

22st Aerospace Testing Seminar

March 21, 2005



Force Limited Vibration Testing

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Part I (Scharton) - - Rationale and Theory



- **Introduction and Historical Perspective**
- **Force Limiting Rationale**
- **Derivation of Force Limits**
- **Force Limits Validation from Flight Measurements**

Part II (Chang) - - Instrumentation and Testing



- **Test Instrumentation and Supporting Equipment**
- **Force Limited Random Vibration Test Procedure**
- **Force Limited Test Lessons Learned**
- **Examples of Force Limited Vibration Testing**

Introduction and Historical Perspective



- **The history of the vibration over-test problem, impedance simulation work, and previous force control efforts will be summarized.**
- **Problems with response limiting and accelerometer measurements of the static C.G. acceleration will be discussed.**
- **The practice of enveloping the field acceleration spectra and the consequences of ignoring the vibration absorber effect at test item resonances will be described.**

Force Limiting Rationale



- **A two degree-of-freedom coupled vibration system vs. a single degree-of-freedom base excitation case will be used to demonstrate the differences in the responses (with or without force limiting) due to external force or base excitation.**

Derivation of Force Limits



- **The concept of effective mass will be explored from both theoretical and empirical viewpoints.**
- **Two methods of deriving force limits using simple and complex two degree-of-freedom models will be described.**
- **Furthermore, a simple, semi-empirical method that requires only the acceleration specification and data from a low level pretest to determine the apparent mass of the test items will also be presented**

Force Limits Validation from Flight Measurements



- **The prediction of force limits from the above methods will be illustrated by comparisons with analytical models and with interface force data measured at equipment interfaces in ground tests and from actual flight measurements.**
- **The NASA Handbook on force limited vibration testing NASA-HDBK-7004B will be discussed and presented to the participants. The handbook is available at: <http://standards.jpl.nasa.gov/jpl-nasa/>**

Goal of Vibration Testing



- The primary goal of vibration tests of aerospace hardware is to identify problems that, if not remedied, would result in flight failures.
- This goal can only be met by implementing a realistic (flight-like) test with a specified positive margin. In most cases, the goal is not well served by traditional acceleration-controlled vibration tests that indeed screen out flight failures, but in addition may cause failures that would not occur in flight.
- The penalty of over testing is manifested in design and performance compromises, as well as in the high costs and schedule overruns associated with recovering from artificial test failures.

History and Response Limiting



- It has been known for 30 years that the major cause of over testing in aerospace vibration tests is associated with the infinite mechanical impedance of the shaker and the standard practice of controlling the input acceleration to the frequency envelope of the flight data. This approach results in artificially high shaker forces and responses at the resonance frequencies of the test item.
- To alleviate this problem it has become common practice to limit the acceleration responses in the test to those predicted for flight, but this approach is very dependent on the analysis that the test is supposed to validate. Another difficulty with response limiting is that it requires placing accelerometers on the test item at many critical locations, some of which are often inaccessible.

Advent of Force Limiting



- The advent of piezoelectric triaxial force gages has made possible an alternative, improved vibration-testing approach based on measuring and limiting the reaction force between the shaker and test item.
- Piezoelectric force gages are robust, relatively easy to install between the test item and shaker, and require the same signal conditioning as piezoelectric accelerometers commonly used in vibration testing.
- Also vibration test controllers now provide the capability to limit the measured forces and thereby notch the input acceleration in real time.
- To take advantage of this new capability to measure and control shaker force, a rationale for predicting the flight-limit forces has been developed, validated with flight measurements, and applied to many flight projects during the past fifteen years.
- Force limited vibration tests are conducted routinely at the Jet Propulsion Laboratory (JPL) and also at several other NASA Centers, Government laboratories, and many aerospace contractors.

Basic Equations (1)



Vibration test specifications are generally based on free interface acceleration spectra and do not account for any influence of the attached payload. Scharon et al. have derived a theoretical basis for limiting vibration test levels using Norton's and Thevinin's equivalence theorems. The basis for limiting or notching vibration test levels is expressed by equation 1:

$$\frac{A}{A_0} + \frac{F}{F_0} = 1 \quad (1)$$

where A_0 is the free interface acceleration and F_0 is the blocked force. The blocked force can be computed as the product of A_0 and the effective interface impedance. In the case of random vibration, A_0 , F_0 are represented by power spectral densities. The blocked force spectral density is then computed

Basic Equations (2)



For sinusoidal testing, the interface force is expressed as a scaled value of A. $F = Z_{P/L} * A$. The notched input acceleration that satisfies equation 1 can then be calculated:

$$A = \left[\frac{Z_{I/F}}{Z_{I/F} + Z_{P/L}} \right] A_0$$

The magnitude of the notch can be calculated, in dB as:

$$\text{Magnitude of Notch (dB)} = 20 * \log \left[\frac{Z_{I/F}}{Z_{I/F} + Z_{P/L}} \right]$$

References on the Foundation of Force Limiting (1)



1. Blake, R. E., "The Need to Control the Output Impedance of Vibration and Shock Machines," Shock and Vibration and Associated Environments, Bulletin No. 23, 1954.
2. Chang, K. Y. and Scharon, T. D., "Verification of Force and Acceleration Specifications for Random Vibration Tests of Cassini Spacecraft Equipment," ESA/CNES Conference on Spacecraft Structures, Materials, and Mechanical Testing, Noordwijk, NL, March 27-29, 1996.
3. Murfin, W. B., "Dual Specifications in Vibration Testing," Shock and Vibration Bulletin, No. 38, Part 1, 1968, pp. 109-113.
4. Salter, J. P., "Taming the General-Purpose Vibration Test," Shock and Vibration and Associated Environments, Bulletin No. 33, Part III, 1964, pp. 211-217.
5. Scharon, T. D., Boatman, D. J., and Kern, D. L., "Dual Control Vibration Testing," Proceedings of 60th Shock and Vibration Symposium, Vol. IV, 1989, pp. 199-217.
6. Scharon, T. D., "Analysis of Dual Control Vibration Testing," Proceedings of Institute of Environmental Sciences 36th Annual Technical Meeting, 1990, pp. 140-146.
7. Scharon, T. D., "Force Limited Vibration Testing at JPL," Proceedings of the Institute of Environmental Sciences 14th Aerospace Testing Seminar, 1993, pp. 241-251.
8. Scharon, T. D., "Vibration-Test Force Limits Derived from Frequency-Shift Method," AIAA Journal of Spacecraft and Rockets, Vol. 2, No. 2, March 1995, pp. 312-316.

References on the Foundation of Force Limiting (2)



9. Scharton, T., Bamford, R., and Hendrickson, J., "Force Limiting Research and Development at JPL," Spacecraft and Launch Vehicle Technical Information Meeting, Aerospace Corp., Los Angeles, CA, June 7, 1995.
10. Scharton, T. D., "In-flight Measurements of Dynamic Force and Comparison with the Specifications Used or Limiting the Forces in Ground Vibration Tests," European Conference on Spacecraft, Structures, Materials, and Mechanical Testing, Braunschweig, GR, November 1998.
11. Smallwood, D. O., "An Analytical Study of a Vibration Test Method Using Extremal Control of Acceleration and Force," Proceedings of Institute of Environmental Sciences 35th Annual Technical Meeting, 1989, pp. 263-271.
12. Smallwood, D. O., "Development of the Force Envelope for an Acceleration/Force Extremal Controlled Vibration Test," Proceedings of 61st Shock and Vibration Symposium, Vol. I, 1990, pp. 95-104.
13. Scharton, T. D., "Force Limits Measured on a Space Shuttle Flight", Proceedings of the 47th Annual Technical Meeting of the Institute of Environmental Sciences and Technology, ESTECH 2001, April 22, 2001.
14. Talapatra, D. C., McDonnell, R.H., and Hershfeld, D.J., "Analysis of STS-3 Get Away Special (GAS) Flight Data and Vibration Specifications for GAS Payloads", NASA Goddard Space Flight Center, Report 614-1, February 1983.
15. Wada, B. K., Bamford, R., and Garba, J. A., "Equivalent Spring-Mass System: A Physical Interpretation," Shock and Vibration Bulletin, No. 42, 1972, pp. 215-225.

Force Limit Specifications



- Force limits are analogous and complementary to the acceleration specifications used in conventional vibration testing. Just as the acceleration specification is the frequency spectrum envelope of the in-flight acceleration at the interface between the test item and flight mounting structure, the force limit is the envelope of the in-flight force at the interface
- . In force limited vibration tests, both the acceleration and force specifications are needed, and the force specification is generally based on and proportional to the acceleration specification. Therefore, force limiting does not compensate for errors in the development of the acceleration specification, e.g., too much conservatism or the lack thereof. These errors will carry over into the force specification.
- Since in-flight vibratory force data are scarce, force limits are often derived from coupled system analyses and impedance information obtained from measurements or finite element models (FEM). Fortunately, data on the interface forces between systems and components are now available from system acoustic and vibration tests of development test models and from a few flight experiments.
- Semi-empirical methods of predicting force limits are currently being developed on the basis of the limited flight and system test data.

Semi-empirical Force Limits (Sine)



The semi-empirical approach to deriving force limits is based on the extrapolation of interface force data for similar mounting structure and test items. A general form for a semi-empirical force limit for sine or transient tests follows from Reference 4.

$$F_s = C M_o A_s \quad , \quad f < f_o \quad (1a)$$

$$F_s = C M_o A_s (f_o/f) \quad , \quad f \geq f_o$$

where F_s is the amplitude of the force limit, C is a dimensionless constant which depends on the configuration, M_o is the total mass of the payload (test item), A_s is the amplitude of the acceleration specification, f is frequency, and f_o is the frequency of the primary mode, i.e. the mode with the greatest effective mass.

Semi-empirical Force Limits (Random)



The form of Equation (1a) appropriate for random vibration tests is:

$$\begin{aligned} S_{FF} &= C^2 M_o^2 S_{AA} & , f < f_o \\ S_{FF} &= C^2 M_o^2 S_{AA} (f_o/f)^2 & , f \geq f_o \end{aligned} \tag{1b}$$

where S_{FF} is the force spectral density and S_{AA} is the acceleration spectral density.

Comparing Equation (1b) with Figure 2, which is discussed in detail in Section 5.1.1, it may be apparent that C^2 is equivalent to the ordinate in Figure 2, and that the constant C replaces the quality factor Q of the isolated payload system.

The factor (f_o/f) has been included in Equations (1a) and (1b) to reflect the decrease in the payload residual mass with frequency. Sometimes it is appropriate to adjust the exponent of this factor to fit experimental measurements of the apparent mass of the test item.



Figure 1- Simple Two-Degree-of-Freedom System (TDFS)

