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Title: FORCE-LIMITED VIBRATION TESTS APPLIED TO THE FORTE' SATELLITE

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FORCE-LIMITED VIBRATION TESTS APPLIED TO THE FORTE′ SATELLITE

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Abstract

A force limited random vibration test was conducted on a small satellite called FORTE′. This type of vibration test reduces the over testing that can occur in a conventional vibration test. Two vibration specifications were used in the test: the conventional base acceleration specification, and an interface force specification. The vibration level of the shaker was controlled such that neither the table acceleration nor the force transmitted to the test item exceeded its specification. The effect of limiting the shake table vibration to the force specification was to reduce (or "notch") the shaker acceleration near some of the satellite's resonance frequencies.

This paper describes the force limited test conducted for the FORTE′ satellite. The satellite and its dynamic properties are discussed, and the concepts of force limiting theory are summarized. The hardware and setup of the test are then described, and the results of the force limited vibration test are discussed.

Keywords

Force limited vibration test; random vibration test.

Introduction

FORTE′ is a small 193 kg (425 lb) satellite that will be placed in orbit with a Pegasus-XL launch vehicle in late 1996. The satellite and its mission are further described in Ref. 1. Early in the FORTE′ design process it was decided to fabricate two satellite structures; the first being an engineering model (EM) to be used for testing and development and the second being the flight structure. During testing of the EM, using mass simulators for the payload and satellite components, it was discovered that vibration environments were higher than desired and a vibration mitigation program was initiated. The problem with high environments was amplified since, because of schedule, several key components were specified, designed and fabricated before the structure was either analyzed or tested. In certain frequency ranges these early specifications (see Table 1) were significantly lower than the measured vibration environments at the components' locations.

Table 1: FORTE′ Proto-Qualification Vibration Specifications

Frequency (Hz)	PSD (g^2/Hz)
20	0.008
800	0.008
1000	0.014
1300	0.014
2000	0.002

Because of the prohibitive cost of redesigning and requalifying components, the decision was made to attempt lowering the vibration environment by modifying the satellite structure. The use of custom designed viscoelastic vibration dampers and the redesign of component bracketry lowered the vibration levels significantly; at most locations, however, the levels were still above the component specifications. The vibration levels were especially high in frequency bands near the primary vehicle resonances when the structure was excited in the longitudinal (axial) direction. This fact, along with the ease with which force transducers could be placed between the structure and the shake table fixture, led to a program to evaluate force limited vibration.

Structural Response

A modal test of the EM with mass simulators representing components was performed to determine its fundamental vibration frequencies and mode shapes. The results are summarized in Table 2. After the modal test was performed and preliminary random vibration tests were completed it became evident that the vibration levels had to be lowered to prevent the need to requalify several components that had already been qualified and delivered. The first step in mitigating the vibration environment was to add four vis-

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Table 2: Modal Test Results

Mode Description	No Struts	With Struts	Force Limited Configuration
First Bending	35	42	-
First Lower Deck	48	60	52
First Mid Deck	70	60	52
First overall axial	160	135	105

coelastic struts connecting the mid and lower decks. With the addition of these structural members, the fundamental frequencies of the structure were changed, primarily those for which primary motion was in the axial direction. The new frequencies for several of these modes are shown in the last column of Table II.

A series of system-level random vibration tests was performed on the EM structure. A typical power spectral density (PSD) of the measured vibration environment near a critical component is shown in Fig. 1. Response is shown here for the longitudinal direction at the base of the attitude control system scan wheel. From the figure it can be seen that, even after adding viscoelastic damping, the measured vibration levels exceeded the component spectrum. The first peak in the measured spectrum at 52 Hz is a result of the first bending mode of the two satellite decks that are coupled with damping struts. The second peak at 106 Hz is

