NASA HANDBOOK FOR SPACECRAFT STRUCTURAL DYNAMICS TESTING

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ABSTRACT

Recent advances in the area of structural dynamics and vibrations, 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 on behalf of the NASA Office of the Chief Engineer. But to develop the most appropriate overall test program for a flight project from the selection of advanced methodologies, as well as conventional test methods, spacecraft project managers and their technical staffs will need overall guidance and technical rationale. Thus, the Chief Engineer's Office has recently tasked JPL to prepare a NASA Handbook for *Spacecraft Structural Dynamics Testing*. An outline of the proposed handbook, with a synopsis of each section, has been developed and is presented herein. Comments on the proposed handbook are solicited from the spacecraft structural dynamics testing community.

1. SCOPE OF THE HANDBOOK

1.1 Scope

This handbook addresses structural dynamics testing of flight spacecraft and large instruments, and associated dynamic test models and flight structure subsystems for the mission dynamics environments and loads. The handbook concentrates on new dynamics testing methodologies, but summarizes and provides key references for older dynamic and static test methodologies.

1.2 Purpose

Currently a diversity of testing cultures and approaches exist in NASA and industry. New testing technologies need to be disseminated. The handbook summarizes the state of the art in structural dynamics testing, recommends baseline verification programs, and describes and compares the advantages and disadvantages of the various test methodology options.

1.3 Applicability

This handbook recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this handbook and its provisions is the responsibility of program/project management and the performing organization. Individual provisions of this handbook may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints.

2. APPLICABLE / REFERENCE DOCUMENTS

Pertinent NASA standards and handbook and other applicable documents are listed herein. A list of key reference technical papers and documents that best describe new and recently improved testing technologies are provided. "Standard Practices" documents are cited for older, but still relevant test technologies.

3. DEFINITIONS AND ACRONYMS

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

4. TEST DESCRIPTION

4.1 Types of Dynamic Tests

The types of spacecraft structural dynamic tests covered by this document will be vibration, acoustic, and shock. Static testing will be discussed only in regard to the role it plays in complementing the dynamic testing in a complete structural qualification program.

4.1.1 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. Fig. 1 shows a vertical axis base-drive vibration test of the

Mars Exploration Rover (MER) spacecraft mounted on a platform, which sits on top of the shaker. Fig. 2 shows a lateral base-drive vibration test of the MER DTM Rover mounted on a platform that sits on bearings (a "slip table) and is driven horizontally. Stinger vibration tests on the other hand are conducted with the test item either fixed or free, that is with it attached to a massive, nominally immobile platform so that it is "fixed" at the base, or alternately with the test suspended from a soft suspension system so that it is relatively "free" to move. One or more small shakers are then connected to the test item with long rods, commonly called "stingers". Stinger vibration tests are commonly used for modal vibration testing where the object of the test is to generate data for verifying a mathematical model, which has assumed either fixed or free boundary conditions for the test item. 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 vibration tests can be used to generate relatively high-test levels. One of the distinguishing features of the different types of dynamic tests is the frequency range over which it is useful. For large test items such as spacecraft, the useful range of both base-drive and stinger vibration tests is in the range of ten to hundreds of Hertz, above which frequency it is difficult to put much vibration energy into a large test item without excessive motion at the drive location.
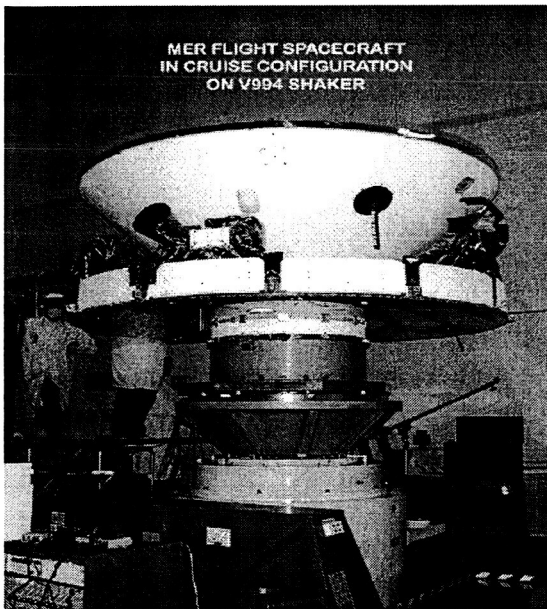