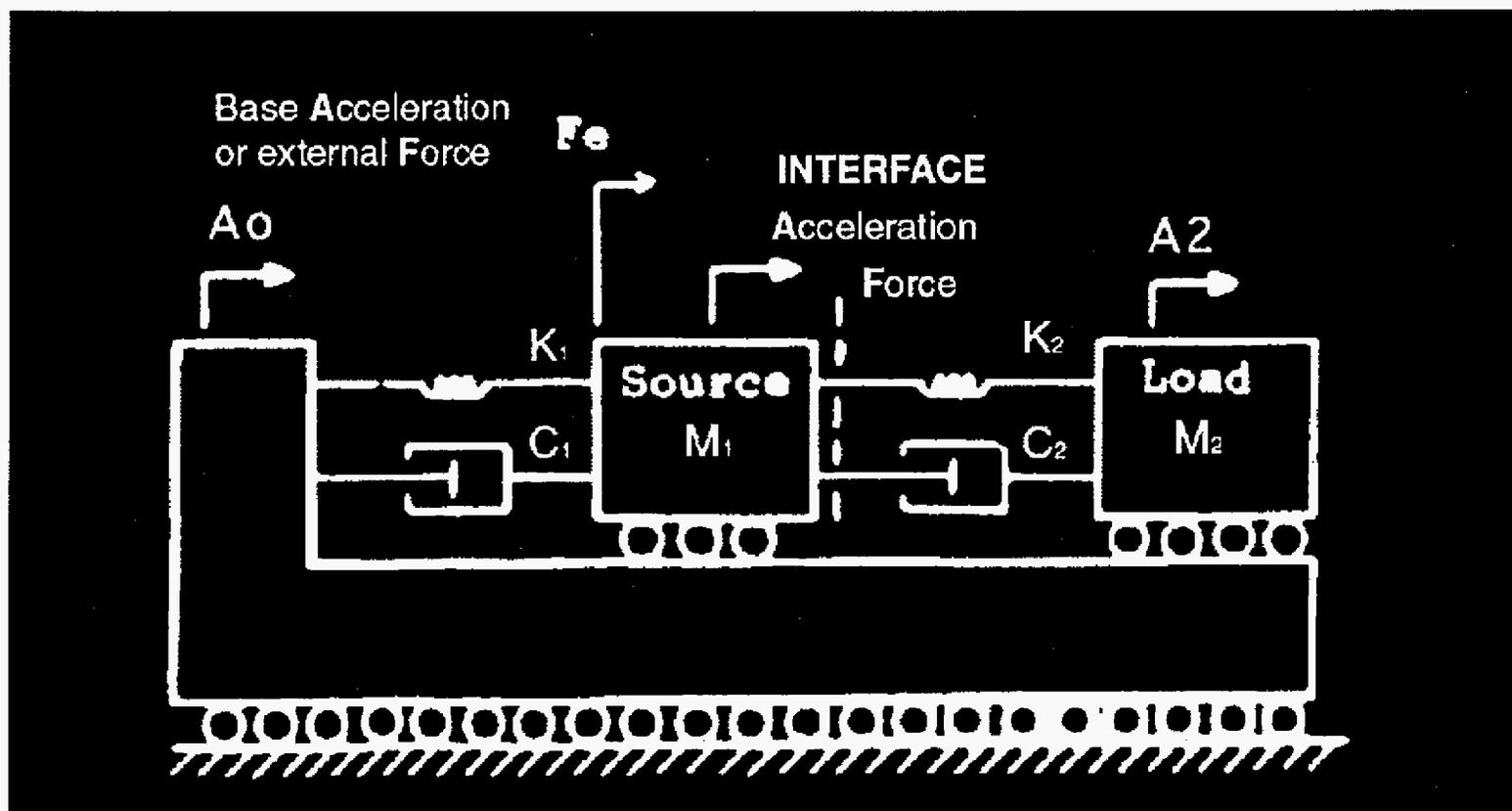
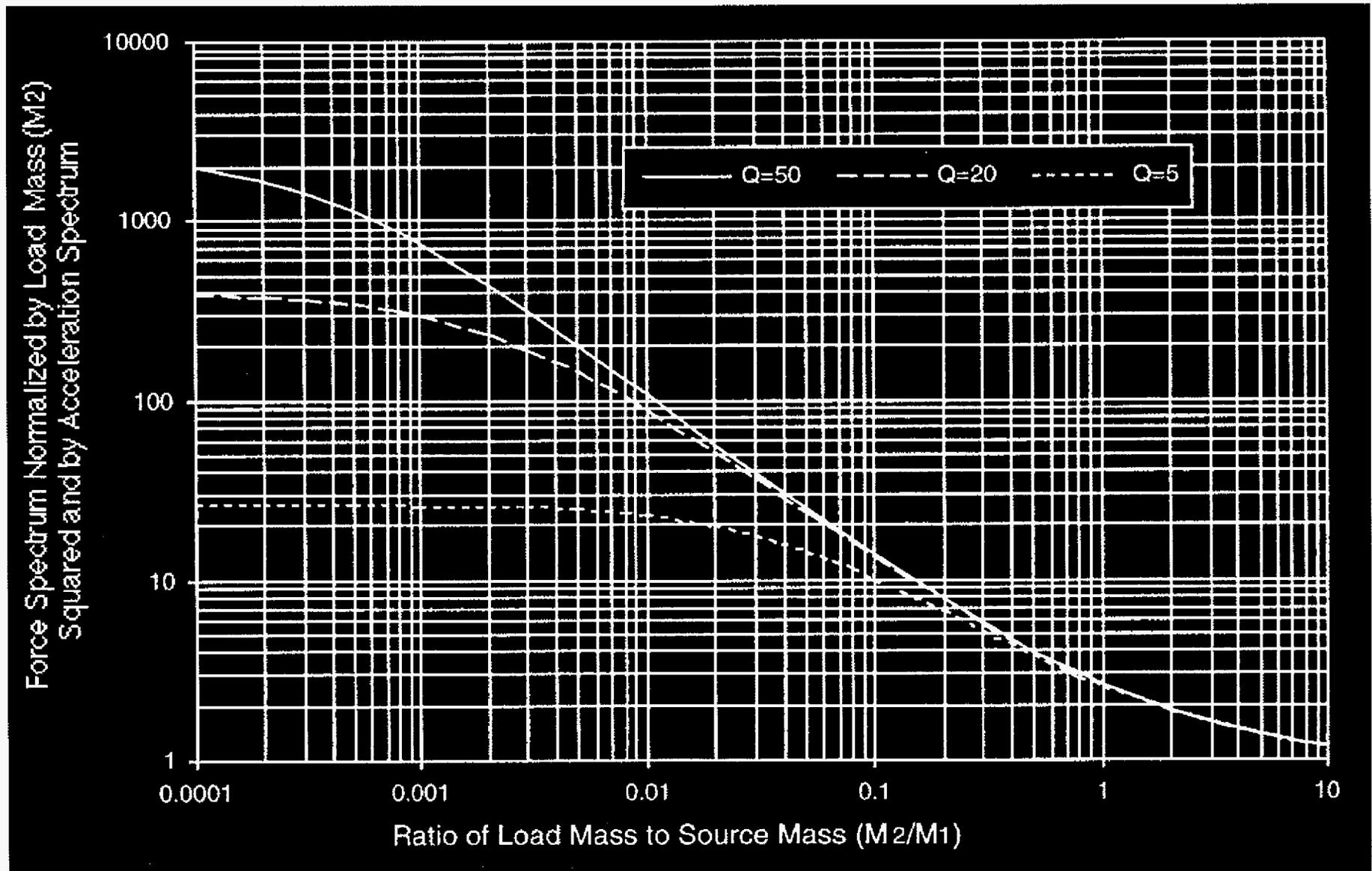
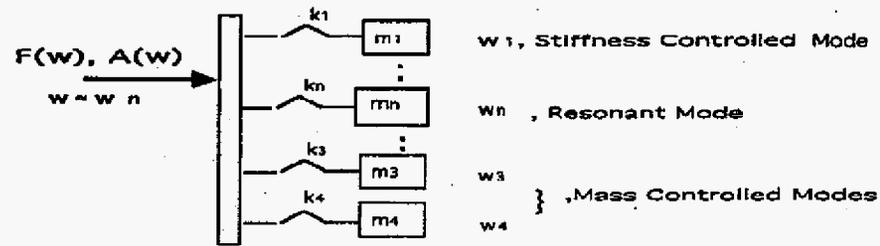


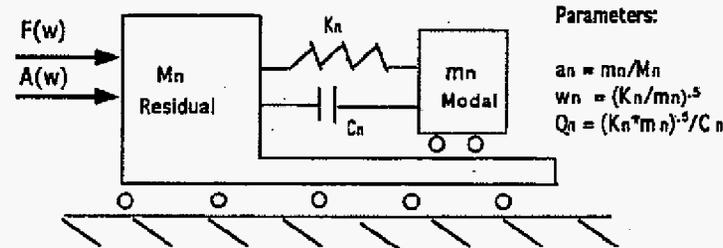
Figure 2-- Basic Force Limiting Result (Simple TDFS)



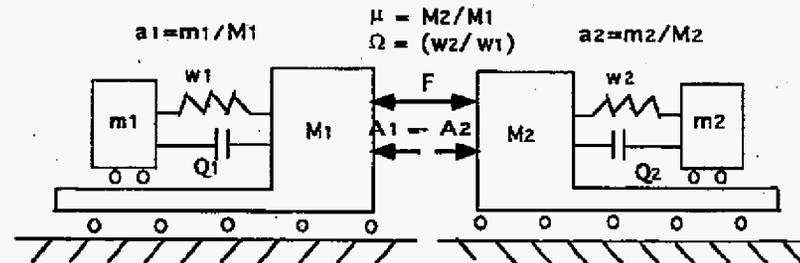
Complex Two-Degree-of-Freedom System (TDFS)



ASPARAGUS PATCH MODEL OF SOURCE OR LOAD



RESIDUAL AND MODAL MASS MODEL OF SOURCE OR LOAD



COUPLED TDFS RESIDUAL AND MODAL MASS MODEL

Governing Equations for Basic Force Limiting Result (Simple TDFS)



The force limit is calculated for the TDFS in Figure 1 with different masses for the source and the payload oscillators. For this TDFS, the maximum response of the payload and therefore the maximum interface force occur when the uncoupled resonance frequency of the payload equals that of the source. For this case, the characteristic equation is that of a classical dynamic absorber, from Reference 8:

$$(\omega/\omega_o)^2 = 1 + (m_2/m_1)/2 \pm [(m_2/m_1) + (m_2/m_1)^2/4]^{0.5} \quad (A1)$$

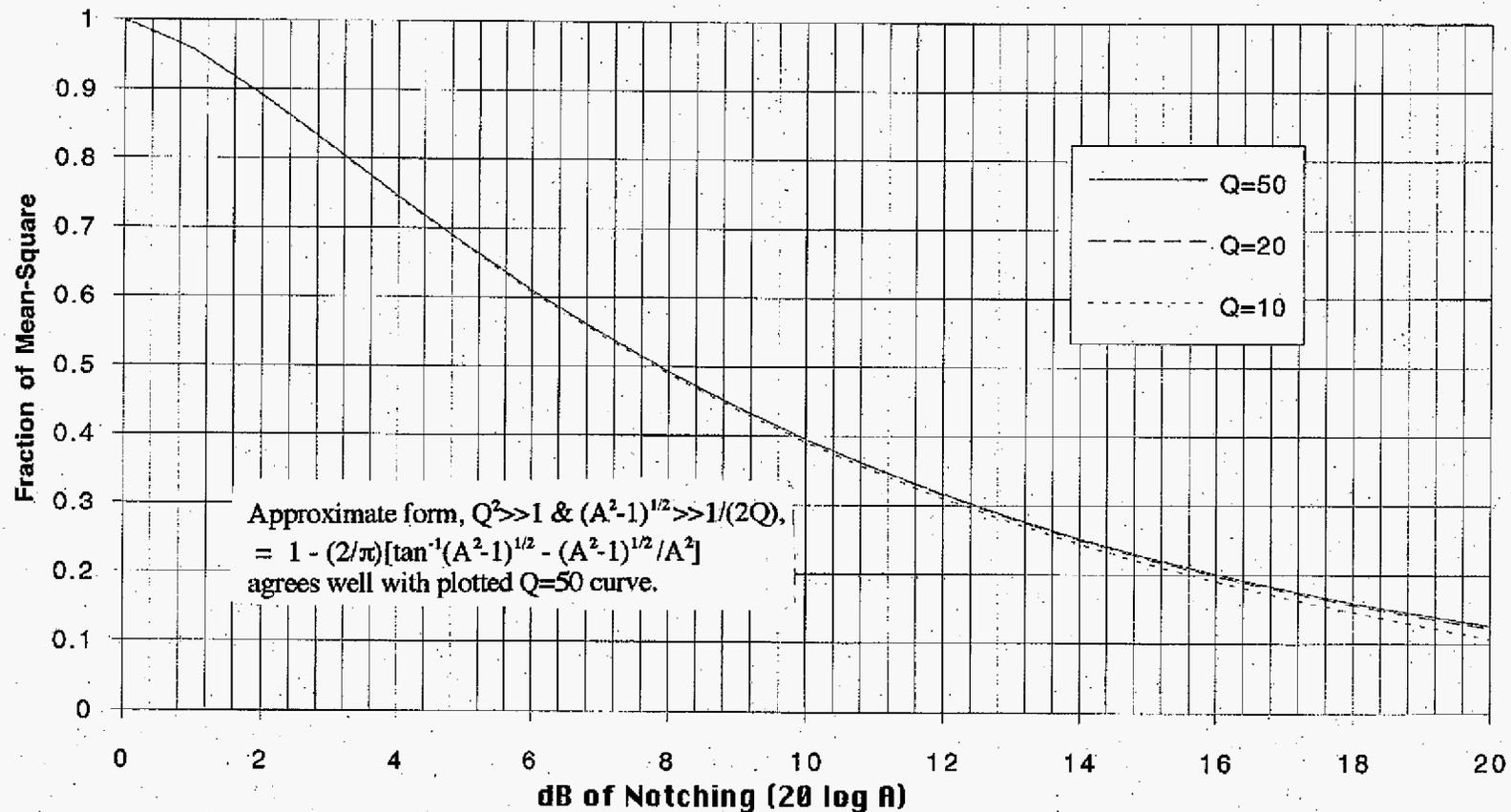
where ω_o is the natural frequency of one of the uncoupled oscillators, m_1 is the mass of the source oscillator, and m_2 is the mass of the load oscillator in Figure 1. The ratio of the interface force S_{FF} to acceleration S_{AA} spectral densities, divided by the magnitude squared of the payload dynamic mass m_2 , is:

$$S_{FF}/(S_{AA} m_2^2) = [1 + (\omega/\omega_o)^2/Q_2^2] / \{[1 - (\omega/\omega_o)^2]^2 + (\omega/\omega_o)^2/Q_2^2\} \quad (A2)$$

where Q_2 is the quality factor, one over twice the critical damping ratio, of the payload.

The force spectral density, normalized by the payload mass squared and by the acceleration spectral density, at the two-coupled system resonances is obtained by combining Equations (A1) and (A2). For this TDFS, the normalized force is just slightly larger at the lower resonance frequency of Equation (A1). The maximum normalized force spectral density, obtained by evaluating Equation (A2) at the lower resonance frequency, is plotted against the ratio of payload to source mass for three values of Q_2 in Figure 2.

