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Title: Force-Limited Vibration Tests at JPL — A Perfect Ten

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A new qualification testing technique, which limits the force applied to the test item by the shaker, has been used successfully in ten Jet Propulsion Laboratory (JPL) projects during the past three years. For typical aerospace structures, the mechanical impedance of the test item and the flight mounting structure are comparable so that the combined motion involves modest interface forces and little amplification. Thus the high amplification resonances and associated failures, which often occur in conventional vibration tests with essentially unlimited force, are test artifacts which can be eliminated by limiting the force in the test to that predicted for flight. The most recent of the ten JPL applications of force limiting was the Wide Field Planetary Camera II for the Hubble Space Telescope first servicing mission scheduled for December 1993. The work described in this paper was carried out by the Jet Propulsion Laboratory, under a contract with the National Aeronautics and Space Administration.

Force-limiting has been used successfully in ten Jet Propulsion Laboratory (JPL) vibration tests during the last three years, and many new applications are planned at JPL and other NASA centers and contractor sites (Scharton 1993). Force-limiting provides a rational and economical solution to the overtesting problem associated with hard mounting of the test item, which has troubled aerospace vibration test engineers for decades. Historically this problem has been addressed either by conducting extensive engineering tests to develop bullet-proof hardware or by incorporating a flight or flight-like mounting structure in the test fixturing to provide a realistic mounting, but these approaches are expensive and seldom used today. Force-limiting costs less than the historical approaches and much less than a test failure of protoflight hardware. Implementation of force-limiting requires: development of a force specification (analogous to the conventional acceleration specification), a vibration test fixture that will accommodate force sensors, and shaker operation with dual control of both input acceleration and force. This paper summarizes the theory and methodology of force-limited vibration testing and describes two applications of the technique to the Wide Field Planetary Camera II (WFPCII) project: assembly random vibration tests of the small Articulating Fold Mirrors (AFM), which are located inside the camera, and the system random vibration test of the complete WFPCII.



Wide Field Planetary Camera II undergoes vibration test using new technique developed at the Jet Propulsion Laboratory.

Theory

The process of deriving an acceleration specification for a vibration test is illustrated in Figure 1. The ragged curve in Figure 1 represents a hypothetical measurement of the mi light acceleration at the interface of the mounting structure and the item to be tested. The vibration test specification is typically derived by averaging, enveloping, and adding a margin (4 dB at JPL) to the data. Unfortunately, the acceleration notches at the load antiresonance frequencies, where the interface force is a maximum and the acceleration is a minimum, are lost in this smoothing process. The load is very responsive at the antiresonance frequencies and acts as a dynamic absorber to reduce the input. Eliminating the notches in the acceleration input results in overtesting in conventional vibration tests by typically 10 dB to 20 dB. In force-limited vibration tests, both the interface acceleration and force are controlled. The reaction forces at the load antiresonance frequencies are limited to values predicted for the flight mounting, and the notches in the input acceleration are automatically restored.

Scharton, "Force-Limited Vibration Tests at JPL," 1992.

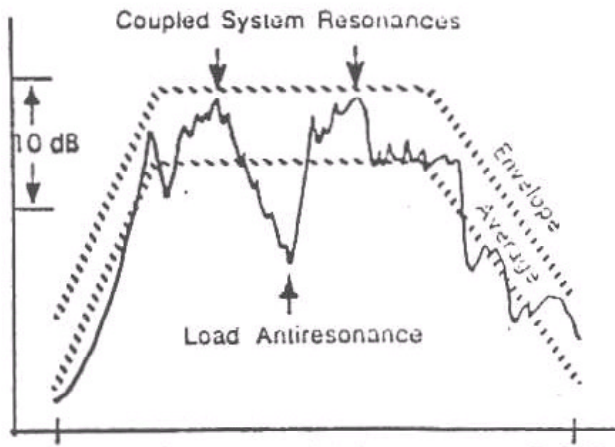


Figure 1. Dynamic Absorber Effect of Load on Interface Acceleration

Equation 1, which may be derived from Norton's and Thevenin's equivalent circuit theorems, provides a theoretical basis for dual control of force and acceleration in vibration tests:

