. If the system-level sine vibration test is run to higher frequencies, then the system model will need to have more fidelity than the FE model developed for the CLA. Spacecraft random vibration tests are typically run to higher frequencies than sine tests, and the analytical model may not be accurate at the upper frequencies of the random vibration test. This inaccuracy of the model to predict failure at higher frequencies is one of the justifications given for running a random vibration test to higher frequencies. Clearly, there are some differences in testing philosophy here, but in any case the best available model should be used to guide the testing, and the test levels should be carefully compared to the best estimates of the flight environment.

The first step in performing the pre-test analysis necessary to support a spacecraft-level vibration test is to simulate the test input and compare the response results with the CLA predictions and with hardware design capabilities. The FE model representing the system-level test configuration is analyzed for the test input, and responses at critical locations are recovered. As noted earlier, at the point in the program schedule where the spacecraft is ready for system-level dynamic testing, the spacecraft FEM has usually been through multiple load cycles. It is, therefore, straightforward to derive a loads transformation matrix (LTM) with response quantities for the test configuration, which matches the LTM developed for the CLA. This makes it possible to quickly determine how the planned system-level test compares with the predicted flight loads and the design capability of the hardware. Since the vibration test is intended to simulate the low-frequency launch environment predicted by the CLA, the comparison between flight loads and expected test responses can be used to identify areas in which input notching may be required to prevent overtest.

For loads at the primary interface of the spacecraft, it is very common to include force gages at this interface, typically at the base of the PAF, so that the test can be limited either by manual notching or by extremal control force limiting. In this way, the interface loads do not exceed those predicted by the flight loads analysis with the appropriate test factor applied. For locations on the spacecraft where it is usually not possible to place force gages at a flight interface, i.e., instrument-to-spacecraft interface, response limits are defined so that when a certain acceleration (or strain) response is measured, it can be equated to a certain load in the structure. In this way, the loads in the hardware can be limited so that they will not exceed the predicted flight load level based on coupled loads. In some cases during testing, it may be necessary to let some hardware exceed its predicted flight response to limit the amount of notching done to the test input. For example, if an electronics box has been designed for 30 g but its predicted maximum flight load is 8 g, it may be worthwhile to let the box response hit 15 g so as to not have to reduce the input by 50 percent in that frequency range and undertest other areas of the spacecraft. Pre-test analysis is used to identify critical areas that should be monitored closely during the test and to determine before the test what notching is required in the input spectrum to protect the hardware during the test.

Other important roles of the pre-test analysis are to help define the instrumentation and to select the locations and orientations of the accelerometers. To facilitate comparison of the test data and pre-test analysis, it is recommended that the accelerometers be primarily located at grid points of the FEM and, if feasible, oriented along the FEM local coordinate system axes, as in the MER spacecraft vibration test. (See Appendix B in this Handbook.) Response accelerometers are the most common form of test instrumentation, but other types of response instrumentation may be used, such as strain gages and deflection sensors, such as linear variable differential transformers (LVDTs) or laser vibrometers. In general, sufficient instrumentation should be chosen so that the response of all subsystems may be monitored during the test. Of first importance are all major interfaces such as spacecraft to launch vehicle and spacecraft to major subsystems, e.g., instrument and deployable interfaces (solar array, antennas). It is common to think that this means that the actual interface should be instrumented with accelerometers; however, this is usually not the case. The most important quantity to measure during a dynamic test is the generated force, not the measured acceleration. However, since it is difficult to measure force directly at most locations on the spacecraft, the interface loads need to be inferred based on the measured accelerations and the relationship between acceleration and force derived from the analytical model. This usually requires that an accelerometer be placed at a location of high response during the test, which tends to be located at a point away from the interface. In addition to monitoring loading at critical interfaces, it is also necessary to determine response locations that can be used to compare with flight loads or with subsystem-level tests to ensure that the hardware can be protected against overtest. Finally, it is important to have sufficient accelerometers on the spacecraft so that the inputs to smaller items such as electronics and panel-mounted equipment can be defined. This usually does not require that each box be instrumented separately but rather that central locations, i.e., center of an equipment mounting panel, be instrumented so that the inputs into a number of components can be determined based on these measurements.

Once all of the instrumentation locations have been determined, it is advisable to re-run the pre-test analysis and calculate the predicted response for all instrumentation being used for the test. The results of this pre-test simulation can be very useful to have available during the test for comparison with the measured test responses. The comparison of analysis and test data after the completion of a vibration run is invaluable to determining if the test article is behaving as expected and as a tool to adjust any notching or response limits derived based on the analysis. Along with the pre-test results, before the start of the test, it is advisable to have pre-determined limits for critical response channels based on subsystem testing and design capability of the hardware available. Having these data will allow decisions to be made quickly based on the results from lower level runs as to whether it is safe to proceed to the next level of input and to identify any changes in the control methodology necessary to protect the hardware from damage. The analytical predictions and hardware design/test capability are also the basis for setting the limit and abort accelerometers, which will control the test and will prevent permanent damage to the spacecraft by shutting the test down before a failure can occur. In most cases, the processed response data can be provided electronically to the test structural analyst after the completion of a test run so that the test results and analytical predictions can be overlaid to quickly assess how well the response of the test article matches the analytical prediction.

Ideally, potential test failures should be identified, but not realized, in the test. A failure can often be detected by comparing the responses in low-level test runs to the predicted responses and to the design limits. Then, if there is a problem, the test can be stopped at the lower level and the problem discussed with the test technical specialists and the project, and appropriate modifications or test departures can be identified and approved before test resumption. Stopping a qualification test to discuss interim results or to completely curtail the test before the target test level is achieved usually requires a very convincing argument. As there is usually little or no time to do additional analysis during the test, the decision to stop the test usually has to be justified by comparing the data with the pre-test analysis.

7.7.2. Derivation of Force Limits for Vibration Tests

Force limits are analogous and complementary to the acceleration specifications used in conventional vibration testing. Just as the acceleration specification is the frequency envelope of the flight acceleration at the interface between the test item and flight mounting structure, the force limit is the envelope of the flight total force at that interface. Both the acceleration and force specifications are needed to conduct a force limited vibration test. The derivation of force limits is based primarily on a consideration of the mechanical impedance of the flight mounting structure, specifically on the ratio of the test item mechanical impedance to that of the flight mounting structure. The most common formulation for specifying force limits is the semi-empirical method, in which a constant (C) replaces Q, commonly used to express the amplification at a resonance of the test item (NASA-HDBK-7004). The validity of the semi-empirical method for defining force limits hinges on the accuracy with which C can be determined for the coupled system of interest. It must be emphasized that C depends on the flight mounting structure and test item and not on the shaker system and mounting configuration. NASA HDBK-7004 discusses four approaches to determine the factor C: a simple two-degree-of-freedom (TDOF) model, an equivalent circuit model, flight and ground test data on similar configurations, and FEM analysis of the flight configuration. It is highly recommended that the C value selected for use in the semi-empirical method be justified with at least one of these four techniques. The key parameter in all of these approaches is the mechanical impedance of the flight mounting structure, which should be calculated or measured or, at the very least, estimated.

7.7.3 Predicting the Peak Response in Random Vibration and Acoustic Tests

The pre-test analysis is also useful for defining the force and acceleration limits and the associated abort levels. For a sine test, the peak responses may be directly calculated or measured. However, for a random vibration test, the peak responses should be calculated by multiplying the overall RMS responses by a peak factor. In this regard, it is a common mistake to use too low a peak factor in both random vibration and acoustic tests. A factor of three is traditionally used, but 5-σ peaks have been observed in the input acceleration, the base reaction force, the test item acceleration and strain gage responses, random vibration tests, and also the acoustic pressure and acceleration responses in acoustic tests. It is well known that, even though the shaker input in a random vibration test is often clipped at 3 σ (three times the RMS), the test item responses can exhibit peaks with much higher values of sigma, because the derivatives may not be clipped and also because the response distribution tends back toward a Gaussian distribution. For example, if the structural response is a narrow-band random Gaussian process dominated by a single resonance with light damping at f_n = 100 Hz, the probability distribution of peaks will be governed by the Rayleigh distribution and the probability is then 5 percent that the 4-σ level will be exceeded in 1.5 sec, or the 5-σ level will be exceeded in 134 sec (NASA-HDBK-7005, p.169). (The example in NASA-HDBK-7005 is for 5-percent damping, but the exact value of damping is not important as long as it is light.) Moreover, recent investigations have shown that extreme peaks occur in random vibration tests even more frequently than predicted by the Rayleigh distribution (Scharton et al., 2006). (Five-σ peaks are typically seen in the input roughly 50 percent of the time during a 60-sec random vibration test run.) That extreme peaks occur more frequently is thought to be associated with the fact that, as the bandwidth of a random process increases, the probability of high peaks moves from Rayleigh to

Gaussian and becomes even greater (Lutes and Sarkani, 2003). The presence of these extreme peaks is not greatly affected by filtering or sensitive to the damping of the system, and the peaks have been observed both at the fundamental structural resonances and at higher frequencies (Lutes and Sarkani, 2003). Peaks of even 6 and 7 σ have been observed in tests with rattling or impacting, which increases the kurtosis (widening of the tails) of the probability distribution (Kolaini and Doty, 2007). One might think that only brittle materials are sensitive to extreme peaks at the higher frequencies, but research and data in the literature indicate that, in the frequency range of random vibration testing, the dynamic and static strengths are approximately equal for even relatively ductile materials such as aluminum (Scharton et al., 2006). In view of the foregoing, it is recommended that a multiplier of 5 be used in pre-test analyses and during analysis of data from low-level runs as the multiplier on the predicted RMS response to estimate the maximum responses that will occur in a random vibration or an acoustic test. If there are doubts about what peak factor to use, some time histories should be reviewed to see what peak factors, i.e., the ratios of the observed maximum peaks to the RMS, are evident in the data, and a somewhat higher peak factor than that observed should be assumed.

In conclusion, it should be noted these high peak factors associated with random vibration and acoustic tests may be viewed as a disadvantage, compared with the relative precision of tests with sinusoidal inputs. For this reason, as well as the inherent uncertainities of a random process, sine tests are often preferred for simulating quasi-static loads and for stuctural qualification. In the higher frequency regimes, spacecraft dynamic loads are usually dominated by vibroacoustic and/or stochastic environments, and the adherence to the maxim of “test as you fly” requires random vibration and acoustic testing.

7.7.4 Pre-Test Analysis for Acoustic Testing

Pre-test analysis for acoustic testing at the spacecraft build level is usually more limited in scope than that required for low-frequency base-driven vibration tests. This is primarily because the base-driven tests need to be adjusted to account for the fact that the test fixture impedance does not replicate the impedance of the launch vehicle, as well as the fact that the test input has been synthesized as equivalent sine or random to replicate what is often a transient-type loading from the launch vehicle. On the other hand, acoustic tests are a more accurate representation of an expected flight environment; therefore, the input is not often adjusted based on results of pre-test analysis or lower level runs.

Pre-test analysis is important in acoustic testing to make sure that there is sufficient calibrated instrumentation to be able to quantify the vibration environment at all locations on the spacecraft. The pre-test analysis should identify those areas of concern and have pre-defined limits set for the instrumentation channels so that decisions to proceed or stop the test can be made quickly and efficiently. These data are also necessary, if post-test functional testing uncovers a problem, to understand if the failure was related to the acoustic test levels experienced during the test or to some other cause. Some critical items are solar arrays and other lightly loaded honeycomb panels, dish antennas, and reflectors. In addition, it is important to have accelerometers on the panels supporting instruments and electronic boxes to identify and evaluate inputs to these items in the acoustic test that exceed or may exceed the levels to which the items were tested at lower levels of assembly.

Predicting how the spacecraft will respond during an acoustic test typically involves using software tools based on SEA, BEM, or acoustic FEMs to analytically simulate the test. These software tools have been specifically developed for analyzing how structures respond under acoustic excitation. SEA is typically used to predict the high-frequency response of the structure above ~300 Hz and requires that there be a large number of structural modes in the frequency range of interest to provide accurate predictions. BEM and acoustic FEM analyses capture the response of the hardware based on fluid-structure interaction equations and are typically effective tools for predicting acoustic response in the frequency range below 300 to 400 Hz. Above these frequencies, these tools become very computationally intensive and are limited by the fidelity of the spacecraft FE model as well. A random vibration analysis may also be performed using finite element analysis (FEA) codes, such as NASTRAN, to determine the response of the low-frequency structural modes to acoustic excitation, if these modes are adequately represented in the spacecraft FE model. However, FEM codes require the pressure at the surface of the test item, which is usually not known. In addition, FEM codes assume that the test item is baffled, which is usually not the case for reflectors and dish antennas. (Baffling prevents the pressure wave from diffracting around the test item, thereby reducing the pressure differential.)

7.7.5 Pre-Test Analysis for Shock Testing

Pre-test analysis for shock testing is typically more limited than that for other spacecraft dynamics tests. Typically, the shock pre-test analyses are limited to empirical scaling techniques that evaluate how the shock level attenuates based on distance from the shock source and type of intervening structure. The most common approach for estimating shock attenuation using empirical methods is based on data from testing performed in the early 1970s by Martin-Marietta for NASA (Kacena et al., 1970). However, in some cases, shock pre-test analysis can be performed using data acquired on a similar structure/vehicle in flight or ground test. These data can then be used to estimate attenuation and scale for distance as an independent method to compare with the results calculated using the standard NASA attenuation curves (NASA-STD-7003). While more complex analytical approaches exist to predict structural response to pyrotechnic-shock, such as modal extrapolation methods and SEA, these are not widely used within the aerospace industry because of their complexity and lack of accuracy. It is also very difficult to analytically predict failure modes and allowables for spacecraft hardware against a given shock environment; therefore, shock pre-test analysis is primarily limited to identifying shock-sensitive hardware and ensuring that these items have been qualified with margin for the expected shock levels before actually firing the shock-producing devices. Shock-sensitive equipment should not be located in proximity, certainly not within 15.2 cm (6 in), to shock sources (NASA-HDBK-7005).

At the spacecraft build level, shock testing typically consists of firing the on-board shock sources, as well as firing the launch vehicle separation system. There is no opportunity with this type of test to evaluate response of the hardware to lower levels of input before performing the full-level test; therefore, the primary focus of pre-test analysis for shock is to select adequate accelerometer locations for measuring the source shock and shock at various on-board locations to understand how the shock attenuates as it travels through the spacecraft structure. As with acoustic tests, one of the primary concerns in selecting instrumentation is having sufficient measurements to be able to determine the shock levels experienced by a particular piece of hardware, should a failure be uncovered during post-test functional testing. Shaker shock testing is not recommended to simulate pyrotechnic shock testing of spacecraft, as it is a poor simulation of the actual shock event and exposes the hardware to a risk of overtest and unrealistic failure.

7.8 Preparation of Written Test Plan

It is necessary to distinguish between the test plan and the test procedure, which is addressed in section 8 in this Handbook. Generally, a draft test plan is prepared well in advance of the actual test and updated as plan details firm up. The test plan serves two major purposes: it provides a description of what is planned, so that others may review it and comment, and it provides coordination and scheduling of the many activities that must fit together for the test item and test facility to be ready and the test to be successful. The test plan provides the basis for the test readiness review, which is typically held 2 to 4 weeks before test start. The test plan will typically cover the topics discussed in this section, including the following:

- Defining the test hardware and coordinate systems.
- Defining the scope and plan for pre-test and post-test analysis.
- Describing the facility and test equipment.
- Defining the test fixture.
- Defining the instrumentation, specifically the accelerometer locations and orientations.
- Defining the test specification and limits.
- Defining the test runs and intermediate data analysis.
- Naming the test director (who often writes the test plan) and other key personnel and defining their responsibilities.
- Describing the safety, cleanliness, and ESD requirements and precautions.
- Delineating the appropriate drawings, references, personnel, and web sites for pertinent information.

Some additional elements often included in the test plan are an Overview/Executive Summary, a List of Applicable Documents, and a List of Acronyms and Abbreviations.

8. TEST IMPLEMENTATION

8.1 Organization and Communication

The organization of the test and individual responsibilities during the test should be as defined in the test plan. Good communication should be maintained between the project, flight hardware engineering, dynamics engineering, and test facility personnel. It is important to keep everyone involved in the workflow informed and available, so that time is not wasted locating the personnel and support equipment required for the next step of the job. Generally, there is a natural pace or rhythm in the conduct of tests, which should be sensed and honored. There are usually several people present in the laboratory to witness a system dynamics test. It is recommended that the test director ask them all to be on the lookout for problems and to speak up if they see or hear anything questionable. It is also essential that the test director acknowledge, address, and resolve any questions that the observers raise during the testing.

The staffing and expected work hours and workweek should be discussed and agreed upon before the testing begins. (During busy periods when equipment from a big project is coming through the test laboratory, it is common for the laboratory personnel to have already been working long hours and weekends. Particularly in small laboratories, critical personnel, such as the shaker operators, may be doing several jobs concurrently.) Generally, it is advisable that single shifts be limited to a 10-hour day and that the schedule avoids doing the most dangerous, high-level tests late at night. If the test involves multiple shifts, it is important that the handoff be thorough, that critical decision makers always be available in person or by telephone, and that the anticipated work and progress be identified at the start of each shift. Tests that require travel away from home necessitate special attention to assure adequate personnel coverage and communication. Finally, it is recommended that the schedule, staffing, and plan have contingencies and options to accommodate unexpected results and/or problems, which often occur during complex test campaigns.

Individuals assigned to provide for test verification should not be those participating in the test. verification of test facilities, test configuration, or test article conformance. The conduct of testing is required to be performed by personnel as required by the specific project Quality Assurance Plan.

8.2 Procedures

The test procedure is usually prepared by the test facility organization and flows down from the requirements in the test plan. A good test procedure is a key element to a successful test. In the spirit of International Organization for Standardization (ISO) 9000, Quality management, “Say what you’re going to do, and do what you say.” One of the major purposes and benefits of preparing a test procedure is that it forces one to think through the details of the test in advance. Of course, there are many other benefits, such as providing a road map so that everyone involved in the test can work together efficiently and know what is scheduled to happen next. However, it is also important to realize that dynamic testing will always involve some uncertainties and surprises, so it is good to maintain a certain amount of flexibility to accommodate the unexpected. The procedure should have signoffs of critical steps, as appropriate, by the test and hardware engineers, by the structural analysis engineer, by the representative of the quality assurance organization, and by the test director. The procedure should be signed off after any change in the procedure and before the full-level test, but, at a minimum, verbal approvals should be obtained before all test runs. Only one person, usually the test director after consultation with the other participants, should have the authority to give the go ahead to the test operator to commence the next run.

8.3 Instrumentation and Data Analysis

Good instrumentation is another key element to success in dynamics testing, and it may include accelerometers, microphones, force gages, strain gages, thermal couples, and occasionally motion sensors. IEST-RD-DTE012.2, Handbook for Dynamic Data Acquisition and Analysis, (updated by Piersol et al., (2006)) is an excellent source of information on data acquisition and analysis. It is essential that all the test equipment and instrumentation be up to date on their calibration and it is highly recommended that all the instrumentation be set up and calibrated end-to-end before the test. It is also important to compare the data from low-level tests with the values predicted by the pretest analysis. In the case of force gage measurements, the ratio of the total force to input acceleration, measured well above the first resonance frequency, may be compared with the total mass of the test item (Scharton and Kolani, 2013).Typically, the real-time data analysis in dynamic tests consists solely of spectral plots. However, it is also highly recommended that the time history data from each run be recorded, so that, if there is a problem, it can be investigated later. For example, excessive rattling or impacting within the test item in a vibration test can be a problem that requires examination of the time histories to resolve. For random and acoustic tests, the time histories are also useful for calculating the ratio of the peaks to the RMS. The real time data should be collected starting the moment the equipment is powered up to be sure that, in case of equipment malfunction at startup, information will be available to perform an analysis if necessary. During the Lunar Atmosphere and Dust Environment Explorer Sine Burst Vibration Mishap in May 2012, the equipment malfunctioned when it was powered before data were collected, making it very challenging to estimate the acceleration levels experienced by the structure.

The test director decides how much data analysis is to be conducted between each test run and how much will be done later. At a minimum, sufficient data analysis should be done after each run to compare the critical results with the pre-test analysis so as to understand what is going on and to determine that it is safe to proceed. A problem often arising during a dynamics test is that one (or more) of the instrumentation channels is observed to be yielding suspicious or obviously bad data (IEST-RD-DTE012.2). The test director then decides if the testing should be stopped to try and fix those channels or to replace them. Obviously the decision depends on how critical those channels are and how much time will be required to investigate and/or fix them. A good rule is to not proceed if a significant portion of the data is not available, not as expected, or not understood. Similarly, it is important that problems with the test item and test equipment be resolved and, further, that the cause of the problem be understood before the test proceeds. Sometimes, waiting until a problem is remedied and understood takes resolve on the part of the test director, as there is often significant pressure to press ahead.

To the degree possible, test plans should identify minimum test-critical instrumentation. Regardless, proceeding with testing or resumption of additional test runs with less than test-plan-specified instrumentation requires approval.

8.4 Equipment Operation and Control

The proper control of dynamic tests is a very important aspect of the test program. Test fixturing is usually statically qualified to ground support equipment margins. The test equipment should be exercised at full level before the test item is installed to ensure that it is operating properly. This pre-test should include test fixturing and a mass simulator, if possible, especially if the weight of the test item or magnitude of the reaction forces is appreciable. All the control accelerometers in the pre-test should be installed in the same positions as for the actual test. The purpose of the pre-test is twofold: to check the equipment and to serve as a dry run to prepare all the personnel for the actual test. In this regard, it is best to have the pre-test as close in time to the actual test as the schedule will permit. During the actual test, the input to the test should be reviewed before and after each run, as well as monitored during the run, to make sure that it is as desired and within the test tolerances. Test hardware should be inspected before testing and between test runs to verify adequacy for performance of the test and safety. In no cases should the test continue when there are unresolved problems with the test equipment. Several mishaps have resulted from the use of equipment with problems that were not explained or resolved.

Control schemes vary depending on the type and the purpose of the tests. Any change in the control scheme or parameters, however, should be reviewed by the test director and relevant technologists, and restart of testing should begin with repeat of the lowest level run.

8.4.1 Acoustic Tests

Acoustic tests are nearly always controlled by frequency averaging the output of several microphones surrounding the test article. Reverberant chamber acoustic tests typically require 4 or more control microphones, whereas DFATs require considerably more control microphones, typically 8 to 12, because of the larger spatial variations associated with DFAT tests. Acoustic tests are usually controlled (and the input acoustic signals averaged) in one-third octave constant percentage frequency bands to accommodate the large frequency range of interest in acoustic tests (typically 20 to 10,000 Hz). If, however, the test item has critical resonances at low frequencies where the modal density of small acoustic test chambers is low, it may be advantageous to control in narrow bands to ensure that the test item specification is met at the test item resonances. Otherwise, the test level may be too low if there are no acoustic modes at the structural resonances or too high if a structural mode is strongly coupled to an acoustic mode (Kolaini, et al., 2009). A narrow-band vibration test control system was used successfully at one laboratory to provide narrow-band control of acoustic testing in a reverberant chamber (Larkin and Smallwood, 2003). (Also, a recommended practice for DFAT is to use narrow-band control (Larkin and Smallwood, 2003).)

The control strategy is somewhat different for reverberant chamber and DFAT acoustic tests. Reverberant chamber tests, for the most part, use single-input single-output (SISO) control, i.e., the input to the control system is the average of a number of control microphones and the output is the excitation signal applied to all the acoustic drivers. (The excitation into different drivers may be shaped to accommodate the different frequency characteristics of the drivers.) The early DFAT, e.g., the QuikSCAT acoustic test described in Appendix D in this Handbook, was also conducted with SISO control. However, state-of-the-art DFATs now use MIMO, i.e., the signal from each control microphone is processed separately by the control system and multiple drive signals are generated by the control system. Each drive signal is applied to multiple drivers, and the distribution and amplitude of the drive signals applied to the various drivers are controlled by a matrix switch. Larkin (2012) reported that the spatial variations in DFATs have been reduced from approximately 12 dB with SISO control to 3 dB with MIMO control.

8.4.2 Random Vibration Tests

Random vibration tests are controlled either with a single input accelerometer or, in the case of large test items such as a spacecraft, by averaging or taking the maximum of the PSDs of two or more input accelerometers in each control frequency band. It is essential that the accelerometers be positioned to define the maximum acceleration at the interface between the test item and the fixture. If the fixture is rigid in the test frequency range, one or two in-axis and two cross-axis accelerometers will usually suffice. If the fixture is not rigid, the remedial measures described in section 7.4 in this Handbook should be employed, i.e., damping, notching, and/or maximum control. Modifications to test fixtures for specific tests become the record of testing and require documentation. In random vibration tests, the PSD of the input acceleration is controlled in narrow bands, typically 1 to 4 Hz, depending on the number of control bands available and the upper frequency limit of the test. Extremal control is typically employed when force transducers or response accelerometers are included in the control scheme. In extremal control, the input accelerometers control the test to the input specification, except at strong structural resonances where the force and acceleration response limits may take over and cause notching of the input acceleration at the resonance frequencies. (See section 8.5 in this Handbook.) Low-pass filters are often employed on the control channels in random vibration tests when high-frequency rattling of the test article repeatedly causes the test to abort.

8.4.3 Sine Vibration Tests

Swept sine vibration tests are controlled to either an RMS or peak (1.414 times the RMS) acceleration specification. The sweep rate is usually part of the specification. Faster sweep rates limit the amount of response buildup as the input sweeps through resonances but provide less resolution for identifying the resonance frequencies and damping. If the sweep rate is too fast, force or acceleration limit notching may not have time to develop fully before the resonance frequency is passed, i.e., the measured acceleration or force may overshoot the limit. An excessive number of control channels may further reduce the control system's ability to fully develop notches. If significant noise or nonlinearities are present, tracking filters are often employed on the control signals so that only the acceleration in a narrow band around the excitation frequency is included in the control. A related issue concerns the fact that no facility is capable of producing pure sine wave excitation, so sometimes the specification includes a definition of the allowed total harmonic distortion (THD).