Reduction of Mean-Square Response by Notching Input to SDFS



SVF2 Experiment to Validate Force Limiting



➤ **Successful Shuttle Vibration Forces (SVF2) Experiment on STS-96**

- External forces on Hitchhiker (HH) canister measured in 3 axes, 20-2000 Hz
- Acceleration at top of canister measured in 2 axes, 20-2000 Hz
- Only acceleration near HH canister CG measured in 2 axes with SVF1 on STS-90 (no force data, because of instrumentation problems)

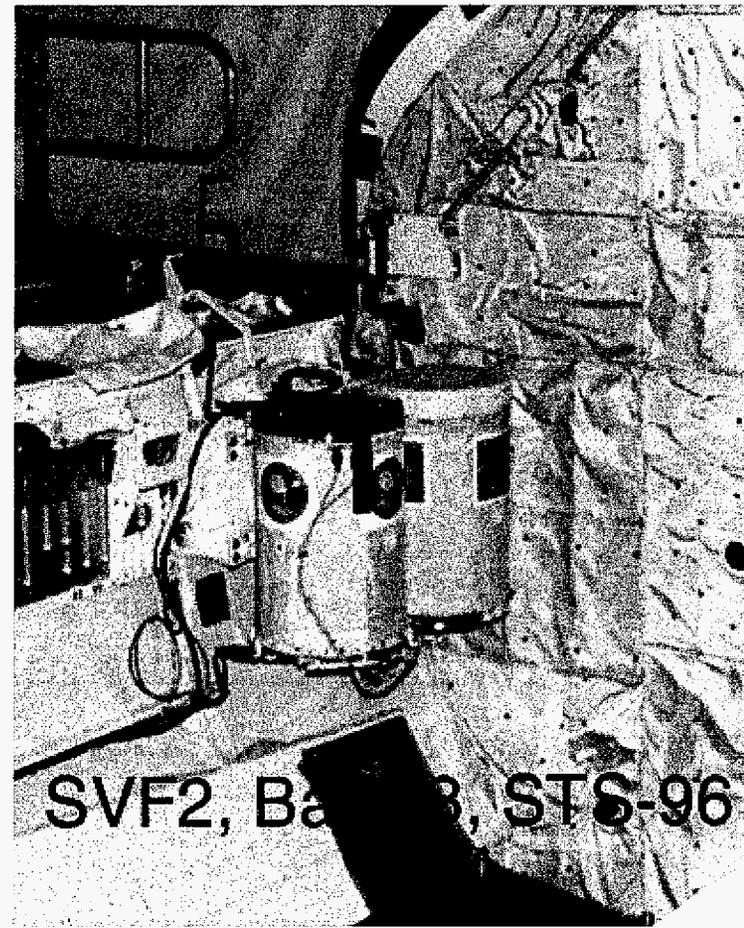
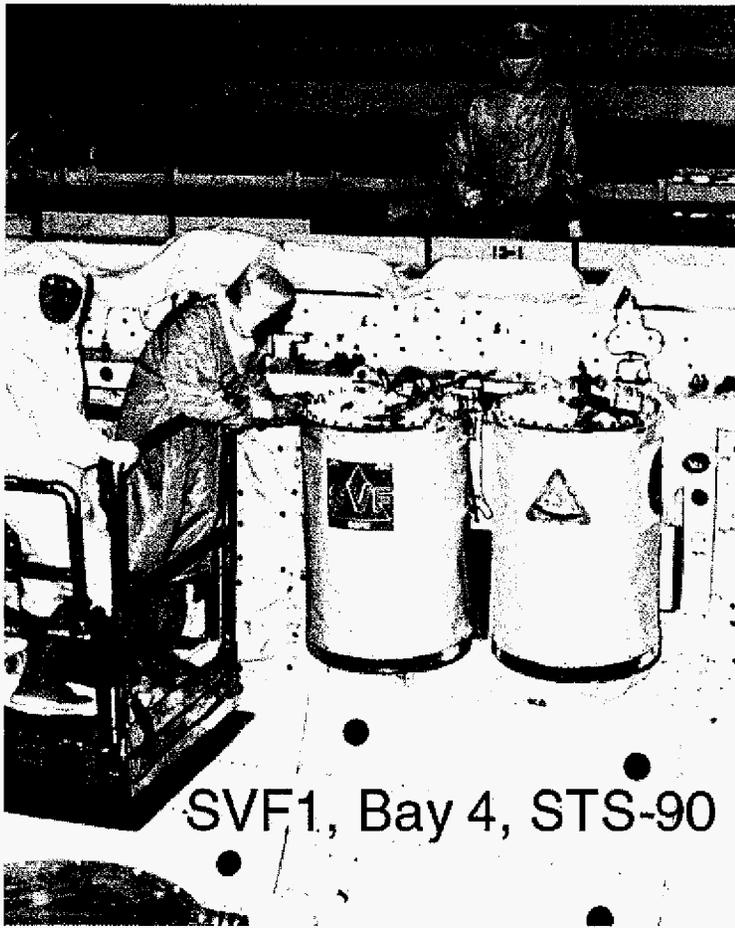
➤ **Objective: Cost effective structural design/analysis/test methods**

- Validation of methods used to derive force limits for vibration tests and
- Validation of shuttle lift-off, random vibration design load methodology

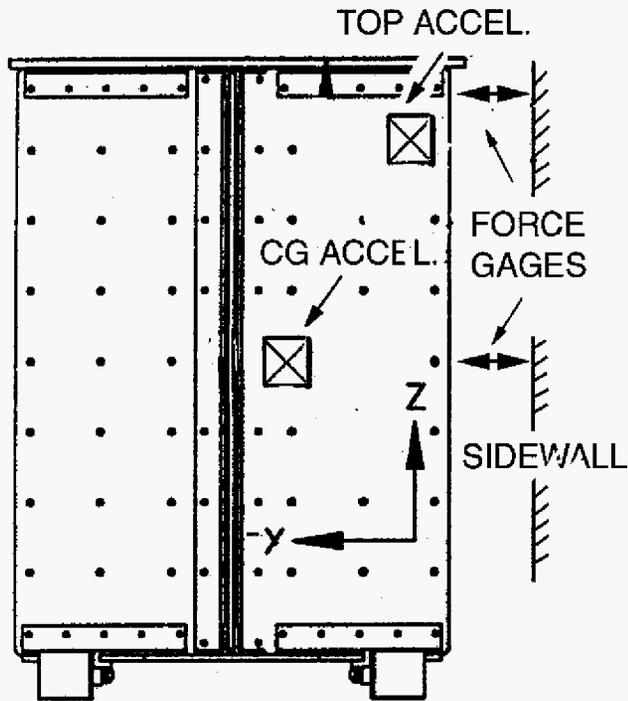
➤ **Conclusions:**

- Data support force limit methodology, and indicate lower (~50%) random vibration loads than design limits currently used for HH sidewall payloads
- Additional flights desirable to provide : low frequency loads, adapter beam inputs, force data at other shuttle locations, and flight-to-flight variations

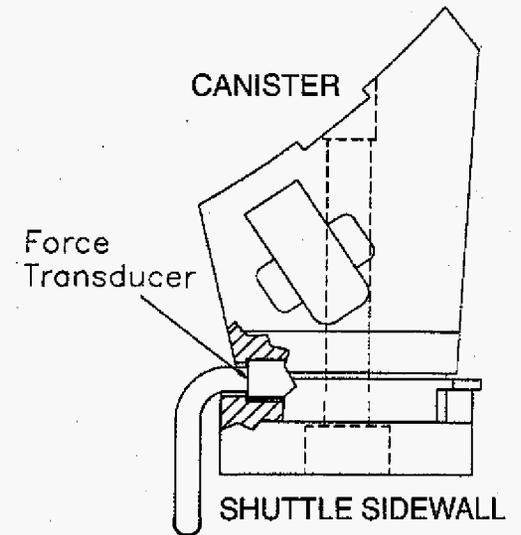
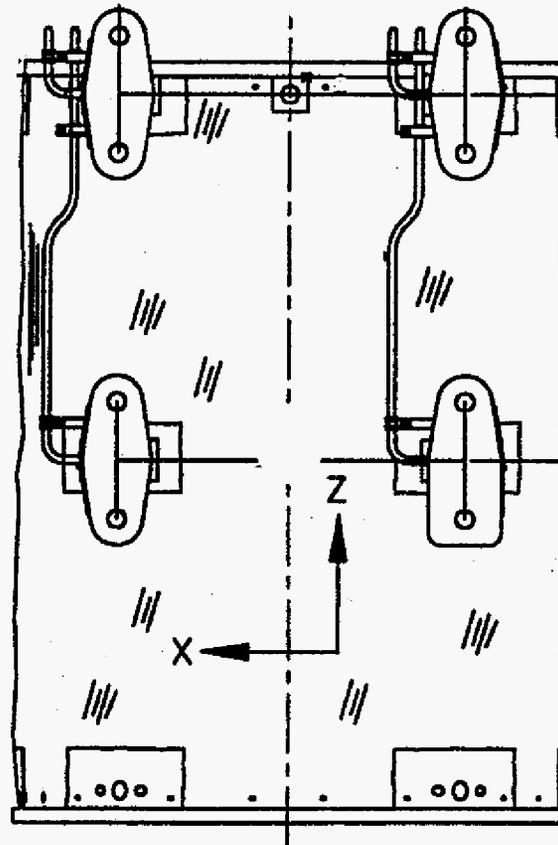
SVF Experiment Installation on STS-90 & 96



SVF Experiment Hitchhiker Canister and Brackets

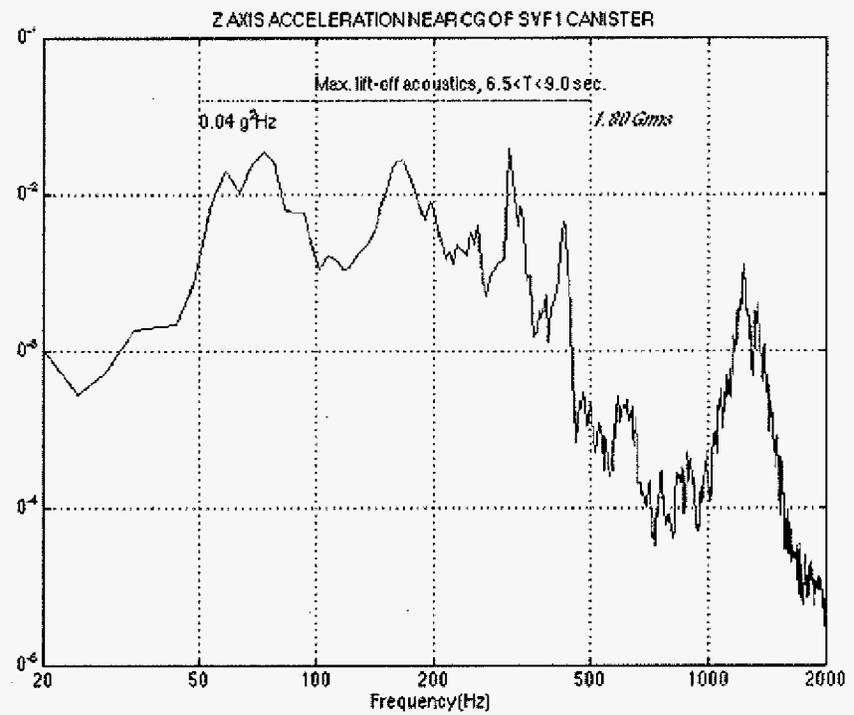
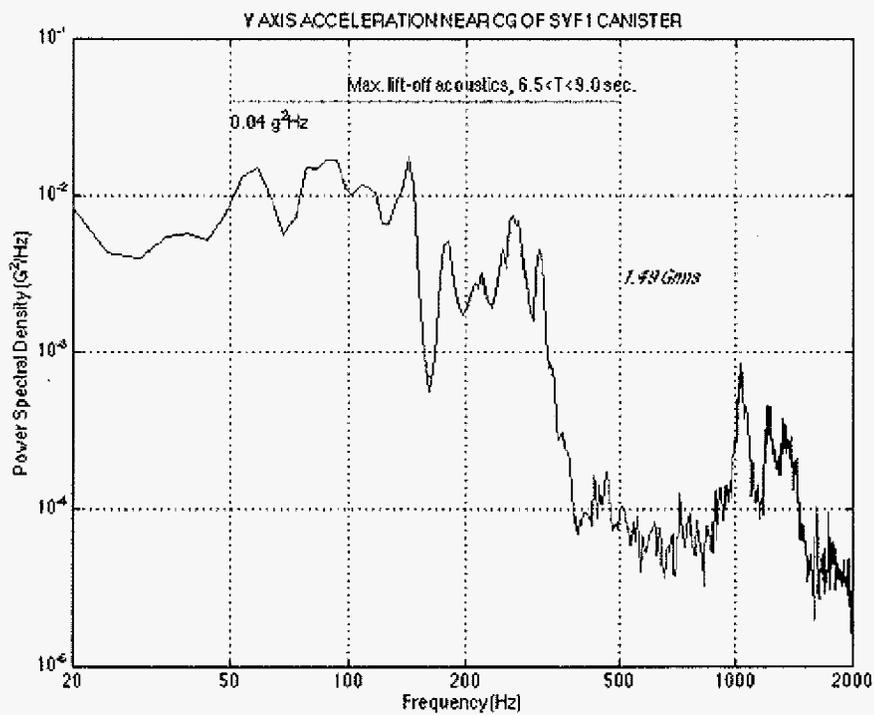


Payload Ballast Structure (Signal Conditioning and WBSAAMD Recorders)