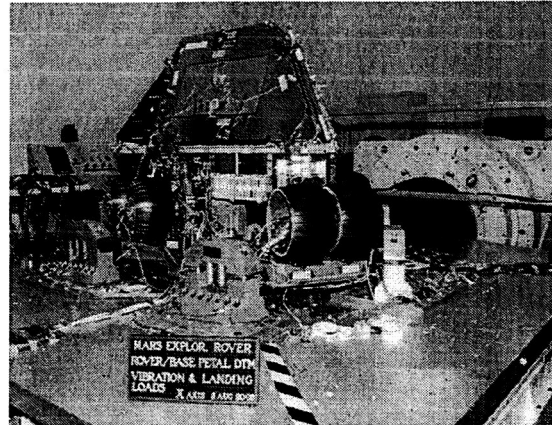Fig. 1. MER Spacecraft in Vertical Vibration Test

Fig. 2. MER DTM Rover in Lateral Vibration Test

4.1.2 Acoustic Tests

Acoustic tests are typically conducted with the test item located in a large reverberant chamber, which is excited with one or more electro-pneumatic drivers with horns mounted in the walls of the chamber. The sound waves in an acoustic test conducted in a reverberant chamber usually have bounced off the chamber walls many times before striking the test item, and this results in an acoustic field that is relatively uniform in frequency and space. An alternative acoustic test configuration employs a large number of electro-dynamic speakers arranged in a circle closely surrounding the test item, which may be located in a vibration or acoustic test chamber or in an open space such as a high bay. In this configuration 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. Direct acoustic tests are characterized by relatively large frequency and spatial variations because of the constructive and destructive interference of the sound waves from different speakers at various positions on the test item. Acoustic tests provide energy at relatively high frequencies compared to vibration tests. While the specified frequency spectrum in spacecraft acoustic tests typically ranges from tens to thousands of Hertz, most of the energy in an acoustic test is concentrated above a hundred Hertz.

4.1.3 Shock Tests

At the spacecraft level, shock tests are typically conducted by initiating the device that causes the shock environment in flight. 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: 1) suspending the spacecraft, 2) firing the separation charge, and 3) allowing the launch vehicle adapter section below the separation plane to drop a few inches onto a soft cushion. The other pyrotechnic devices on the spacecraft should also be fired, if

possible in the sequence and in the environment (thermal and/or vacuum) that they are fired in flight. The frequency range of spacecraft shock tests is typically from hundreds to thousands of Hertz, with most of the energy concentrated above a thousand Hertz.

4.2 Types of Excitation in Vibration Tests
Three types of excitation are used in spacecraft vibration tests: sine, random, and transient. Each of these three classes of time history has many variations, the most commonly used ones of which will be discussed herein. In addition, sometimes two types of excitation are combined to simulate a particular environment, e.g., sine on random is often used to simulate gunfire.

4.2.1 Sine
The most frequently used form of excitation in vibration tests used to be a swept sinusoid, which involves sweeping from a lower frequency limit to an upper frequency limit at a rate usually specified in octaves/minute. For example, a swept sine vibration test of a spacecraft might involve a sinusoid with amplitude of one "G", the acceleration of gravity, swept from 5 Hz to 80 Hz at a rate of four octaves/minute, which would take four minutes to complete. Another type of sine test is "sine dwell". In this case, the frequency is fixed and the test proceeds for a fixed time duration or number of cycles.

4.2.2 Random
A random vibration test is specified by the power spectral density (PSD) of the input acceleration, which defines the distribution of average vibration energy with frequency, and by the duration of the test. The square root of the integral of the acceleration PSD over frequency is the root-mean-square (rms) acceleration. The most appropriate measure of the severity of a random vibration test is the maximum PSD value or the PSD value at the frequency of the resonances of the test item. It is a common mistake to use the rms value of the input as a measure of its severity. The problem with the rms value is that it depends strongly on the values of the PSD at very high frequencies and on the upper frequency limit, which are often irrelevant.

4.2.3 Transient
All the inputs in vibration tests are transient in the sense that they are of limited duration, but here transient refers to inputs, which last only a fraction of a second or so. Many different types of transient waveform may be used for vibration tests of spacecraft, and transient excitation may be characterized in many ways, including: waveform, duration, frequency content, level, etc. Except for 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 levels. Wave forms include: a classical half-sine or a modification thereof, a bundle of sinusoidal cycles of a single frequency and with slowly increasing and decreasing amplitude, or less frequently, a wavelet with many frequencies, or a complex time history, which may be representative of an actual in-flight event.

