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FORCE LIMITED VIBRATION TESTING

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ABSTRACT

A new method of conducting laboratory vibration tests of spacecraft equipment has been developed to more closely simulate the vibration environment experienced when the spacecraft is launched on a rocket. The improved tests are tailored to identify equipment design and workmanship problems without inducing artificial failures that would not have occurred at launch. These new, less-destructive type of vibration tests are essential to JPL's protoflight test approach in which laboratory testing is conducted using the flight equipment, often one-of-a-kind, to save time and money. In conventional vibration tests only the input vibratory motion is specified; the feedback, or reaction force, between the test item and the vibration machine is ignored. Most test failures occur when the test item goes into resonance, and the reaction force becomes very large. It has long been recognized that the large reaction force is a test artifact which does not occur with the lightweight, flexible mounting structures characteristic of spacecraft and space vehicles. In the new vibration tests, both the motion and the force provided to the test item by the vibration machine are controlled, so that the vibration ride experienced by the test item is as in flight. Reaction force limiting has been used successfully at JPL in three vibration tests of flight instruments during the past year, and it is anticipated that the new technique will be widely employed soon at JPL and eventually throughout the aerospace industry.

INTRODUCTION

The acceleration input specified in a vibration test of aerospace hardware typically exceeds the relevant flight input for several reasons. Figure 1 illustrates the relative effects of smoothing, enveloping and adding margins to flight vibration data. The test specification tends to smooth, or average, over the frequency variations in the flight data because these variations depend on the details of the flight mounting and attached hardware. A consequence of this smoothing is the elimination of flight data interface acceleration notches which may be caused by the large reaction forces at resonances of the attached hardware. These innocuous looking notches are very important because vibration testing with a smoothed acceleration specification may result in overtesting at the resonance peaks of lightly damped test items by up to a factor of one-hundred. (The factors discussed in this example are applicable to linear amplitudes of vibration. For spectral densities, square the factors; for dB levels, take twenty times the log of the factors.) In most cases the effect of not notching the acceleration test spectrum overshadows the effects of enveloping the flight data to account for spatial, flight-to-flight, and other variations, and of applying margins to the flight data for design and test. Enveloping factors are typically in the range of two to three, which generally include the 95th percentile. Design and test margin factors range from one-and-a-quarter to two; the Jet Propulsion Laboratory (JPL) uses one-and-a-half.

Figure 2 illustrates a zoom analysis of the frequency dependence of force and accelerations at one of the notches shown in figure 1. The force at the interface between the mounting structure and the test item, the interface acceleration, and the response acceleration of the test item are plotted as functions of frequency for both flight and vibration test mounting configurations. The interface acceleration is notched in flight but smooth in a conventional vibration test, as discussed previously. The interface force increases moderately at a test item resonance in flight, as the interface acceleration notches down. The interface force increases greatly at a test item resonance in a vibration test with constant interface acceleration. The ratio of interface force to interface acceleration is the same in flight and in a test; the ratio is given by the test item apparent weight which has a peak at the test item resonance. The response acceleration of the test item has the same frequency dependence as the interface force; in fact, the response is equal to the interface force times the test item modal mass for the resonance. The plots in figure 2 show that for flight mounting, the interface force increases to a limit value at resonance and the interface acceleration decreases from a limit value. Limiting the interface force in a vibration test (that is the force delivered to the test item by the shaker) is equivalent to limiting the test item response at resonances.

THEORY

The following exact relationship for the dual control of shaker acceleration and force has been the subject of several recent investigations [1-7]:

$$1 = A/Ao + F/Fo \tag{1}$$

where A is the acceleration of the source, Ao is the source free acceleration, F is the force between the source and load, and Fo is the source blocked force. The quantities in Eq. 1 are complex functions of frequency and it is difficult to predict or measure the associated phase angles. It may be seen from the results in [5] that the interface acceleration A and force F may both exceed the respective free Ao and blocked Fo values at the resonances of the coupled system. Therefore, the magnitudes of these quantities do not obey equation 1, but equation 1 is satisfied when phase is taken into account [5].

A more useful relation for vibration testing is the extremal dual control equation [1,4]:

$$|A| < A1 \text{ and } |F| < F1 \tag{2}$$

where A1 and F1 are limit magnitude values appropriate to a vibration test specification. To be useful for extremal control of a shaker, Eq. 2 must be applicable at all frequencies and particularly at the coupled system resonances where as shown in [5] the free acceleration and blocked force are not adequate limits. It is essential that the acceleration limit A1 and force limit F1 in Eq. 2 be chosen so that the respective coupled system values are enveloped.