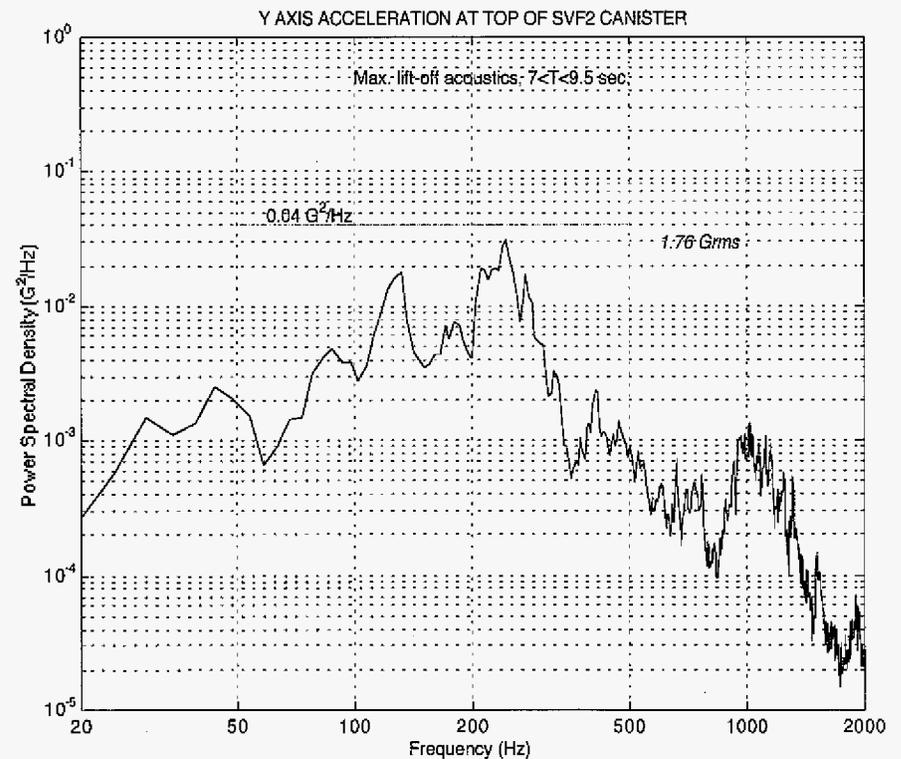
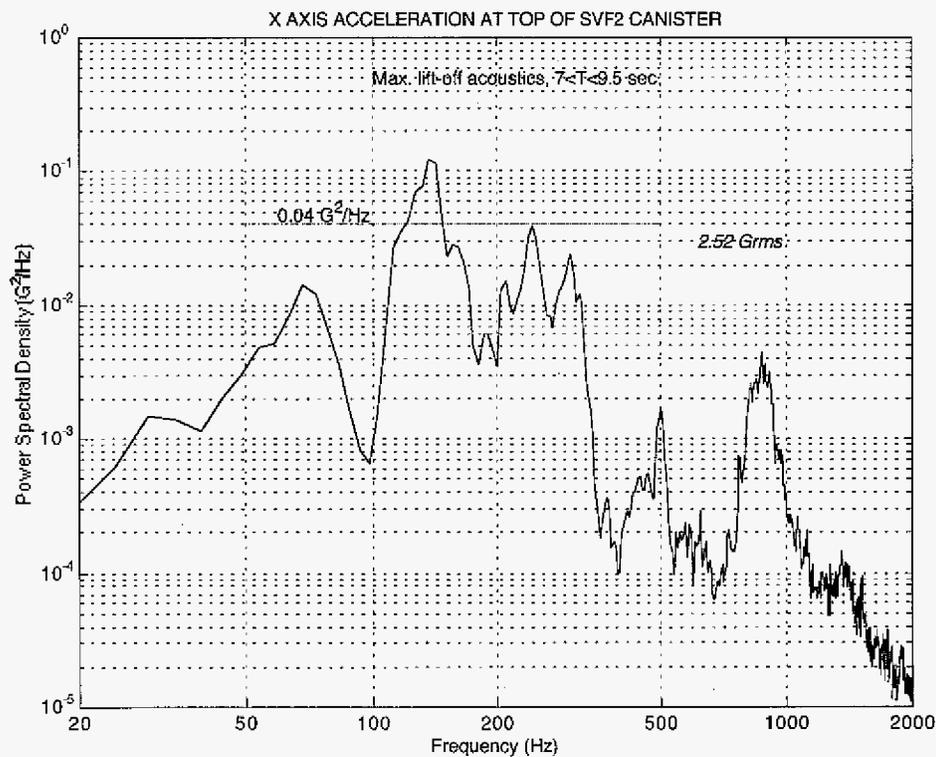


Modified Brackets

SVF1 (STS-90) ACCELERATION DATA MEASURED NEAR TOP OF CANISTER



SVF2 (STS-96) ACCELERATION DATA MEASURED NEAR TOP OF CANISTER

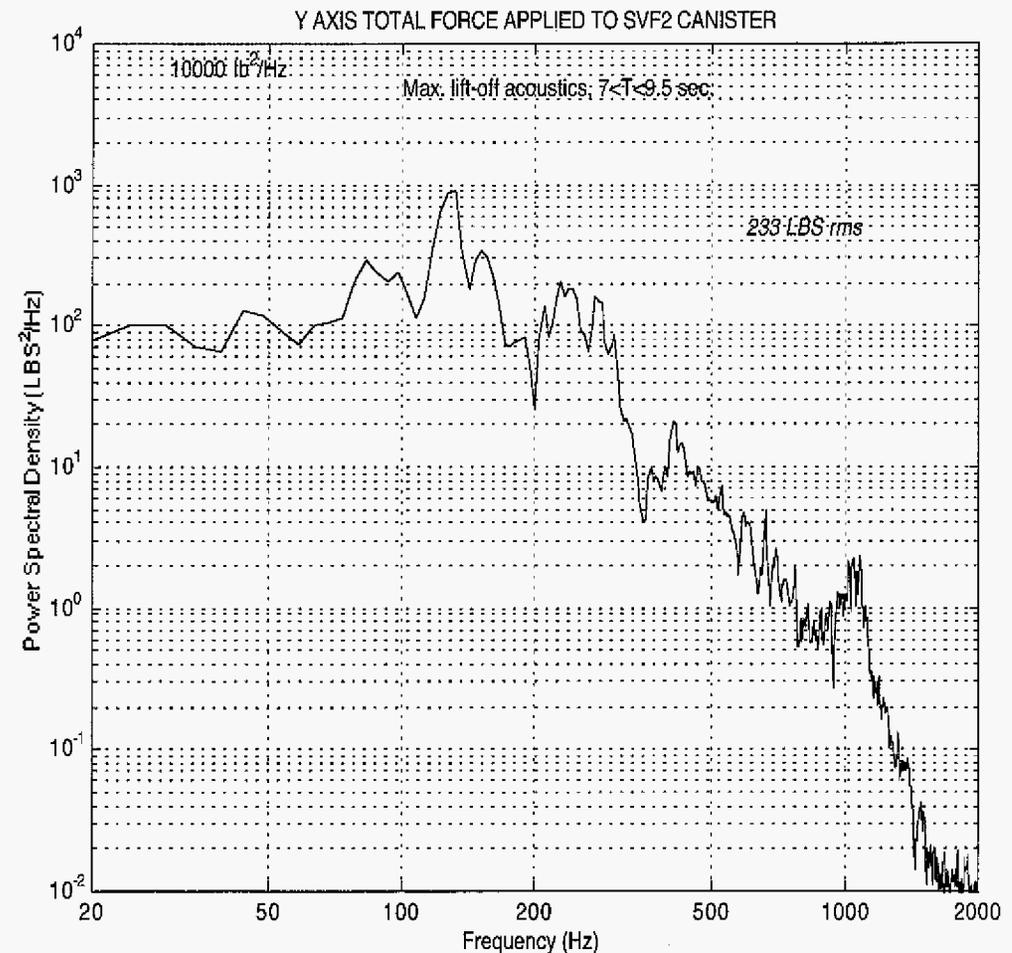


SVF2 (STS-96) FORCE DATA

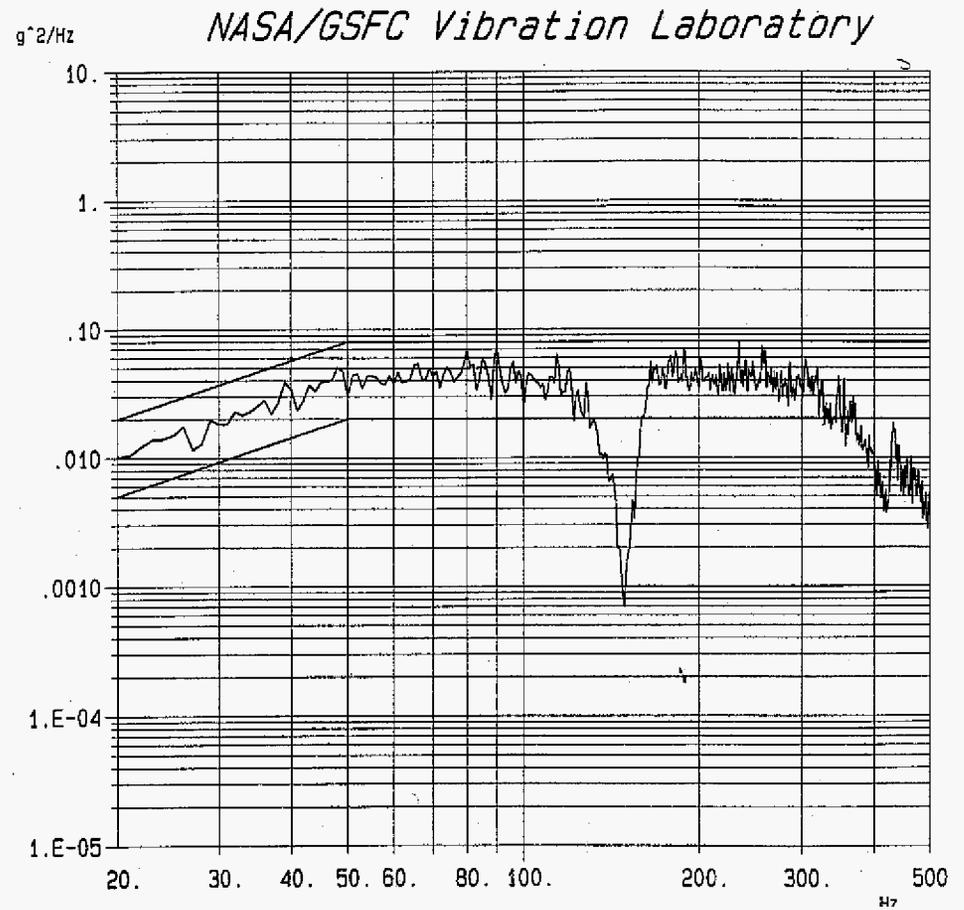
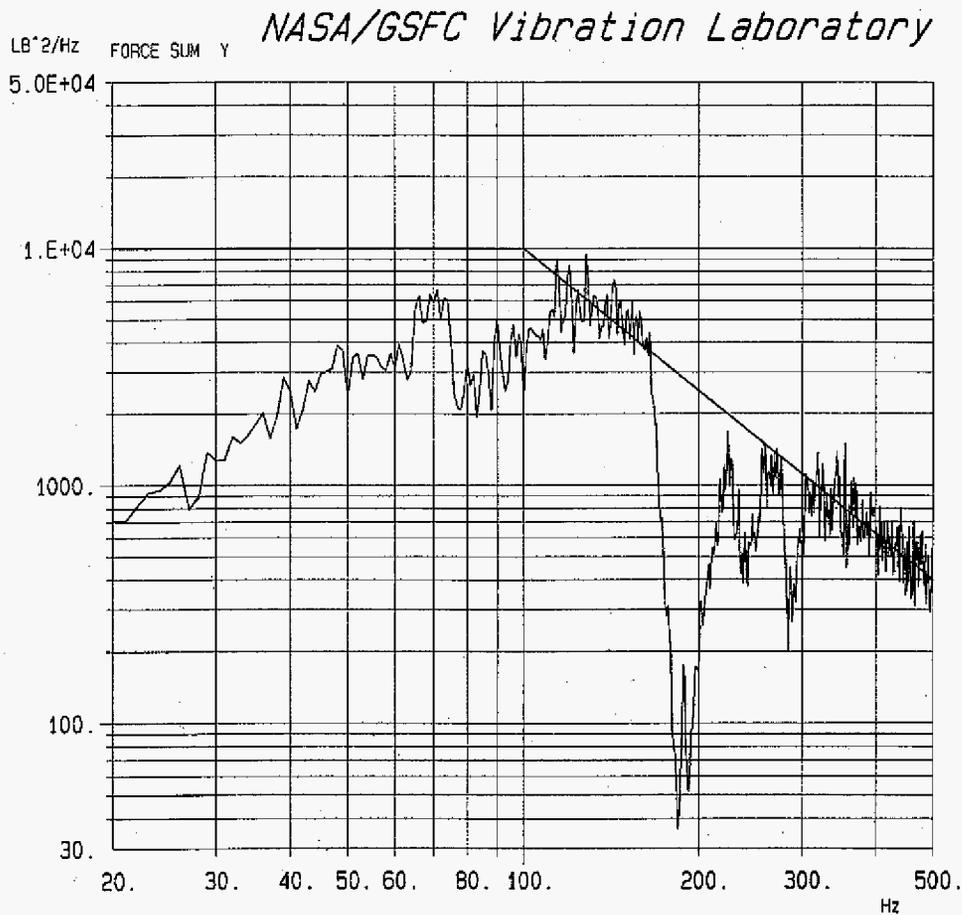
Total Y-Force Between Sidewall and Canister



- Measured force spectrum is ~ 6 dB less than force limit used in random vibration test (3 dB is test margin) and still resulted in ~16 dB of notching (see next viewgraph)
- Measured force of 233 lb rms divided by total canister weight of 230 lb gives CG acceleration of 1.0 g rms or 3.0 g peak, which is less than 8.0 g HH design limit for y-axis