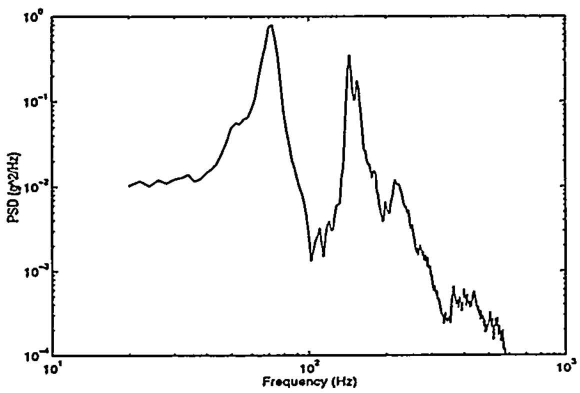

Fig. 1. Power spectral density (PSD) for longitudinal direction at the scan wheel.

a result of the complete satellite "plunging" in the axial direction. The higher frequency peaks are caused by coupling between the satellite axial motion and its second lateral bending modes.

Force Limiting Overview

A conventional random vibration test consists of driving a slip table or shaker head to a pre-specified acceleration spectrum. The dynamic coupling between the launch vehicle and the payload is not taken into consideration directly; the base acceleration specification is generally derived from flight data with "similar" payloads, but the specification is not "custom-tailored" for each individual payload. This testing philosophy can result in significant overtest in some frequency bands of the conventional vibration test - specifically, near certain natural frequencies of the test item in its tested (fixed-base) boundary condition. Near these frequencies, the test item behaves like a vibration absorber when it is mounted on the launch vehicle: the acceleration at some locations of the test item reaches a peak (which may be damaging to the structure or components mounted at these locations), but the acceleration at the test item / launch vehicle interface is sharply reduced. This effect results in a deep valley in the interface acceleration that would be measured in flight, but conventional acceleration specifications (envelopes) that are based on the flight data "smooth over" such valleys. This is one cause of overtest in conventional vibration tests.

A force-limited vibration test attempts to reduce this source of overtest by limiting the excitation based on both the interface acceleration specification and an interface force specification. At those frequencies where the payload would act like a vibration absorber and reduce the interface acceleration of the coupled launch vehicle and payload, the interface force will govern the vibration level of the test. In all other frequency ranges, where there are no vibration absorber effects, the conventional base acceleration will govern the vibration level of the test.

The result is a more realistic vibration environment - more realistic because, in the actual flight conditions, the payload really will cause antiresonance "valleys" in the interface acceleration spectrum. A force limited vibration test is simply an attempt to account for these in-flight acceleration valleys during the test. Several force-limited vibration tests have been described in the literature (see, for example, the references in [2]).

Physical Test Setup

The force limited vibration testing option was applied only to the random vibration test for the longitudinal direction. Vibration levels were not nearly as high in the lateral direc-

Fig. 2. Mounting of a force transducer between the booster separation ring and the satellite.

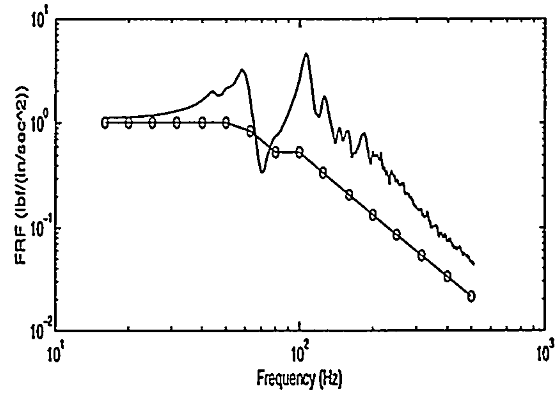

Fig. 3. Dynamic mass FRF for FORTE'. Also shown is the skeleton for this FRF.

tions and implementation of the required force transducers was difficult for these directions. In addition, the needed impedance data for the booster in the lateral direction was not available. For the axial direction eight force transducers could conveniently be placed under eight of the twenty flexures that attach the satellite to the booster separation ring (Fig. 2). For excitation in the axial direction most of the load goes through these eight flexures, which are located at the corners of the octagonal lower deck. Longeron-type members transfer load from the remainder of the satellite to these eight locations.