$$1 = A/A_0 + F/F_0 \quad [1]$$

where: A is the interface acceleration, A_0 is the source free acceleration, F is the interface force, and F_0 is the source blocked force (Scharton 1990 IES). Equation 1 is exact but difficult to apply because each term is a complex function of frequency, and phase is ignored in current vibration test controllers. An approximate form of equation 1 useful for control of vibration tests is the extremal control equation:

$$|A| \leq |A_s|, \text{ and } |F| \leq |F_s| \quad [2]$$

where the free acceleration and blocked force are replaced by specifications that envelope the interface values in the coupled system. Most vibration controllers have the capability for extremal control, that is, to select the larger of two or more feedback signals in each narrow frequency analysis band for control to a vibration specification. However, older controllers allow only one specification. In this case, to implement dual control, a filter must be used to scale the shaker force control signal to an equivalent acceleration. New controllers allow separate specifications for each control channel so that Equation 2 may be implemented without any complications.

Force Specifications

There is little in-flight data on the interface vibratory force between payloads and the mounting structures, so current methods of developing force specifications use

ground measurements and analysis. Two methods of deriving force specifications are the blocked-force method and the two-degree-of-freedom system (TDFS) method. In the blocked-force method, the force specification is taken as the product of the conventional acceleration specification and the square of the effective mass of the source or mounting structure (Piersol 1989). In this discussion, it is assumed that the force and acceleration specifications are in the form of spectral densities applicable to random vibration testing, but the methods are likewise applicable to sinusoidal tests. The effective mass is defined as the smoothed magnitude of the ratio of drive point force to acceleration as a function of frequency. It is essential that the peaks and valleys of the frequency response function be smoothed out so that the result is insensitive to the damping value. The effective mass may be determined by finite element analyses, by impact hammer testing, or by mounting the structure on a shaker (see for example Kern et al 1992). The blocked-force method is relatively simple and is independent of the load, so it is well suited to requirements documents developed early in a program. However, it is necessary to add considerable margin to the source effective mass in order to guarantee a conservative (upper bound) force specification with the blocked-force method.

In the TDFS method used at JPL to predict force specifications, information on both the source and load effective masses is used (Scharton 1990 S & V and Smallwood 1990). The force specification is taken as the product of the acceleration specification, the square of the load effective mass, and an amplification factor calculated from a TDFS analysis. The amplification factor shown in Figure 2 depends primarily on the ratio of the load to the source effective mass and weakly on the quality factor Q . Ratios of both the peak and mean-square responses of the TDFS are shown. For very small (0.0001) values of the load to source mass ratio, the load has no effect on the source and the peak amplification factor is Q^2 ; there is no overttest in this case. For larger ratios, there is considerably less amplification because of the previously discussed notching at the load antiresonance frequencies. When the load and source masses are comparable, which is common in aerospace structures, there is virtually no amplification between the source and the load. The TDFS method is more accurate than the blocked-force method because in addition to the source effective mass, the TDFS method uses the load effective mass which can be accurately measured on the shaker in a low-level vibration test preceding the qualification test.