FORCE SPECIFICATIONS

There are a number of approaches available for defining the force limit [6,7] in Eq. 2. Herein, the source impedance method [2,4 & 7] is described. The acceleration limit in Eq. 2 is that normally used to specify a conventional hard-base-drive vibration test, i.e. the envelope of the interface acceleration between the source and load. In a random vibration test the acceleration specification is the spectral density As in G**2/Hz. In the source impedance method, the corresponding force spectral density limit is calculated as the product of the acceleration specification As and the square of the source effective mass Ms in lb mass. If the measured force in the test set-up includes the force used to move a test fixture of mass Mf, the appropriate total force spectrum Fs in lb**2/Hz is:

$$Fs = As * [Ms^{**}2 + Mf^{**}2] \tag{3}$$

where it has been assumed that the fixture force and load force are 90 degrees out of phase at load resonance (see Fig. 13 of [4]).

The force spectrum calculated using the source impedance method will in general differ from that calculated more accurately using the method in [6] or the two-degree-of-freedom method in [7]. The correct way to calculate the force is to multiply the load mass M2 times the load acceleration A2, whereas with the source impedance method the source mass M1 is multiplied times the source acceleration A1. The factor needed to correct the source impedance force spectrum is the product of the ratio of mean-square (or peak) load to source responses times the ratio of squared load to source masses. For M2/M1 <0.4, the source impedance method yields forces larger than the two-degree-of-freedom method and is therefore conservative for qualification purposes (see Fig. 3 in [7]). For M2/M1 > 0.4, the source impedance method becomes unconservative for qualification, and the more exact calculation methods of [6 and 7] must be used.

An extremal control approach, similar to that described in [4], can be used to automatically implement force limiting. In the extremal approach, the shaker control system compares several measurement channels with appropriate reference spectra and adjusts the shaker drive until one channel is equal to the reference and the other channels are equal to or less than their references. When one channel is force and the other is acceleration, the extremal dual control approach of Eq. 2 is automatically implemented. Unfortunately, most shaker controllers, including JPL's, currently provide for only one reference spectrum.

Figure 3 shows the flow diagram which can be used to implement extremal dual control with existing test equipment. Channels 1 and 2 are redundant control accelerometers in the shake direction and channel 3 is the force transducer signal. S1 and S2 are the control accelerometer charge amplifier sensitivities in volts/g, Sf is the force transducer charge amplifier sensitivity in volts/lb, and S3 is the pseudo-accelerometer sensitivity in volts/g input to channel 3 of the controller. The one-third octave spectrum shaping filter gain settings are calculated from S3, Sf, and the acceleration As and Force Fs specifications as shown in Fig. 3.

The effective source mass Ms can be measured as a function of frequency with a modal impact hammer, if the mounting structure of the test item is available. Alternatively, the source mass can be determined from a finite element model of the mounting structure. Data must be obtained in each of three directions at each of the mounting points. The raw data will show peaks and valleys associated with anti-resonances and resonances. The effective mass is a smooth curve through the data. Foster's theorem says that the effective mass is a decreasing function of frequency [8]. If a finite element model is used, the effective mass is the sum of the modal masses of all modes with resonant frequencies at and above the frequency of interest. The total effective mass in each direction is calculated by summing the masses at each of the attachment points.

TEST RESULTS

A vibration retest of a spacecraft flight instrument, the Mars Observer Camera (MOC) was conducted using force limiting [9]. The MOC is a principal investigator supplied instrument being built by the California Institute of Technology Division of Planetary Sciences for Arizona State University. The MOC instrument is part of the JPL Mars Observer spacecraft configuration scheduled for launch in 1992. Figure 4 is a schematic of the MOC configured for a vertical axis vibration test. The MOC consists of an f/10 reflector telescope with approximately a 14" aperture and a graphite epoxy tube approximately 30" in length. The camera also includes a wide angle lens assembly located along one side of the tube.

The test fixture consisted of a 2" thick, 18" diameter, 50 lb aluminum plate to which the MOC was attached at three mounting feet as shown in Figure 4. The input acceleration was controlled using the extreme of two control accelerometers mounted on this fixture plate. Four triaxial piezoelectric force transducers (Kistler model 9067) were sandwiched between the fixture plate and a 2", thick 20" diameter shaker base plate which was attached to the shaker head. To enable the transmission of shear forces across the transducers in the lateral tests, the force transducers were preloaded axially to 8400 lb with a 1/2" through bolt torqued to 70 ft-lb. The outputs of the four force transducers in the test axis direction were summed to provide total lateral shear or vertical force. In the horizontal axis tests, the vertical direction outputs of the two transducers further from the shaker were summed and multiplied by two to estimate the total vertical moment force. The summed transducer output was attenuated by a charge amplifier to accommodate the high sensitivity force transducers. The output of the charge amplifier was sent to a one-third octave spectrum shaping network and the shaker controller for force limiting as described in Figure 3.