The load transducers used were PCB Model No. 201B04, which had a maximum range of 5000 lbf compression. The transducers were preloaded to approximately 20% of their maximum compressive range to assure that their maximum tensile range was not exceeded. Shim stock was placed as needed between the transducers and the shake table fixture to equalize the loads as closely as possible when low-level random vibration was applied to the structure. For the actual force-limited test, the signals from the eight transducers were summed and averaged by the vibration control system.

Determination of Force Limiting Spectrum

The limit force spectrum was determined using the "TDFS" method of Scharton [2]. The computations were performed at 1/3 octave band intervals from 16 Hz to 500 Hz. The TDFS method requires as input the dynamic mass FRF's of both the launch vehicle and the payload; the measurement of these FRF's is described below. To account for uncertainties in measurement of these FRF's and uncertainties in the TDFS method of determining the force spectrum, a margin was added to the TDFS calculations: the envelope is greater than the TDFS spectrum by a minimum of 1.5 dB (1.5 dB margin).

The dynamic mass FRF of the FORTE' payload was determined in a random vibration test on a shaker, with the structure mounted vertically and supported by eight force transducers as described in the previous section. The skeleton and the FRF are shown in Fig. 3. The FRF was measured at the proto-qualification vibration level (0.008 g^2/Hz, constant from 20 to 800 Hz), and again at a level reduced by -12 dB (0.0005 g^2/Hz, constant from 20 to 800 Hz). The level at which the measurements were made did not significantly affect the dynamic mass FRF's. Thus for the system random vibration test of the flight vehicle, the dynamic mass can be determined at low levels of vibration, minimizing exposure of flight components to potentially damaging levels of vibration.

The dynamic mass FRF of the Pegasus launch vehicle was determined in a modal "tap test"[1]. In this test, only the avionics section and the third stage of the rocket were included. The dynamic mass FRF was determined by averaging the acceleration measurements at each of the tap locations around the payload interface. The dynamic mass skeleton of the launch vehicle was used as supplied. This skeleton is shown in Fig. 4.

The limit force spectrum calculated by the TDFS method is shown in Fig. 5, along with the envelope that was used as the limit force specification. The estimated interface force PSD is also shown in Fig. 5. At all frequencies where the

1. This test was performed by Bruce Wendler (Aerospace Corp.) in March 1995. The test was performed on the Pegasus (hybrid) launch vehicle in support of a force-limited vibration test for the MSTI program. The actual data that was supplied by Mr. Wendler included only the skeleton of the dynamic mass FRF.

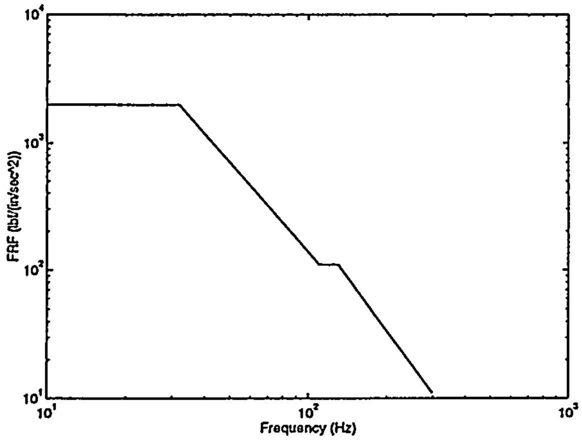

Fig. 4. Skeleton of the dynamic mass FRF for the FORTE' launch vehicle.