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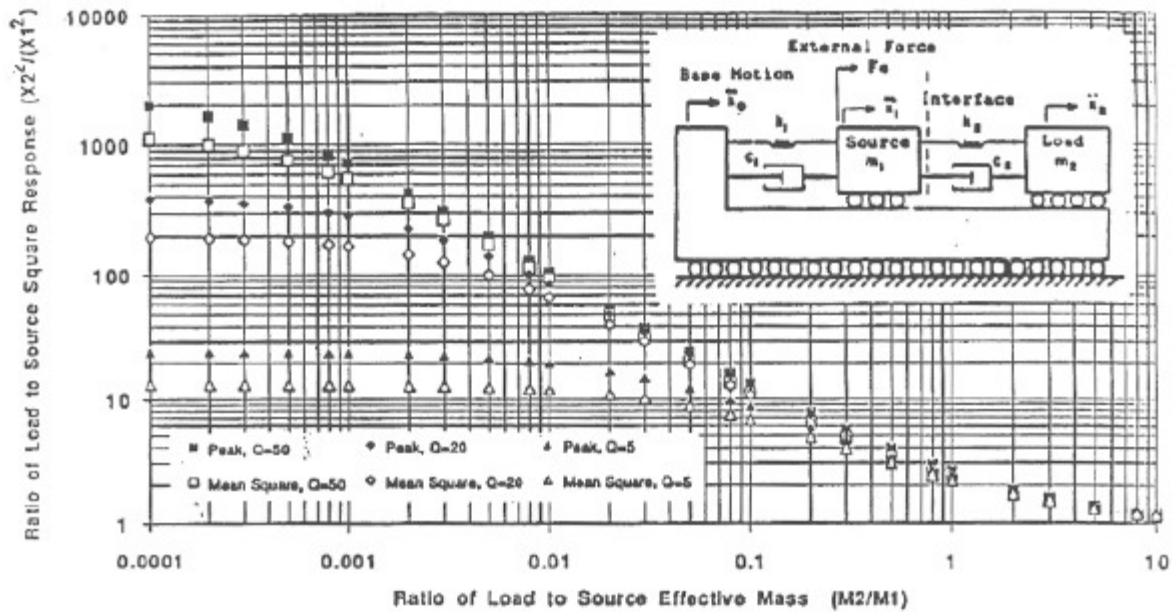


Figure 2. Response Ratio for Calculating Interface Force Spectrum Using Two-Degree-of-Freedom Model

Articulating Fold Mirror Vibration Test

There are three articulating fold mirror (AFM) assemblies in the Wide Field Planetary Camera II for the Hubble Telescope first servicing mission scheduled for December 1993 (Fanson and Ealey 1993). The role of the AFM is to provide a means for very accurate on-orbit alignment of the optical beam on the secondary relay mirrors, which contain the correction for the Hubble primary mirror spherical aberration. The AFM uses three small electrostrictive actuators to articulate the mirror. By necessity the AFM is small and delicate; the total unit weighs approximately 100 grams, and the articulating portion, the mirror and bezel, weighs less than 30 grams.

Figure 3 shows an AFM mounted in the vibration test fixture designed to accommodate three small (approx. 2.5 cm square) commercially available triaxial force transducers. Coaxial spacers are used to mate the transducers with the #2 screws which normally attach the AFM to a bulkhead of the optical bench of the WFPCII. The effective mass normal to the WFPCII bulkhead was measured with an impact hammer to be 3.2 kg at 800 Hz, the first axial resonance of the AFM. The force specification was determined using the TDFS method curves in Figure 2. Notice that even with the small ratio of AFM modal mass to bulkhead effective mass of approximately 0.01 and the measured Q of 50 the peak in-flight response ratio predicted by Figure 2 is still 14 dB less than Q^2 , the application expected in a conventional vibration test.

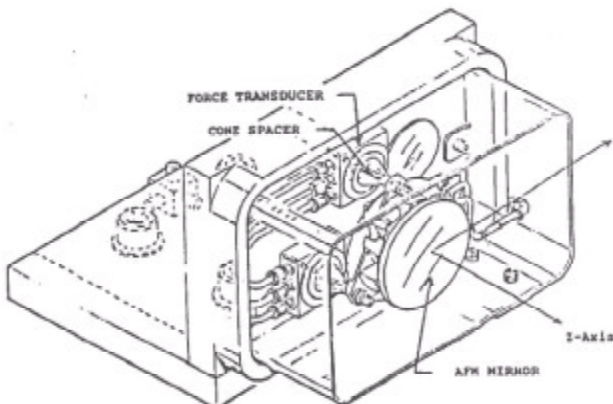


Figure 3. Vibration Test Fixture for Articulating Fold Mirrors

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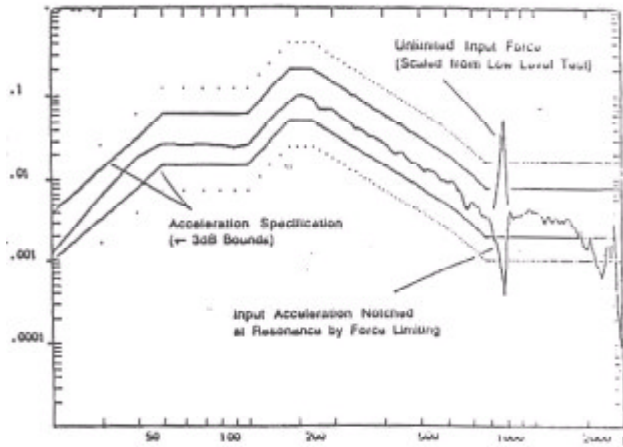