The MOC vibration test was conducted in JPL's environmental test facility during the two day period January 19 and 20, 1991. After some initial difficulties setting up JPL's data acquisition system to record the force data and trouble shooting accelerometer channels, the tests went smoothly. The additional time associated with implementing the force limiting technique for the first time was saved by not having to calculate and implement manual notching. The fact that a complicated three-axis test was completed in two, admittedly long, days speaks to the efficiency of the technique. The MOC was well instrumented with accelerometers and the response data at critical locations was analyzed between runs before going to higher test levels. The MOC passed the test without any structural or performance degradation.

Figure 5 shows the measured vertical force in the minus 18 dB vertical random vibration test without and with force limiting. Also shown is the force specification calculated from Eg. 3 by taking the fixture plus mounts (squared mass) times the acceleration specification and subtracting 18 dB. The force limiting reduced the force peak at 285 Hz by about 9 dB. However, some off-resonance response below 100 Hz is also reduced. Following the -18 dB run, some adjustments were made to the force specifications by changing the one-third octave filter gain settings; specifically, the non-resonant force limiting below 100 Hz was eliminated and the amount of force limiting at the first resonance at 285 Hz was increased.

Figure 6 compares the control acceleration spectrum for the full level vertical random vibration test with the 0.2 G**2/Hz specification. The force limiting resulted in approximately a 15 dB notch at the fundamental resonance at 285 Hz. Notice that the 285 Hz notch is a gradual ramp down and a sharp step increase corresponding to the mirror image of the force excess of the specification in Fig. 5. This asymmetric notch shape is a characteristic of the force limiting approach. It is believed that this notch shape is more representative of flight than the symmetric notches typically used in manual notching to limit response acceleration to calculated limit loads. The notches at 400 and 630 Hz were put in by increasing the filter gain in these one-third octave bands after the -12 dB run in order to keep the acceleration responses at two critical locations under the limit load levels. Unfortunately, these resonances were masked by the large force required to move the 50 lb fixture, so that the notches are one-third octave wide instead of being narrower in width like the resonances.

CONCLUSIONS

Force limiting has been utilized successfully at JPL in three vibration tests of flight instruments, one of which was the MOC described herein. In each case, the test item received a softer ride than it would have in a conventional vibration test with only acceleration control. However, the author is convinced that each test was a realistic representation of the flight environment, plus some margin. Force limiting offers a rational means of eliminating the costs and schedule delays associated with both overdesign and overtesting in aerospace and automotive industries.

Wide spread application of force limiting will require more experience and flight force data to develop generic force specifications. Techniques for predicting the overturning moments in lateral axis tests and for combining the effective masses at multiple mounting points are needed. Improved force gage mounting methods are needed to alleviate the disadvantages of having large test fixture mass between the force gages and the test item. Finally, new vibration test control systems need to incorporate the capability of specifying separate references for each control channel; a feature currently offered by only one major manufacturer.

ACKNOWLEDGEMENT

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REFERENCES

1. T. Scharton and D. Kern, "Using the VAPEPS Program to Support the TOPEX Spacecraft Design Effort," Shock and Vibration Bulletin, No. 59, October 1988.

2. A. Piersol, P. White, E. Wilby, J. Wilby, and P. Hipol, "Vibration Procedures for Orbiter Sidewall-Mounted Payloads," Astron Report on USAF Contract F04701-87-C-0010, Phase II Report, February 1989.

3. D. Smallwood, "An Analytical Study of a Vibration Test Method Using Extremal Control of Acceleration and Force," Proceedings of the IES, 35th Annual Technical Meeting, Anaheim, CA, May 1989.

4. T. Scharton, D. Boatman, and D. Kern, "Dual Control Vibration Testing," Shock and Vibration Bulletin, No. 60, November 1989.

5. T. Scharton, "Analysis of Dual Control Vibration Testing," Proceedings of the IES, 36th Annual Technical Meeting, New Orleans, LA, April 1990.

6. D. Smallwood, "Development of the Force Envelope for an Acceleration/Force Extremal Controlled Vibration Test," Shock and Vibration Bulletin, No. 61, October 1990.

7. T. Scharton, "Force Specifications for Extremal Dual Controlled Vibration Tests," Shock and Vibration Bulletin, No. 61, October 1990.

8. E. Skudrzyk, Simple and Complex Vibration Systems, Pennsylvania State University, University Park, PA, pp. 32, 1968. (Foster's Theorem brought to author's attention by D. Smallwood)

9. T. Scharton, "Dual Control Vibration Tests of Flight Hardware," Proceedings of the IES, 37th Annual Technical Meeting, San Diego, CA, May 1991.