FORCE LIMIT AND NOTCHING IN Y-AXIS RANDOM VIBRATION TEST OF HH CANISTER

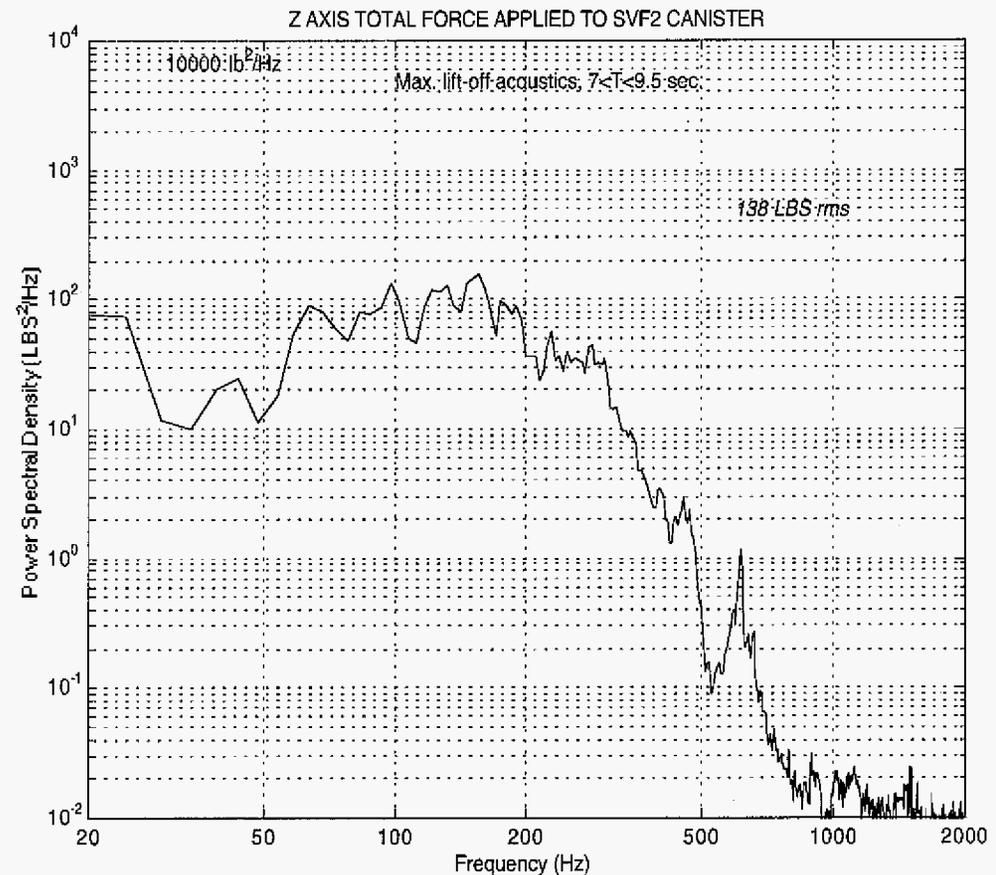


SVF2 (STS-96) FORCE DATA

Total Z-Force Between Sidewall and Canister



- Measured force spectrum is ~ 13 dB less than force limit used in random vibration test (3 dB is test margin)
- Measured force of 138 lb rms divided by total canister weight of 230 lb gives CG acceleration of 0.6 g rms or 1.8 g peak, which is less than 5.4 g HH design limit for z-axis

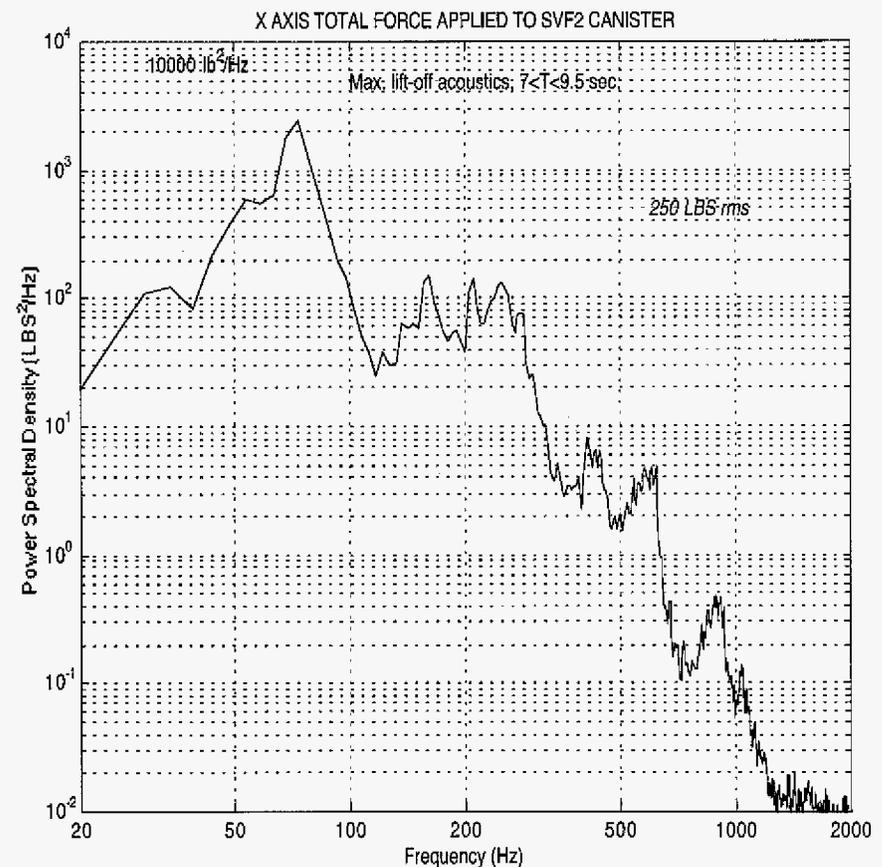


SVF2 (STS-96) FORCE DATA

Total X-Force Between Sidewall and Canister



- Measured force spectrum is ~ 6 dB less than force limit used in random vibration test (3 dB is test margin)
- Measured force of 250 lb rms divided by canister weight of 230 lb gives CG acceleration of 1.1 g rms or 3.3 g peak, which is less than 5.4 g HH design limit for x-axis



Summary of SVF2



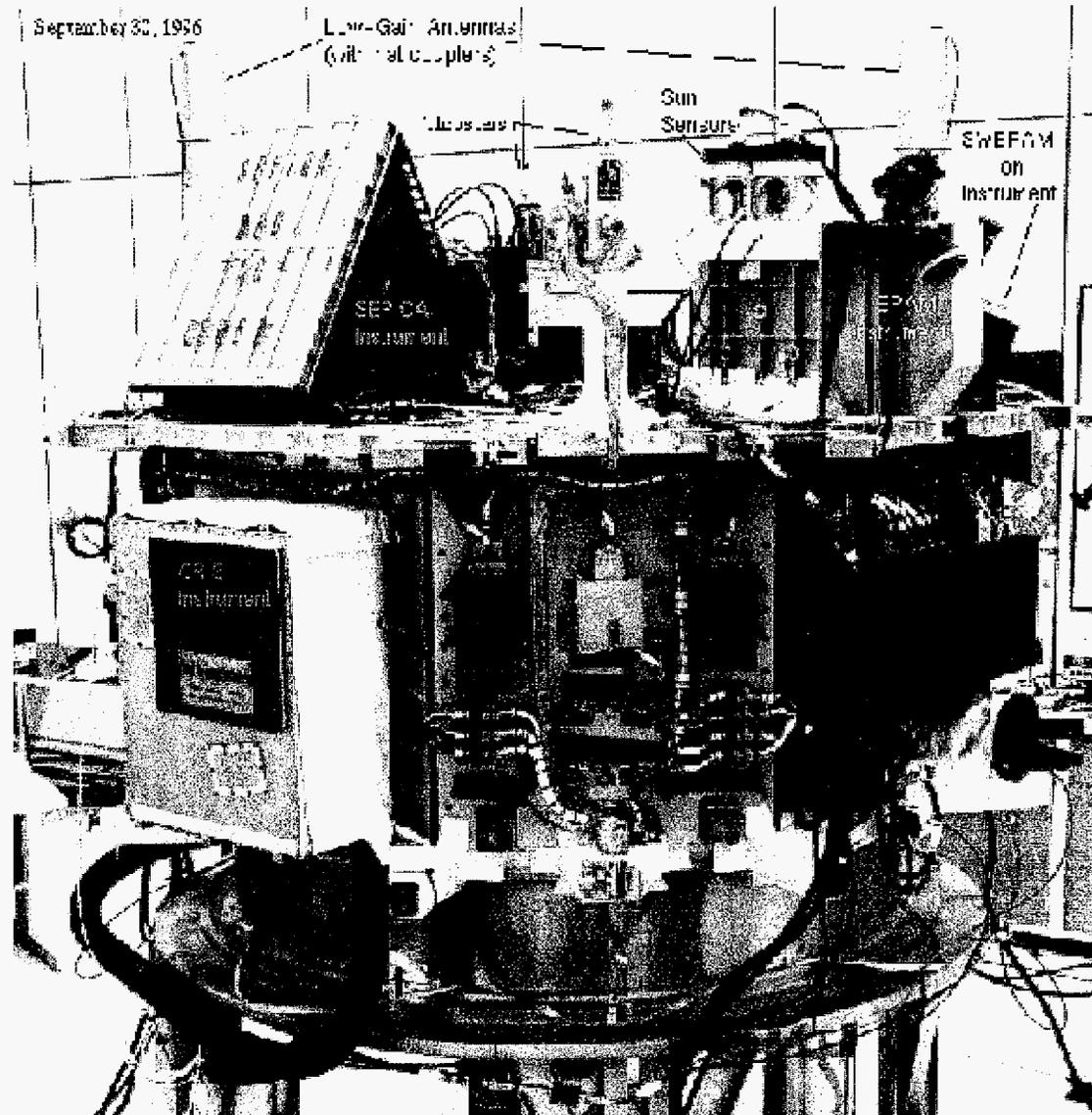
- **SVF2 was successful, thanks to continued NASA HQ support and extraordinary effort by team members at GSFC and JSC**
- **SVF2 data indicate maximum random vibration CG load of ~4 g in y-axis, i.e. ~50% lower than current HH design limit of ~8 g**
- **The SVF2 force limiting experiment, with a payload weight of 230 lb, yielded a value of the semi-empirical method constant of $C^2 = 1.9$.**

ACE Experiment to Validate Force Limiting

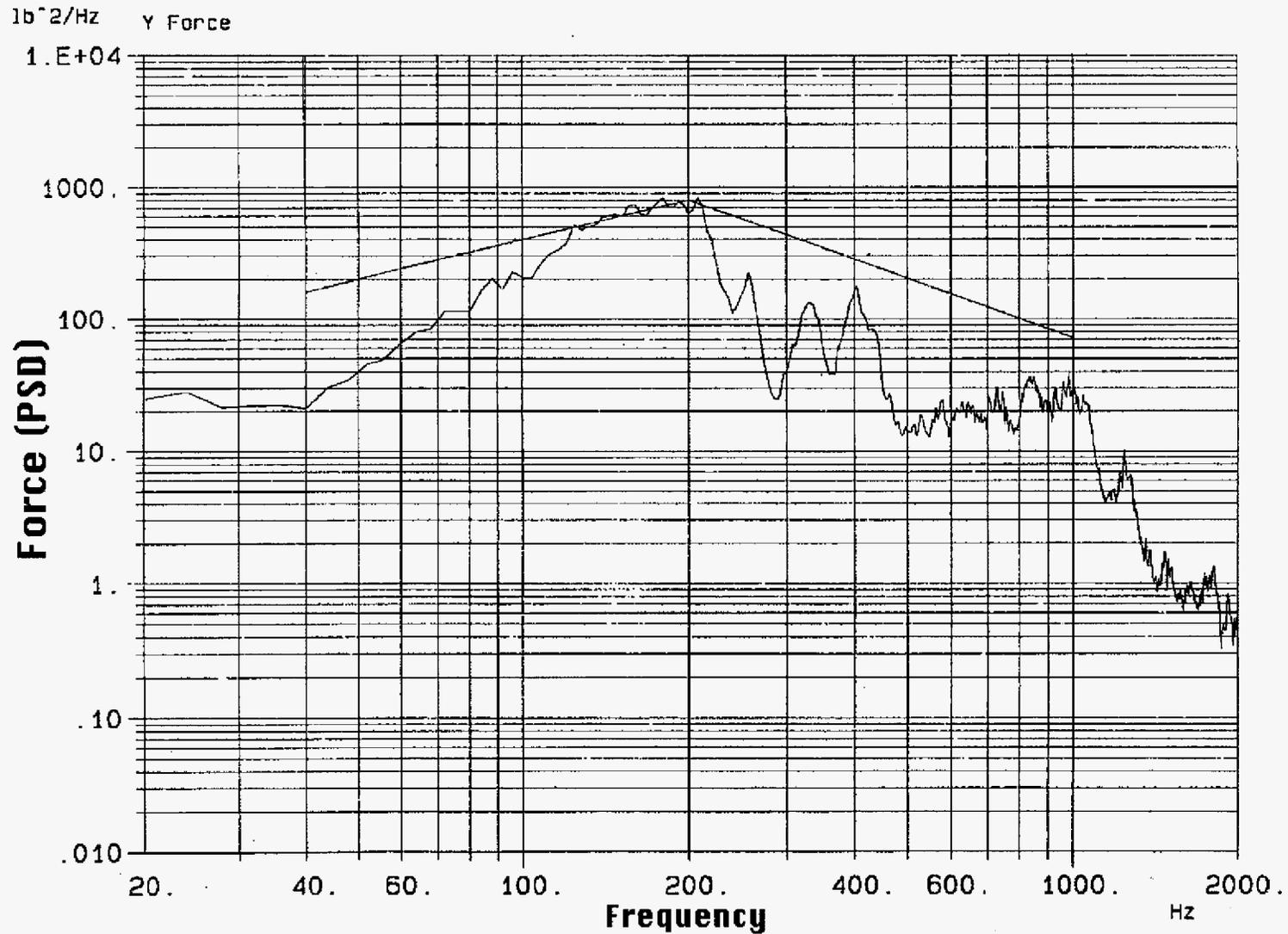


- The flight data described in Reference 10 were measured at the interface of the Cosmic Ray Isotope Spectrometer (CRIS) instrument and the Advanced Composition Explorer (ACE) spacecraft.
- The data were recorded during a one second interval corresponding to the time of maximum acoustic loading during the lift-off of the Delta II 7920-8 launch vehicle.
- Following figure shows the 65 lb (30 kg) CRIS instrument mounted on the left side of the ACE spacecraft bus, which is a two-deck octagon honeycomb structure, 65 in. (1.6m) across and 40 in. (1m) high.