Sine burst vibration tests are usually conducted open loop. The controller first generates a low-level broadband noise signal to calculate a transfer function between the voltage drive to the amplifier and the shaker acceleration, and this ratio is then multiplied by the specified acceleration to obtain the drive signal for the actual test. Once the test starts, there is little or no opportunity to stop or modify the input during the test. (See the description of the HESSI accident in section 4.3 in this Handbook.) Various techniques are being investigated and, in some cases, being used to stop the test if the input is not as expected. Even then, there are difficulties with the overshoot and with the transients caused by suddenly stopping a test, which is sometimes called a hard shutdown. One problem associated with a hard shutdown is what one does with the energy stored in the shaker amplifier and in the shaker itself, once the controller decides to shut the test down; the decision to shut down in itself takes some time. Some test facilities have developed soft shutdown control algorithms for specific input waveforms. Before using a facility, the project should determine that a soft shutdown approach is the standard response to problems that occur whenever possible and that a hard shutdown is the last resort only in an emergency or in case of equipment or power failure.

8.5 Limiting and Notching

It is essential that the input in a base-drive vibration test be limited at the structural resonances of the payload on the shaker to avoid overtesting. The overtesting problem is caused by the very large impedance of the shaker and fixture in comparison to that of the flight mounting structure (NASA-HDBK-7004). To minimize the problem of overtesting at the payload resonances, it is common practice to limit the test item responses, i.e., the forces between the shaker and the test item, the test item accelerations, or both, to the values predicted for the flight mounting configuration. Force limiting is the recommended approach for several reasons. First, usually the responses at every position of the spacecraft may be controlled by limiting only the total interface force in the direction of excitation. For example, in both the Cassini Flight Spacecraft vibration test described in Appendix A in this Handbook and also the MER #1 Flight Spacecraft vibration test described in Appendix B in this Handbook, only one channel, the total in-axis force, was used to limit the full-level tests. On the other hand, limiting the spacecraft acceleration responses may require 10 to a 100 limit channels for a large spacecraft. Second, the force limits derived from published prediction methods are relatively insensitive to the detailed analysis of the payload, so that a vibration test with force limiting is generally less dependent on the analysis than a test with response limiting. The use of force limiting does require the installation of force gages between the shaker and test item. (See also sections 6.6 and 7.4 in this Handbook.) In the vertical test set-up for the MER #1 Flight Spacecraft, shown in figure 1, force transducers were sandwiched between the lower and upper rings; in the lateral test setup shown in figure 2, the force transducers were incorporated in the fixtures at each mounting location. The limiting process is the same whether force or acceleration response is measured and limited, i.e., the spectrum of the measured signal is compared with the specified limit and the controller automatically generates notches in the spectrum of the acceleration control signal to prevent the response limits from being exceeded. (The notches are mirror images of the response in an unlimited test that would have exceeded the limit.) In random vibration tests, the PSD of the input acceleration is notched, whereas in sine sweep vibration tests, the peak input acceleration is notched. Acoustic tests could also be response limited if narrow-band control is used, but this is not common. If there is more than one limit channel, as in a typical test with acceleration response limiting, any or all of the limit channels may contribute to the notching of the control, and it is often difficult to determine how much each of the limit channels contributes to a given notch.

Note that the input and limiting spectrums should be specified and controlled starting below the primary mode of the test article in each test axis. In the case of a spacecraft being vibration tested on its flight spacecraft vibration isolation system, the input spectrum and the force and accelerometer response limit spectra started at 10 Hz, but the 7.5-Hz lateral mode of the spacecraft on the isolation system was excited by the inputs above 10 Hz. Data below 10 Hz were not being displayed, and the error was not discovered until the -3-dB run when loads nearly exceeded the spacecraft test limits (Gibbs et al., 2009).

It is common practice in vibration tests to place limits on some accelerometer channels to ensure that the design limits or test levels at lower levels of assembly are not exceeded. (However, if the force limit discussed in the previous paragraph is selected properly, these acceleration response limits will usually not control the test.) There is always a compromise between the complexity of the test setup and operation and the number of safeguards and limits one may wisely implement. The balance depends on the complexity of the test hardware, the capabilities of the test equipment, and the experience of the test laboratory and the test operators. If too many limit channels are used, the vibration controller may be slow to update the input and to sense overtesting. Therefore, it is recommended that no more than 10 limit channels be used in a system vibration test, and fewer may be appropriate for smaller test items or for slower controllers. In a swept sine vibration test, the controller has to be fast enough to sense exceeding of the limits and to implement the notching before the critical frequency is swept by. If, for some reason, it is not possible to do the limiting in real time, the notching may be done manually between runs. However, in this case, the notches will, of necessity, be wider than when they are put in automatically; therefore, some of the spacecraft nonresonant response will be reduced, and secondary structures and equipment on the spacecraft may be under tested at these frequencies.

NASA-HDBK-7004 contains three force-limiting guidelines that may be applied to acceleration response limiting as well. First, any form of response limiting, which includes limiting of the base reaction force, as well as limiting of the acceleration responses on the test item, should only be applied to highly resonant, structure-like test items and not to electronic boxes or brick-like items. If it is necessary to reduce the response of the latter, the input acceleration specification should be reduced. Second, the limits or notch depths should not be set arbitarily. For example, the constant C in the semi-empirical method of force limiting should be selected with some consideration of the flight mounting structure impedance, and a force limit or an acceleration response limit should be set with some consideration of the CLA or limit loads. Finally, avoid excessive notching. It is recommended that notches exceeding 14 dB, which will reduce the RMS response by approximately 50 percent, be carefully reviewed. (See NASA-HDBK-7004C, section 5.1.) (Notch depth is dependent on analysis bandwidth; the analysis bandwidth for evaluation of notch depth is assumed to be the same as the shaker control system bandwidth.) If more than a 50-percent reduction in RMS response is desired, it is suggested that reducing the input acceleration be considered. In the evaluation of the notches, it should be kept in mind that lightly damped resonances result in deeper notches. A simple guideline for accessing notch depth for lightly damped resonances is to compare the notch with Sweitzer's notching method, i.e., that the input acceleration is notched so as to reduce the response to half its original value in decibels (Schweitzer, 1987). (For example, a 20-dB resonance becomes a 10-dB resonance and a 10-dB notch.) However, as with the semi-empirical method, Sweitzer's method should not be applied without supporting rationale.

In addition to the spectral limits previously discussed, the peak or instantaneous level of selected input and response channels may be monitored in sine and random vibration tests, and the test may be shut down if the peak limits are exceeded. It is a good idea to resolve all of these shut-down problems at the lower test levels using scaled-down limits, because, as mentioned in the last section, the sudden termination of a full-level vibration test can cause high loads that are problematic in themselves. In acoustic testing, it is common to shut down the test if a specified number of one-third octave bands are above tolerance. To avoid possible operator error, it is preferable to automatically scale peak limits with the test run input level rather than to adjust the limits manually.

8.6 Test Runs

The number of test runs depends on the complexity of the test item, the number of test configurations and/or axes, and the problems encountered during the test. In each configuration, it is common to begin with a low-level run to obtain a baseline signature, which is normally repeated for comparison after the full-level testing before going to another test axis or configuration. In the past, the signature runs were typically slow (1 or 2 octave/min), low-level sine sweeps, but it is becoming common practice to use low-level, long duration (typically 4 min) random excitation to obtain the signatures. There are normally a number of low-level tests before going to the full-level test. For example, in a random vibration test, a typical sequence might consist of runs at -18 dB, -12 dB, -6 dB, and full level, with some data analysis and review between each run. Sometimes the -18-dB run is conducted both without and with limiting. (If notches deeper than 18 dB are anticipated, it may be necessary to start the unnotched run at -24 dB.) It is best in the lower level runs to have all of the limits scaled down with the inputs, so that any problems may be identified and corrected by adjusting the limits before the full-level test. In random vibration and acoustic tests, the lower level runs are usually conducted for a shorter interval of time than the full-level test, the only requirement being the data sample length necessary for proper analysis. A typical duration for the lower level random and acoustic runs is 30 sec. The approval of the test director, who will typically seek concurrence from the structural analyst, is required before proceeding to the next higher level run.

Before making a test configuration change, such as changing test axes, the control and response data needs to be thoroughly evaluated to ensure that test requirements were met, that no spacecraft anomalies are evident in the data, and that all sensors are properly functioning. It is good practice to have some sort of functionality check, i.e., electrical, mechanical, optical, between configuration changes, along with the quality verification of the test setup to proceed according to the procedure requirements.

Changes to tests or instrumentation from those represented by the approved test plan require approval by the test director in consultation with engineering and quality and the customer. This includes test or instrumentation modification related to unexpected test response.

9. INTERPRETATION OF TEST RESULTS

Sometimes, either the differences between the test data and the pre-test predictions are so great or significant changes are observed in the data obtained during the testing sequence that it is prudent to interrupt the test and conduct additional analyses and model correlation. In these cases, testing should not resume until the differences and/or changes are reconciled; in the case of changes, it may be necessary to repeat the testing conducted before the changes occurred.

Upon the completion of a system dynamics test, the following questions may be asked:

- Did any structural, electrical, functional, or facility anomalies occur during or after the test?
- What post-test data analysis should be conducted?
- Was there any undertesting or overtesting that needs to be addressed?
- Was there any significant wear or deterioration of the test item, as compared to the pre-test inspection data, that should be remedied or taken into account in future testing or service?
- Are the test data consistent with model predictions; if not, why not?
- How could the test procedure be improved for future tests?
- Was anything learned from this test that would affect other testing in the same or other programs?
- Should the test data and, perhaps, the analytical model be incorporated into a database for future use?
- What should be the form and distribution of the test report?
- Should the results be distributed to a larger community through a presentation at a technical meeting or a paper in an archival journal?

9.1 Structural Integrity

The most notable thing that can happen in a dynamics test is a structural failure. Sometimes, a structural failure is accompanied by a loud noise and visual observations, such as separation of the parts or even pieces falling off. More often, however, a structural failure is observed only when the test item fails to operate properly in a post-test mechanical or functionality test or when the test item is disassembled and loose parts and/or other damage are found. The before-and-after test traces observed in the vibration signature tests are seldom identical. Sometimes, a small change is cleverly recognized as the indicator of a key structural failure, while at other times the cause of a frequency shift or, in some cases, even the complete disappearance of a frequency peak is never determined. (See section 9.4 in this Handbook.) Therefore, it is usually difficult to make the decision to stop testing or to disassemble the test item to look for damage on the basis of signature changes; such a decision usually requires a caucus and consensus of the technical specialists and the project personnel. After the test, if no structural damage is observed in a visual inspection or upon disassembly of the test item, it may be said to have passed the test. Of course, the test item may still have undergone some wear, e.g., the ball joints may have loosened, or the structure may have used up some of its fatigue life, e.g., through the growth of small but undetectable fatigue cracks; this reduction of life should be taken into account in future testing or service.

9.2 Functionality

The equipment that operates during launch is usually powered on and monitored during the dynamics testing to ensure normal operation of the equipment during launch. Sometimes other equipment is powered on and monitored during the dynamics test to aid in early identification of intermittencies or failures, before continued exposure to the dynamic environment causes additional damage. Electrical failures, however, are more common in tests at lower levels of assembly in which the dynamics test levels are higher. Sometimes test failures are found during other tests, after the dynamics testing; these tests may include electrical, mechanical, optical, and other functionality or environmental tests, such as thermal vacuum or electrostatic tests. In the latter cases, it is often difficult to tell when the failure occurred and if it was associated with the dynamics testing or if the dynamics testing contributed to the failure.

9.3 Failures, Redesign, and Retest

In the event of a test failure, the project normally appoints an anomaly investigation team. The most important step in the investigation of a failure in a dynamics test is to determine the root cause of the failure.. It is critical, but often difficult, to determine the root cause, i.e., to get to the bottom of the problem. It is important to distinguish between the cause of the failure, consequences of the failure, and things that might have been done to prevent the failure, which are usually many. Without knowledge of the root cause, it is difficult to determine how to correct the problem or whether it is fixed. One of the first tasks in the anomaly investigation is to determine if any overtesting occurred, perhaps because of problems with the facility, control, or specification. If the investigation reveals a mishap, which would be based on test equipment failure, accident, wrong procedure, etc. – an unintended risk of the test, then a mishap investigation board would be appointed. Within NASA, the severity of the mishap determines who the appointing official is.

Many failures occur because of a cascade of events, and some because of a coincidence of events. For example, a bolt or a restraining pin may back out, perhaps during an earlier test run, and then high loads and excessive motion may result in stresses exceeding the design limit. Other times, it is just a case of the design margins of a number of parts in a mechanism being too low. A common mistake of this kind is the use of too low a multiplier, typically 3, on the predicted RMS response to estimate the maximum response that will occur in the test. (A multiplier of 5 is recommended in section 7.7 in this Handbook.)

Sometimes, the cause of the failure remains somewhat ambiguous, even after considerable investigation. In these cases, it is recommended that the suspected cause of failure be verified by retesting the old design with additional instrumentation. If the failure is determined to be associated with a design problem, it is a good practice to modify the design so that all of the relevant design margins are significantly increased and the chances of another failure are significantly decreased. Finally, it will be necessary to test the new design to the exact specified test plan configuration and parameters to verify that the problem has been fixed. A review of the test specification is recommended at this point to ensure that the new part is not overtested.

Failures in verification testing to specific and approved project quality planning require documentation by non-conformance report.

Retests may also be appropriate when a system-level test has been performed without a major instrument or component. If a good dynamic simulator was used for the missing hardware and the missing hardware was separately qualified, the main concern may be the workmanship of the interconnections, i.e., cables, waveguides, plumbing lines. Any significant disassembly and reassembly of the system after testing is complete may also be reason for a workmanship retest. Retesting in such situations is decided on a case-by-case basis. Flight acceptance levels are usually employed for retest if no significant design changes were made, as determined by concurrence of the dynamic environments, structures, quality, and project staff. Often, only the tests considered most likely to reveal workmanship defects are repeated.

9.4 Post-Test Analysis

Post-test analyses may be conducted for a number of reasons, including the following:

- To understand some phenomena that occurred during the test, e.g., a frequency shift in the pre- and post-test vibration test signatures.
- To correlate the analytical model with the test data.
- To extrapolate the dynamic response of the test item to a different test or flight environment.

- To understand why a test failure occurred.
- To predict the dynamic behavior of the test item after a design change.
- To extrapolate the data to predict the response of a new, untested design.

One example of post-test analysis is to understand some unexpected test phenomena involving changes in the resonance peaks during a vibration test. Shifts and splitting of a resonance peak are often observed when one compares the pre- and post-test vibration test signatures. Shifts to lower frequency and splits can sometimes be explained by insufficient preload in bolted joints, which can cause a reduction of stiffness or, in the case of splits, cause a single mass to start behaving as two masses. Shifts to a higher frequency might imply part of a mass has broken off. Sometimes, however, if and when the decision is made to stop the test or to inspect the test item after the test, no physical evidence is found to explain even the most obvious changes in the signatures.

Perhaps the most common reasons for post-test analysis are to investigate differences between the analytical predictions and the test data, to tune the model to the test data, and, hopefully, to physically understand and justify the changes to the model. The four characteristic parameters for each mode are the resonance frequency, the mode shape, the damping, and the effective modal mass. The effective modal mass is a very important parameter in a modal analysis as it is a measure of how effectively the mode can be excited from the base of the test item, i.e., by a shaker or by the launch vehicle (Wada et al., 1972). Measurement of effective modal mass requires measurement of the shaker force in a base-drive vibration test. Various parameter identification methods are available for reconciling dynamics test data and analytical models (Heylen, 2002). Some of the most sophisticated of these are the Bayesian techniques, which assign an uncertainty to both the test data and the model parameters. It is important that any changes to the model parameters that result from the application of parameter identification methods be scrutinized for their physical credibility. Sometimes, the differences between the predicted and measured frequencies of even the fundamental modes are large. For example, in the base-drive vibration test of the MER Rover, the measured frequencies of the first three modes were approximately 20 percent higher than those in the analytical model used for the CLA. (See Appendix B in this Handbook.) In the post-test analysis, it was found that the predicted and measured frequencies could be reconciled by including in the model the stiffening effect of the shear panels in the Rover truss structure (Scharton and Lee, 2003).

The most common form of extrapolation of test data involves scaling the test data to another test or flight condition with a different input. For example, sometimes data from heritage tests of flight hardware are scaled up to a higher test input for a new program. Also, data from relatively short-duration vibration tests are sometimes scaled to predict cumulative damage associated with retesting or repeated space or aircraft flights (NASA-HDBK-7005, p. 176).

A failure during a vibration test is a compelling reason for post-test analysis, both to understand the cause of the failure and to make such changes as necessary to assure that the failure will not occur again. Sometimes, there is no obvious cause for a structural failure, but the post-test analysis will indicate that some of the margins were very low. Other times, the post-test analysis may reveal that, when carefully scrutinized, the test levels were too high or, conversely, that the design loads were too low. If a design change is required, the pre-test analysis routine begins again, with emphasis on the region that failed previously and usually on significantly increasing the relevant margins.

Hardware design changes often occur after the dynamic tests of a DTM but are unusual after the vibration test of a flight spacecraft, unless a failure occurs in the test. The extrapolation of predictions from a test-verified dynamics model to a slightly modified hardware configuration is the subject of research in the field of FE model reconciliation (Avitabile, 2002).

The most challenging type of post-test analysis involves extrapolating data and analyses from previous tests to predict the response of a new test item that has not been tested or perhaps even been built. The starting point for this work is to build a database that includes the physical properties, analyses, and data for spacecraft that have been tested. An approximate but very useful method of extrapolation for vibroacoustic test data is the EXTRAP 1 routine, which was incorporated into the VibroAcoustic Payload Environmental Prediction System (VAPEPS) SEA code[2]. In that method, the ratio of the measured to the predicted transfer functions for the baseline system is multiplied by the predicted transfer function for the new system to provide the extrapolation of the baseline data to the new system. As with most extrapolation schemes, the accuracy of the EXTRAP 1 method relies on the degree of the physical and dynamic similarity between the old and new systems. The VA One™ code contains a similar SEA extrapolation module[3].

9.5 Test Documentation

Documentation of test results provides the certification that the test was conducted to the program requirements. Any test deviations and any facility or test article anomalies are noted in the test report. The report will also serve as a basis for evaluation of any anomalies detected during subsequent ground tests, ground operations, or flight. The report, preferably integrated into an electronic test database, will also contribute to improved dynamic response predictions for future spacecraft. Typically, the test report includes descriptions of the test article, the test setups, the test facility, the test input levels, and instrumentation locations; a test run log; representative data plots; descriptions of any deviations or anomalies. The test inputs and responses should be compared with the specifications and pre-test analyses to assess how completely the test objectives were achieved. The criteria used to determine that the objectives were indeed satisfied should also be discussed. (See sections 9.3 and 9.4 in this Handbook.)

Responsibility for writing the test report should be assigned before the start of test so that the writer can gather information and take notes for the report as the test proceeds.

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[2] Circa 1990-1995, the EXTRAP 1 Routine in VAPEPS SEA computer code was developed by Lockheed Martin Company and supported by JPL. It is now unsupported.
[3] The VA One™ SEA computer code is available from ESI Group, San Diego, CA.

In addition, it is very helpful if someone, typically the test director, writes a summary email at the end of each day of testing. The summary should document progress, problems, and the plan for the next day. If the data are available in spread sheet form, it is particularly useful if all the data obtained that day are disseminated to the test team for their review.

APPENDIX A

CASE HISTORY OF CASSINI SPACECRAFT VIBRATION TESTING

A.1 Purpose and/or Scope

The purpose of this appendix is to provide guidance in the form of a case history of the Cassini spacecraft vibration testing. References for this appendix are included in section 2 of this Handbook.

A.2 Cassini Mission Overview

Saturn and its moon Titan were the destinations for the Cassini mission, a project developed jointly by NASA, the European Space Agency (ESA) and the Italian Space Agency. The NASA portion of the mission was managed by JPL. Launched in October 1997 on a Titan IV-Centaur rocket from Cape Canaveral in Florida, the Cassini spacecraft first executed two gravity-assist flybys of Venus, then one each of Earth and Jupiter, to send it on to arrive at Saturn in June 2004. After arriving at the ringed planet, the Cassini orbiter released the ESA Huygens probe, which descended to the surface of Saturn's moon Titan. The launch weight of the Cassini spacecraft and Huygens probe was ~5,800 kg (12,800 lb). Because of the very dim sunlight at Saturn, solar arrays are not feasible there, and the spacecraft power was supplied by a set of three RTGs, which used heat from the natural decay of plutonium to generate electricity.

The Cassini project encompassed an extensive dynamics test program that included acoustic tests of a dynamic test model (DTM) of the spacecraft and of the flight spacecraft, as well as force-limited vibration tests of the instruments, assemblies, and flight spacecraft.

A.3 Cassini Spacecraft Acoustics and Vibration Testing

Three acoustic tests of the Cassini Spacecraft DTM were conducted. Figure 7, Cassini DTM Spacecraft in JPL Acoustic Chamber, shows the spacecraft in the acoustic chamber. Each test involved different configurations of the DTM, flight, and engineering model spacecraft hardware and science instruments (Chang and Scharton, 1996). The primary objective of these tests was to provide experimental verification of the predicted acoustically induced random vibration test levels at equipment locations on the spacecraft before the random vibration tests of the flight hardware were conducted. The DTM measurement locations included the attachment interfaces of the science instruments, RTGs, reaction wheels, and other spacecraft assemblies. In many cases, both the interface acceleration and interface force were measured; in some cases, the acceleration response at a position near the equipment static CG was also measured.

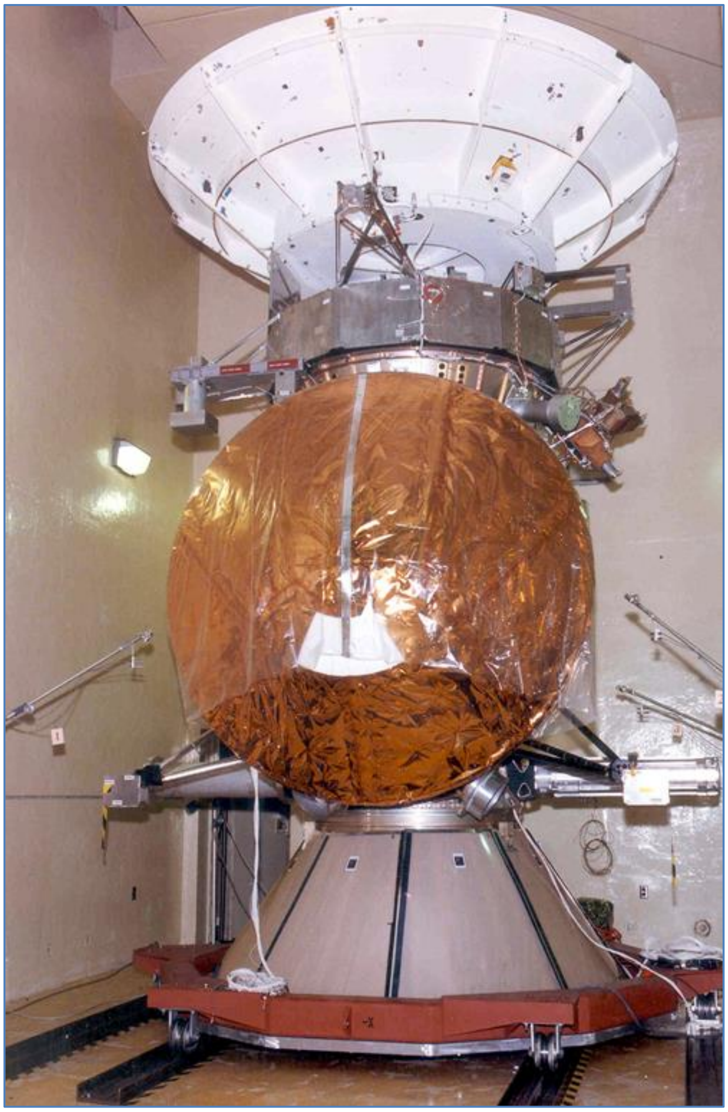

Figure 7—Cassini DTM Spacecraft in JPL Acoustic Chamber

Figure 8, Comparison of Cassini RTG Interface Acceleration Data Measured in DTM Spacecraft Acoustic Test and RTG Random Vibration Test Specification (Zone 1 Specification), shows the acceleration data measured in different axes at the RTG base during the September 1995 Cassini spacecraft DTM acoustic test shown in figure 7. Also shown in figure 8 is the random vibration test acceleration specification (0.08 g^2/Hz) for Cassini equipment in zone 1 of the spacecraft, where the RTG is located. (Both the acoustic test data and the random vibration test specification have 4 dB of margin over the predicted flight environment.) Comparison of the DTM acoustic test data and the RTG test specification in figure 8 indicates remarkable agreement, i.e., the specification just envelopes the data over the complete frequency range from 20 to 1,000 Hz. The RTG random vibration test is shown in figure 9, Dynamic Model of Cassini RTG Mounted for Axial Vibration Test.