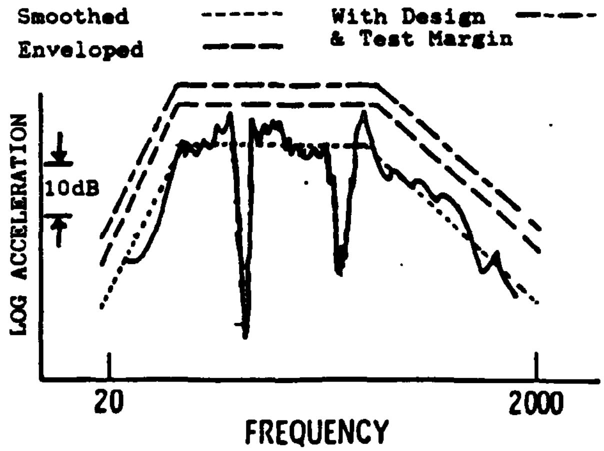

Fig. 1 Smoothing, Enveloping and Adding Margins to Flight Data

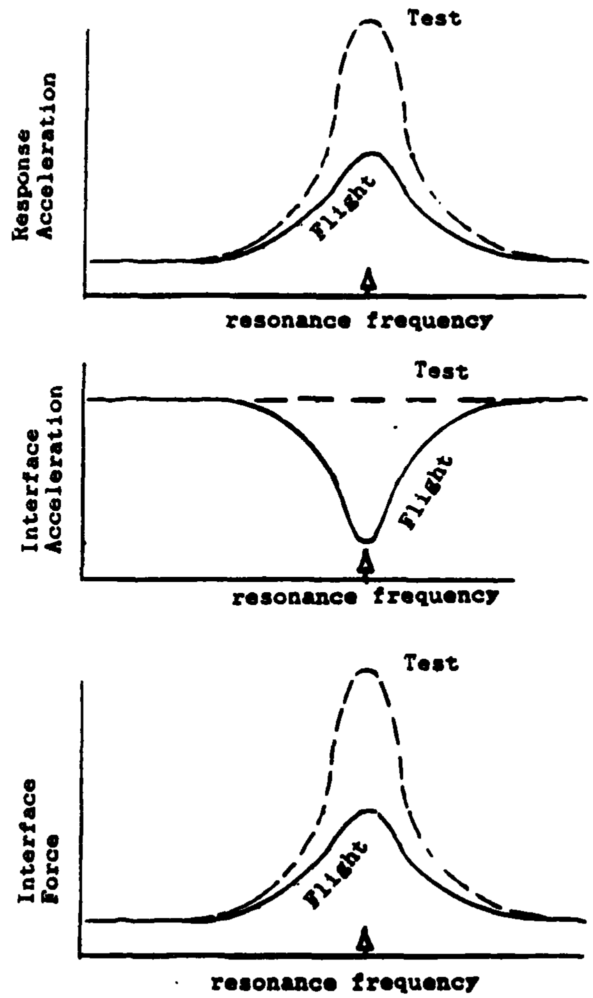

Fig. 2 Zoom Analysis of Force and Accelerations at Resonance of Test Item

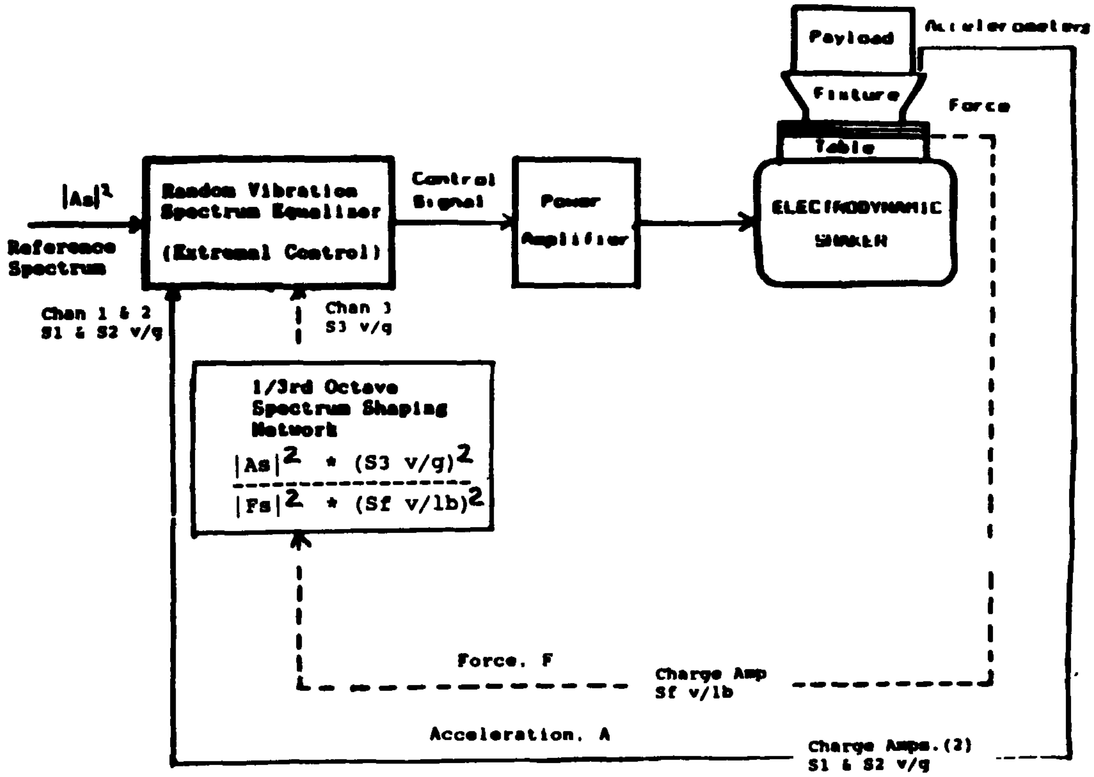