4.3 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 may be conducted open loop with little danger, because there is very little nonlinearity and only a weak interaction between the acoustic field and the test item. However, even acoustic tests are commonly conducted with a closed loop control system because it speeds up the process of equalization to the test specification as the level is increased. Sinusoidal tests are generally controlled to a peak or rms level, and random tests to a PSD level. In both cases there is some preset tolerance and some threshold for automatic shut down. In addition to control, it is common practice in spacecraft vibration tests to have some limit channels, which are used to modify the control if these channels start to exceed their specified limits. 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, which are typically those frequencies where the test item has resonances. Acceleration responses measured at various positions on the test item are the most common signals used for limiting, but the advent of compact and stiff triaxial force gages has made limiting the forces between the shaker and the test item increasingly popular.

5. PURPOSES AND COMPARISON OF DIFFERENT TESTS

There are generally three reasons for conducting dynamics tests of spacecraft: qualification, workmanship, and verification.

5.1 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 that they

would cause failure of many electronic components, mechanisms, optics, and structures were these items not designed to survive them. These high levels of vibration and sound are generated by the launch vehicle and other sources such as pyrotechnic devices and a spacecraft landing on Mars. The most straightforward way of testing for these 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. In fact, it is common practice to define the flight environments using parameters of the dynamic tests that can be reasonably conducted, e.g. random vibration PSD's, one-third octave band acoustic levels, shock spectra, which is the maximum response of a single-degree-of–freedom system, etc. It is in this context that spacecraft designers often complain that they are designing to pass a test. Of course it is always good practice to periodically compare the test simulations with actual flight data to insure that the conservatisms that invariably creep into test specifications do not become excessive.

5.2 Flight Failures Due to Dynamic Environments

Since dynamic tests of spacecraft are both expensive and risky, it is reasonable to ask: "How many flight failures have there been due 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 Rangers 4 and 6 spacecraft failures were caused by launch vibration and that the Galileo 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. In addition, it is appropriate to ask: " How many problems have been discovered in spacecraft dynamics tests that would, or may, have caused flight failures? This is also difficult to answer, but there are probably many. At JPL, the vibration test of the Cassini spacecraft identified an electrical grounding problem between the spacecraft bus and the radioactive isotope thermoelectric generators (RTG), which could have been a serious problem in flight.

5.3 Workmanship Dynamics Tests

A secondary reason for conducting dynamic tests of spacecraft is to identify workmanship defects, which if undetected would cause problems or failures in flight. Most workmanship defects are detected at lower levels of assembly, but there are some interface and interconnection problems that can only be detected in the system level tests. (The Cassini spacecraft RTG problem mentioned in the last paragraph is an example of an interface problem, as the RTGs were extensively vibration tested at the subsystem level.) It is, however, important that the test levels in workmanship dynamics tests be low enough so that they do not cause problems that would not occur in flight.

5.4 Model Verification

The third reason for conducting dynamics tests of spacecraft is to verify dynamics models. This is the justification for modal testing, and tests to verify jitter and in-flight vibration models. In these cases it is also important that the test levels and durations be such that the tests are nondestructive.

5.5 Roles of Test and Analysis

In structural dynamics, the roles of testing and analysis are complementary, and one cannot overstate the value of pre- and post-test analysis. Since testing tends to be expensive, it is important to use analysis to plan the tests so that they may be conducted efficiently, and after the tests to use analysis to extend the test results to other loading and hardware configurations.

5.6 Advantages and Disadvantages of Various Tests

The various types of dynamics tests have different purposes, different frequency ranges of applicability, and also different advantages and disadvantages, so it is very 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 dynamics test programs. All dynamics tests are risky in that even handling a built-up spacecraft involves some risk, and some tests, like open loop transient tests on shakers have proven to be particularly risky. In general, acoustic tests are the most benign, followed by modal vibration tests, random vibration tests, sinusoidal sweep vibration tests, and finally shaker transient loads tests. On the other hand, acoustic tests are basically limited to detecting workmanship and high frequency problems. Random vibration tests are generally safer than sine sweep tests, because they are easier to limit and notch, since one may dwell at lower levels until the control system has adjusted the notches. In a sine sweep test on the other hand, the control system has to put the notch in "on the fly", and sometimes the resonance frequency is passed before the notch is fully implemented. Shaker transient loads tests are the most dangerous because they are of very short duration and open loop, so that over testing may occur before there is any chance of rectifying the situation. The shaker failure that occurred during the HESSI spacecraft vibration test is an example of this. However, shaker transient tests are still popular because they are inexpensive and save schedule compared with the extensive static test programs that they can replace.