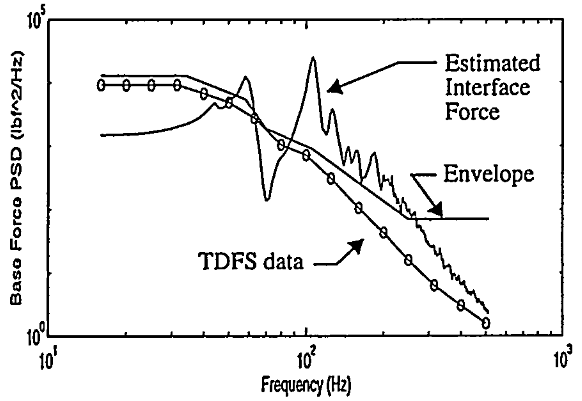

Fig. 5. Force specification used in the force-limited vibration test. Also shown is the estimated interface force PSD.

actual interface force is greater than the limit force envelope, the vibration test was force-controlled.

Results of Limiting

To give an indication of the magnitude and frequency range of the force limiting effect in the dual-controlled vibration test, the actual (as-tested) base acceleration can be compared to the base acceleration specification, as in Fig. 6. For a conventional vibration test with no force limiting, the base acceleration would be identical to the specification (a constant 0.008 g^2/Hz spectrum from 20 to 800 Hz). In the force-limited vibration test, the shaker control system reduced the base acceleration whenever the measured interface force reached the limit force specification. The force limiting had the largest affect at the fixed-base resonant frequencies of the structure, in this case-mainly at 106 Hz.

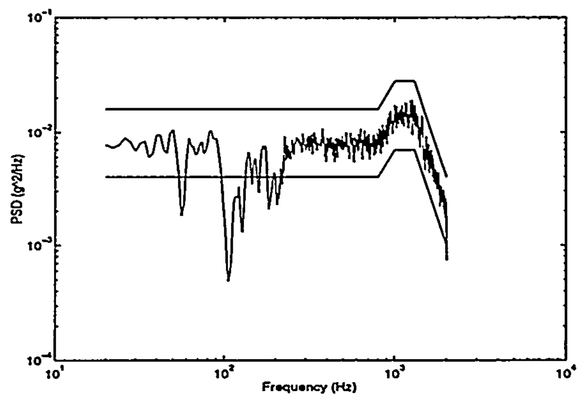

Fig. 6. Base acceleration PSD measured during the force-limited vibration test.

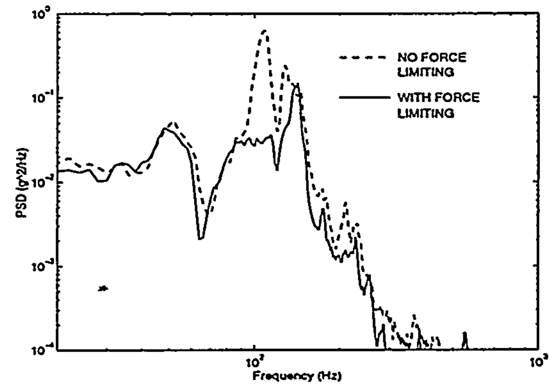

Fig. 7. PSD at scan wheel measured in a conventional vibration tests and in a force-limited test.

The maximum reduction ("notch") in the base acceleration PSD was about 10 dB at this frequency.

The acceleration PSD at a critical component on FORTE' measured during the force limited vibration test is compared to the same measurement made during a conventional test (i.e., no force limiting) in Fig. 7.

Conclusions

Using a force limiting random vibration test has proven to be effective in providing a more realistic and lower vibration level to satellite and payload components. The force limited test provided a reduction in the base acceleration as large as 10 dB in some frequency bands during a test of the FORTE' small satellite.

References:

1. Butler, Thomas, "Testing Experience with the FORTE' Small Satellite", 16th Aerospace Testing Seminar, Manhattan Beach, CA, 12-14 Mar 96.

2. Scharton, Terry, "Vibration-Test Force Limits Derived from Frequency Shift Method" Journal of Spacecraft and Rockets, Vol. 32, No. 2, March-April 1995.

Acknowledgments

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