Figure 3. Diagram for Extremal Control of Acceleration and Force

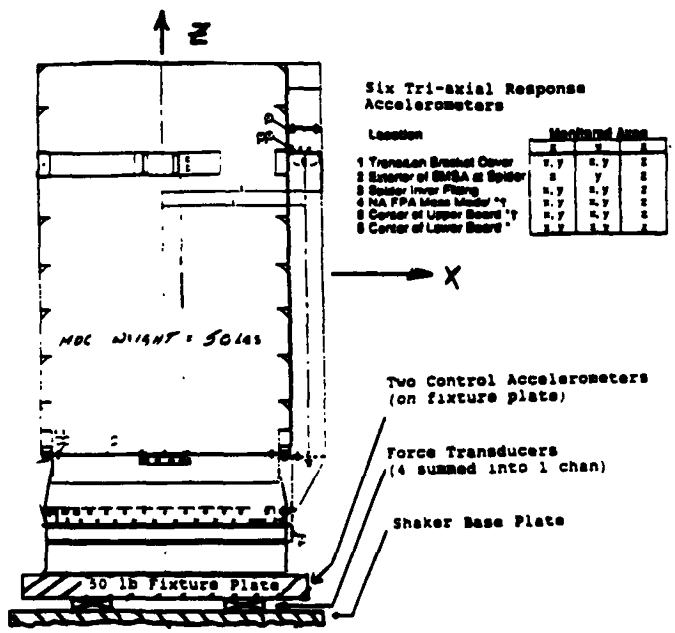

Figure 4. Mars Observer Camera Test Set-up
for Vertical Axis Vibration Test

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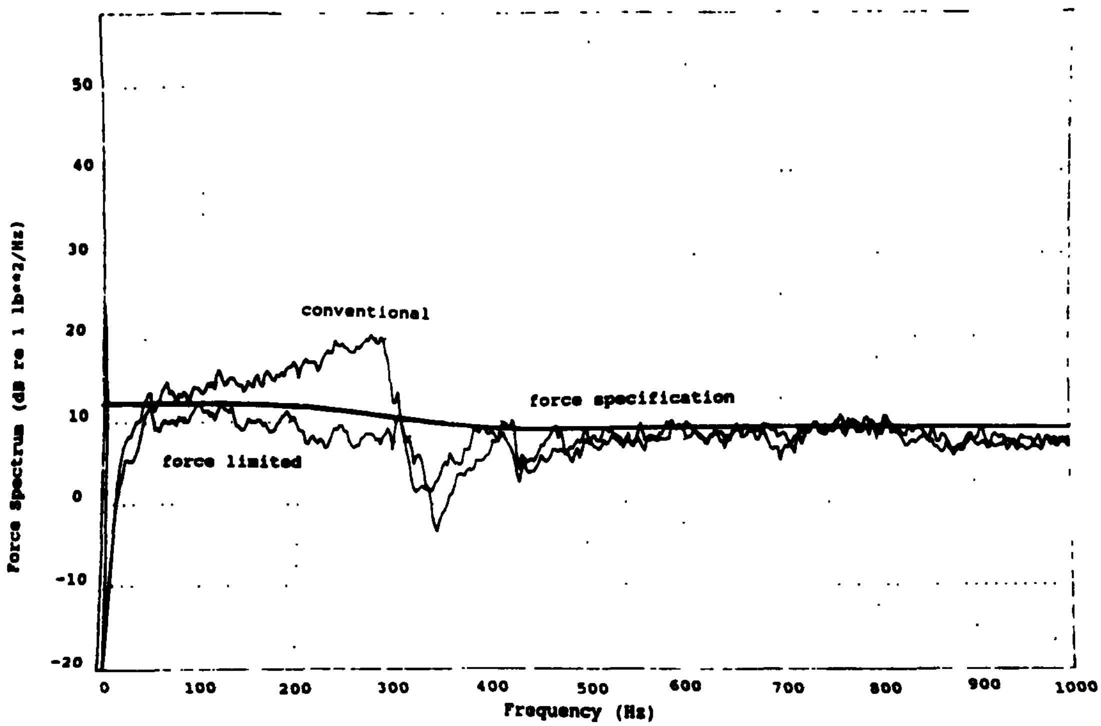