6. TEST PROGRAM AND TEST PLAN

The term "test program" generally refers to the strategy, or plan, for testing all the hardware associated with a given program, whereas the term "test plan" generally refers to the plan for testing a specific hardware item, such as the flight spacecraft. Herein both are discussed. The "test procedure", which generally refers to the detailed steps of conducting the test, is discussed in the next section, 7.0 Test Implementation.

6.1 External and Institutional Requirements

The first step in putting together a dynamics test program 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, or from the launch vehicle contractor, or from the spacecraft provider, etc. Some of these requirements may be difficult to change, and some may be negotiable, but they should always be scrutinized to make sure that they are applicable and the best approach for the subject system. Often each institution has its own institutional test requirements, which may depend on the ultimate customer or risk category of the mission. In the past, these requirements were often contained in various standards and compliance with the standards was mandatory. Now there tends to be much more flexibility and a willingness to let each project 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 Flow

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. (This is the same philosophy as dad testing a swing before the child uses it. Of course, if dad breaks the swing, the child will be unhappy, but it's probably better than having the swing break later with the child on it.) For example, tests conducted on the flight structure are usually at lower levels than those conducted earlier on a qualification structure. Similarly, the tests at higher levels of assembly are usually at lower levels than those conducted on the units/components.

6.3 Design and Test Specifications and Margins

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 parts. The design specifications for most systems include a specification based on the dynamics tests that are planned. The test specification is generally lower than the design specification, and higher than that predicted for the flight environment. (An exception are workmanship and re-work tests, which may be conducted at or sometimes below flight levels in order to identify flaws without risking any failures that would not occur in flight.) The ratios of the design and test levels to the predicted flight level are often called "margins". For example, for a vibration test, the design margin might be 1.4 and the test margin 1.2. 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.

Test specifications for random and sweep sine vibration tests and for acoustic tests should generally be relatively smooth functions of frequency. One should 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 frequency response function predicted by a finite element method (FEM) code. It is also good to provide some flexibility, or room for negotiation in the case of flow-down specifications, so that the specification may be adjusted if preliminary tests with a mass simulator or with low-level inputs show that the project would be better served by modifying the specification.

6.4 Baseline Requirements

A set of baseline dynamic test requirements should be defined at the beginning of each program. (The alternative, i.e. to have the baseline program evolve as a result of descoping later in the program, will usually involve a non-optimal program and wasted resources.)The baseline program should include sufficient testing to satisfy the requirements for: 1) Qualification (validation) of the ability of the system to withstand the flight dynamic loads, 2) Workmanship testing, and 3) Verification of models used to predict responses to loads and environments, which cannot be adequately or reasonably simulated in a test. (Deployment of booms in a zero gravity environment might be an example of the latter.) For example, almost everyone would agree that the baseline dynamic test requirements for a spacecraft should include an acoustic test. Most would also include some type of modal test, and many would include a vibration test with the spacecraft mounted on a shaker. The number and type of system structural dynamics tests depend on the culture of the institution, the heritage of the spacecraft, the severity and nature of the flight environment, the amount of static testing, the credibility of the analyses, and of course, cost and schedule constraints.

6.5 Test Options

Testing options might be whether the acoustic test is conducted in a reverberant chamber or with speakers in a high bay; or whether the modal test is conducted with the spacecraft mounted on an inertial mass, on a shaker, or, typically for verification of in-flight models,

suspended freely; or whether the vibration test uses transient, sine, or random excitation. Other test options involve the decision of when and how to test large subsystems and subassemblies, and the fabrication and testing of dedicated test structures or units, called structural development models, qualification test models, or something similar.

6.6. Combining Tests

Sometimes the various types of dynamics tests may be combined with considerable savings of cost, schedule and handling risk. The specialists in each of these disciplines sometimes argue that combining these tests compromises the accuracy and utility of each test, and they are strictly speaking correct. However, sometimes compromises are necessary. For example, in the QUIKSCAT program a quasi-static loads test, frequency identification test, random vibration test, and acoustic test were all four conducted in the space of approximately one week with the spacecraft mounted to a shaker in the vibration test cell [Ref. D]. 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 program, one year from contract initiation to launch readiness, would not accommodate the schedule for conducting four separate tests, and combining these tests satisfied the requirements of a baseline program and encompassed all four types of test.