Figure 4. Notched Acceleration input in Z Axis Protoflight Level Random Vibration Test of Articulating Fold Mirror Qualification Unit

The results of the Z axis protoflight random vibration test of the AFM qualification unit are shown in Figure 4. The un-notched input acceleration spectral value of $0.004 \text{ G}^2/\text{Hz}$ at 800 Hz was determined from measurements during the acoustic test of the optical bench of WFPCII, the original camera on the Hubble Space Telescope. Figure 4 also shows the total axial force input to the AFM, i.e., the sum of the Z axis outputs of the three force transducers in Figure 3. The force shown in Figure 4 is actually scaled up from a low level (18 dB down) test without force-limiting to show what the force would have been in the full-level test if the force were not limited. In the signal conditioning, the force feedback signal was multiplied by the ratio of the acceleration specification to the force specification so that external control of both force and acceleration could be implemented by comparing both signals to the acceleration specification, as previously discussed. For this reason, the force signal in Figure 4 can be compared directly with the acceleration specification.

Figure 4 shows that in the protoflight level test with force-limiting, the controller automatically notched the acceleration input by the amount the force signal would exceed its specification, i.e., about 10 dB, or 4 dB less than permitted in Figure 2. The notch is very sharp and approximately the mirror image of the force peak. It is impractical to manually put in such sharp notches. Also without the force sensors to detect the frequency of the force peak, it is difficult to place the notch at the correct frequency. Therefore manual notches are of necessity broader than they need to be.

WFPCII System Random Vibration Test

The complete WFPCII (weight 284 kg) was subjected to a vertical axis protoflight level random vibration test as shown in Figure 5. A large (approx. 10 cm diam.) commercially available triaxial force transducer was located just below each of the three latches as indicated in Figure 5. Force specifications for all three components of force at all three latches were derived using the TDFS method with impact hammer test data on the effective mass of the honeycomb container which NASA GSFC is providing to carry WFPCII in the Space Shuttle.

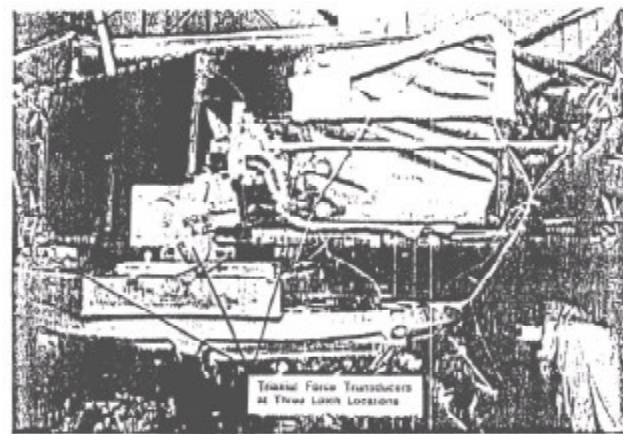


Figure 5. Wide Field Planetary Camera II Mounted on Shaker for Axial Random Vibration Test

The three components (x, y and z) of force at each of the three latches were recorded and analyzed in a low-level sine test preceding the random vibration test.

After a low-level random run, it was determined that three of the four control channels available on the older controller were essential to control the high frequency acceleration input at each of the three latches, so only one control channel was available for force-limiting. (New controllers have 32 to 64 control channels.) On the basis of analysis and the low level data, it was decided to limit the vertical force at the A latch (at the far left in Figure 5) which reacts most of the loads because of the outboard (to the right in Figure 5) center of gravity of the camera.