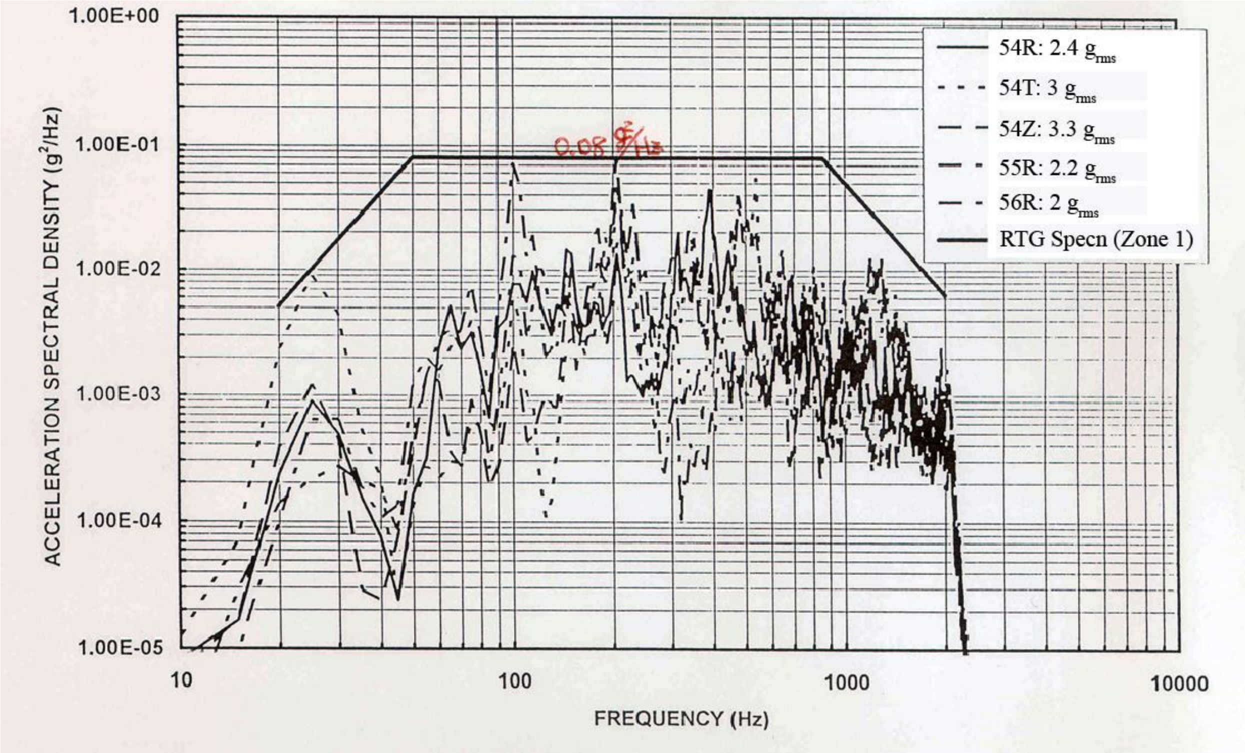

Figure 8—Comparison of Cassini RTG Interface Acceleration Data Measured in DTM Spacecraft Acoustic Test and RTG Random Vibration Test Specification (Zone 1 Specification)

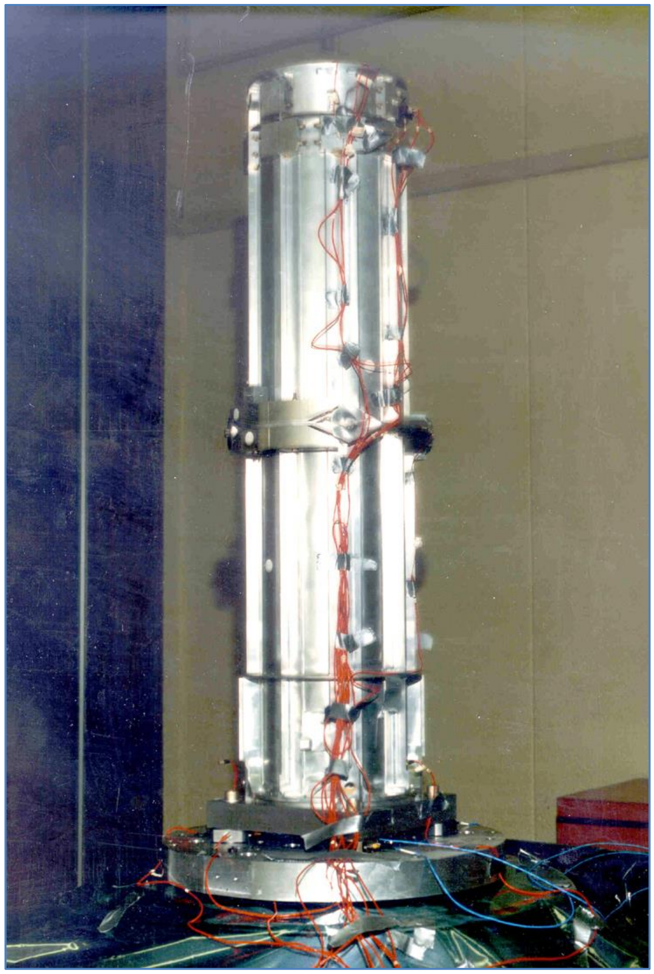

Figure 9—Dynamic Model of Cassini RTG Mounted for Axial Vibration Test

Figure 10, Cassini Flight Spacecraft Mounted on Shaker for Vertical Random Vibration Test, is a photograph of the Cassini flight spacecraft, with the high-gain antenna removed, mounted on the shaker for the vertical random vibration test, which was conducted at JPL in November 1996 (Scharton and Chang, 1997). The weight of the Cassini spacecraft for the vibration test was 3,809 kg (8,380 lb), which is less than the weight at launch primarily because, for the test, the tanks were loaded to only 60 percent of their capacity with referee fluids. Most of the orbiter's 12 instruments are mounted on the Remote Sensing Pallet, shown at the upper left, and on the Fields and Particles Pallet, shown at the upper right in figure 10. Seven more instruments are located in the Huygens probe at the right in figure 10. The conical spacecraft/launch vehicle adapter bolts to the fixture upper ring at eight locations, and eight large tri-axial force gages are sandwiched between the upper and lower fixture rings to measure the force input to the spacecraft in the vibration tests. Two of the three dynamic-model (non-radioactive) RTGs are shown spaced 120 deg apart just above the conical spacecraft/launch vehicle adapter in figure 10.

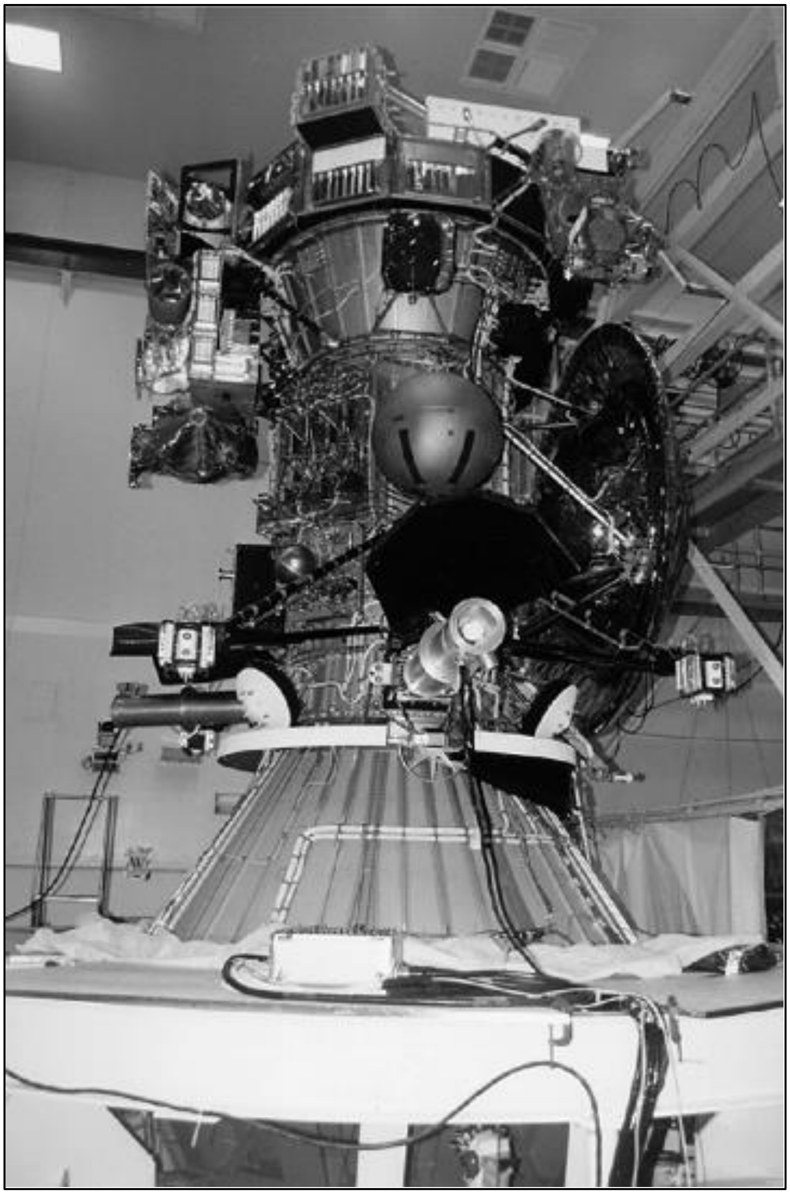

Figure 10—Cassini Flight Spacecraft Mounted on Shaker for Vertical Random Vibration Test

Figure 11, Comparison of the Acceleration Specification for the Cassini Spacecraft Base-Drive Random Vibration Test with the Launch Vehicle Specifications and Flight Data, compares the acceleration specification for the Cassini flight spacecraft base-drive random vibration test with the launch vehicle specifications and with acceleration data from a previous flight of the Titan launch vehicle. The acceleration specification was originally somewhat higher (0.04 g^2/Hz compared to 0.01 g^2/Hz), but the specification was lowered in the 10 to 100 Hz frequency regime after reviewing the results of an extensive FE model pre-test analysis, which indicated that excessive notching would be required with the higher level input. The specification was subsequently lowered in the 100- to 200-Hz frequency regime as well to accommodate the force capability of the shaker power amplifier, which was over 10 years old and frequently exhibited instabilities during the 2-month period preceding the Cassini spacecraft vibration test. The Cassini final specification (0.01 g^2/Hz) is less than the Booster Powered Phase specification at frequencies greater than ~80 Hz but exceeds the maximum envelope of the TIV-07 Flight Data shown in figure 11.

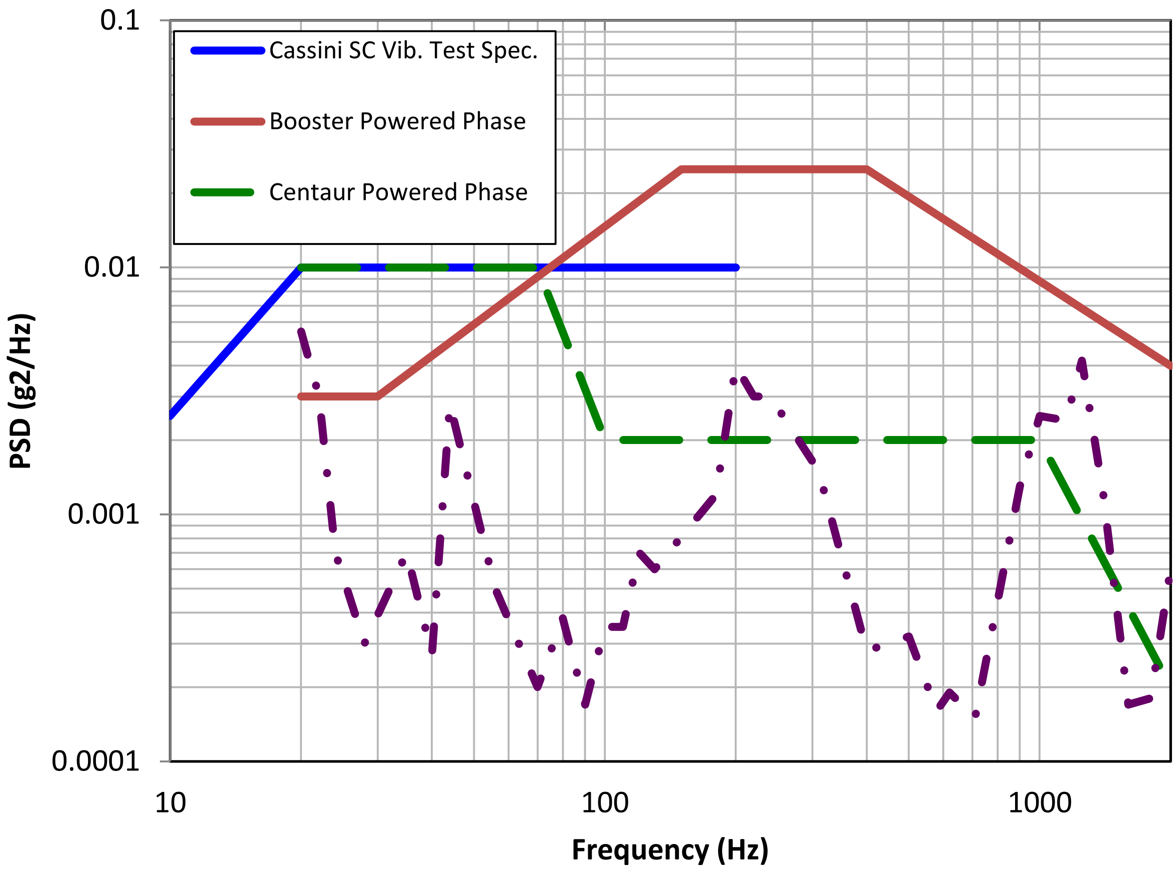

Figure 11—Comparison of the Acceleration Specification for the Cassini Spacecraft Base-Drive Random Vibration Test with the Launch Vehicle Specifications and Flight Data

Figure 12, Force Specification for Cassini Flight Spacecraft Random Vibration Test, shows the force specification for the Cassini flight spacecraft random vibration test. The force specification was derived by multiplying the acceleration specification (0.01 g^2/Hz) by the square of the total weight (4,230 kg (9,300 lb)) of the spacecraft, launch vehicle adapter, and upper fixture ring, and also by a factor of one-half. This corresponds to the semi-empirical method of deriving force specifications with $C^2 = 1/2$ and n = 0 (NASA-HDBK-7004C). The choice of $C^2 = 1/2$ was selected on the basis of the pre-test analysis and to keep the proof test, which had a margin of 1.25 over the test limit loads, within the shaker force capability. The force specification was not rolled off at the spacecraft fundamental resonance, because neither the FEM pre-test analysis nor the actual vibration test data showed a distinctive, fundamental resonance of the spacecraft in the vertical axis. During the test, it was not necessary to modify or update the force limit specified in the test procedure, which is quite remarkable considering the complexity of this test.

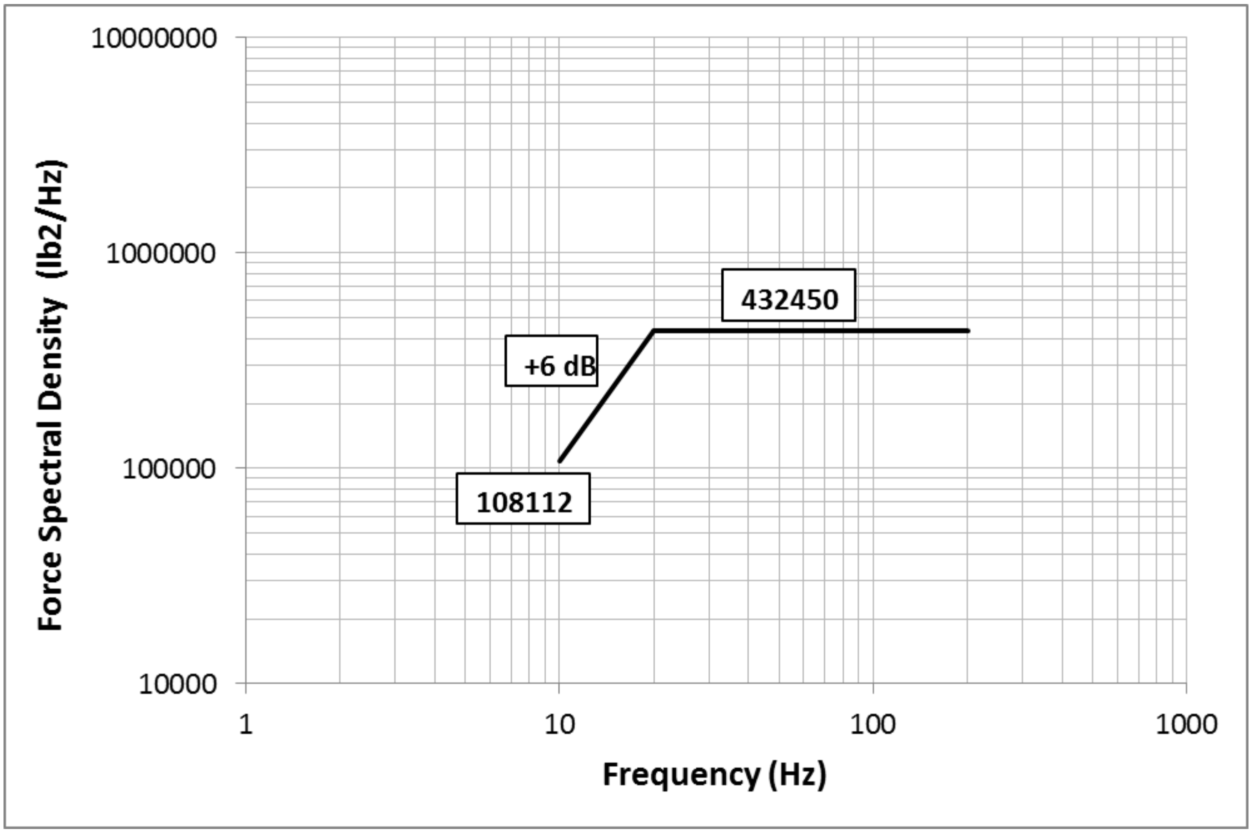

Figure 12—Force Specification for Cassini Flight Spacecraft Random Vibration Test

Figure 13, Acceleration Input in Cassini Flight Spacecraft Full-Level Random Vibration Test, and figure 14, Total Vertical Force Measured in Cassini Flight Spacecraft Full-Level Random Vibration Test, respectively, show the input acceleration and force spectra measured in the full-level random vibration test of the Cassini flight spacecraft. Comparison of the measured acceleration input with the specification of figure 11 shows notching of ~8 dB at the Huygens probe resonance at 17 Hz, of ~7 dB at the RTG resonance at 30 Hz, and of ~13 dB at the tank resonance at 38 Hz. The other five components of the total input force vector, two transverse forces and three moments, as well as the responses at over a hundred critical positions on the spacecraft, were monitored during the test, but only the total vertical force signal was used in the controller feedback to notch the acceleration input in the full-level test. A comparison of the measured force with the specified force in figure 12 verifies that the force was at it's limit over the entire frequency range where notching occurred in the input acceleration. The choice of C^2 = 1/2 resulted in the input acceleration being 3 dB less than the specification at frequencies below the first resonance at 17 Hz. This could have been avoided by not rolling off the force specification below 20 Hz.

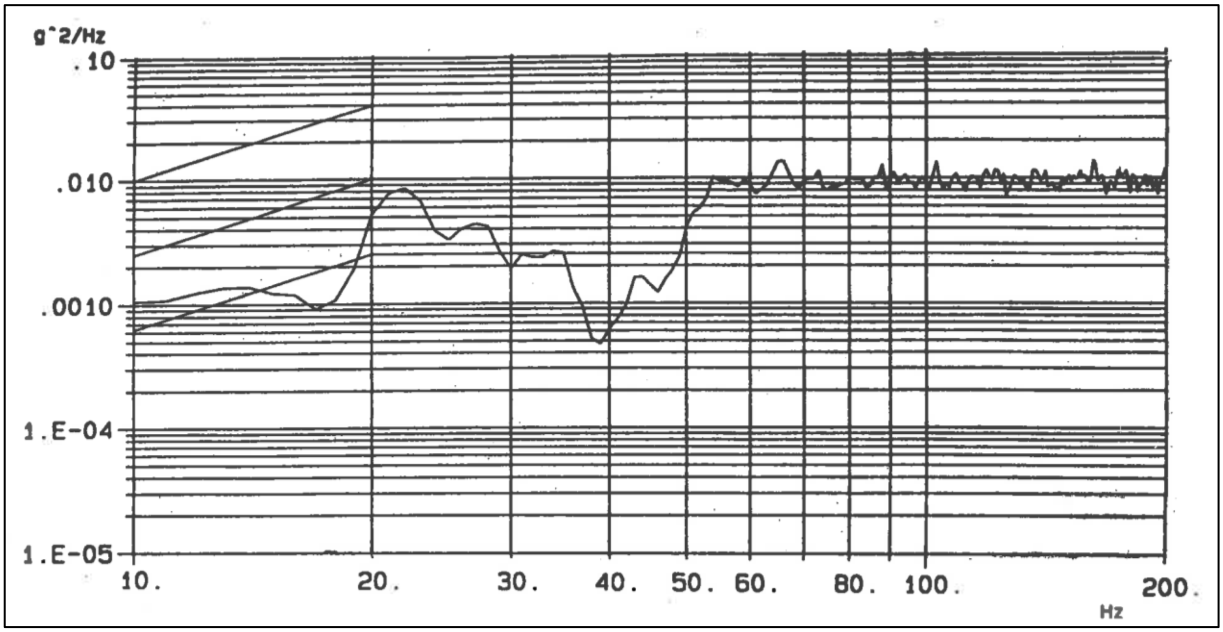

Figure 13—Acceleration Input in Cassini Flight Spacecraft Full-Level Random Vibration Test

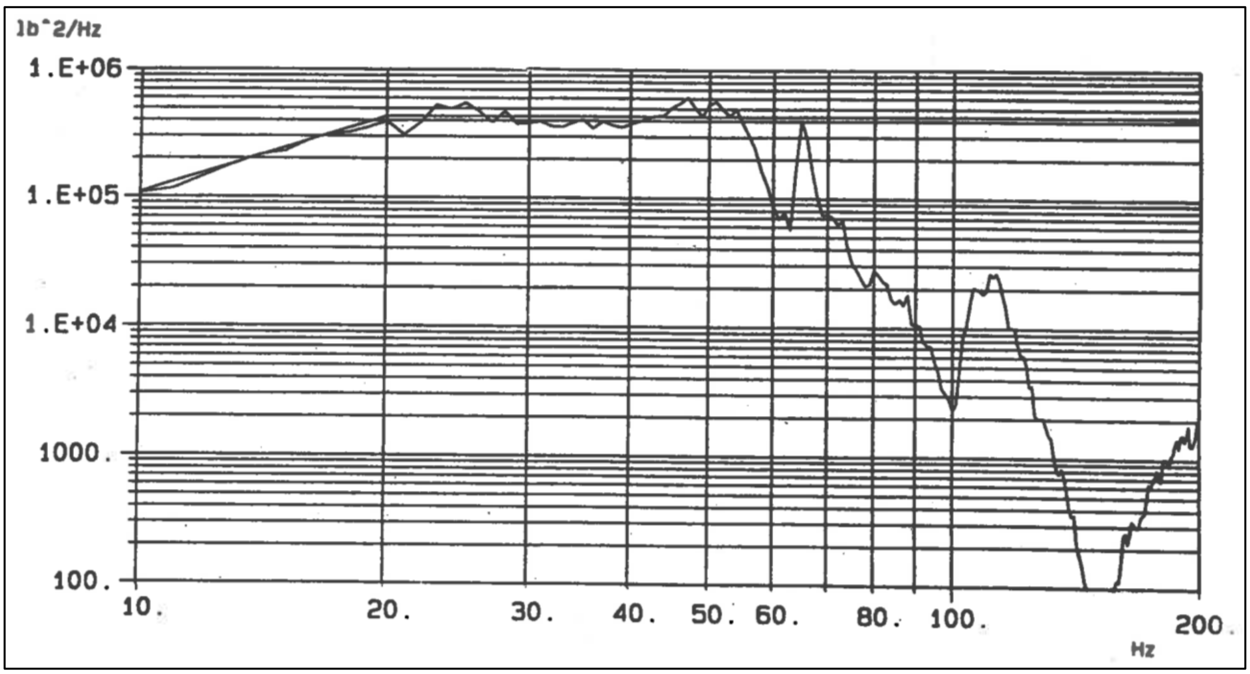

Figure 14—Total Vertical Force Measured in Cassini Flight Spacecraft Full-Level Random Vibration Test

Figure 15, Acceleration Inputs to Fields and Particles Pallet Instruments in Cassini Full-Level Random Vibration Test (Comparison with Instrument Random Vibration Test Specification), and figure 16, Acceleration Inputs to Remote Sensing Pallet Instruments in Cassini Full-Level Random Vibration Test (Comparison with Instrument Random Vibration Test Specification), show the acceleration inputs measured near the feet of a number of instruments mounted on the Fields and Particles Pallet and on the Remote Sensing Pallet, respectively. A comparison of the measured data with the random vibration test specifications for the instruments mounted on these pallets, which specifications are also indicated in figures 15 and 16, shows that many of the instruments reached their instrument build-level random vibration test specifications during the spacecraft vibration test. In addition, several major components of the spacecraft, including the Huygens probe upper strut, the three RTGs, the magnetic canister struts, and the Fields and Particles Pallet struts, reached their flight limit loads during the spacecraft vibration test. The only anomaly after the test was that the electrical resistance between the engineering model RTG and the spacecraft structure measured after the test was found to be less than that specified. This interface problem was uncovered only in the system vibration test, in spite of extensive vibration testing of the engineering model RTG by itself, as shown in figure 9. The insulation between the RTG adapter bracket and the spacecraft was redesigned to correct this problem.