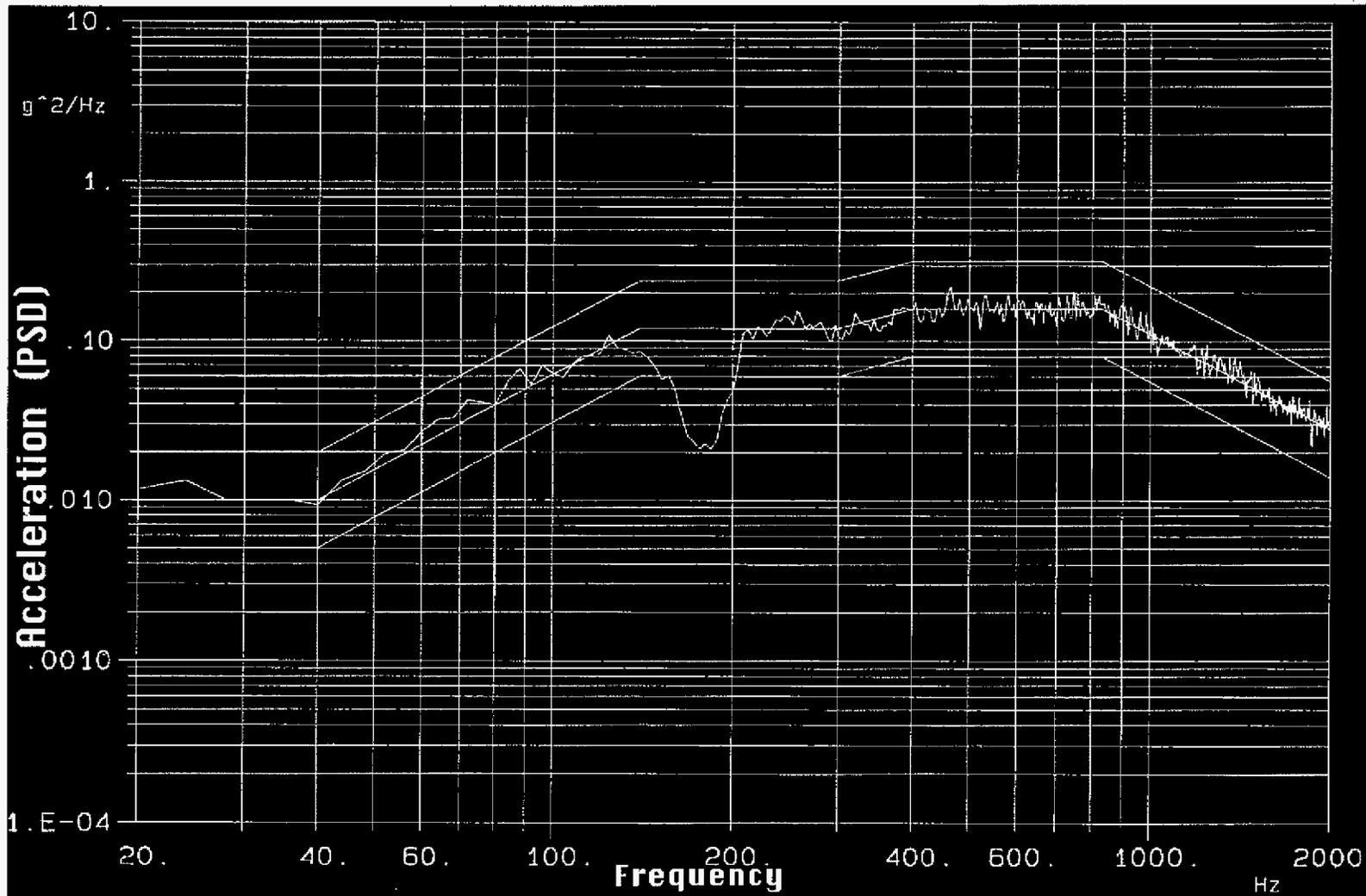
CRIS Instrument on ACE Spacecraft



Total Vertical Force In CRIS Random Vibration Test

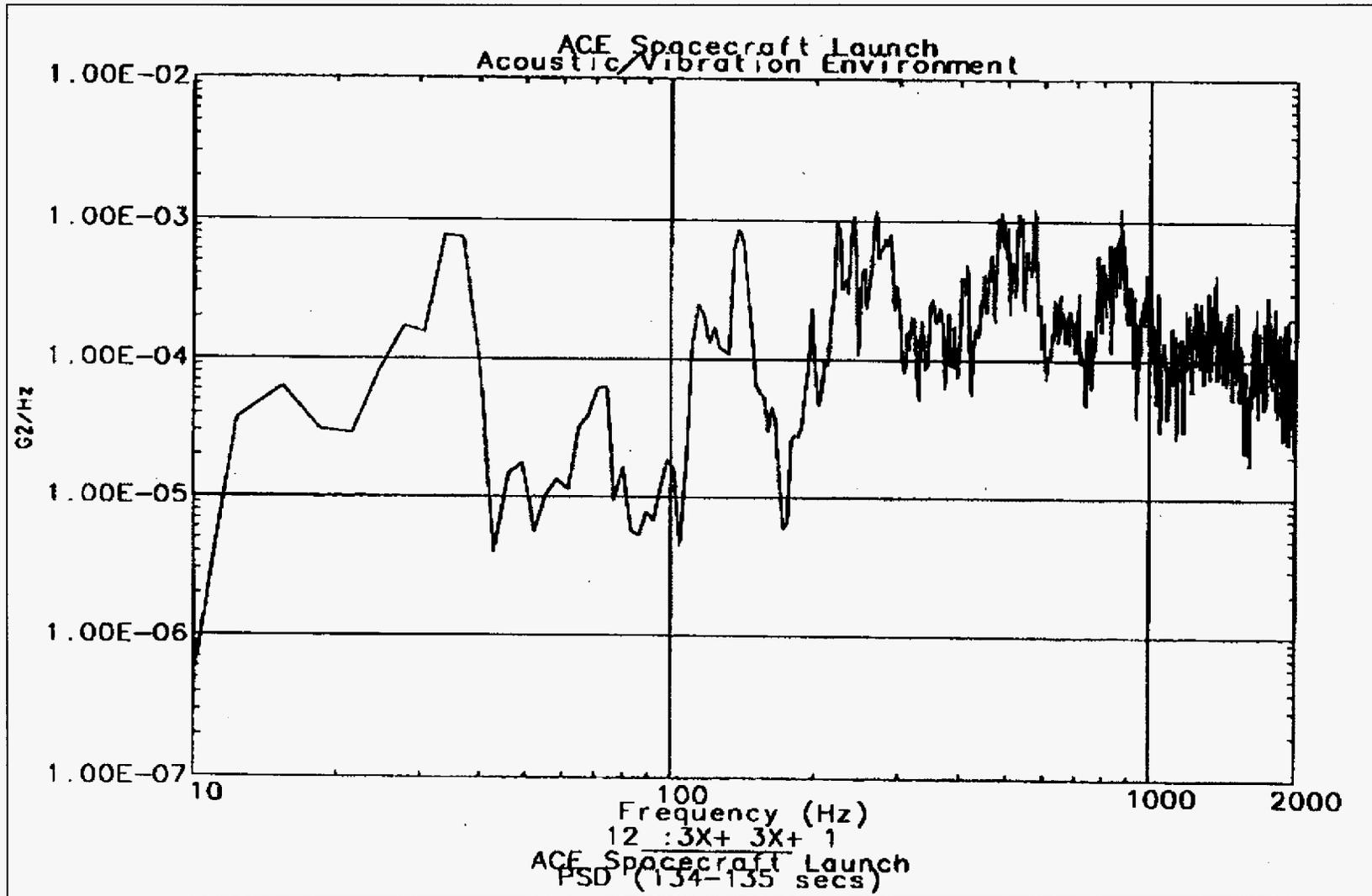


Notched Acceleration Input In CRIS Random Vibration Test

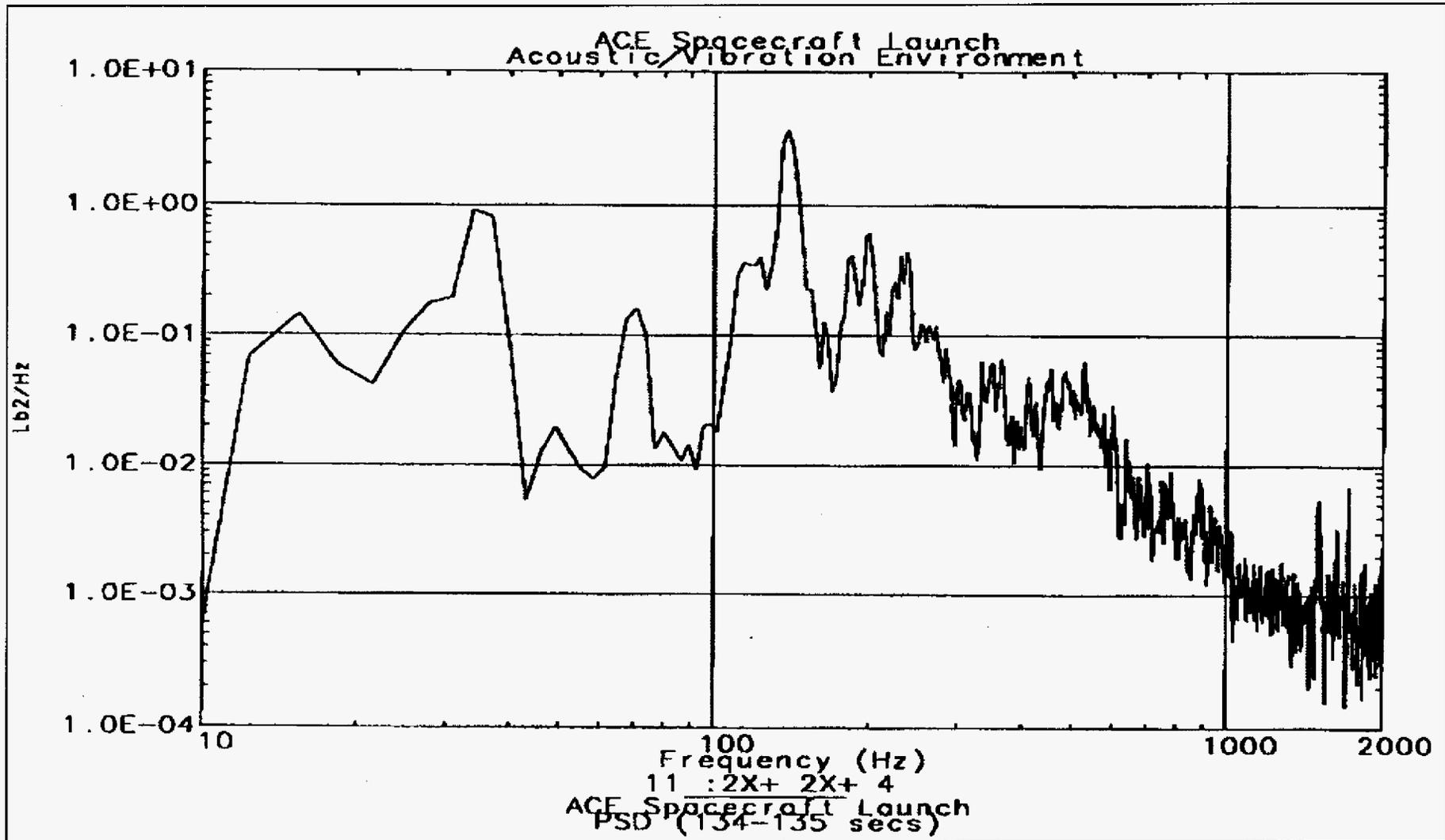


Spectral Density of In-Flight Normal Acceleration

Measured Near One Mounting Foot of CRIS Instrument



Spectral Density Of In-Flight Normal Force Measured Under CRIS Instrument



Summary of ACE Flight Force Limiting Experiment



- The measured flight acceleration input PSD to the CRIS instrument was 20 dB lower than the vibration test specification.
- The measured flight force input PSD to the CRIS instrument was 20 dB lower than the vibration test limit.
- Even with this very high force limit, approximately 7 dB of notching resulted in the vibration test.
- The ACE force limiting experiment, with a payload weight of 65 lb, yielded a value of the semi-empirical method constant of $C^2 = 1.7$