The acceleration measured at each of the three latches is compared with the acceleration specification for the protoflight random vibration test in Figure 6, and the vertical force measured at each of the three latches is compared to the force specification for the A latch in Figure 7. Comparison of Figures 6 and 7 shows that limiting the A latch vertical force resulted in notching of the acceleration input at 35 Hz, 100 Hz and 150 Hz. The acceleration

Scharton, "Force-Limited Vibration Tests at JPL," 1992.

notch at 70 Hz was effected by reducing the vertical force specification at 70 Hz to compensate for the A latch transverse force not being in the control loop. Above 300 Hz, one of the three control accelerometers is at the specification at every frequency. Comparison of the notched vibration input in the AFM assembly test with the vibration levels measured a year later on the optical bench in the WFPCII system acoustic test confirmed that the AFM test levels enveloped the system acoustic test levels, as they should for a valid screening test.

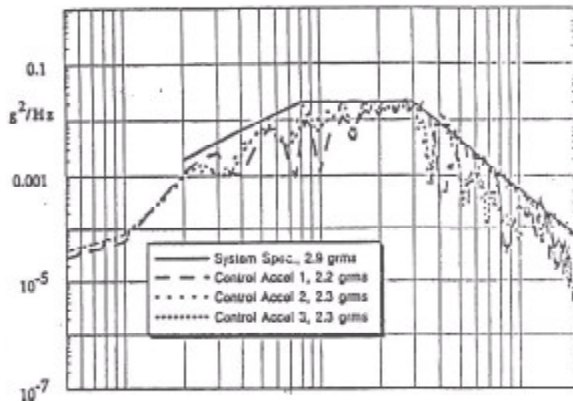


Figure 6. Measured and Specified Acceleration input at Three Latches of Wide Field Planetary Camera II in Random Vibration Test

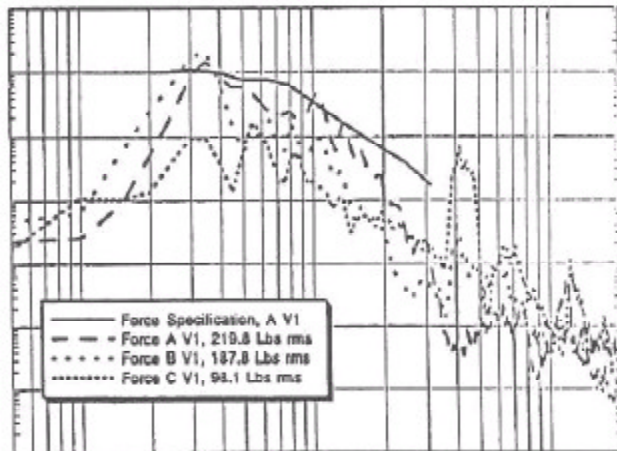


Figure 7. Measured and Specified Axial Force at Three Latches of Wide Field Planetary Camera II in Random Vibration Test

Conclusions

The AFM and WFPCII force-limited vibration tests were successful, as were the other eight JPL applications of force-limiting, in that the overttest associated with conventional hard-mount vibration tests was minimized. There were no test failures, except for some obvious workmanship problems in electronic box tests. In cases where system test data was available for comparison with assembly and instrument test results (as in the case of WFPCII), the validity of the force-limiting was confirmed. In no instances did force-limiting significantly increase the time required for testing, and in some cases the time was less than for comparable conventional tests with extensive manual notching and peak limiter trips. An additional benefit was that, in comparison to conventional tests, little time and energy were spent debating the correctness of the test or notching levels since all parties (project designers, analysts, dynamic environments engineers, and test engineers) tended to concur with the force-limiting approach.

Recommendations

It is recommended that other NASA centers and contractors adopt force-limiting. It is the author's opinion that the fundamental aspect of force-limiting is the measurement and control of both the shaker force and acceleration, in essence—the shaker impedance. The test item anti-resonances on the shaker cannot be satisfactorily defined and removed by analysis. There are many approaches to denying a force specification and new and better methods are certain to evolve. Certainly there is a need for in-flight interface force data. It is hoped that the shaker controller suppliers will continue their current efforts to upgrade controllers to facilitate force-limiting.

Scharton, "Force-Limited Vibration Tests at JPL ," 1992.

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