6.7 Hardware Definition

The first item discussed in both the test program and the test plan is usually the test item(s). The extent and configuration of the test item for the test must be described. Will it consist of flight hardware, some engineering models, mass simulators, or a combination of these? Will any items be missing? Will it be powered in the launch configuration? Usually the plan will include some drawings, solid models pictures, or photos of the test hardware showing the major components and interfaces. The coordinate system(s) and interfaces should also be defined.

6.8 Facility

The test facilities should be identified in the test program and specifically described in the test plan. The facility must have the capability to safety implement the test specification and meet the cleanliness, handling, and other test requirements. This is sometimes a challenge. However, the safety of the hardware is the one thing that should not be compromised. It is a good idea to inquire as regards to the recent use of the facility to conduct the corresponding type of dynamics tests of similar hardware, i.e. of similar weight and size. (For example, some project managers don't want to be the first customers to use new equipment, and most probably would not want to be the last to use old equipment.) Also it is appropriate to inquire as regards

the experience of the specific operators in conducting similar tests.

6.9 Instrumentation

Instrumentation is discussed briefly here, instead of under test conduct, because it is often necessary, or at least advantageous, to install some of the instrumentation before the test. The most common form of instrumentation for structural dynamic tests is accelerometers, which may be of a variety of size, sensitivity, frequency rage, etc. depending on the applications. Other types of instrumentation include force gages, strain gages, and occasionally temperature sensors. Often many of the interior instrumentation locations are only accessible at specific times during the build-up of the test item. (These may be removed after the test if the test item is partially disassembled, or sometimes the cables are cut and the accelerometers actually fly.)

6.10 Fixtures

Dynamics testing usually requires that the test item be mounted on some type of fixture, which is often specific to the test item. The fixture configuration, and its interfaces to the test item and the vibration source, as well as other ground support equipment, must be defined, fabricated, and fit checked in advance of the test.

6.11 Schedule

The test plan must include a schedule of events leading up to the test and a detailed schedule of the conduct of the test.

6.12 Test Organization Relationships

The single most important step in organizing a spacecraft dynamics test is to have one person identified as the test director, responsible for the safety of the spacecraft during the test, for the instrumentation, for the test conduct, for data analysis, and alas, for writing the test report. All information flow and important decisions must flow through the test director, or their delegate for specialized tasks. All of the other interrelationships and responsibilities for the test conduct 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, 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 shaker and all other systems operate properly and do not malfunction. The test laboratory will also provide people to operate the vibration equipment, set-up and run the instrumentation, and

conduct the data reduction. It is the responsibility of the test director to coordinate all of these activities.

6.13 Risks: Test Safety, Flight Failure, and Cost / Schedule
The three greatest risks to the flight hardware during dynamic testing of are: 1) handling damage, 2) shaker system malfunction, and 3) overtesting. Overrunning of the program cost and schedule are of course also risks, which are very important to the program, since projects are often descoped, or sometimes even canceled due to cost and schedule overruns. These risks of damaging the hardware during the test and then perhaps overrunning the cost and schedule must be balanced against the risk and embarrassment of a flight failure due to the dynamic environment or to a workmanship problem.

6.14 Pre-test Analysis
Pre-test analysis is one of the most important aspects of test planning, because it provides insight into what to expect and how to deal with it in advance of the actual test. This causes the actual test to go much faster, and also allows the attention during the test to focus on new problems that could not be anticipated. The most common type of pretest analysis consists of a simulation of the actual test using numerical models, which may consist of finite element models (FEM) for vibration testing, statistical energy analysis (SEA) or boundary element models (BEM) for acoustic testing, and appropriate high frequency modeling for shock, although the latter are rare.

6.15 Preparation of Written Test Plan
It is useful to distinguish between the test plan and the test procedure, which will be addressed in the next section. Generally, the test plan is prepared well in advance of the actual test. The test plan serves two major purposes: 1) It provides a description of the what is planned, so that others may review it and comment, and 2) It provides coordination and scheduling of the many activities that must fit together in order for the test item and test facility to be ready and the test to be successful. The test plan will typically cover the topics discussed in this section including: 1) Defining test hardware, 2) Describing the facility and test equipment, 3) Defining the test fixture, 4) Defining the instrumentation, 5) Defining the test specification and limits, 6) Defining the test runs and intermediate data analysis, 7) Naming the test director, who often writes the test plan, and other key personnel and defining their responsibilities, and 8) Describing the safety and cleanliness requirements and precautions.