Conclusions



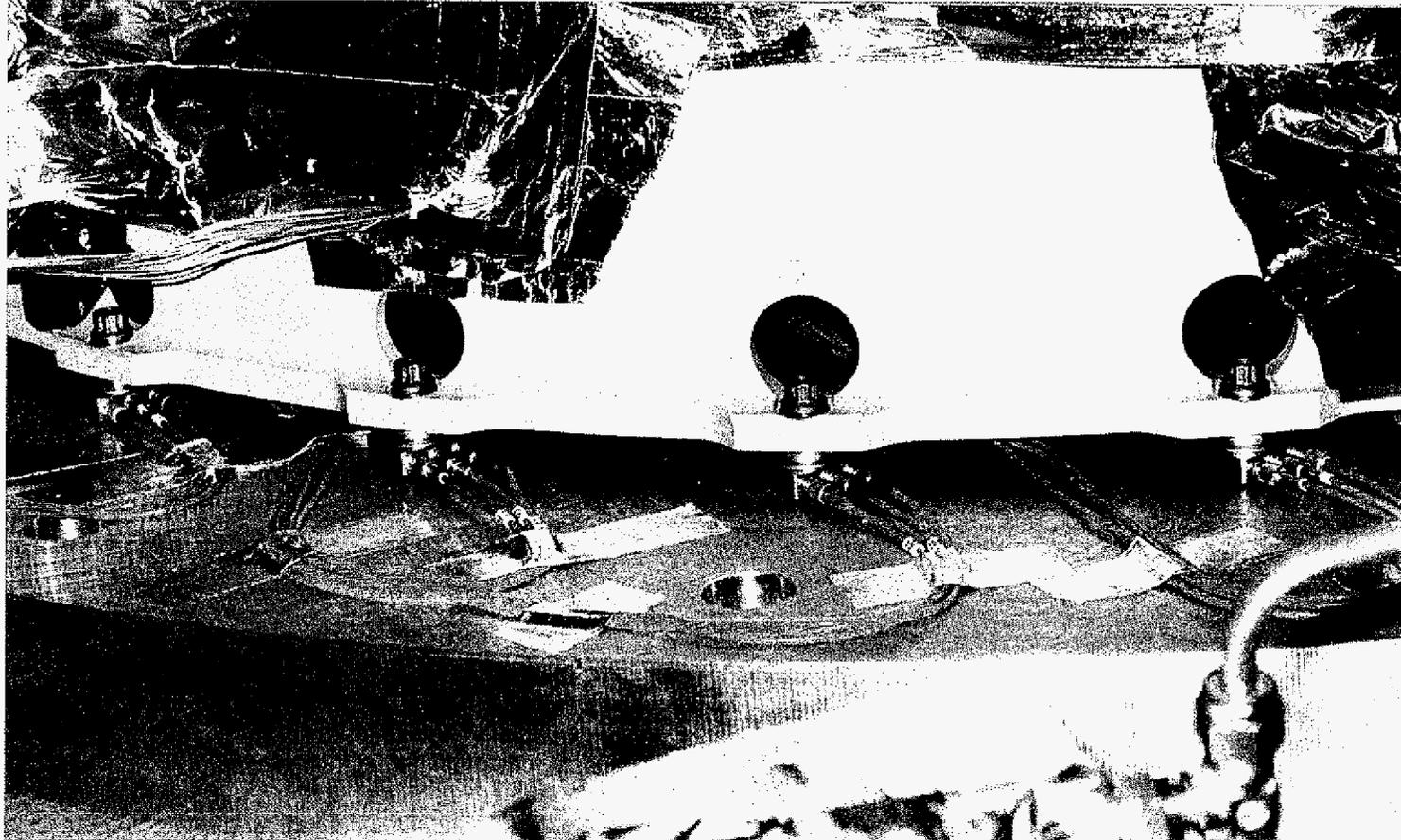
- **Force limiting alleviates vibration overtesting associated with the near infinite impedance of shakers as compared to the compliance of aerospace structure**
- **Force limiting only helps at payload resonances; it's no good for electronic boxes and other “bricks”.**
- **Force limiting does not make up for a bad, i.e., too conservative, acceleration specification.**
- **Usually, only the in-axis force needs to be measured and controlled. (Only one channel of instrumentation is typically needed for notching.)**
- **Force limiting has been validated by two flight experiments and several system acoustic tests**
- **Force limiting has been utilized on many spacecraft, and unit vibration tests at JPL, GSFC, and NASA contractors during the past 15 years (Part II of tutorial)**
- **Application of force limiting is described in NASA-HDBK-7004B, which is available at:**

<http://standards.jpl.nasa.gov/jpl-nasa/>

Test Instrumentation and Supporting Equipment

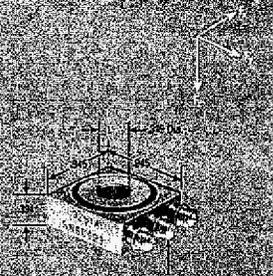
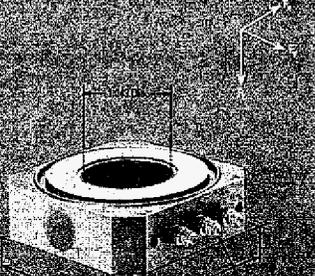
- **Piezo-electric Force Transducers**
- **Signal Processing and Conditioning Systems**
- **Test Fixtures**
- **Vibration Controller Systems**

Force Transducers



Multi-Component Force Transducers



<p>High Impedance Triaxial element designed to measure axial dynamic and quasi-static forces up to $\pm 1,100$ lbs and shear forces to ± 550 lbs, bidirectionally in each axis. Applications include use individually or in biomechanical platforms and cutting force dynamometers. See page 39 for recommended preloading hardware.</p>  <p><i>Request Data Bulletin 9251 for more details.</i></p>	<table border="1"> <thead> <tr> <th colspan="2">SPECIFICATIONS</th> <th>9251A</th> </tr> </thead> <tbody> <tr> <td>Measuring range: F_z</td> <td>lb</td> <td>$\pm 1,100^*$</td> </tr> <tr> <td>F_x, F_y</td> <td>lb</td> <td>$\pm 550^*$</td> </tr> <tr> <td>Overload</td> <td>%</td> <td>20</td> </tr> <tr> <td>Maximum moment: M_z & M_x, M_y</td> <td>ft-lb</td> <td>$\pm 13.3^{**}$ & $\pm 10.3^*$</td> </tr> <tr> <td>Threshold</td> <td>lb</td> <td>0.002</td> </tr> <tr> <td>Sensitivity (nom.): F_z & F_x, F_y</td> <td>pC/lb</td> <td>-18 & -35</td> </tr> <tr> <td>Linearity & hysteresis</td> <td>%FSD</td> <td>$\leq \pm 1$ & ≤ 0.5</td> </tr> <tr> <td>Cross talk: $F_z \rightarrow F_{x,y}$</td> <td>%</td> <td>$\leq \pm 1$</td> </tr> <tr> <td>$F_x \leftrightarrow F_y$</td> <td>%</td> <td>$\leq \pm 3$</td> </tr> <tr> <td>$F_{x,y} \rightarrow F_z$</td> <td>%</td> <td>$\leq \pm 3$</td> </tr> <tr> <td>Rigidity: z & x,y direction</td> <td>lb/μin</td> <td>8.7 & 1.7</td> </tr> <tr> <td>Operating temperature range</td> <td>$^{\circ}$C</td> <td>-60 to 150</td> </tr> <tr> <td>Temperature coefficient of sensitivity</td> <td>%/$^{\circ}$C</td> <td>± 0.02</td> </tr> <tr> <td>Capacitance (each channel)</td> <td>pF</td> <td>30</td> </tr> <tr> <td>Insulation resistance</td> <td>Ω</td> <td>$> 10^{13}$</td> </tr> <tr> <td>Weight</td> <td>g</td> <td>32</td> </tr> </tbody> </table> <p><small>*Standard mounting with 5.6k lb preload **Without simultaneous shear load</small></p> <p>Recommended Cables 1631A(X)</p>	SPECIFICATIONS		9251A	Measuring range: F_z	lb	$\pm 1,100^*$	F_x, F_y	lb	$\pm 550^*$	Overload	%	20	Maximum moment: M_z & M_x, M_y	ft-lb	$\pm 13.3^{**}$ & $\pm 10.3^*$	Threshold	lb	0.002	Sensitivity (nom.): F_z & F_x, F_y	pC/lb	-18 & -35	Linearity & hysteresis	%FSD	$\leq \pm 1$ & ≤ 0.5	Cross talk: $F_z \rightarrow F_{x,y}$	%	$\leq \pm 1$	$F_x \leftrightarrow F_y$	%	$\leq \pm 3$	$F_{x,y} \rightarrow F_z$	%	$\leq \pm 3$	Rigidity: z & x,y direction	lb/ μ in	8.7 & 1.7	Operating temperature range	$^{\circ}$ C	-60 to 150	Temperature coefficient of sensitivity	%/ $^{\circ}$ C	± 0.02	Capacitance (each channel)	pF	30	Insulation resistance	Ω	$> 10^{13}$	Weight	g	32						
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Force Transducers Selection



- **Three Sizes of Tri-axial Measurements
(Maximum Force Ranges, Hole Size)**
- **Sizes of Fasteners (or Bolts)**
- **Force Measurement Requirements**
- **Preload and Bolt Torque Values**

Force Transducer Installation Guide

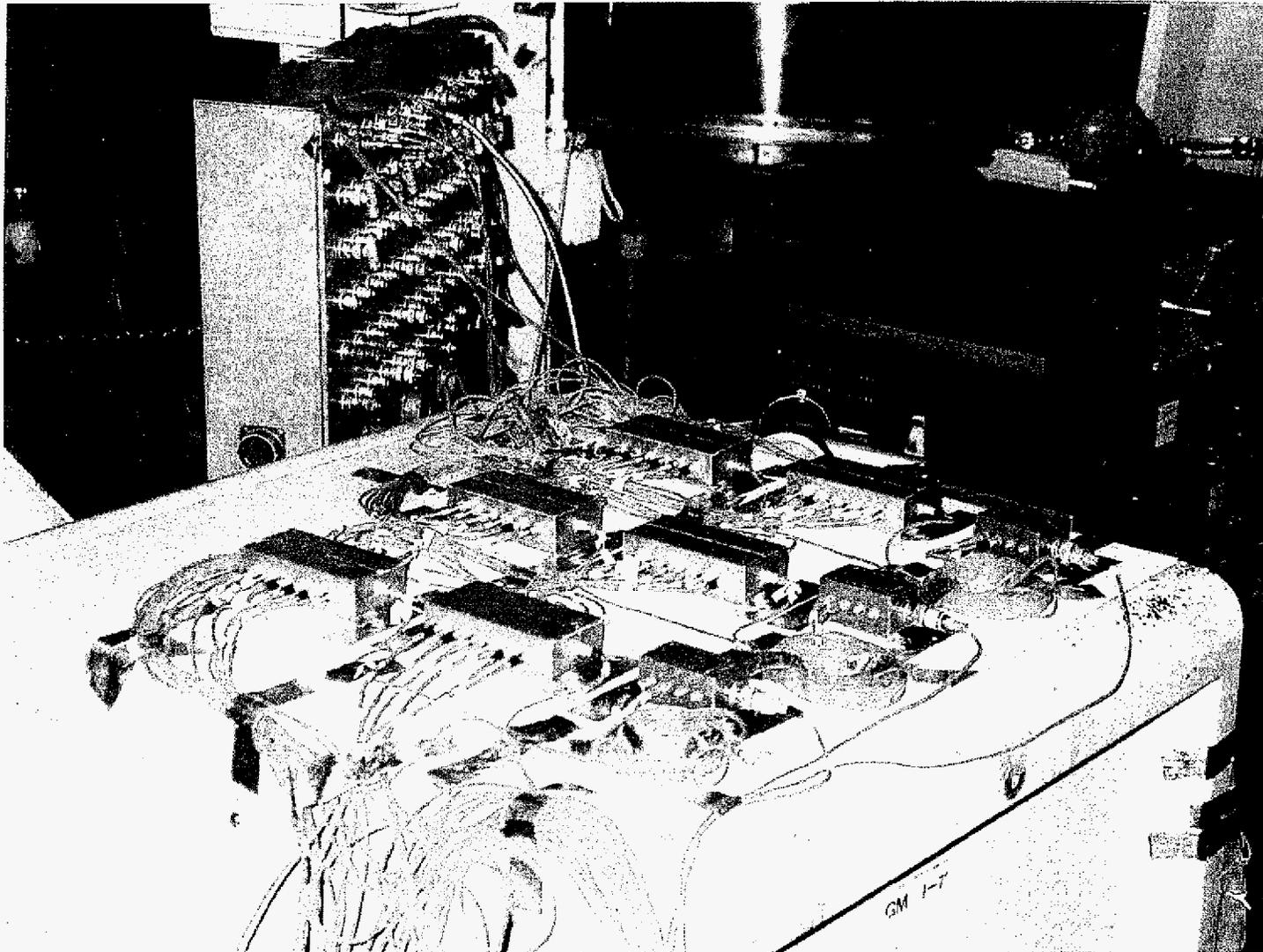


- **If practical, use one gage at every mounting bolt**
- **To minimize errors, use as high a preload as possible without overstressing components and have a smooth, flat surface on gages and on mating plates**
 - Preload must be sufficient to prevent unloading due to dynamic forces and moments
 - Preload must be adjusted so that combined static and dynamic loads do not exceed manufactures recommended load set on transducers
- **Transducers, with long time constant charge amplifier, may be used to measure preload during installation**
- **Approx. 10% of load will be shunted through mounting bolt, i.e. load divides as relative stiffness of transducer and bolt**
- **Transducers come calibrated and sensitivity is primarily due to material properties of quartz**
- **Best way to calibrate, and check out, system is by comparing the measured total force and acceleration at low frequencies, well below resonances, to**
 $F = MA$



- **Electrical Interconnections**
- **Total Force Measurement or Individual Force for Moment Calculation**
- **Charge Sensitivity and Amplifier Range Settings**