Figure 5. Force in Conventional & Force Limit Vert. -18 dB Random Tests

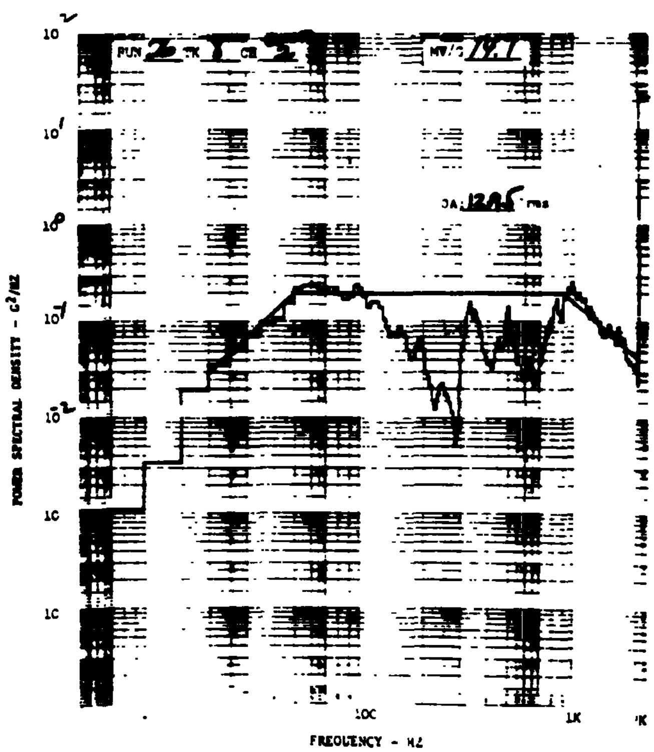
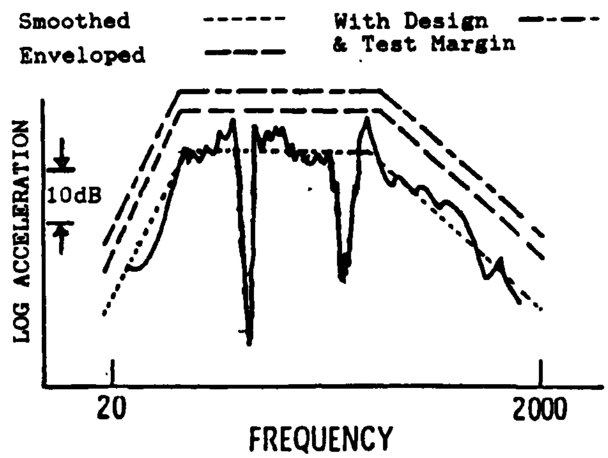


Figure 6. Input Acceleration in Force Limit Vert. Full Level Random Test



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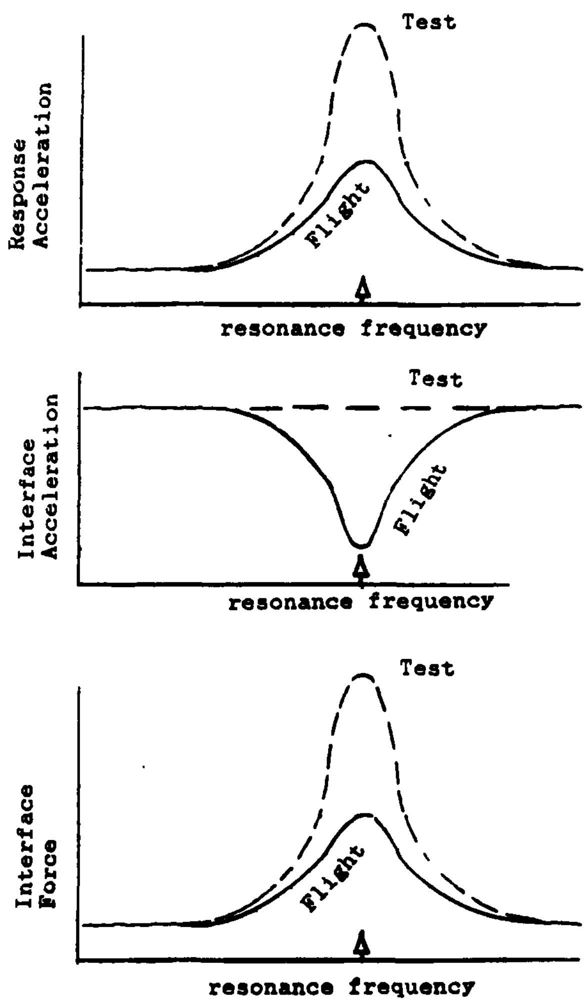