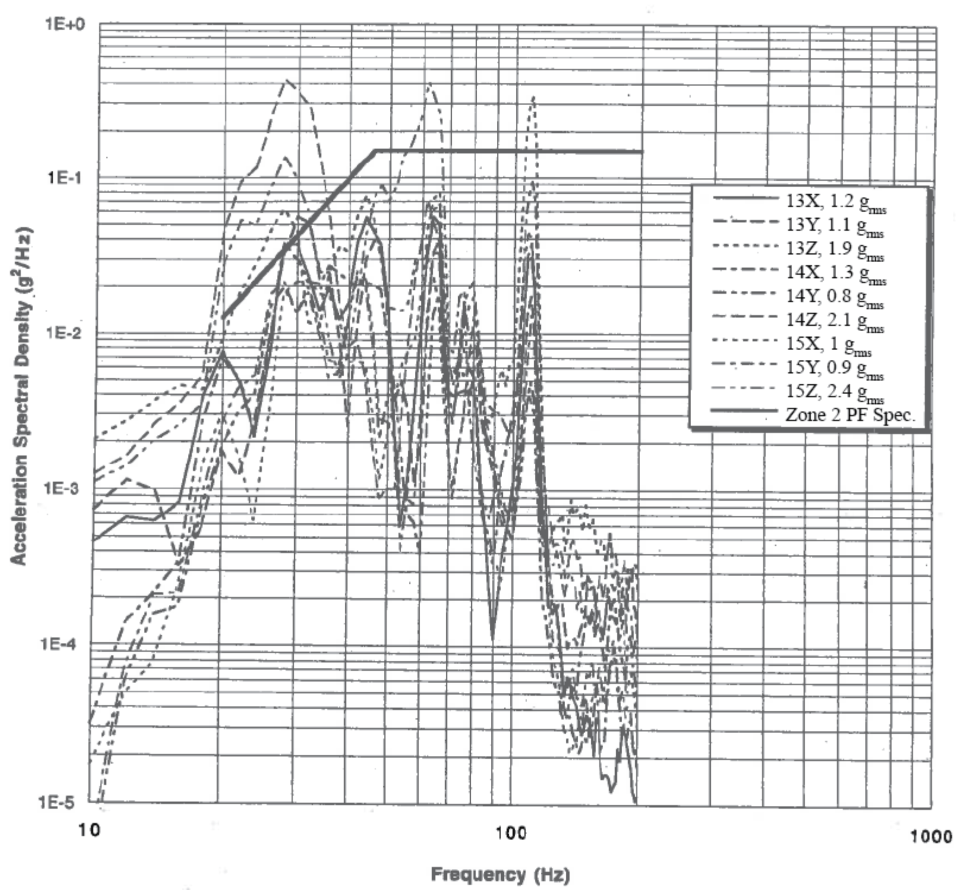

Figure 15—Acceleration Inputs to Fields and Particles Pallet Instruments in Cassini Full-Level Random Vibration Test (Comparison with Instrument Random Vibration Test Specification)

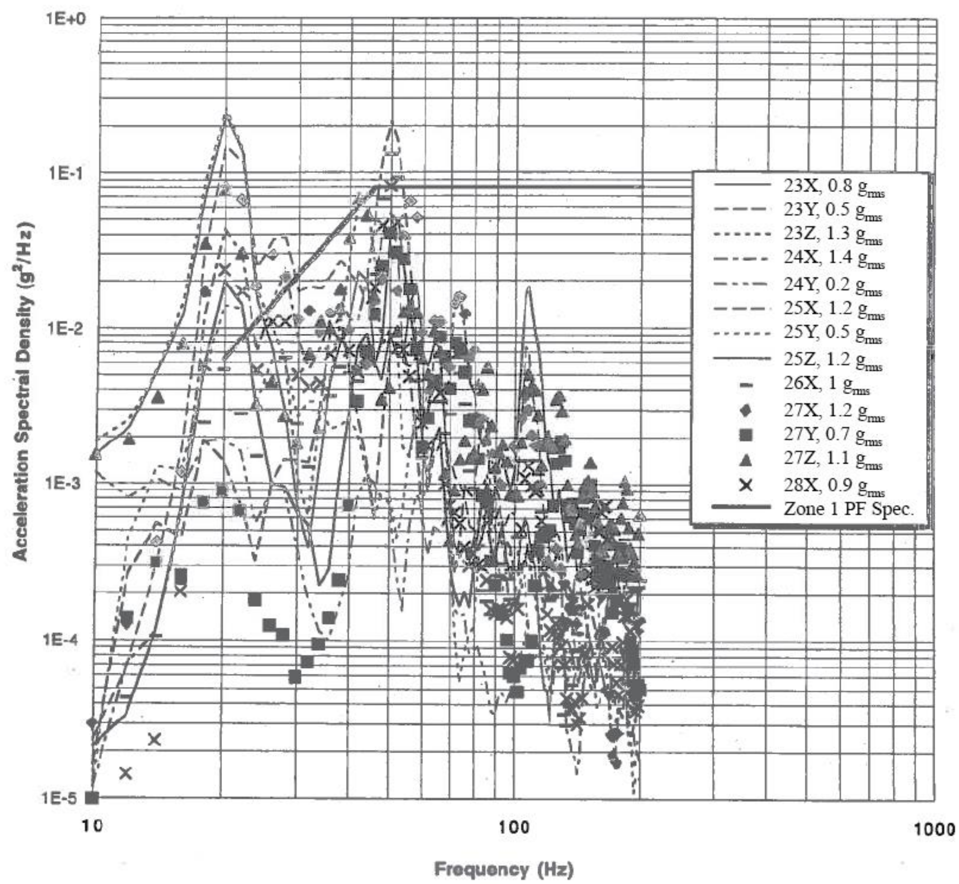

Figure 16—Acceleration Inputs to Remote Sensing Pallet Instruments in Cassini Full-Level Random Vibration Test (Comparison with Instrument Random Vibration Test Specification)

APPENDIX B

CASE HISTORY OF MARS EXPLORATION ROVER SPACECRAFT VIBRATION TESTING

B.1 Purpose and/or Scope

The purpose of this appendix is to provide guidance in the form of a case history of the MER spacecraft vibration testing. The reference for this appendix is included in section 2 of this Handbook.

B.2 MER Spacecraft Vibration Testing

NASA's twin robot geologists, the Mars Exploration Rovers, launched toward Mars on June 10 and July 7, 2003, in search of answers about the history of water on Mars. They landed on Mars on January 3 and January 24, 2004. The two MER spacecraft were designed, built, tested, and managed by JPL for NASA. Vibration tests of the MER Flight #1 Spacecraft were conducted at JPL in October 2002. Tests were conducted in each of three mutually perpendicular axes, which corresponded to the spacecraft coordinate system axes, starting with the vertical Z axis test and continuing with the lateral X and then the Y axes tests. Figure 1 in this Handbook shows the spacecraft mounted on the shaker for the vertical Z axis vibration test. In figure 1, the MER Flight #1 Rover and Lander are inside the conical-shaped, white MER Aeroshell (needed for entry into the Martian atmosphere), shown at the top of the spacecraft stackup. The large diameter cylindrical ring below the Aeroshell is the MER Cruise Stage, which is required for the journey from Earth to Mars. The small white cylinder below the Cruise Stage is the launch vehicle adapter (LVA), and the grey cylinder below the LVA is the PAF supplied by the launch vehicle provider. The weight of the forgoing elements was approximately 986 kg (2,174 lb). The shaker fixture incorporates eight large tri-axial force gages sandwiched between a fixture adapter plate and a lower ring, which sits on top of the head expander (grey) supported by the shaker body (white). The weight of the fixture adapter plate used to interface the PAF to the force gages was approximately 103 kg (227 lb), so that the total weight on the force gages was approximately 1,089 kg (2,401 lb). A total of 137 accelerometers mounted at various positions on the spacecraft measured and recorded the spacecraft response during the test (Scharton and Lee, 2003).

The primary objective of the MER spacecraft random vibration test was to identify any hardware problems that might compromise the mission. The test served as a workmanship test of the assembled spacecraft and a qualification test of everything but the primary structure for the launch dynamic environments. A secondary objective was to provide validation of the FEM model submitted for the final CLA. However, it should be noted that, even though the base-drive vibration tests were sufficient to identify a consistent discrepancy between the measured and predicted frequencies of the three fundamental modes, the quality of the modal data obtained in these base-drive tests was not as accurate as that obtained in separate fixed-base modal tests using high-sensitivity accelerometers.

The instrumentation included two control accelerometers and two monitor accelerometers mounted to the fixture adapter plate in the axis of shake, plus two cross-axis accelerometers mounted to the fixture adapter plate in the two axes perpendicular to the axis of shake.

Before installing the flight hardware on the shaker, the test facility was checked out in both the axial and one lateral orientation by running a low-level random and the unnotched, full-level protoflight random vibration test, with a factor of two multiplier on PSD, using a 1,000-kg (2,200-lb) mass simulator with a CG height of 1.17 m (46 in). Unfortunately, however, the force gages were not present in the facility checkout. Ideally, all the fixturing and control instrumentation should be checked out and proof tested before installing the spacecraft on the shaker, and the control accelerometers should not be moved before the actual test.

The base acceleration specifications for the MER flight spacecraft vertical and lateral base-drive random vibration tests are shown in table 2, Vertical (Z Axis) Random Vibration Test Acceleration Input, and table 3, Lateral (X and Y Axes) Random Vibration Test Acceleration Input.

Table 2—Vertical (Z Axis) Random Vibration Test Acceleration Input

Frequency (Hz)	**PSD**
10 to 20	+6 dB/octave
20 to 200	0.01 g^2/Hz
Overall	1.4 g_{rms}

Durations: 30 sec for low-level and 1 minfor full-level test

Table 3—Lateral (X and Y Axes) Random Vibration Test Acceleration Input

Frequency (Hz)	**PSD**
10 to 30	+12 dB/octave
30 to 200	0.01 g^2/Hz
Overall	1.3 g_{rms}

Durations: 30 sec for low-level and 1 min for full-level test

The test levels were chosen so that the responses at the three fundamental frequencies would not exceed those predicted by the CLA and that the response of the Rover inside the Aeroshell would not exceed those measured previously in the Rover DTM vibration test.

The total force in each axis was limited to the values given in table 4, MER Flight #1 Spacecraft Random Vibration Test Force Limits (All Axes), which are based on the semi-empirical formula in NASA-HDBK-7004 with C equal to unity. In table 4, f_o is the first predominant resonant frequency in the axis of test.

Table 4—MER Flight #1 Spacecraft Random Vibration Test Force Limits (All Axes)

Frequency (Hz)	**Force Spectral Density**
10 to f_o	1.1×10^6 N^2/Hz (5.4×10^4 lb^2/Hz)
f_o to 200	-3 dB/octave, X and Y axes -6 dB/octave, Z axis

Low-level random surveys with the input specified in table 5, Low-Level Random Survey Acceleration Input, were performed periodically. As a minimum, random surveys were conducted before and after each axis of testing to assess the structural integrity of the test item. Additional random surveys were inserted in the test sequence at the discretion of the test director to assess the structural integrity after high responses or an observed anomaly. There was no force or response limiting in any of the low-level random survey runs.

Table 5—Low-Level Random Survey Acceleration Input

Frequency (Hz)	**PSD**
5 to 200	0.00005 g^2/Hz

Wideband: 0.1 g_{rms}; Duration: 4 min

In addition, some low-level, stinger-drive modal tests were conducted with the shaker translation and slip table bearings locked out to approximately fix the base of the spacecraft. Some additional, high-sensitivity modal accelerometers were installed for the modal tests.

Nominally, the sequence of runs in each axis was as follows, although deletion of some runs or the insertion of additional runs was sometimes done at the discretion of the test director:

- Low-level random signature survey.
- -18-dB random test with force limiting.
- -12-dB random test with force limiting.
- -6-dB random test with force limiting.
- Full-level random test with force limiting.
- Low-level random signature survey.

Figure 17, Ratio of the Base Reaction Force to Acceleration Input (Apparent Mass) in the Low-Level Z-Axis (Vertical) Random Vibration Test, shows the magnitude of the ratio of base reaction force to acceleration input (apparent mass) in the low-level random survey conducted before the Z-axis (vertical) random vibration test. The low-frequency asymptote is comparable to the total weight of 1,089 kg (2,401 lb), which provides an end-to-end calibration of the force gage for the vertical axis test set-up. The data show the first Z-axis resonance at approximately 46 Hz, which is to be compared with the pre-test FEM prediction of 40 Hz.

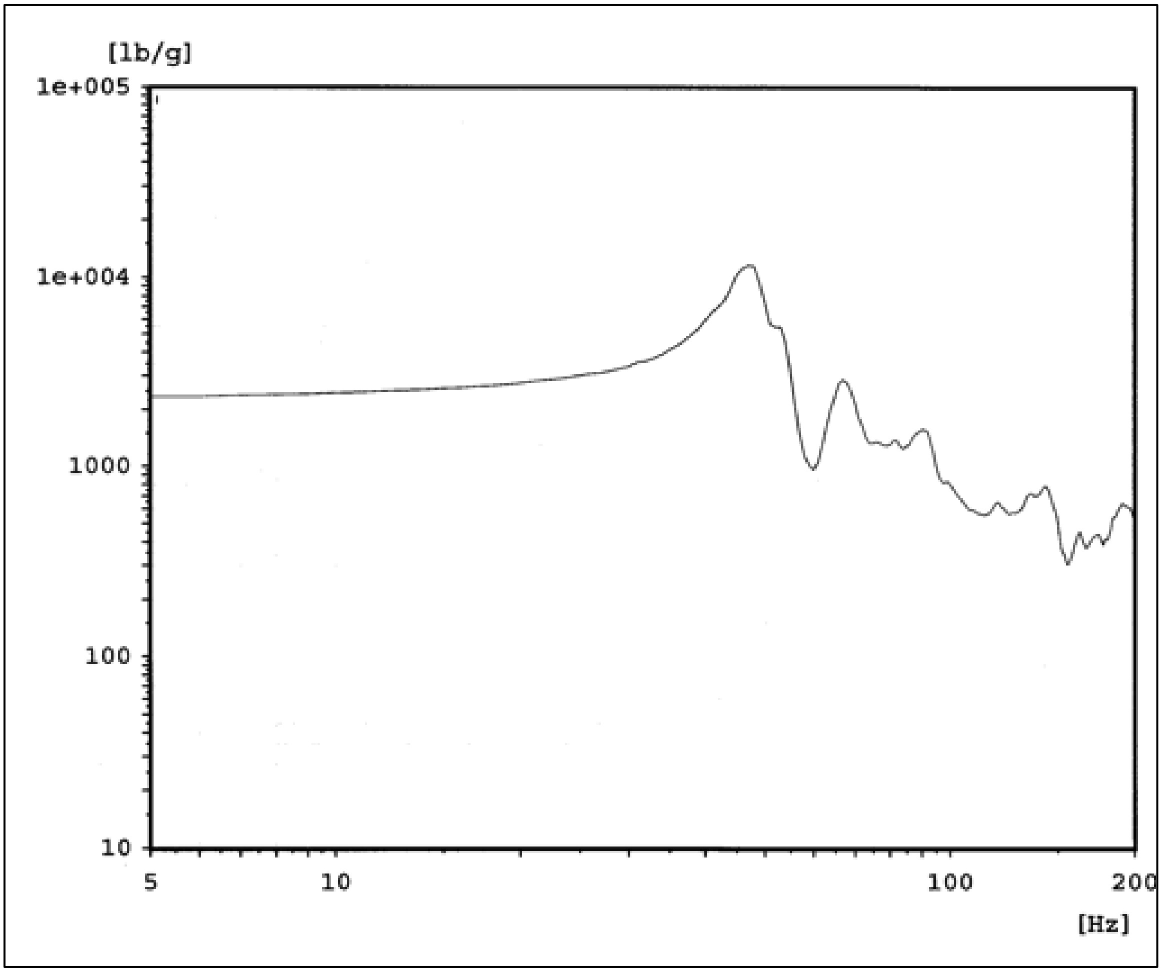

Figure 17—Ratio of the Base Reaction Force to Acceleration Input (Apparent Mass) in the Low-Level Z-Axis (Vertical) Random Vibration Test

Figure 18, Composite Control Acceleration in Full-Level Z-Axis (Vertical) Random Vibration Test, shows the composite control, the higher of the two control accelerometers in each frequency band, for the full-level (0-dB) Z-axis vertical random vibration test. (The tolerance band, ±3 dB, on the input acceleration is also shown.) Limiting the total force in the Z axis to the value specified in table 4 resulted in approximately 12 dB of notching at 46 Hz, i.e., at the frequency of the fundamental vertical axis mode of the MER flight spacecraft.

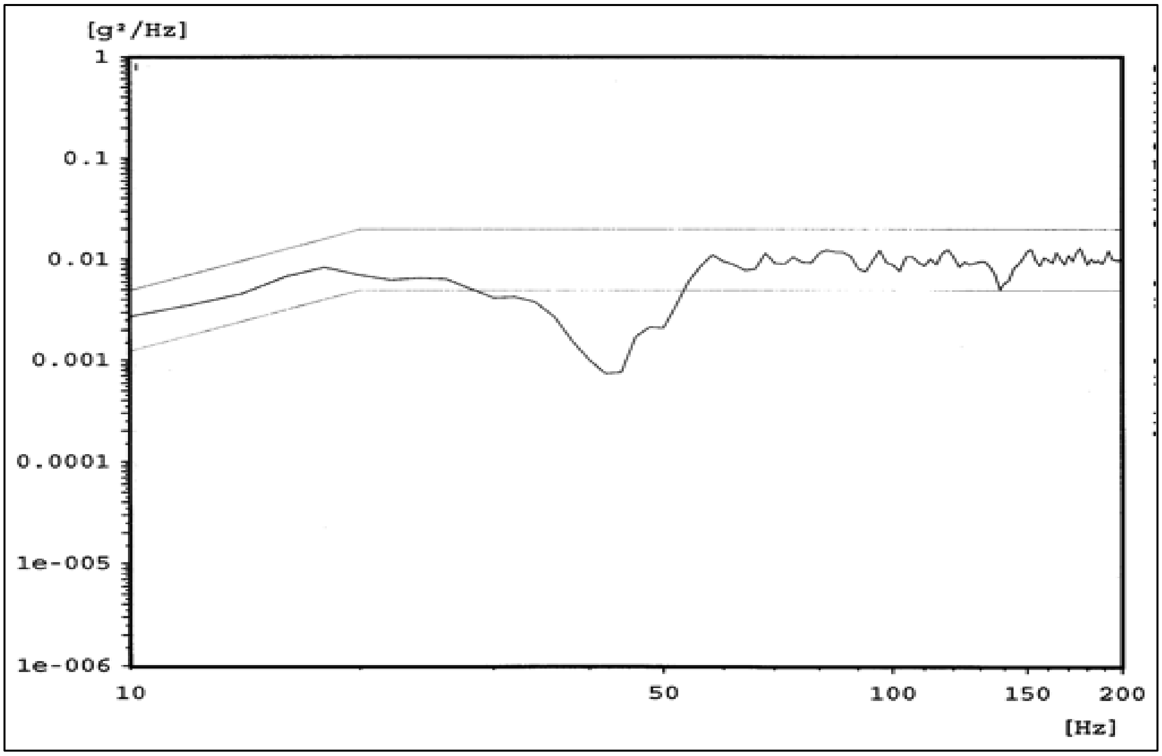

Figure 18—Composite Control Acceleration in Full-Level Z-Axis (Vertical) Random Vibration Test

Figure 19, Normal Direction Acceleration Response of the Rover -Y Solar Array in Full-Level Z-Axis (Vertical) Random Vibration Test, shows a normal direction response of the Rover -Y solar array in the full-level (0-dB) Z-axis vertical random vibration test. The maximum spectral density response of the solar array in the spacecraft vibration test was approximately 1 g^2/Hz at approximately 65 Hz, which considerably exceeds the maximum input vibration specification for the MER assembly build-level solar array vibration tests and the maximum response of the solar array in the acoustic test of the Flight #1 spacecraft, both of which were approximately 0.1 g^2/Hz. The larger response of the solar array at 65 Hz in the MER spacecraft vibration test than in the spacecraft acoustic test is an example of the general rule that, below 100 Hz, structures (in this case, even a light-weight solar panel) respond more in vibration tests than in acoustic tests. (See table 1 in this Handbook.)

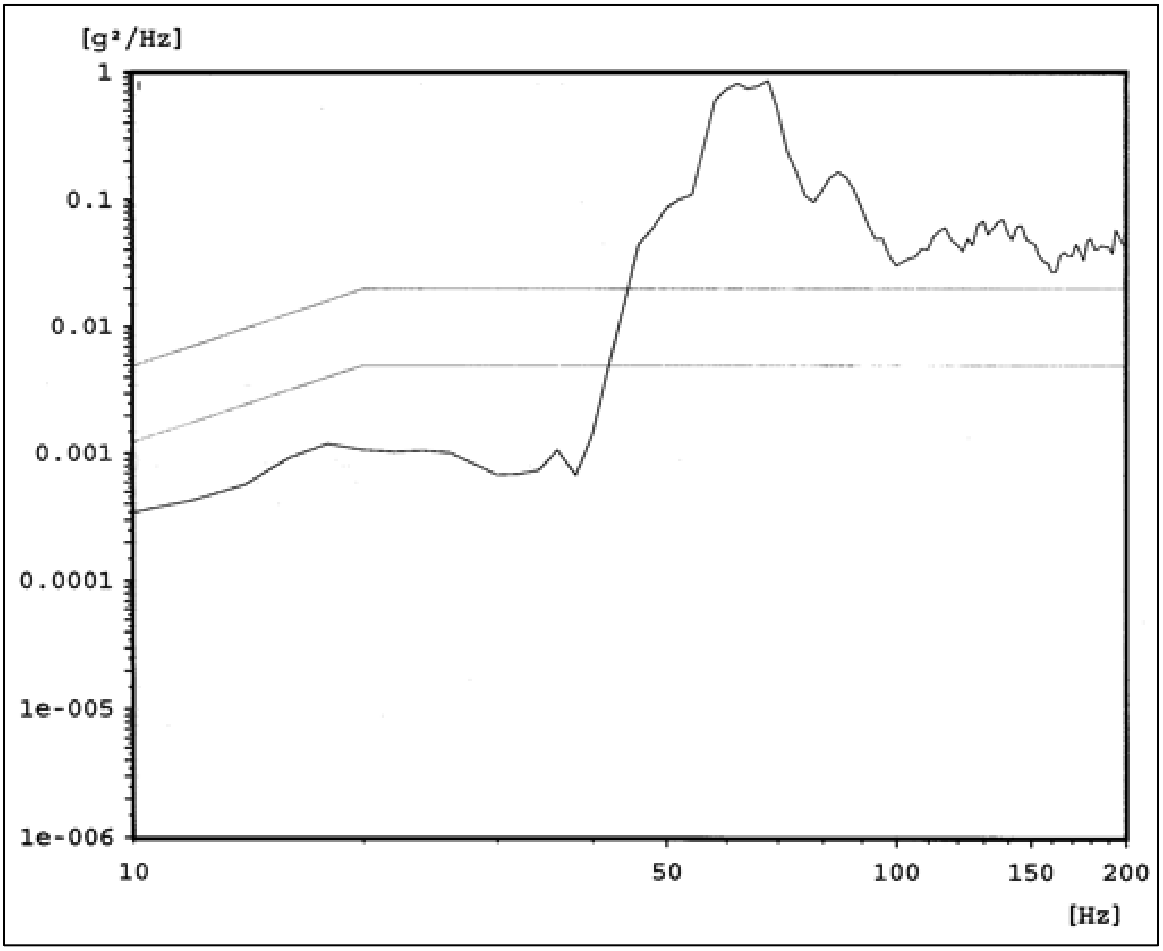

Figure 19—Normal Direction Acceleration Response of the Rover -Y Solar Array in Full-Level Z-Axis (Vertical) Random Vibration Test

Figure 20, In-Axis Acceleration Response of the Lander Base Petal in Full-Level Z-Axis (Vertical) Random Vibration Test, shows an in-axis acceleration response of the Lander base petal in the full-level (0-dB) Z-axis vertical random vibration test. Notice that in the 20 to 70 Hz frequency range, the base-petal response in this spacecraft test exceeds the 0.02 g^2/Hz input to the base petal in the Flight #2 Rover base-petal random vibration test, which was conducted subsequently.