7. TEST IMPLEMENTATION

7.1 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 the key to a successful test. As ISO 9000 says "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, including providing a road map so that everyone involved in the test can work together efficiently and know what's 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.

7.2 Facilities and Personnel
Good communication and smooth interfacing with the test facility and its personnel is very important. In all cases, it is essential that good communication and a harmonious working relationship be established between the flight hardware, dynamics engineering, and facility people. Generally, there is a natural pace or rhythm in the conduct of tests, which should be sensed and honored. The chains of command and individual responsibilities should be as defined in the test plan, and of course the test director should be in charge of all aspects of the test.

7.3 Instrumentation and Data Analysis
The instrumentation is the heart of a dynamic test and may include accelerometers, microphones, force gages, and strain gages. It is important that the instrumentation be set-up and calibrated, preferably end-to-end before the test. Typically, the real time data analysis in dynamic tests consists 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 of the test item in a vibration test can be a problem that requires examination of the time histories to resolve. The test director must decide how much data analysis is to be conducted between each test run and how much will be done later. As a minimum, sufficient data analysis must be done after each run to understand what is going on and to insure that it is safe to proceed. 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 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 the project personnel often want to press ahead.

7.4 Equipment Operation and Control
The proper control of a vibration test is a very important aspect of the test program, because overtesting and test failures are not that uncommon. The first priority is to

insure that the shaker does not malfunction and that the operators do not make an error in operating the equipment. (One good practice to help prevent the latter is to limit the working hours to a standard day, and to avoid doing the most dangerous, high level tests late at night or the very first thing in the morning. (This is particularly important in small laboratories where one operator or instrumentation person may be doing many jobs and may have been working very long hours.) The test equipment should be exercised at full level, plus a margin, before the test item is installed to insure that it is operating properly. This pretest should include any test fixturing, and a mass simulator if the weight of the test item or reaction forces are appreciable, i.e., greater than 50 % of the shaker capability. All the control accelerometers in the pretest should be installed in the same positions as for the actual test. The purpose of the pretest is two fold: 1) to checkout the equipment and 2) as a "dry run" to prepare all the personnel for the actual test. In this regard, it is best to have the pretest 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.

7.5 Response Limiting and Notching
It is also important that the input in a vibration test be limited at the structural resonances to avoid overtesting. This may be accomplished by placing limits on the responses, typically accelerations or forces. The limits may be on the peak level of the time histories, on the frequency spectra, or on the overall, that is the integral over all frequencies, of the responses. If there are rattles or spikes on the data, which interfere with control or limiting, it may be necessary to low-pass filter some of the data channels. There is always a compromise between the complexity of the test set-up and operation, and the number of safeguards and limits one may wisely implement. The balance depends on the sophistication of the test hardware, test equipment, and operators. For example, if too many limit channels are used, the vibration controller may be slow to update the input and to sense over testing.

7.6 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 signature, or health monitoring run, which is normally repeated after the full level testing before going on to another test axis or configuration. It is also good practice to have some sort of functionality check, i.e., electrical, mechanical, optical, etc., between configuration changes. There are normally a number of low-level tests, before going on 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 without and with limiting. It is best in the lower level runs to have all of the limits scale down with the inputs, so that any problems may be identified and corrected, by adjusting the limits, before the full-level test. Typically the lower level runs are conducted for a shorter interval of time, the only requirement being the time necessary to acquire valid data. Thirty seconds is typical for the lower-level runs

8. INTERPRETATION OF RESULTS

There is a tendency to heave a sigh of relief and move on after the completion of a system dynamics test. Of course it is always good news if nothing as dramatic as a structure failure occurs, but it is always a good idea to ask what has been learned from the test. Some questions, which may be asked include: 1) Were the test inputs correct? 2) Was there any under or overtesting? 3) How could the test procedure be improved for future tests? 4) Were there any structural, electrical, or functional failures of the test item? 5) Was there any significant wear of deterioration of the test item, which should be remedied or taken into account in future testing or service? 6) Are the test data consistent with model predictions, and if not, why not? 7) Was anything learned from this test, which would effect other testing in the same or other programs? 8) And finally, how should the test results be documented? 9) What should be the form and distribution of the test report? 10) Should the test data, and perhaps the analytical model, be incorporated into a database for future use? 11) Should the results be documented and distributed in a meeting presentation or paper in an archival journal?