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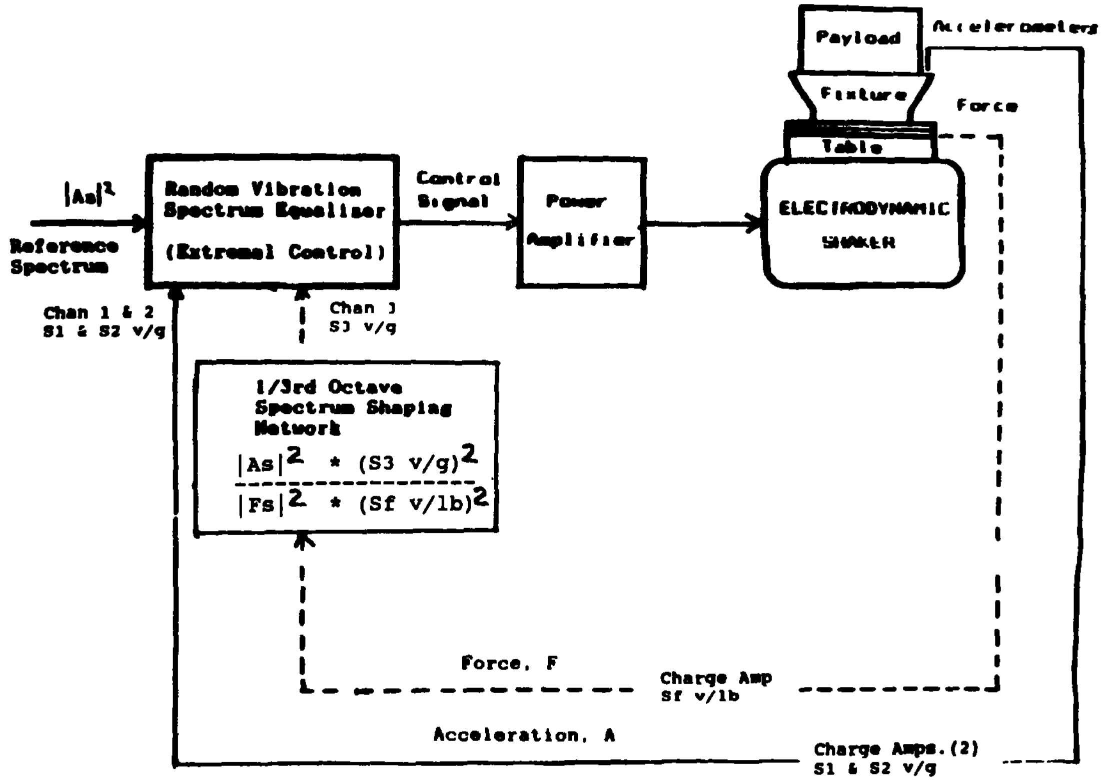

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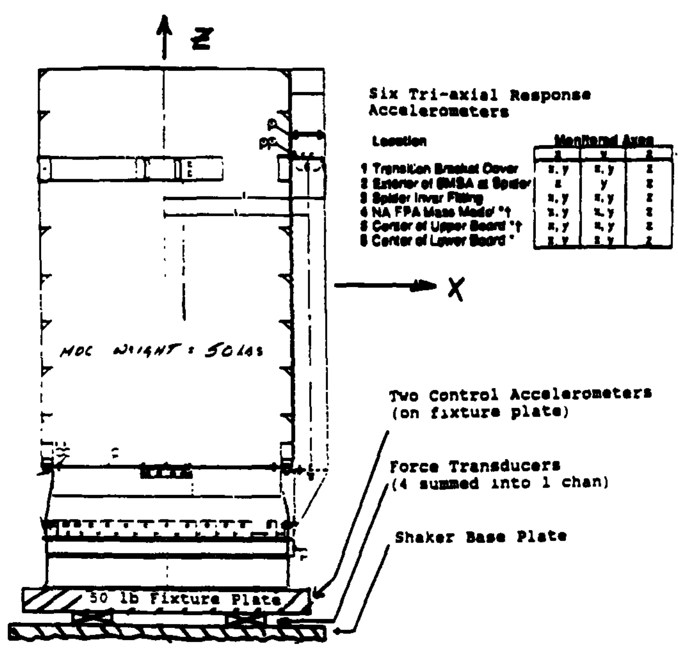