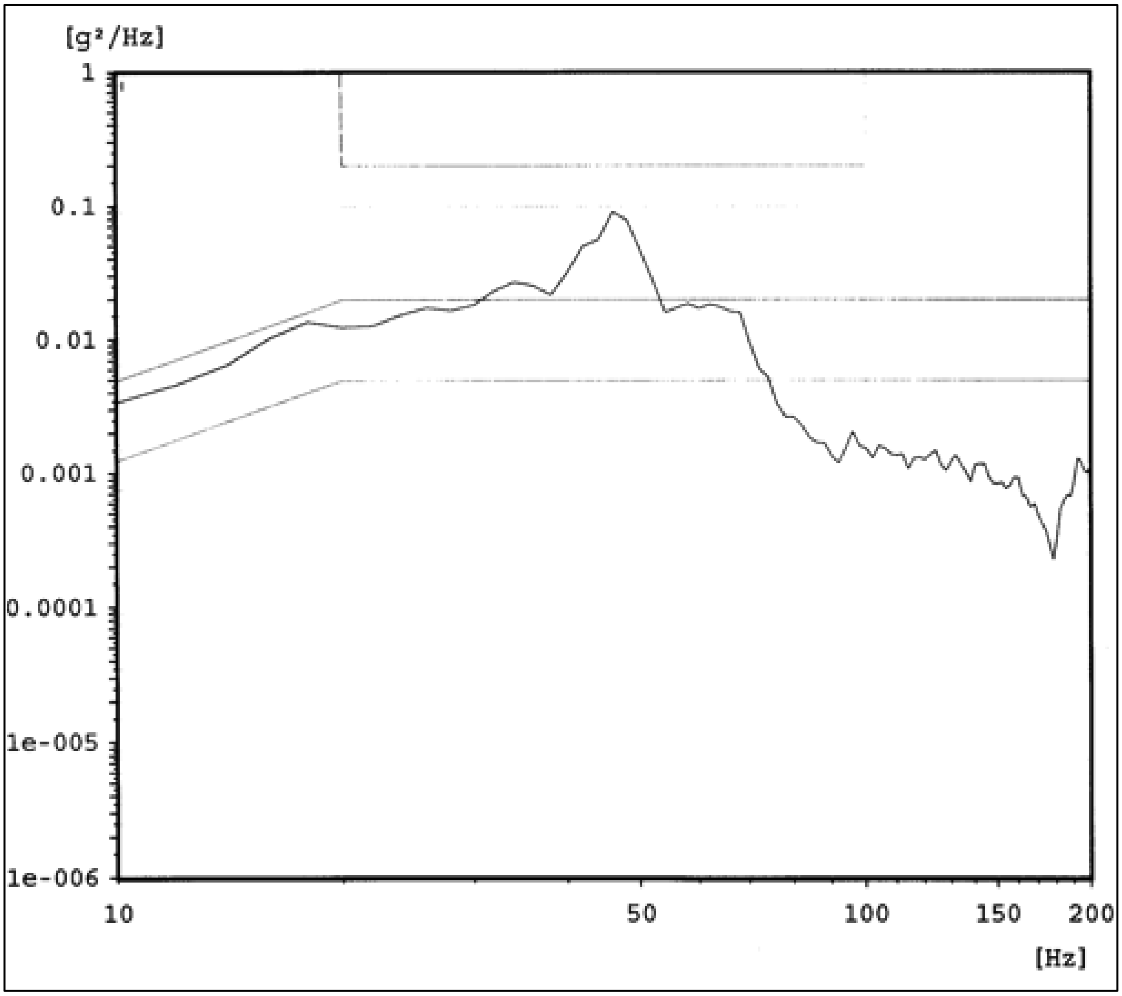

Figure 20—In-Axis Acceleration Response of the Lander Base Petal in Full-Level Z-Axis (Vertical) Random Vibration Test

Figure 21, Comparison of the In-Axis Force Measurements in the Pre-Test and Post-Test Z-Axis Low-Level Random Surveys, shows a comparison of the in-axis force measurements in the pre-test and post-test Z-axis low-level random surveys, which were conducted to assess the possibility of structural damage to the spacecraft during the high-level random vibration runs. The curves in figure 21 are the force PSDs measured with an acceleration input of 0.00005 g^2/Hz and should not be confused with information in figure 17, which is a force/acceleration transfer function. The pre-test and post-test plots in figure 21 were judged to be nominally identical, except for statistical variations, which are to be expected in a random vibration test, so the vibration testing of the spacecraft proceeded to the lateral axes.

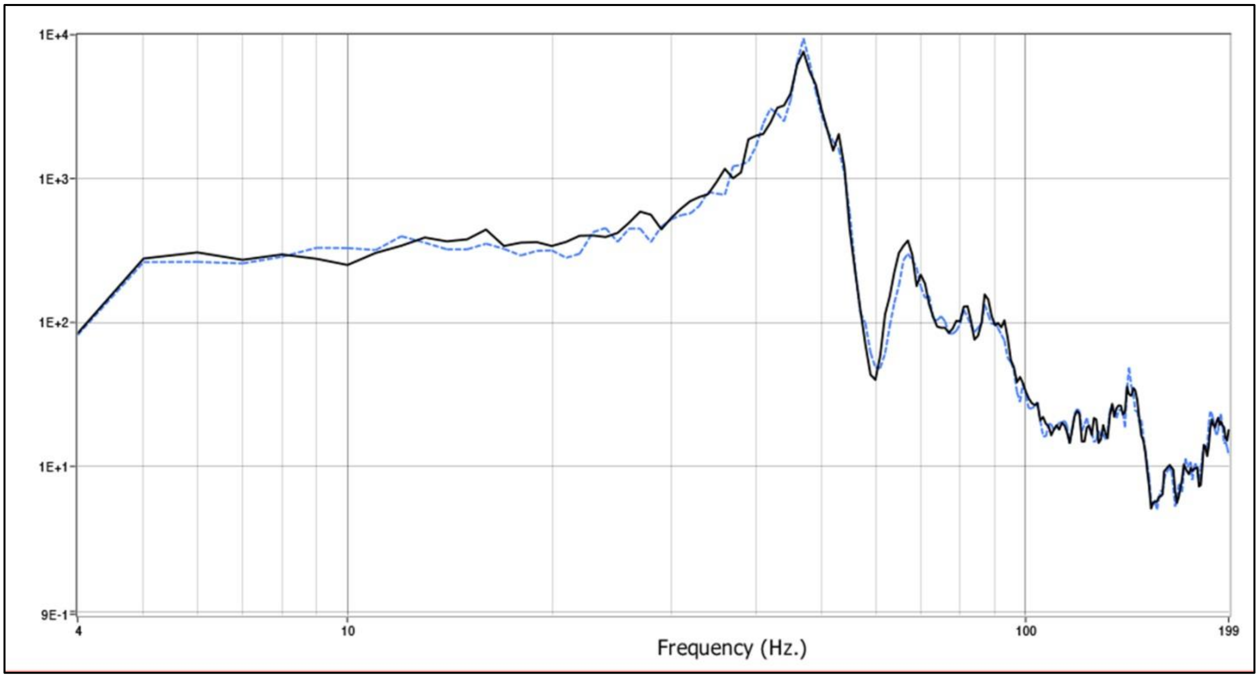

Figure 21—Comparison of the In-Axis Force Measurements in the Pre-Test and Post-Test Z-Axis Low-Level Random Surveys

Figure 22, Ratio of Base Reaction Force to Acceleration Input (Apparent Mass) in Low-Level X-Axis (Lateral) Random Vibration Test, shows the magnitude of the ratio of the base reaction force to acceleration input (apparent mass) in a low-level random survey conducted before the X-axis lateral random vibration test. The low-frequency asymptote is comparable to the total weight of 1,089 kg (2,401 lb), which provides an end-to-end calibration of the force gage setup for the X-axis test. The data show the first X-axis lateral resonance at approximately 16 Hz, which is to be compared with the pre-test FEM prediction of 14 Hz.

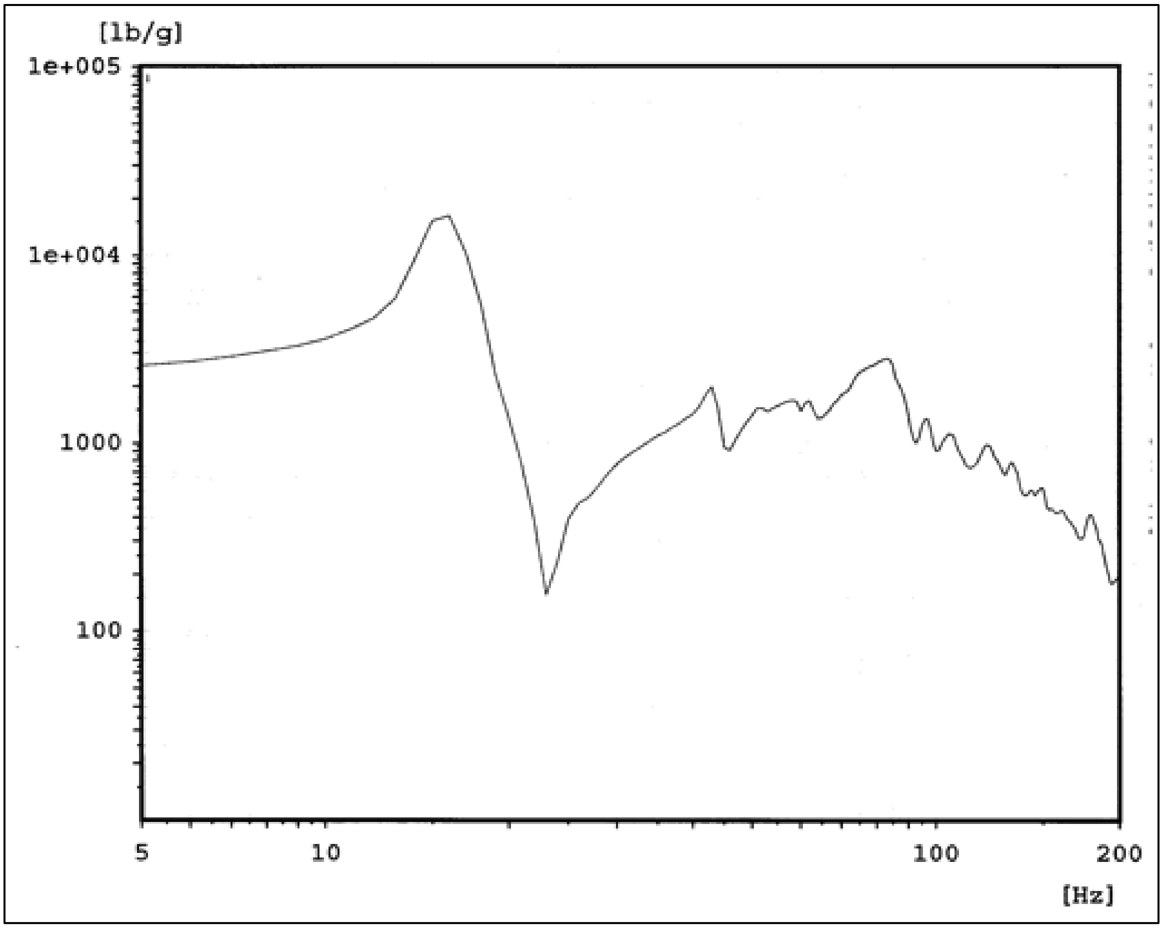

Figure 22—Ratio of Base Reaction Force to Acceleration Input (Apparent Mass) in Low-Level X-Axis (Lateral) Random Vibration Test

After the -18-dB X-axis run, the force limit specified in table 4 was reduced by a factor of two (3 dB) because the amount of notching was too little and the projected full-level responses were too high. Figure 23, Composite Control Acceleration in Full-Level X-Axis (Lateral) Random Vibration Test, shows the composite control, the higher of the two control accelerometers in each frequency band, for the full-level (0-dB) X-axis lateral random vibration test. Even with the reduced force limit, only about 3 dB of notching were obtained at the spacecraft fundamental resonance of 16 Hz, and in the mid-frequency range, from ~60 Hz to 120 Hz, where the Rover and its assemblies have resonance frequencies.

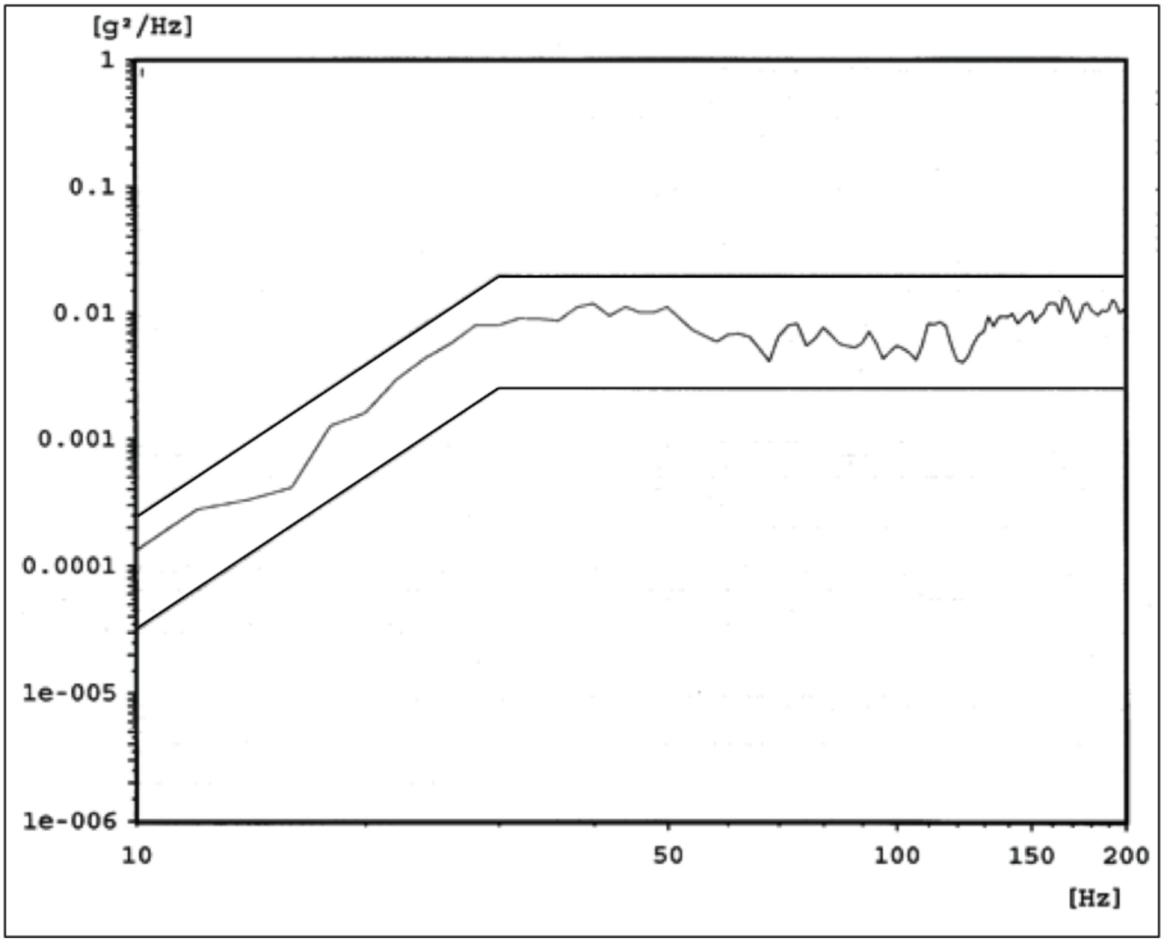

Figure 23—Composite Control Acceleration In Full-Level X-Axis (Lateral) Random Vibration Test

Figure 24, Time Histories of Selected Acceleration Responses in Full-Level X-Axis (Lateral) Random Vibration Test, shows the time histories of selected acceleration measurements in the full-level (0-dB) X-axis random vibration test. The time histories show high peaks (40 to 90 g), ragged waveforms, and high-frequency responses, all of which are characteristic of impacting.

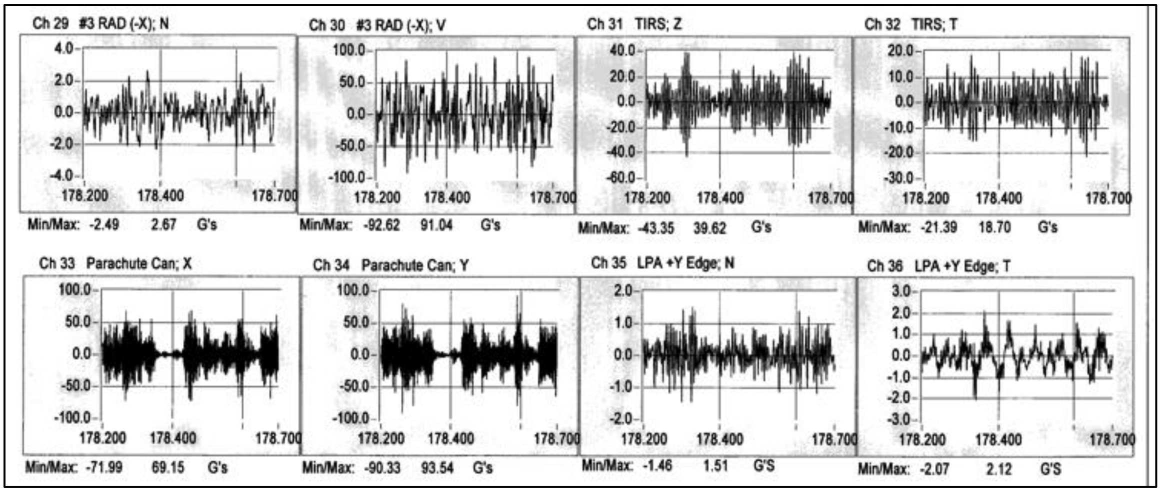

Figure 24—Time Histories of Selected Acceleration Responses in Full-Level X-Axis (Lateral) Random Vibration Test

Figure 25, Ratio of the Base Reaction Force to Acceleration Input (Apparent Mass) in the Low-Level Y-axis (Lateral) Random Vibration Test, shows the magnitude of the ratio of the base reaction force to acceleration input (apparent mass) in low-level random survey conducted before the Y-axis lateral random vibration test. The low-frequency asymptote is comparable to the total weight of 1,089 kg (2,401 lb), which provides an end-to-end calibration of the force gage axis setup for the Y-axis test. The data show the first Y-axis lateral resonance at approximately 17 Hz, which is to be compared with the pre-test FEM prediction of 14 Hz.

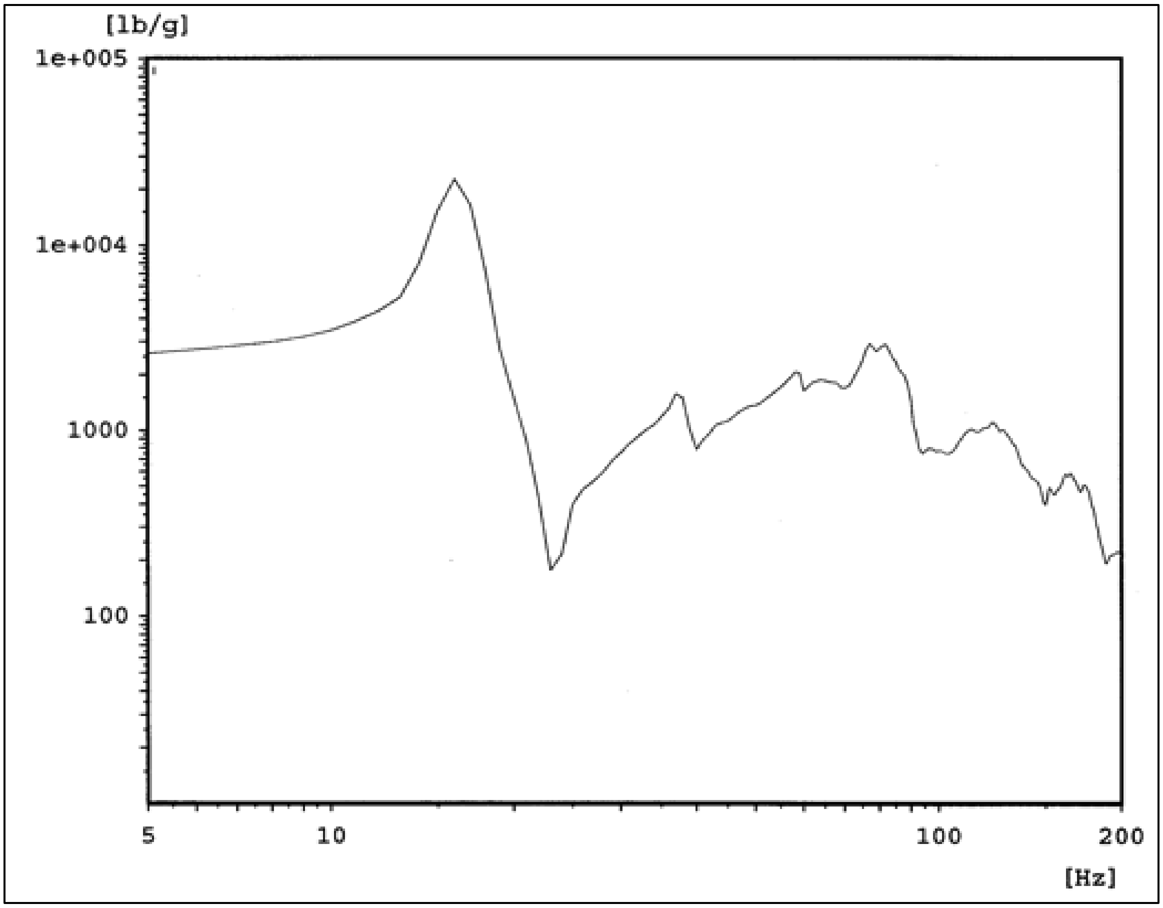

Figure 25—Ratio of the Base Reaction Force to Acceleration Input (Apparent Mass) in the Low-Level Y-Axis (Lateral) Random Vibration Test

The Y-axis lateral axis testing was curtailed after the -6-dB run, because it was felt that going to full level would not yield benefits sufficient to justify the risks and wear-and-tear associated with a second full-level lateral test. The reasons for this decision were fourfold:

1. Because of the high cross-axis response in the X-axis test, it was felt that the X-axis test provided most of the lateral modal data and lateral exercising of the structure and assemblies.

2. While random surveys showed hardware to be healthy, lack of visual confirmation because of the encapsulated payload added risk to hardware with little benefit.

3. Curious behavior of some critical channels added additional risk to continuing the testing.

4. Response of hardware in the -6-dB level Y-axis test was judged adequate for functional verification of hardware based on tests of other spacecraft, together with the consideration that full-level testing of the MER Flight #1 Spacecraft had been successfully conducted in the other two axes.

Figure 26, Composite Control Acceleration in Full-Level Y-Axis (Lateral) Random Vibration Test, shows the composite control, the higher of the two control accelerometers in each frequency band, for the -6 dB Y-axis lateral random vibration test. As in the high-level X-axis tests, the force limit specified in table 5 was reduced by a factor of two (3 dB). Even with the reduced force limit, only about 3 dB of notching was obtained at the spacecraft fundamental resonance of 16 Hz. A maximum notch of approximately 6 dB resulted in the 60-Hz to 120-Hz range, where the Rover and its assemblies have resonance frequencies. In general, the responses in the Y-axis lateral test were comparable to those in the X-axis lateral -6-dB test.

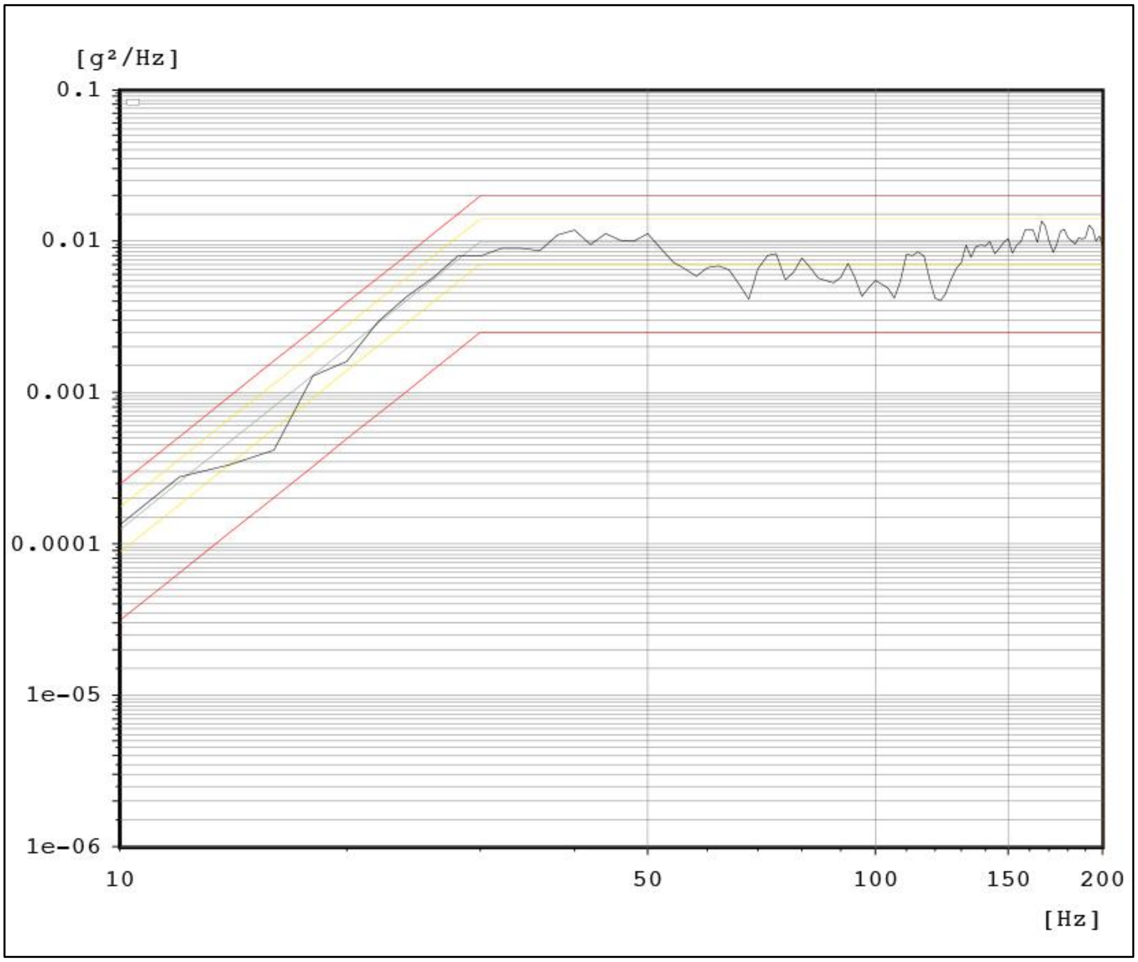

Figure 26—Composite Control Acceleration in Full-Level Y-Axis (Lateral) Random Vibration Test

In summary, the MER Flight #1 Spacecraft survived a vigorous three-axis random vibration test with no apparent damage. Overtesting was avoided by a combination of force limiting, and acceleration input shaping. No response limiting was utilized. The responses at some interfaces and assemblies exceeded the input in subassembly tests, even though the force specifications for the lateral axes tests were reduced 3 dB. Some of the time histories showed characteristics of impacts. The fundamental frequencies measured in all three axes were about 20 percent higher than predicted by the CLA FE model. Testing in the last of the three axes, the Y-axis lateral, was curtailed after the -6-dB run, because it was decided that the marginal benefit from a full-level run in the third axis was not sufficient to justify the risk and wear-and-tear of the flight hardware.