8.1 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 and even pieces falling off. More often a structural failure is observed only when the test item fails to operate properly in a post-test mechanical functionality test, or when the test item is disassembled and loose parts and/or other damage is found. The before-and-after test traces observed in the vibration signature tests are seldom identical. 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. Sometimes, a small change is cleverly recognized as the indicator of a key structural failure, while other times the cause of a frequency shift or in some cases even the complete disappearance of a frequency peak is never determined. This decision of whether to stop or proceed with testing after a signature change usually requires a caucus of the technical specialists and the project personnel. When

none of these changes occur during the test, no damage is observed in a visual inspection, and the test item performs normally in a mechanical functionality test, it may be said that the test item maintained it's structural integrity, and in that regard passed the test. Of course the item may still have undergone some wear, e.g. the ball joints may have loosen up, or the structure may have used up some of it's fatigue life, e.g. through the growth of a small but undetectable fatigue crack.

8.2 Functionality

Frequently test failures are found after the dynamics tests during the test item functionality tests, which may include electrical, mechanical, optical, or thermal testing or some combination of these. Sometimes the electronics are powered on in the launch configuration and monitored during the dynamics test to insure normal operation of the equipment, which must operate during launch, or sometimes just to aid in identifying intermittencies or failures early before continual exposure to the dynamic environment causes additional damage. Electrical failures are perhaps more common in tests at lower levels of assembly, where the dynamics test levels are generally higher.

8.3 Post-test Analysis

Post-test analyses may be conducted for a number of reasons, including: 1) to tune the analytical model with the test data, 2) to understand why a structural test failure occurred during the test, 3) to predict the dynamic behavior of the test item after a design change, and 4) to extrapolate the dynamic response of the test item to a different test or flight environment. Modal dynamic tests are conducted expressly for the purpose of tuning the analytical model, but data from environmental base-drive vibration tests and even static tests are also often used to improve the model.

The merging of test and analysis in order to extrapolate dynamic test data to predict the response of a modified or new test item in a dynamics test is the most challenging type of post-test analysis.

8.4 Test Failures, Redesign, and Retest

The first step in dealing with a test failure is to determine the root cause of the failure. If the failure is a major one, NASA headquarters may appoint a failure review board to help in this regard. It is very important, but often difficult to determine the root cause of a structural failure. Without knowledge of the root cause it is impossible to determine how to correct the problem or whether it is fixed. Because most good structural designs are redundant, many failures occur because of a cascade of events. For example, a bolt or a restraining pin may back-out and then 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 on the root mean

square in a random vibration test in order to estimate the maximum stress that will occur during the test. Even though shaker random vibration inputs are clipped at three sigma, responses can exhibit peaks with higher values of sigma. For example for a part with a high resonance frequency of 500 Hz, the commonly used three sigma limit may be exceeded in a random vibration test after only a few seconds!

Often the cause of the failure remains somewhat ambiguous. 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 usually good practice to change the design so that all of the relevant design margins are significantly increased, so that the chances of another failure are very small. Finally, it will be necessary to test the new design to verify that the problem has been fixed. A review of the test specification is recommended at this point, to insure that the new part is not overtested.

8.5 Verification and Validation

Verification testing is usually conducted to check or more often collaborate an analytical model or to assure that the design indeed meets the specified requirements. An example might be to verify that the test item, say a spacecraft, has a fundamental axial resonance above 30 Hz. Or in the case of a modal test, the test data may be used to improve the finite element 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. Also, one of the reasons for conducting a random vibration or acoustic test is often to verify the workmanship of the test item.

Validation testing is more fundamental than verification testing. Validation implies more of an end-to-end check of the whole design and fabrication process including the starting points and assumptions. System qualification tests for a predicted flight dynamic environment such as random vibration or acoustics are examples of validation tests.

APPENDIX A. SURVEY OF INSTITUTIONAL PRACTICES

APPENDIX B. CASE HISTORIES

Big vs. Small, High vs. Moderate Risk, (MER, Cassini, MLS, TES, QuikSCAT, and GALEX)

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