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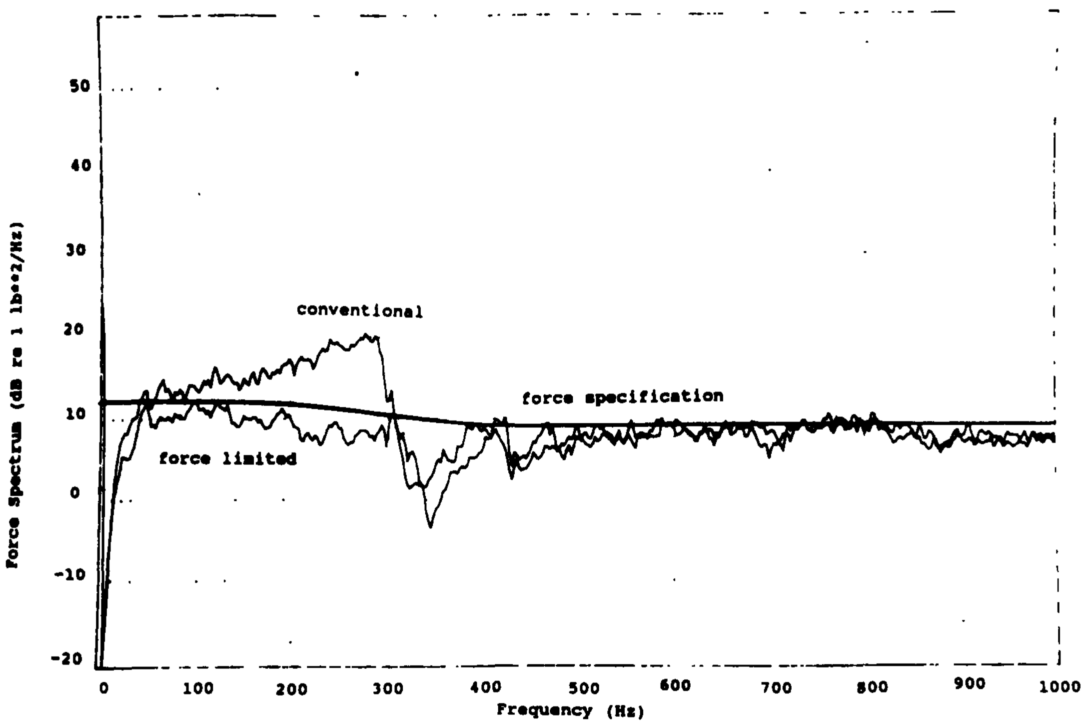

Figure 5. Force in Conventional & Force Limit Vert. -18 dB Random Tests

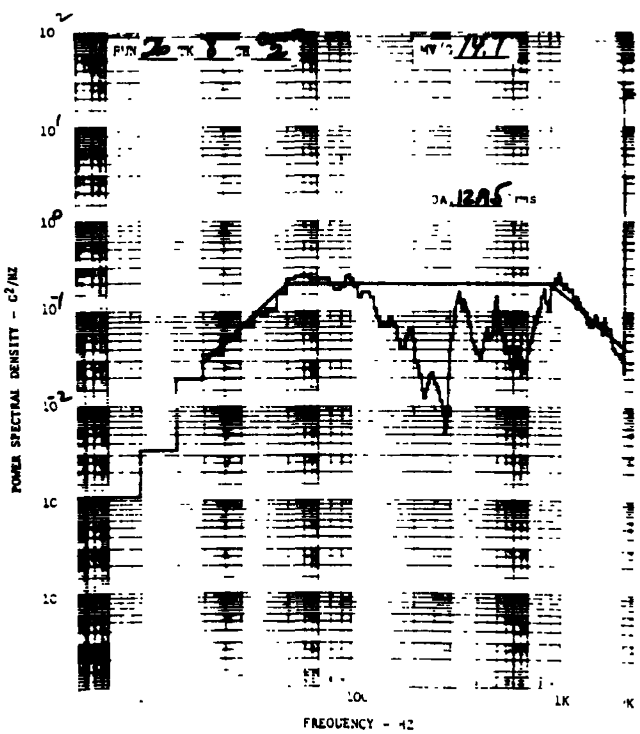

Figure 6. Input Acceleration in Force Limit Vert. Full Level Random Test

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