APPENDIX C

CASE HISTORY OF SWIFT OBSERVATORY SINE VIBRATION TESTING

C.1 Purpose and/or Scope

The purpose of this appendix is to provide guidance in the form of a case history of the Swift Observatory sine vibration testing. The references for this appendix are included in section 2 of this Handbook.

C.2 Swift Observatory Sine Vibration Testing

C.2.1 Swift Mission Overview

Swift is a first-of-its-kind multi-wavelength observatory dedicated to the study of gamma-ray burst (GRB) science. Its three instruments work together to observe GRBs and afterglows in the gamma-ray, X-ray, ultraviolet (UV), and optical wavebands. The main mission objectives for Swift are to:

- Determine the origin of GRBs.
- Classify GRBs and search for new types.
- Determine how the blastwave evolves and interacts with the surroundings.
- Use GRBs to study the early universe.
- Perform the first sensitive hard X-ray survey of the sky.

Swift discovers approximately 100 gamma ray 200 bursts per year. The Swift Observatory has the capability to view bursts that are ~3 times fainter than the Burst and Transient Source Experiment (BATSE) detector aboard the Compton Gamma-Ray Observatory. Swift's Burst Alert Telescope (BAT) detects and acquires high-precision locations for GRBs and then relays a 1- to 4-arc-min position estimate to the ground within 15 sec. After the initial burst detection, the spacecraft swiftly (~20 to 75 sec) and autonomously repoints itself to bring the burst location within the field of view of the sensitive narrow-field X-ray and UV/optical telescopes to observe afterglow. Swift can provide redshifts for the bursts and multi-wavelength lightcurves for the duration of the afterglow. Swift measurements are of great interest to the astronomical community, and all data products are available to the public via the internet as soon as they are processed. The Swift mission represents the most comprehensive study of GRB afterglow to date. The hardware was developed by an international team from the US, the United Kingdom, and Italy, with additional scientific involvement in France, Japan, Germany, Denmark, Spain, and South Africa. Figure 27, Swift Observatory in GSFC Clean Room, shows the fully integrated Swift Observatory

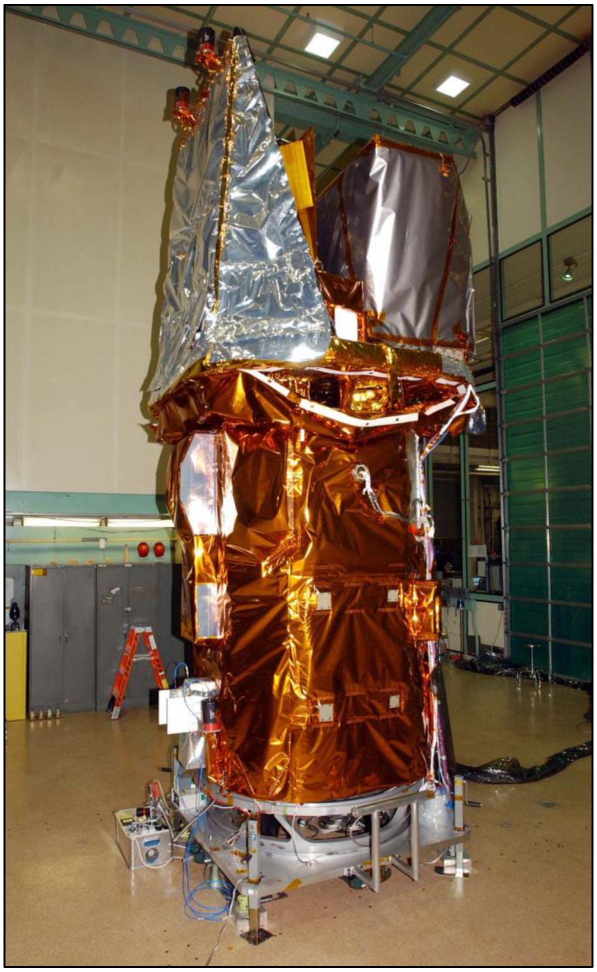

Figure 27—Swift Observatory in GSFC Clean Room

Swift is part of NASA's medium explorer (MIDEX) program. The satellite was launched into a low-Earth orbit on a Delta II 7320-10 rocket on November 20, 2004, from the Kennedy Space Center in Florida.

C.2.2 Test Configuration

The Swift Observatory in the test configuration was 5.4 m (17 ft 10 in) tall, including the Boeing-provided 6915 test PAF. The entire spacecraft fits within a 2.7-m (107 in) diameter envelope. The total weight of the test article was 1,575 kg (3,465 lb) including the 79-kg (174 lb) test PAF. The observatory was in full flight configuration with the exception of the BAT and associated electronics. These items were replaced with mass simulators, as the BAT instrument had electronics issues and was not available in time for the test. The BAT instrument was of sufficient size (~270 kg (~600 lbs)) that a high-fidelity simulator that emulated the mass properties and dynamic characteristics of the instrument was developed specifically for the Swift Observatory test. The flight blankets were installed for the test but were not fully closed out. The observatory had protective covers installed over the star trackers, and the entire observatory was double bagged during the test. The sine vibration test was conducted on the Ling C220 shaker in the north vibration cell (Building 7, Room 036) of the Goddard Space Flight Center (GSFC. Figure 28, Swift Observatory on Vertical Shaker, shows the Swift Observatory in the vibration cell with the shaker in the vertical position. Figure 29, Swift on Slip Table for Lateral Axis Test, shows the observatory being installed on the slip table for testing in the lateral axis.

Figure 28—Swift Observatory on Vertical Shaker

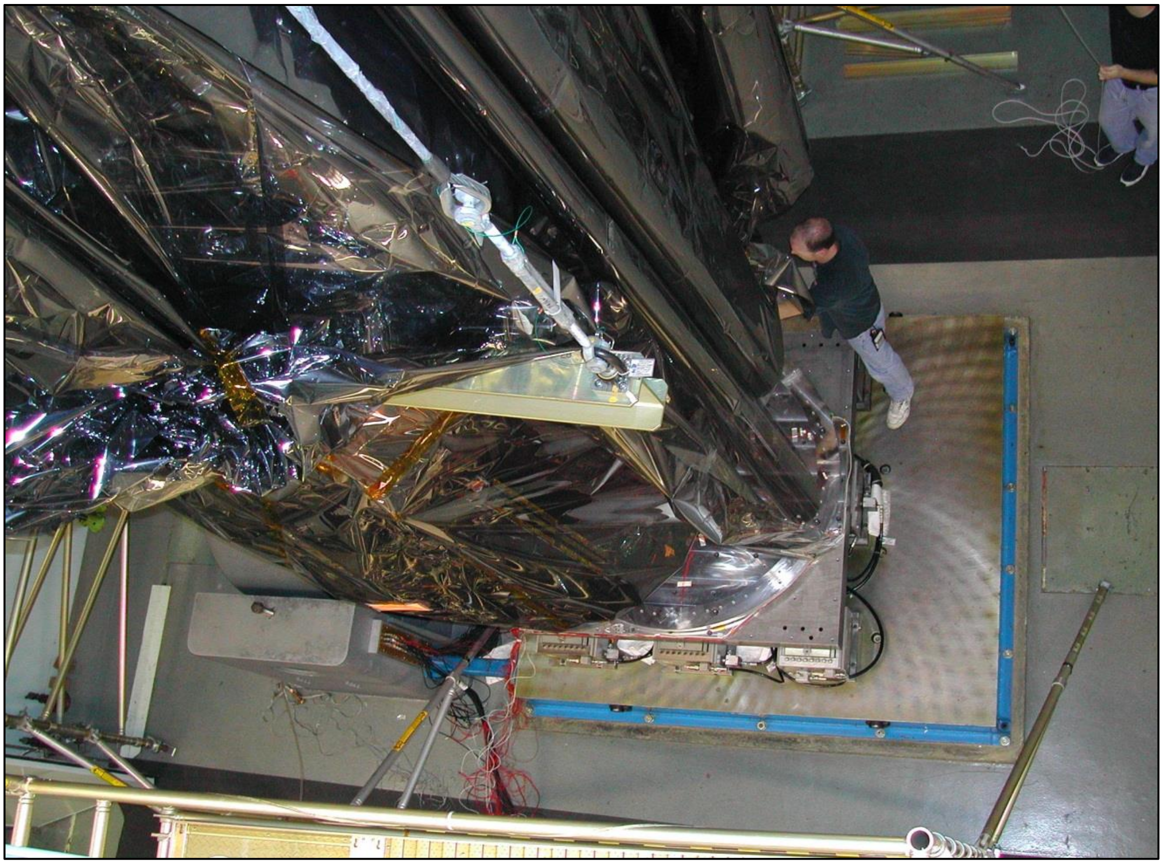

Figure 29—Swift on Slip Table for Lateral Axis Test

C.2.3 Test Objective

The purpose of the sine sweep testing performed on the Swift Observatory was to subject the as-built flight hardware to the low-frequency launch environment of the Delta II 7320-10 launch vehicle. Spacecraft-level sine vibration testing is performed for all GSFC missions as required under GSFC-STD-7000, General Environment Verification Standard, and GSFC-STD-1000, Goddard Open Learning Design (GOLD) Rules for Design, Development, Verification, and Operation of Flight Systems, which define the verification approach followed for all flight hardware. The sine test is used to both qualify the flight hardware for the low-frequency launch environment and to provide a workmanship screen for hardware that is sensitive to the mechanically transmitted vibration but that does not respond significantly to vibroacoustic input. This type of hardware, e.g., blankets, hoses, wiring harnesses, and mechanisms, cannot be easily analyzed and typically cannot be adequately tested at lower levels of assembly. After the test was complete, a full functional test of the observatory was performed to ensure that all systems functioned properly after being exposed to the low-frequency launch environment. The sine test as performed at GSFC was not considered a strength test, as all hardware must be strength qualified before being integrated into the observatory; rather, the sine test was considered a dynamic environments test in which functionality of the hardware was verified after being exposed to the appropriate vibration inputs.

C.2.4 Test Levels

GSFC has a long history of launching payloads on a Delta II launch vehicle. Fourteen payloads have flown on the Delta II launch vehicle since 1989. For all of these payloads, GSFC has developed mission-specific sine vibration environments based on a combination of CLA results and flight data for periods of sustained sine experienced by the Delta II during launch. All GSFC Delta II payloads have been sine tested from 5 to 50 Hz as is consistent with the frequency content of the CLA performed for this launch vehicle. GSFC sine vibration testing is limited to 50 Hz, based on the fact that the Delta II has no significant transient or sinusoidal launch events that are mechanically transmitted to the payload above 50 Hz and that the significant launch environments above 50 Hz are driven by the vibroacoustic environment, which is covered by acoustic testing of the flight observatory. Therefore, the approach that GSFC has used for observatory-level sine testing for the Delta II vehicle has been to test up to 50 Hz, consistent with the CLA frequency range, and to notch the test input to limit responses based on CLA results.

All GSFC payloads are treated as protoflight hardware so that sine testing is typically performed with a 1.25 test factor based on the MEFL. However, acceptance sine testing with a test factor of 1.0 may be performed if it can be shown that all hardware has been successfully qualified at either lower levels of assembly or by previous observatory testing as in the case of rework or testing of multiple similar spacecraft.

The test levels for Swift were derived based on a combination of CLA results and flight data. The method used to derive sine test levels based on CLA results is to take the time history data at the observatory interface and convert it to equivalent sinusoidal input through the use of the SRS technique. The SRS results are divided by the assumed Q to get the equivalent sine input for a single DOF system. For Swift, the time histories for the 32 cases were converted to equivalent sine using the above methodology and then enveloped to derive an observatory-level input spectrum. The envelope of the SRS/Q curves from the 32 lift-off cases is shown in figure 30, Swift Sine Vibration Test Levels, as a dotted line. A Q=20 (2.5 percent of critical damping) was assumed for Swift. This is a typical value used at GSFC for deriving sine specification inputs unless other damping data for the observatory are available.

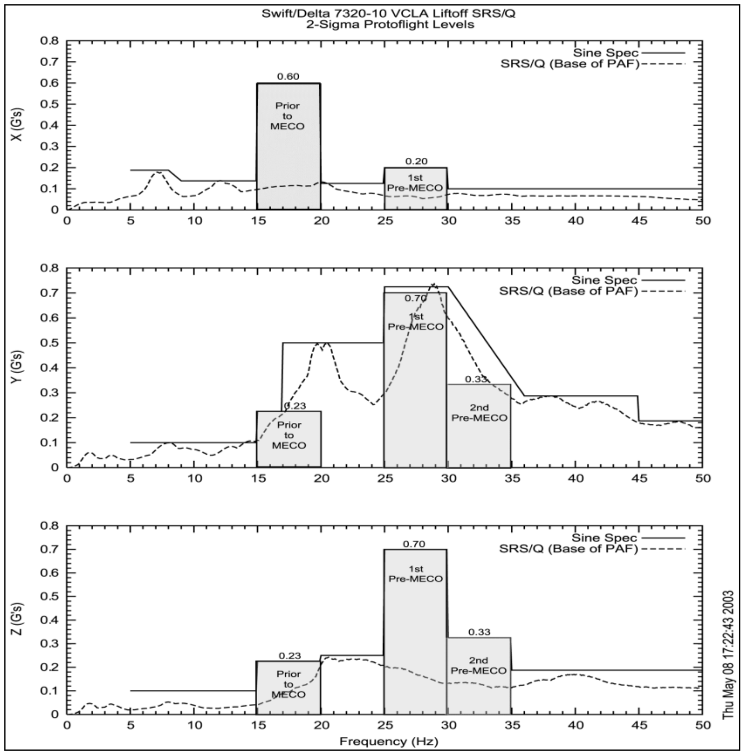

Figure 30—Swift Sine Vibration Test Levels

Once the CLA interface accelerations have been converted to equivalent sine, then the levels are adjusted to account for periods of sustained sinusoidal input from the launch vehicle. The Delta II experiences three events associated with main engine cutoff (MECO) having periods of sustained sinusoidal vibration. These events are the prior-to-MECO (~18 Hz), 1st Pre-MECO (~28 Hz), and 2nd Pre-MECO (~33 Hz). A 2-σ level (97.72/50) has been derived for each of these MECO events based on almost 35 Delta II flights, which is consistent with the statistical derivation for sinusoidal environments as defined in NASA-STD-7002. The peak 2-σ levels for the MECO events for the Delta II launch vehicle are shown in table 6, Delta II MECO Levels. The peak MECO levels defined in 5 Hz frequency bands are then added to the sine levels derived based on the CLA as described in the preceding paragraph.

Table 6—Delta II MECO Levels[1, 2]

Launch Event	**Frequency** (Hz)	**Thrust** (g, 0-peak)	**Lateral** (g, 0-peak)
Prior-to-MECO	15-20	0.48	0.18
1st Pre-MECO	25-30	0.16	0.56
2nd Pre-MECO	30-35	-----	0.26

Notes:

1. GSFC defines 2 σ as 97.7 percent probability with 50 percent confidence (97.7/50).
2. GSFC database includes all Delta II two-stage launches from flights 192 through 291.

The final sets of test levels for the Swift payload are shown in table 7, Swift Observatory Sine Vibration Levels, and also in figure 30 as a solid line. The levels shown in the figure are the protoflight levels used to test the spacecraft, which include the 1.25 test factor for protoflight qualification. It should be noted that a nominal sweep rate of 4 octave/min is used for the sine test, except in the 25- to 35-Hz range, where the sweep rate is slowed to 1.5 octave/min to more accurately replicate the duration of the pre-MECO events in flight.

Table 7—Swift Observatory Sine Vibration Levels

Axis	**Frequency** (Hz)	**Acceleration**[1] (g, 0 to peak)	**Sweep Rate** (octave/min)
Thrust (X)	5-8[2]	0.19	4
	9-15	0.14	4
	15-20	0.60	4
	20-25	0.13	4
	25-30	0.20	1.5
	30-35	0.10	1.5
	35-50	0.10	4
Lateral (Y)	5-15	0.10	4
	15-17	0.23	4
	17-25	0.50	4
	25-30[3]	0.73	1.5
	36-45	0.29	4
	45-50	0.10	4
Lateral (Z)	5-15	0.10	4
	15-20	0.23	4
	20-25	0.25	4
	25-30	0.70	1.5
	30-35	0.33	1.5
	35-50	0.10	4

Notes:

1. Above levels may be notched so observatory responses do no exceed 1.25 times the predicted flight limit loads as determined by CLA.
2. Linear acceleration transition from 0.19 g at 8 Hz to 0.14 g at 9 Hz.
3. Linear acceleration transition from 0.73 g at 30 Hz to 0.29 g at 36 Hz.

C.2.5 Instrumentation

The response instrumentation used for the Swift sine vibration test consisted of both force gages and response accelerometers. Strain gages were not used for this test. A total of 179 channels were patched into the dynamic data acquisition system (DDAS). The response channels included 4 triaxial-input monitors (12 channels), 8 force gages (24 channels), and 3 channels for the summed force in each axis. The remaining 140 channels were dedicated to response accelerometers located on the observatory. The response accelerometers were chosen to ensure that all critical areas on the observatory could be monitored during the test. Measurements at these locations would be used to notch the test so that the response of the hardware would not exceed either CLA predictions (times 1.25) or the known capability of the hardware. Additional accelerometer locations were selected to make sure that the vibration levels at all locations on the spacecraft could be characterized in the event that a problem was uncovered during post-test functional testing and it became necessary to evaluate the vibration levels experienced by a particular item of spacecraft hardware.

In addition to measuring the loads at each of the individual force gages and the force sums in the DDAS, the interface moments were also measured. The interface moments were calculated as a post-processing step at the completion of each test run based on the data for each of the individual force gages and their geometric location around the interface bolt circle. Figure 31, Force Gage Placement for Swift Sine Test, shows the force gage placement and the equations used to calculate the overturning moments at the test article interface to the shaker table. The force gages were sandwiched between a PAF jnterface ring and the vibration plate, which mounts to either the shake head expander in the vertical direction or to the slip table in the lateral directions. The overall test configuration for the Swift sine vibration test, including force gages, is shown in figure 32, Swift Observatory Test Configuration.

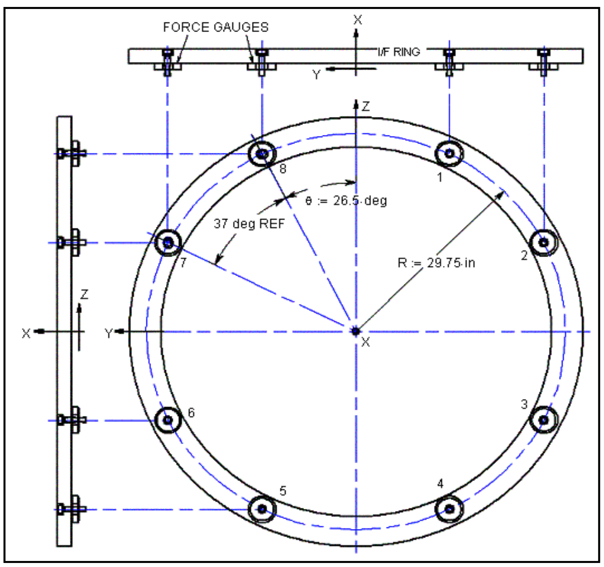

Figure 31—Force Gage Placement for Swift Sine Test

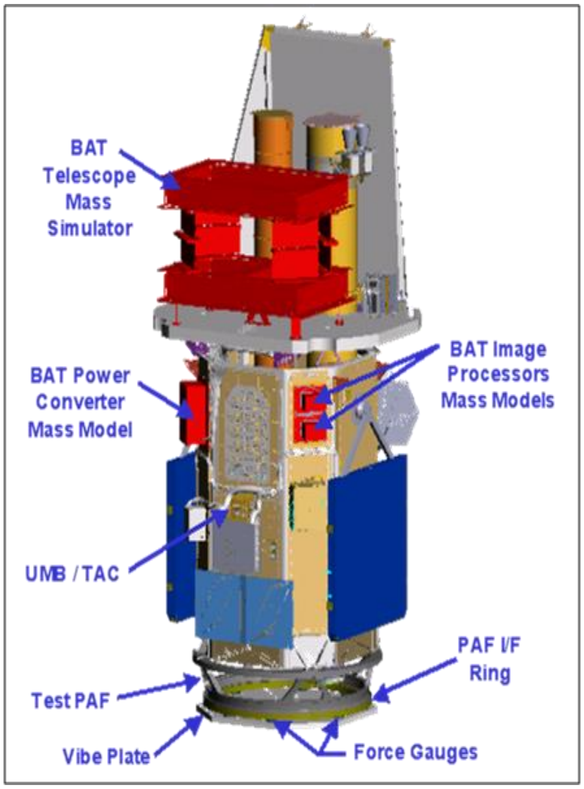

Figure 32—Swift Observatory Test Configuration

Two in-axis control accelerometers mounted to the vibration plate were used to control the test. A maximum control scheme was used in which the highest responding control accelerometer would control the test. In addition to the in-axis control accelerometers, eight cross-talk monitors were patched into the control system to allow the cross-axis inputs to be measured in real time, although these were not used for control. In addition, for each axis of the test a subset of the response accelerometers was patched into the control system for use as response limiters and abort accelerometers. The response limits were used to control the test input to ensure that specific areas of the Swift Observatory would not see acceleration levels that exceeded 1.25 times the CLA predictions for those locations. The location and levels of the abort accelerometers were selected to shut the test down if the input levels were going to result in loads that would exceed the known capability of the hardware based on either subsystem-level testing or analysis.

C.2.6 Test Flow and Notching Criteria

Each axis of the Swift sine test followed the same basic flow. Each axis started with a signature sine sweep. The signature sweep was run at 0.05 g from 5 to 150 Hz at 4 octave/min. This was then followed by one-quarter, one-half, and full-level runs with the shaped input spectrum. After the full-level run was completed, the signature sweep was repeated. The signature sweep runs were performed with the full-level limits and aborts in place. The one-quarter and one-half level sweeps were performed with the response limits and abort limits scaled proportionally to the input level. After completion of the intermediate level runs, the data were reviewed to determine if any changes were required to the input, response, or abort limits and to track the measured responses scaled to the full-level input to determine if any limits would be exceeded. After completion of the full-level test, the signature sweep was rerun and compared with the pre-test signature sweep run to determine if there were any significant differences, such as frequency shifts or amplitude changes, that would indicate damage.

Before the start of all observatory dynamic testing (sine and acoustic), the Swift Observatory underwent a full comprehensive performance test (CPT) to ensure that all systems were working properly. Between each axis of test (before changing from one axis to another), limited performance testing and aliveness testing was performed to verify that no obvious damage had been sustained by the observatory. Another full CPT was performed after completion of all dynamic testing before entering thermal vacuum testing.

The primary goal of the test instrumentation was to monitor critical areas during the test to allow for notching to prevent overtest and to measure observatory responses for comparison with known capability based on subsystem level testing and analysis. The control strategy used during the Swift sine vibration test was to control the input to the observatory so that the loads generated at critical interfaces did not exceed 1.25 times the predicted flight loads. The critical interfaces identified for Swift were the base of the PAF, the Instrument Module interface with the spacecraft bus, the interfaces of the major instruments (BAT, X-Ray Telescope (XRT), and Ultraviolet/Optical Telescope (UVOT), sunshade interface, and solar array interface. For the base of the PAF, the force gages were used to calculate the RSS bending moment at the observatory interface to the PAF by post-processing the normal forces at each mounting location after completion of each run and manually reducing the input level as necessary to limit the root sum square (RSS) moment to 1.25 times CLA predictions. For the other critical interfaces, several accelerometer locations were identified to track critical interface forces based on the ratio of measured acceleration to force based on the analytical model. These accelerometers were input into the control system as limit channels. All accelerometers that were in the control loop were bolted on or were located at redundant accelerometer locations so that the hardware would not be in jeopardy if a control accelerometer failed. For other locations that could not be bolted onto the hardware, manual notching was used. For all response locations that were put into the control loop, an abort level was set at 1.4 times (3 dB) the limit value, with the exception of the interface moments which were set at 1.15 times the limit level for added protection. Table 8, Sine Limits for Each Axis of Sweep, shows the accelerometer channels that were in the control loop for real-time response limiting for the Swift sine vibration test and the corresponding limit and abort levels that were used. Dashed lines in the table indicate that a limit was not set for that response channel for a particular axis of input. The limits shown in table 8 were derived based on pre-test analysis which simulated the protoflight-level sine sweep and related acceleration response to interface loads at critical locations. In addition, after the completion of each run, all accelerometers were checked against pre-defined allowables to ensure that no channel would significantly exceed either the as-tested capability or the known design capability of the hardware.

Table 8—Sine Limits for Each Axis of Sweep[1]

Location Identification	Description	Direction	X Sweep	Y Sweep	Z Sweep
301 X	Force Sum	X	4,943 kg (10,875 lb)	-----	-----
301 Y	Force Sum	Y	-----	3,007 N[4] (6,615 lb)	-----
301 Z	Force Sum	Z	-----	-----	3,007 N [4] (6,615 lb)
91	Top of BAT Sim (-Y -Z)	X	2.8 g	-----	-----
		Y	-----	3.3g/2.8 g[2,4]	-----
		Z	-----	5.4 g	3.6 g[4]
77	XRT/FPCA	X	3.3 g	-----	-----
		Y	-----	-----	5.3 g
		Z	5.5 g	4.5 g	5.5 g
83	XRT Door	X	3.3 g	-----	-----
		Y	-----	4.2 g	-----
		Z	2.5 g	-----	3.8 g
75	UVOT Door	X	3.6 g	-----	-----
		Y	-----	4.2 g/5.4 g[3]	4.7 g
		Z	-----	3.9 g	3.9 g
78	Sunshade +Y Antenna	X	3.8 g	-----	-----
		Y	-----	9.0 g	10.6 g
		Z	-----	10.0 g	11.7 g
42	Solar Array Outer Corner +Y	Y	-----	15 g	-----
54	Radiator +Y Upper	Z	-----	7.9 g	-----

Notes:

1. Aborts should be set at 1.4 times the above limits unless otherwise noted.
2. Limit set at 3.3 g from 5 to 15 Hz and 2.8 g from 15 to 50 Hz.
3. Limit set at 4.2 g from 5 to 15 Hz and 5.4 g from 15 to 50 Hz.
4. Abort set at 1.15 times limit.

C.2.7 Test Results

All three axes of test were completed successfully for the Swift Observatory. Specific results from each of the axes are discussed in the following paragraphs.

The lateral Y-axis was run first. Figure 33, Swift Y-Axis Force Sum for the 0-dB Sine Run, shows the in-axis force sum measured during the full-level test. The fundamental mode of the observatory can be seen from the data at 9.6 Hz. Comparison of the pre-/post-signature sweep data showed good agreement in general. However, review of the signature data for the accelerometer located at the XRT door for the cross-axis response in the X and Z directions showed significant differences between the pre- and post-signature runs. Figure 34, Signature

Comparison at XRT Door (X Response, Y Input), shows the signature overlay for the X-axis response at the XRT Door location. The difference in the signature responses indicates a possible change in the XRT door related to the full-level Y-axis input. The manufacturer of the hinge and latch mechanisms, was consulted regarding the change in test data. The company noted that small clearances in the hinge and latch mechanisms to allow for thermal expansion are the reason for the change in vibration signatures. It was determined that it was safe to proceed with the remainder of the sine vibration testing. Post-test deployment of the door confirmed that the door survived the sine test without damage.

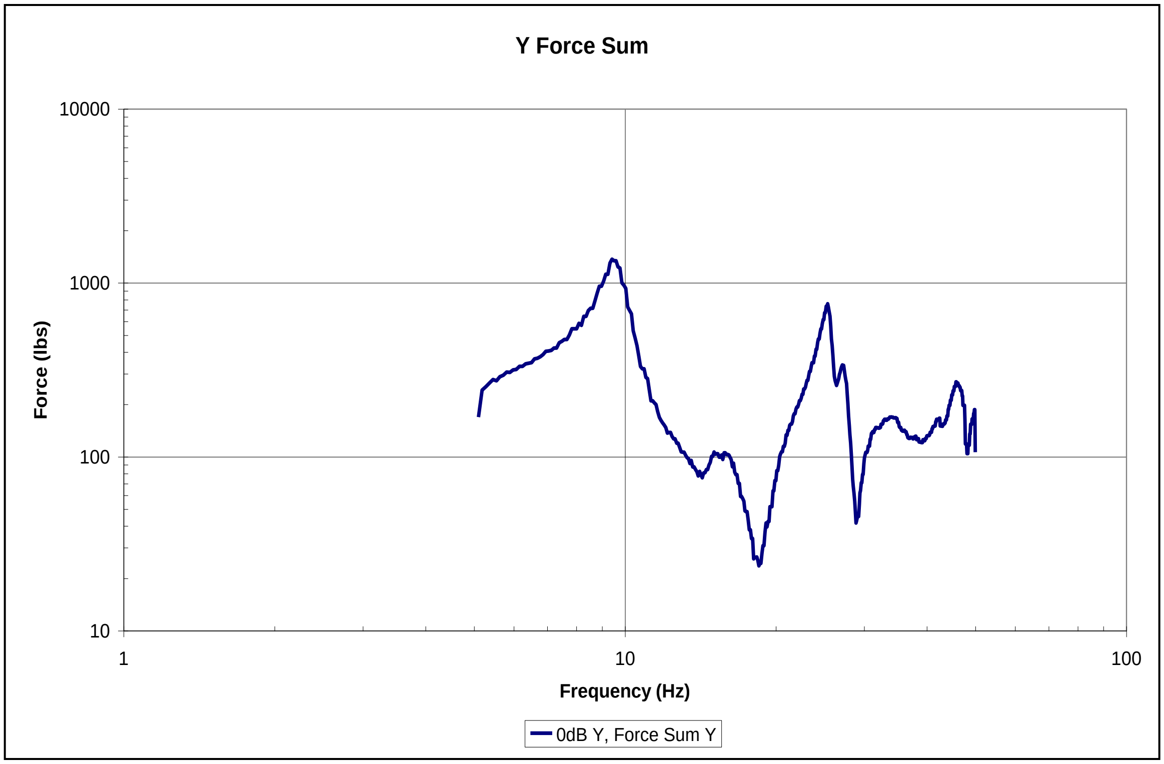

Figure 33—Swift Y-Axis Force Sum for the 0-dB Sine Run

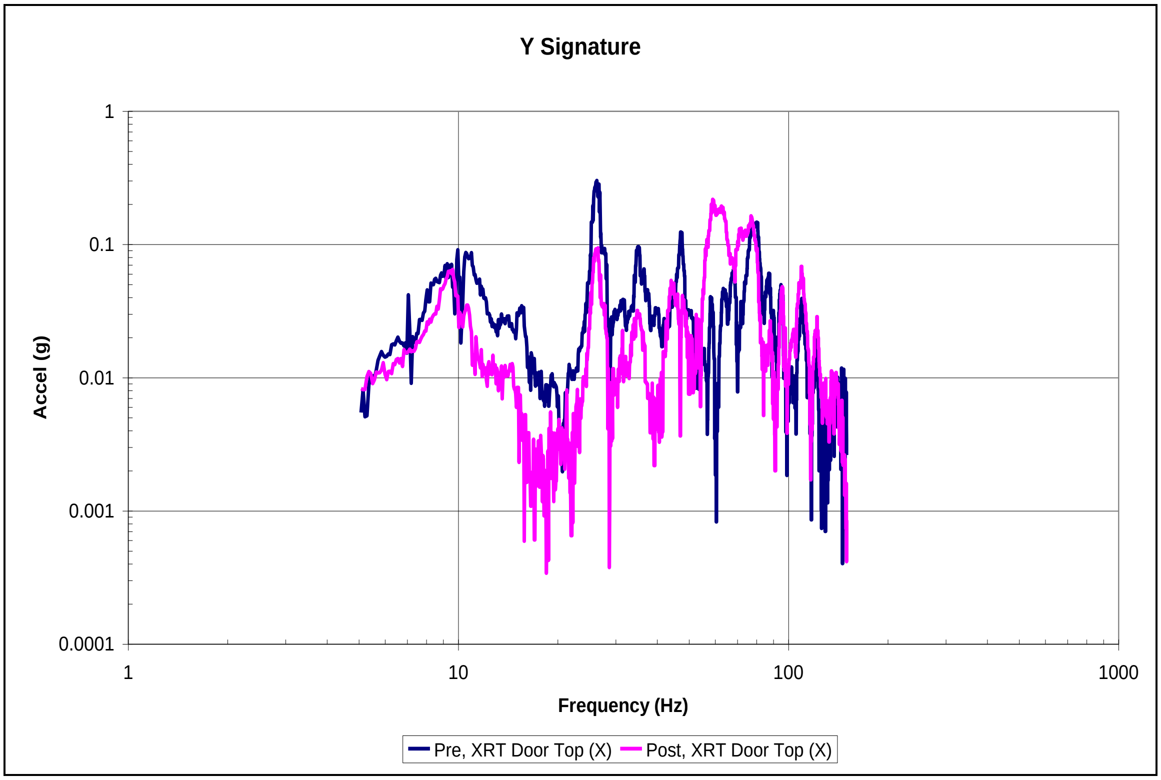

Figure 34—Signature Comparison at XRT Door (X Response, Y Input)

The lateral Z-axis was run next. Figure 35, Z-Axis Force Sum for 0-dB Sine Run, shows the in-axis force sum measured during the full-level Z-axis test. The fundamental mode of the Swift Observatory in the Z-axis can be seen in the plot at just below 10 Hz.

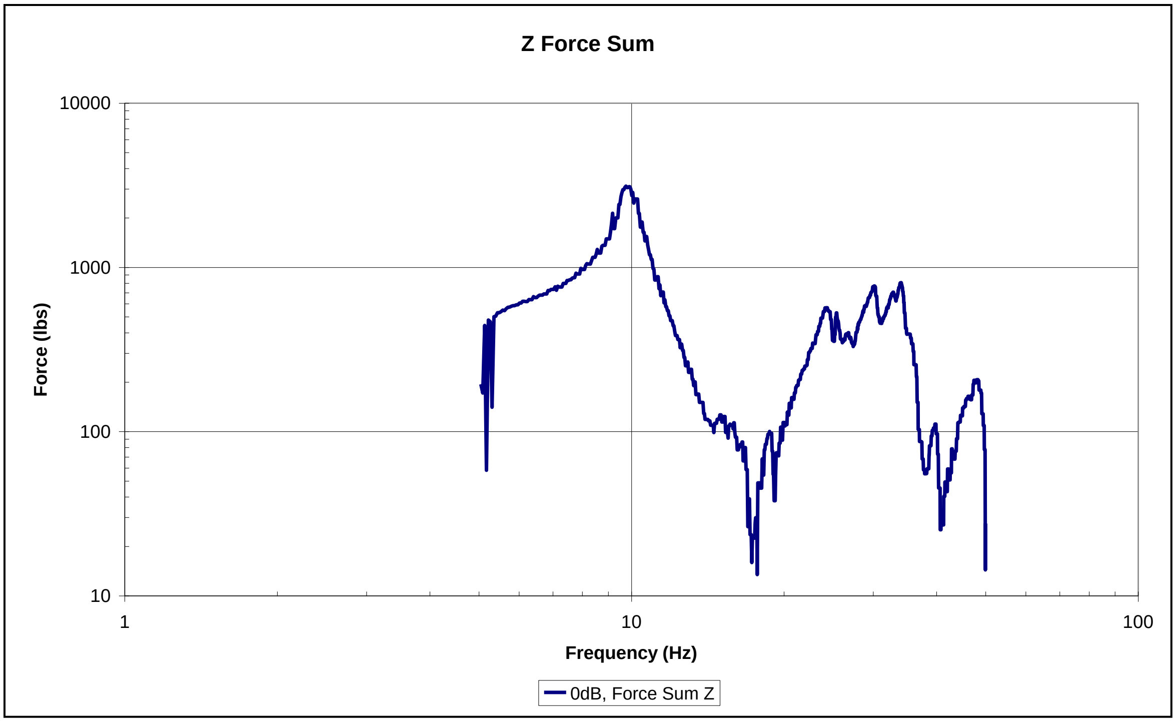

Figure 35—Z-Axis Force Sum for 0-dB Sine Run

During the one-half level Z-axis sine vibration sweep test, the Y-axis accelerometer on the UVOT door exceeded the scaled response limit for a resonance of the telescope around 35 Hz. The controller was not able to control to the response limit because of the sharpness of the resonance peak. The rocking mode of the UVOT telescope was much less damped than predicted by the pre-test analysis, resulting in very high cross-axis response. Scaling the responses from the half-level test showed that the UVOT door could exceed 6 g, which is above the allowable limit of 4.7 g based on CLA, even with the response limits in place. The remedy was to manually notch the test input to keep the response at or below 1.25 times the CLA prediction. Once the notch was verified at the half-level input, the full level test was run. The response measured at the UVOT door during the full level sine run with the notch in place is shown in Figure 36, Y-Axis Response at UVOT Door for 0-dB Z-Axis Input. It can be seen in this figure that the Y-axis response of the telescope at the door location is around 4.5g, which is less than the allowable limit.

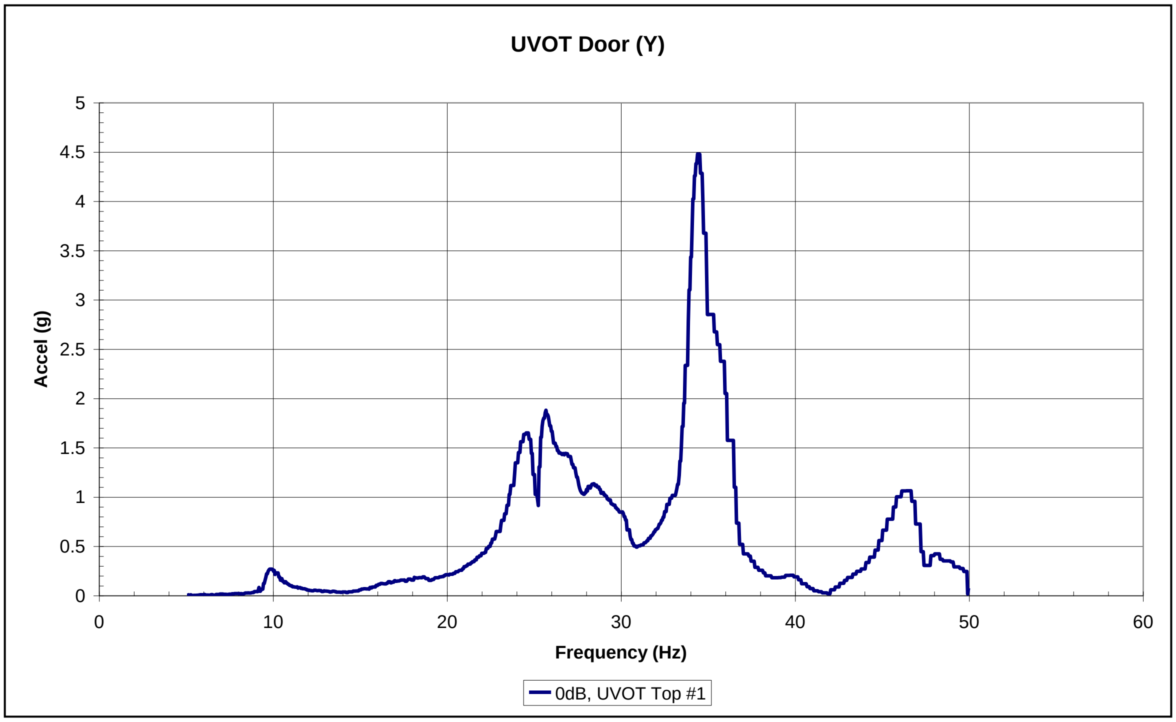

Figure 36—Y-Axis Response at UVOT Door for 0-dB Z-Axis Input

The comparison of the pre- and post-signature runs showed good agreement. An example of the signature comparison at the top of the UVOT telescope is shown in figure 37, Z-Axis Signature Comparison at UVOT Door. After completion of the test, the results from the Z-axis sine test at the UVOT door were used to update the verification CLA results based on the measured response data from the test. The results verified that even with the lower damping values measured during the Swift sine test, the UVOT instrument had been adequately qualified for the predicted flight response.

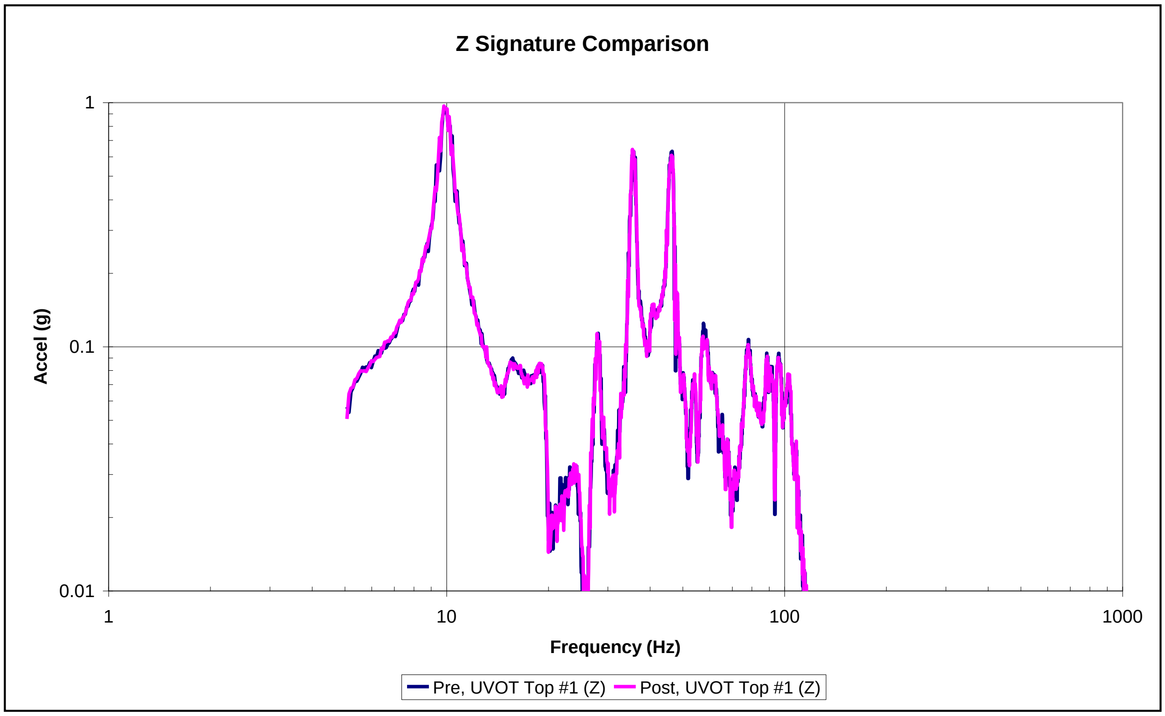

Figure 37—Z-Axis Signature Comparison at UVOT Door

The X-axis (thrust) was the final axis for the Swift Observatory sine test. In this axis, no notching was required based either on interface forces or on response limits. Figure 38, X-Axis Force Sum Comparison (Analysis versus Test), shows an overlay of the measured in-axis force and the prediction based on pre-test analysis. The observatory has a single dominant mode at 44 Hz in the thrust axis. This is captured very clearly in the analytical model, although at a slightly lower frequency (41 Hz). There were no significant differences between the results of the pre- and post-signature sweeps. The signature overlay for a response accelerometer at the top of the UVOT instrument is shown in figure 39, X-Axis Signature Comparison. After completion of the test, an assessment was performed to address the fact that the flight observatory had a slightly higher frequency than predicted by the analytical model. The results of this evaluation showed that the frequency difference between test and analysis was not significant enough to alter the coupled loads results or impact qualification levels of the hardware.

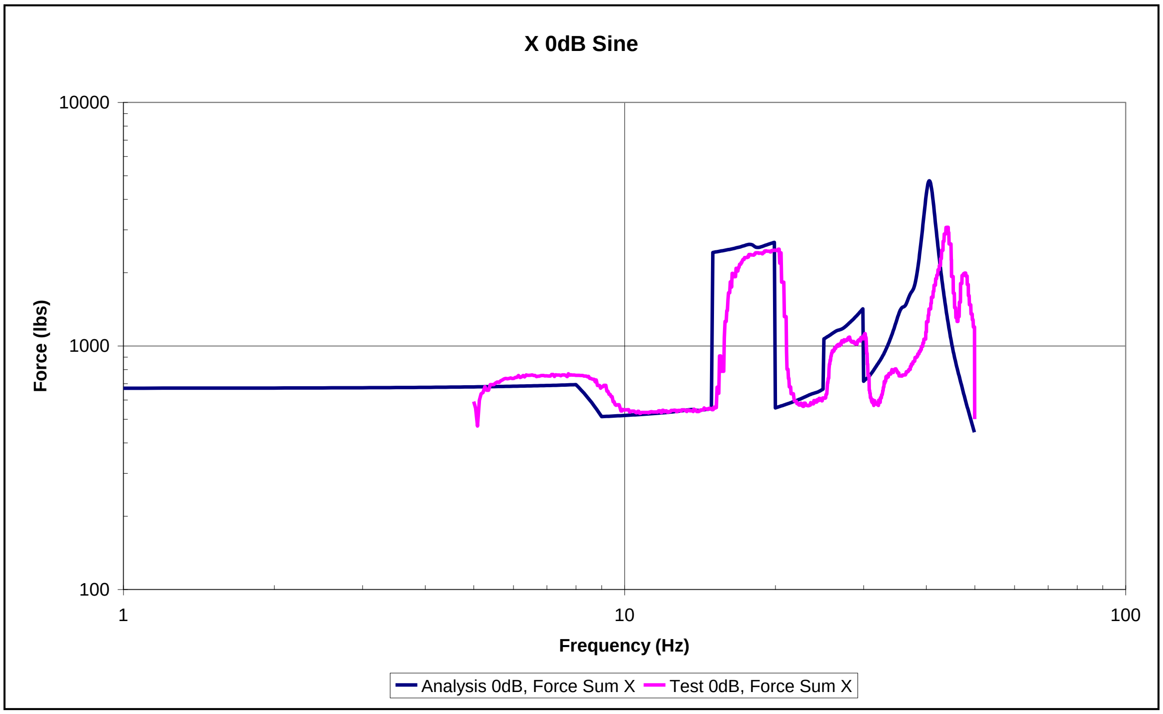

Figure 38—X-Axis Force Sum Comparison (Analysis versus Test)

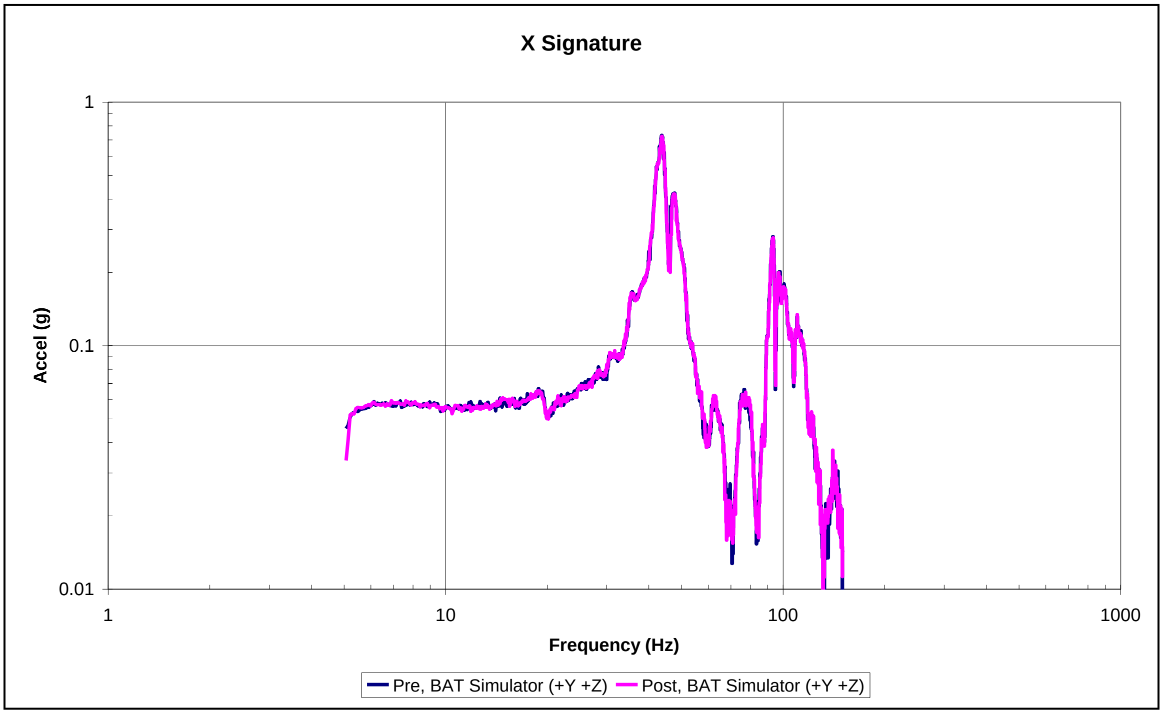

Figure 39—X-Axis Signature Comparison

C.2.8 Conclusion/Summary

The Swift Observatory successfully completed three-axis sine vibration testing to qualify the as-built spacecraft for the low-frequency launch environment. Comparison results of the pre- and post-signature sweeps in each axis showed no significant differences, indicating that the observatory did not experience structural failure during the test. Differences in the pre-/post-signature seen at the UVOT door were evaluated and found to be acceptable based on the expected behavior of the mechanism at that location CPTs conducted after completion of the sine and acoustic testing showed no degradation in performance as a result of being exposed to the dynamic environment. Sufficient instrumentation was in place during the sine test to monitor the response of the test article and to conduct the test safely. Notching was required in the Y-axis because of a higher than expected responses at the top of the UVOT telescope, but the full-level test was completed without incident based on the data gathered from the lower level runs. Post-test evaluation of the response data indicated that all hardware had been qualified properly, even accounting for the lower damping measured during the test.

APPENDIX D

CASE HISTORY OF QUIKSCAT SPACECRAFT DIRECT FIELD ACOUSTIC TEST

D.1 Purpose and/or Summary

The purpose of this appendix is to provide guidance in the form of a case history of the QuikSCAT Spacecraft DFAT. The references for this appendix are included in section 2 of this Handbook.

D.2 QuikSCAT Spacecraft DFAT

D.2.1 Summary

The first known DFAT of a spacecraft was that performed on the QuikSCAT spacecraft at Ball Aerospace Technology Corporation (BATC) in Boulder, Colorado, in October 1998 (Scharton et al., July 1999) (Scharton et al., October 1999). The QuikSCAT spacecraft was designed and built by BATC in an accelerated, 1-year, program managed by GSFC. The spacecraft carries the SeaWinds scatterometer, developed by JPL to measure the near-surface wind speed over Earth's oceans. JPL managed the QuikSCAT mission. 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 3-m (10-ft) high ring of large, electro-dynamic speakers, spaced approximately 1.3 m (4 ft) away from the 2-m (7-ft) diameter, 900kg (2,000-lb) spacecraft. The 31 speaker cabinets were driven with 40,000 RMS W of audio amplifier power. The acoustic specification, with an overall sound pressure level of 135 dB, was achieved 1 m (3.4 ft) in front of the speakers. Many issues have been raised and studied (Kolaini and Kern, 2011) concerning how DFATs compare with conventional reverberant-field acoustic tests, e.g., the maximum obtainable levels and spectrum, the spatial and frequency uniformity, the efficiency of a normal-incidence direct field versus a diffuse 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 of progressive waves coming from a select range of angles.

D.2.2 Introduction

On November 19, 1997, GSFC Flight Center awarded BATC a spacecraft contract for the QuikSCAT replacement mission. The QuikSCAT mission was to replace the June 1997 satellite failure of Japan’s Advanced Earth Orbiting Satellite (ADEOS). JPL provided the payload and scatterometer sensor and managed the mission.

Because of on-going spacecraft bus production capability, BATC was able to propose an aggressive November 1998 launch date, less than 12 months from contract initiation, because their spacecraft bus was specifically designed for remote sensing missions and very little change was required to accommodate the QuikSCAT mission. This allowed BATC to immediately begin procurement of materials, and manufacturing of the bus began while JPL completed the flight spare scatterometer sensor from the ADEOS mission.

By August 1998, as the spacecraft was nearing completion of integration, efficiencies were required to meet the November 1998 launch date. The time allotted for transporting the spacecraft to a remote site to conduct a traditional reverberant acoustic test was significant and was identified as a schedule driver. As an alternative, JPL proposed that a DFAT be performed in BATC's vibration test facility so that 1 to 2 weeks of schedule could be recovered, thereby preserving the launch schedule. Program management embraced this concept, and as there was little or no experience with a DFAT of a spacecraft, a feasibility/demonstration test was conducted. The DFAT specification, which was taken to be the same as the final requirement for the planned reverberant field acoustic test, is shown by the diamond symbols in figure 40, Acoustic Specification for QuikSCAT DFAT.

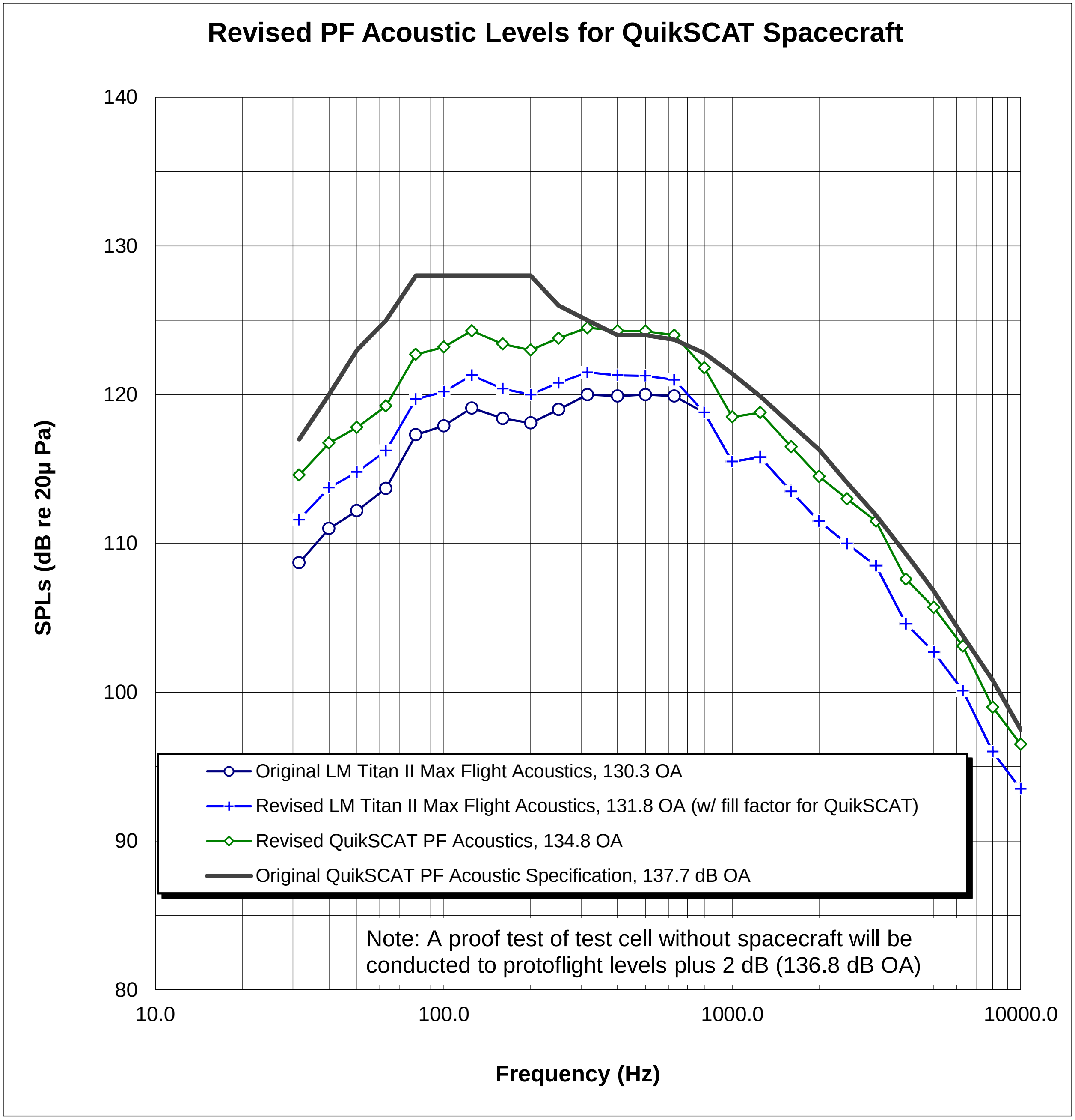

Figure 40—Acoustic Specification for QuikSCAT DFAT

D.2.3 Feasibility Test

A number of audio specialists were contacted, and Audio Analysts, Inc., of Colorado Springs, Colorado, was selected to provide the sound system and audio engineering services for the feasibility test. During the first week of September 1998, two sets of four speaker cabinets were installed in one of BATC's vibration test cells. The cell was constructed with high-transmission loss panels. Measurements of the decay of the SPL with distance from a simple acoustic source indicated that the cell was nearly anechoic for distances up to 2.13 m (84 in) from the speakers, over the entire frequency range of the acoustic test. Thus, reverberation provided little amplification to assist in attaining the required levels. With the eight speakers arranged to occupy one quadrant of a circle, it proved feasible to generate the required acoustic spectrum at a microphone located ~1.07 m (~42 in) in front of the speakers. In addition, a safety survey showed that the acoustic levels in the high bay and offices adjacent to the test cell would be annoying, but not hazardous, during the full-level run. Thus, it was determined to proceed with the spacecraft acoustic test, with the full-level test to be conducted at night to avoid disturbing workers in the surrounding offices.

D.2.4 Spacecraft Test

During the first week of October 1998, 31 speaker cabinets and the QuikSCAT spacecraft were installed in BATC's vibration facility. (An immovable object prevented the use of an additional speaker.) One of the problems in a DFAT such as this is balancing the requirements for achieving the required levels, which necessitates being close to the source, with the desire to achieve uniform acoustic coverage of the test item, which requires being farther away from the source. In the acoustic direct field, the acoustic levels fall off 6 dB every doubling of distance from a point source. However, the directivity of the high-frequency tweeters was such that their total angle of spreading was only about 30 deg, so it was not practical to place the speakers too close to the spacecraft. The final configuration of speakers selected for the QuikSCAT spacecraft acoustic test is shown in plan view in figure 41, Speaker Plain View, and in elevation view in figure 42, Speaker Elevation View. The speaker cabinets are arranged in a circle with their front surfaces on a 2.13-m (84-in) radius. Eight microphones are spaced at 45-deg intervals on a 1.07-m (42-in) radius, at an elevation of 2.09 m (82.5 in), which corresponds to the center of the two-speaker stack. This arrangement provided good acoustic coverage of the spacecraft bus and solar panels but did not provide uniform coverage of the top and bottom of the spacecraft, as shown in figure 43, Acoustic Coverage of High-Frequency Tweeters. Since the solar panels of the spacecraft are located ~0.91-m (36 in) from the center, there was only about 15.2 cm (6 in) between the microphones and the panels. Figure 44, Spacecraft Vibration Test,and figure 45, Spacecraft Acoustic Test, are photographs of the QuikSCAT spacecraft being installed on the shaker table in the vibration test cell.

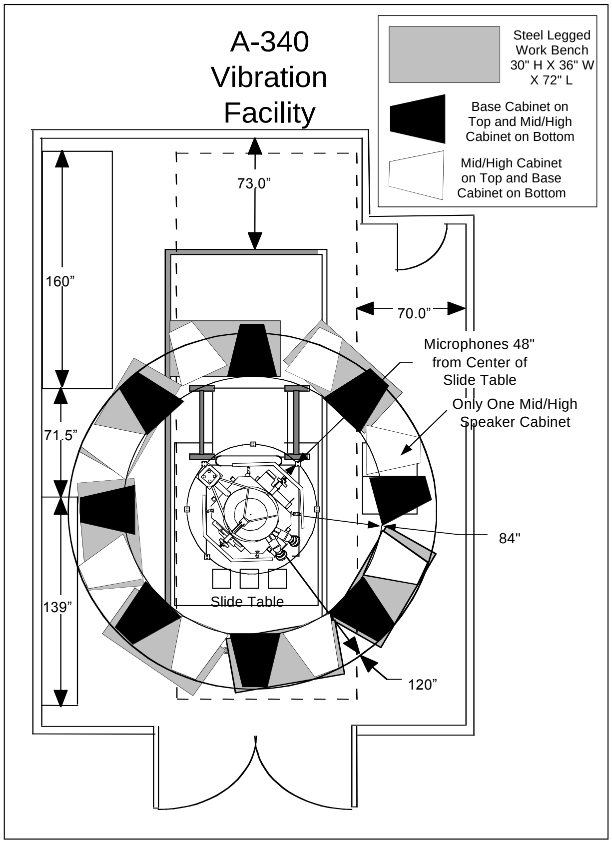

Figure 41—Speaker Plan View

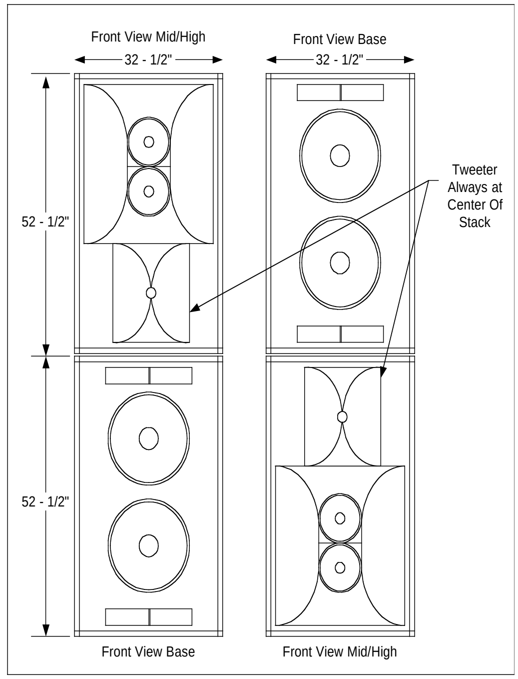

Figure 42—Speaker Elevation View

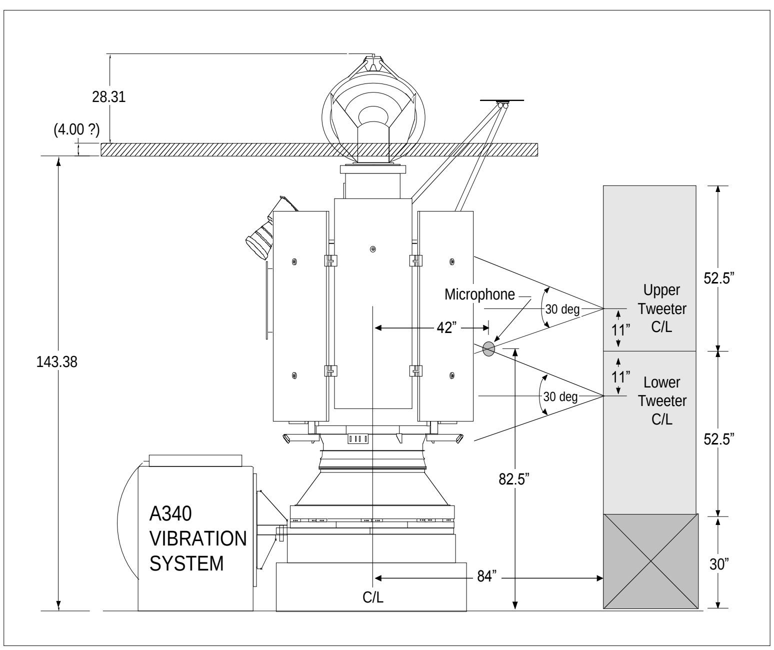

Figure 43—Acoustic Coverage of High-Frequency Tweeters

Figure 44—Spacecraft Vibration Test

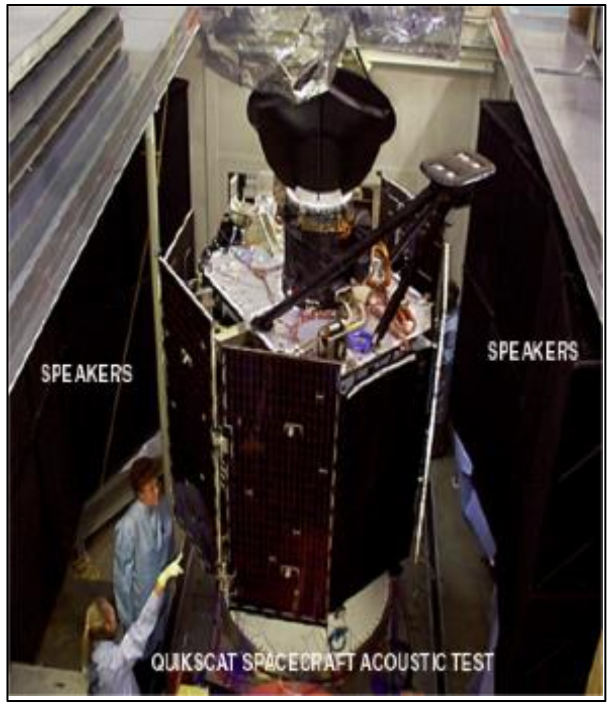

Figure 45—Spacecraft Acoustic Test

D.2.5 Test Results

During a series of low-level runs, the average of the eight equally spaced microphones shown in figures 41 and 43 were computed, and the spectrum was adjusted to the desired specification shown in figure 40. The results for the full-level test are shown in figure 46, Comparison of Microphone Measurements with Test Specification, which compares the data for the eight individual microphones with their average and with the test specification. The shortfall of about 3 dB above 200 Hz was caused by an error in interpreting the specification, but the levels are within a ±3-dB tolerance band. In future tests, this deficiency can easily be rectified, as the acoustic spectrum was purposefully attenuated above 200 Hz. The shortfall below 50 Hz was related to a limit in the low-frequency capability of the sound system and, perhaps, to the acoustical characteristics of the test cell. Figure 45 shows the scatterometer on top of the spacecraft protruding out through a hole in the ceiling of the test cell. It was anticipated that the levels would be lower there as previously discussed, and this was justified on the basis that the scatterometer had received its own acoustic test. However, in the complete installation, a penthouse was constructed over the scatterometer to prevent high noise levels in the surrounding high bay. A rover microphone used during low-level tests showed a local acoustic resonance in the penthouse, so that the levels there were actually higher than the spacecraft acoustic specification but no higher than the acoustic levels to which the scatterometer had been previously qualified.

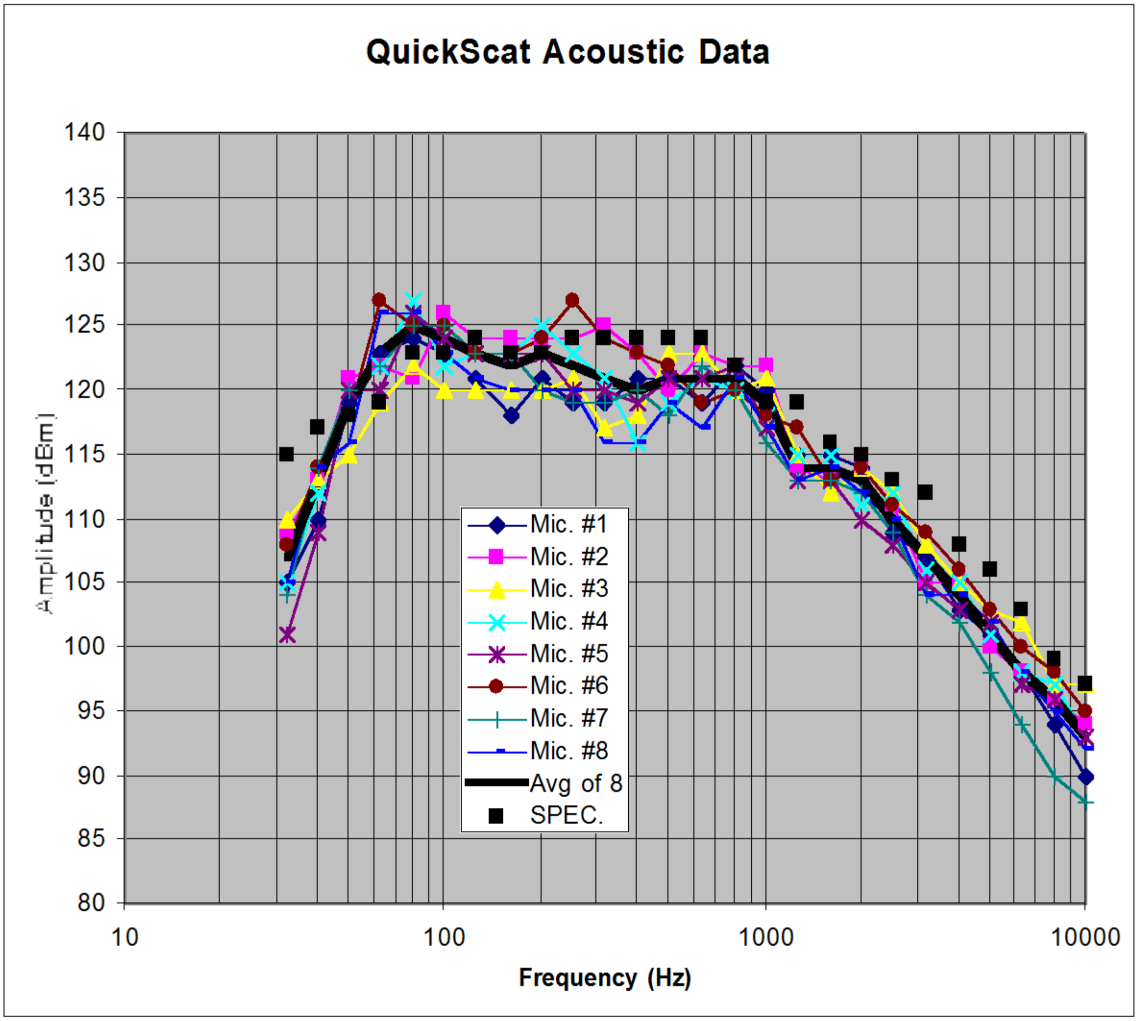

Figure 46—Comparison of Microphone Measurements with Test Specification

There were two other concerns regarding the DFAT: phasing of the speaker drive signals and the relative efficiency of direct, normal acoustic waves in exciting the spacecraft structure, as compared to a reverberant field. The first concern was somewhat mitigated by the rapid decay of the levels with distance from the speakers and the relatively large size of the spacecraft. This combination resulted in very little interaction of the various speakers, particularly at the higher frequencies. To further mitigate the interaction, the electric signals into each of the four quadrants of speakers were delayed.

Regarding the concern about acoustical efficiency, it is known that a normal incidence wave is more effective in exciting low-frequency modes of a panel than is a reverberant field. To illustrate this, figure 47, BEM of the Efficiency of Normal, Diffuse, and Grazing Angles of Incidence in Exciting a Solar Panel, shows the maximum response of a solar array shield, on another spacecraft, calculated with a boundary element code for a normal (z), a grazing (x), and a reverberant field. The maximum response of what happens to be the second bending mode of the panel/shield combination at ~43 Hz occurs for the normal wave and the minimum response for the grazing wave. Alternately, it is known that the reverberant field is more effective in exciting high-frequency vibrations because of acoustic and panel bending wavelength coincidence effects. Before the QuikSCAT acoustic test, a number of experts were polled and asked if the acoustic spectrum for this relative efficiency effect should be adjusted. However, there was no consensus, so no adjustment was made in this test to account for the acoustical excitation efficiency.

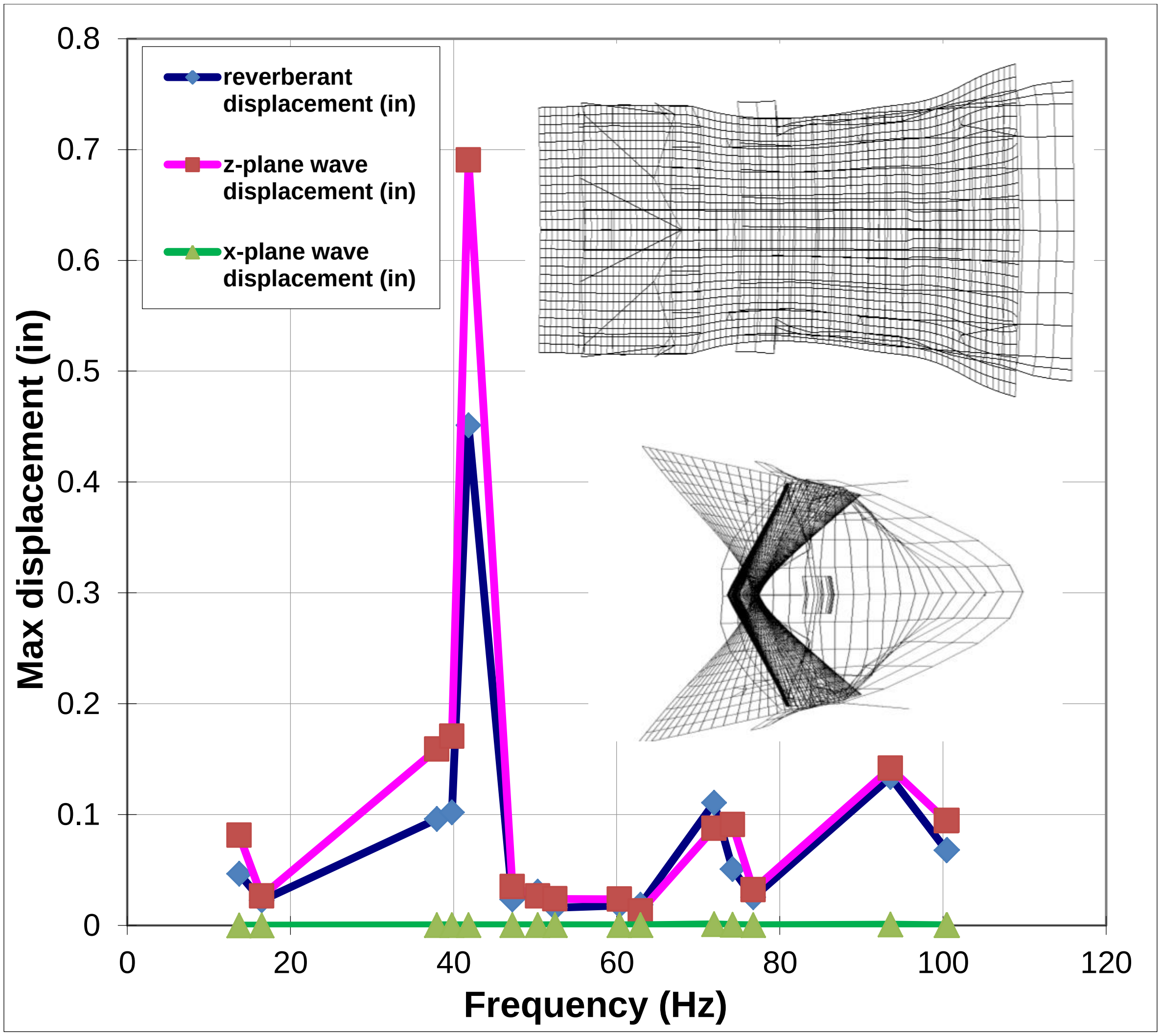

Figure 47—BEM of the Efficiency of Normal, Diffuse, and Grazing Angles of Incidence in Exciting a Solar Panel

D.2.6 Conclusion

The QuikSCAT DFAT was a success. The DFAT is very attractive from cost, schedule, and logistics viewpoints, particularly for companies that do not have an acoustic test facility. Many technological improvements, including considerable increases in the acoustic level and spatial uniformity, have been developed and implemented in DFAT tests of a large number of spacecraft during the past 15 years (Larkin, 2012).