Signal Summing Boxes



Test Fixtures



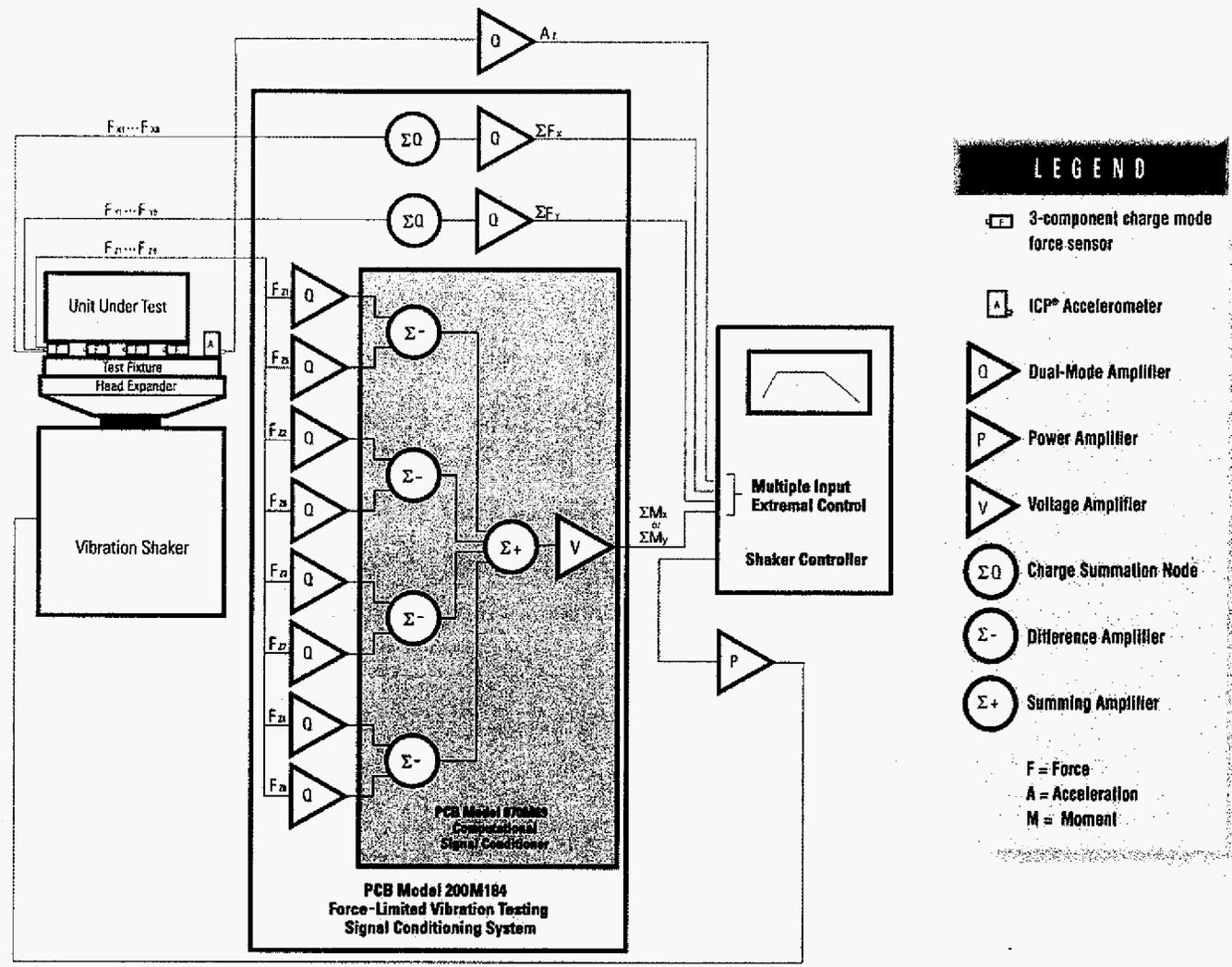
The preferred method of configuring the force transducers is to sandwich one transducer between the test item and conventional test fixture at each attachment position and use fasteners which are longer than the conventional ones to accommodate the height of the transducers. In this configuration, there is no fixture weight above the transducers and the transducer force is identical to the force into the test item. Sometimes the preferred approach is impractical, e.g. if there are too many attachment points or the attachments involve shear pins in addition to bolts. In these cases it may be necessary to use one or more light-weight intermediate adapter plates as an interface between the test item and the force transducers. The requirement is that the total weight of any intermediate adapter plates above the force transducers do not exceed 10% of the weight of the test item. For example, if the test item mounts at three feet and each foot involves two bolts and a shear pin, a candidate design would be to have a small plate attached to a big stud for each foot. The small plate would pick up the two mounting bolts and shear pin, and the stud would go through a medium sized force transducer into a shaker fixture plate. Alternately, if the mounting configuration involves sixteen small bolts in a circular pattern, the fixture might consist of one intermediate ring which accepts the sixteen small bolts and is mounted on four equally spaced larger sized force transducers.

Vibration Controllers



Most of the current generation of vibration test controllers have the two capabilities needed to implement force limiting. First, the controller must be capable of extremal control, sometimes called maximum or peak control by different vendors. In extremal control, the largest of a set of signals is limited to the reference spectrum. (This is in contrast to the average control mode in which the average of a set of signals is compared to the reference signal.) Most controllers used in aerospace testing laboratories support the extremal control mode. The second capability required is that the controller must support different reference spectra for the response limiting channels, so that the force signals may have limit criteria specified as a function of frequency. Controllers which support different reference spectra for limit channels are now available from most vendors and in addition upgrade packages are available to retrofit some of the older controllers for this capability. If the controller does not have these capabilities, notching of the acceleration specification to limit the measured force to the force specification must be done manually in low level runs.

Force-limited Testing Shaker Control System



Force Limited Vibration Test Procedure



- 1. Conduct a low-level sine-sweep (or random vibration with a flat frequency spectrum) in each axis to measure the dynamic signature of the test hardware and the reaction force. Reduce data and update the effective masses and resonance frequencies used to derive the force specification.**
- 2. Perform two low-level random vibration runs (often -18 dB) without and with force limiting, using the same acceleration spectral shape as the full level and a scaled down force limit. Compare the forces measured in these two test runs to verify that amount of notching achieved by force limit is appropriate. Modify force limits if needed and repeat the tests again.**
- 3. Execute an intermediate-level run and then proceed to the full-level run after it is determined that the notchings are correct. The intermediate level results can be again used to verify the acceleration notches due to force limiting and if there is significant disagreement, the force limit specification may be adjusted before progressing to full level.**
- 4. Perform the low-level sine-sweep post-test again for “health” monitoring. Keep the number of test runs as low as feasible to avoid accumulating unnecessary fatigue damage of the test hardware. Thus ideally, each axis may be conducted with no more than five to six runs.**

FORCE LIMITED TEST LESSONS LEARNED



- **The force limited test approach has been successfully conducted on many science instruments, spacecraft equipment and flight spacecraft and has been extremely beneficial for surviving the required verification tests. In all cases, the use of force limiting reduced the degree of over test without compromising the test objectives.**
- **Force limiting offers a rational and justification for notches to reduce over testing in shaker vibration testing. The magnitude of the notch, once the force spectral density threshold is reached, can be impressive. Some notches even reach the depth of 16 dB or more.**
- **Force limiting results in narrower and more accurate notches than manual notching and adapts to nonlinear changes of resonance response. Also, due to non-linearity of the test hardware, the notches in full level tests are usually less than in low-level runs.**
- **Both force and overturning moment limits can be specified for the shaker random vibration test. Both limits can be used simultaneously. However, this control scheme is more complex and time-consuming.**

FORCE LIMITED TEST LESSONS LEARNED

(Cont'd)



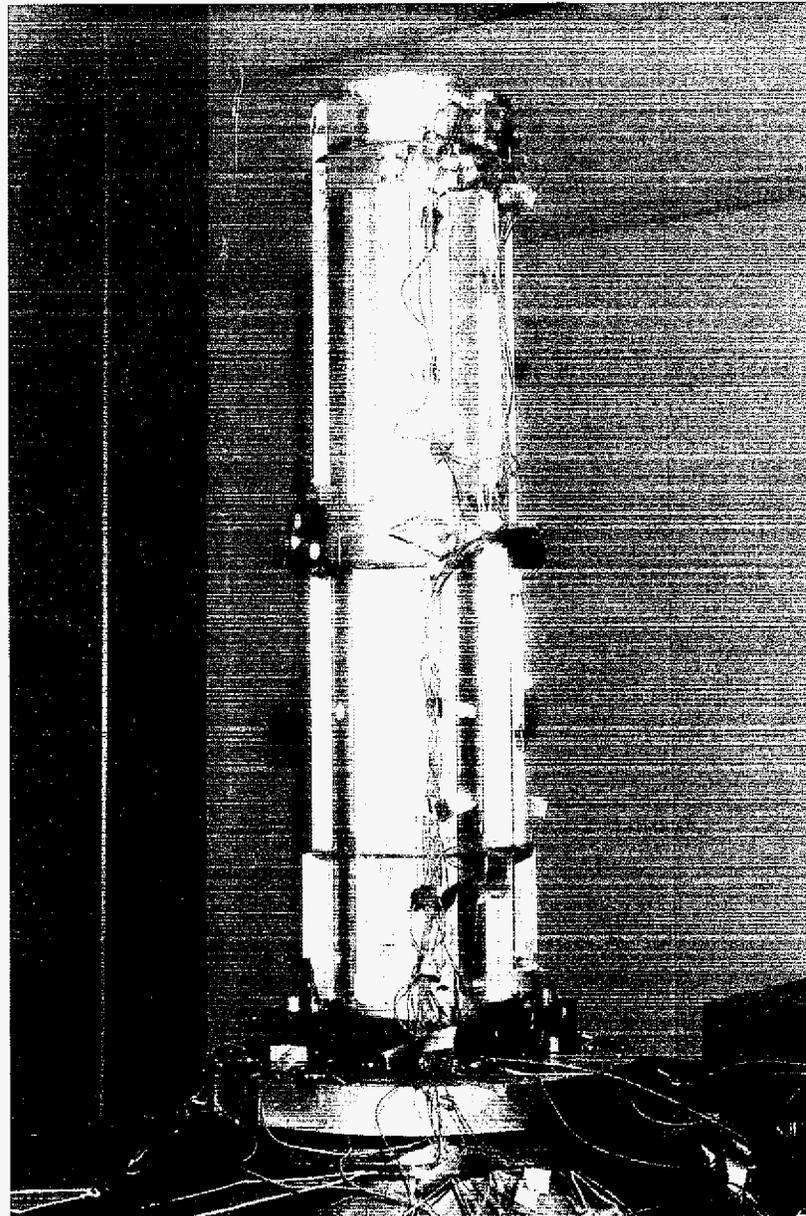
- **In most cases, either force or moment limits create similar notch profiles. The force limit provides more direct and effective notching. Thus, the moment limit is usually redundant.**
- **If only one-axis force transducers are available, moment limiting is acceptable for lateral vibration testing.**
- **Only the summed force is needed for each axis of direction, which greatly simplifies and expedites the test process.**
- **The attachment bolt and the force gage react the interface loads at each attachment. The portion of load carried by each is dependent on the relative stiffness between bolt and transducer. In all cases, the apparent attenuation must be evaluated in the low-level test runs.**
- **Poor input spectrum control can arise in the force-limited test. It can be caused by slow servo loop response time associated with a large number of limit channels employed in a multiple control strategy.**
- **Force limiting should not be perceived as a method of compensating for errors in the acceleration specification. Rather, it is a method of automatically inserting notches in the acceleration spectrum at the proper frequencies and of the proper depth.**

Examples of Force Limited Vibration Testing

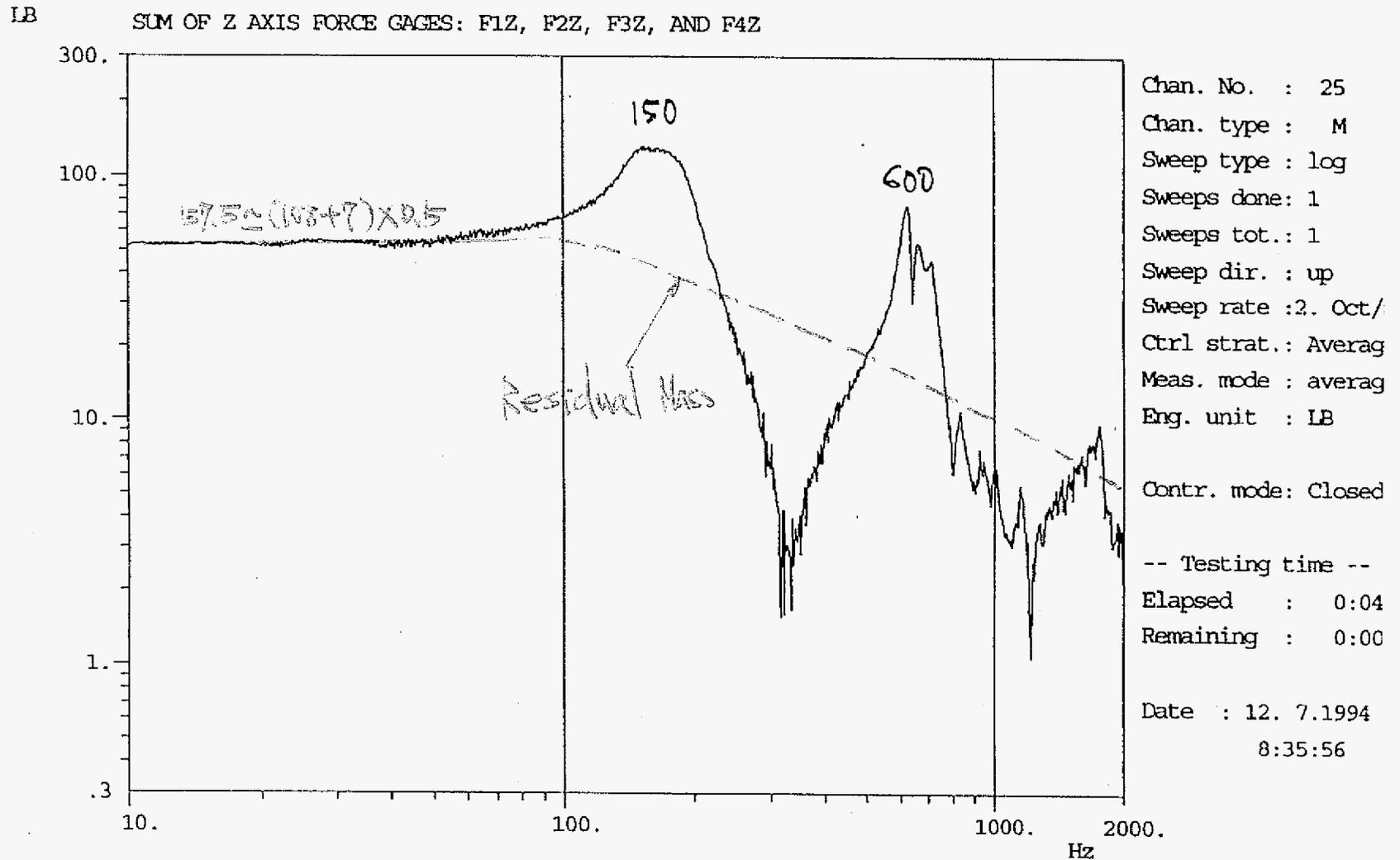


- **Equipment Component Random Vibration Test**
RTG (CET, Component Evaluation Test) for Vertical Test
- **Science Instrument Random Vibration Test**
Cassini CDA for Lateral Vibration Test
- **Spacecraft System Vibration Qualification Test**
DS1 Spacecraft for Lateral and Vertical Tests

RTG/CET Installation for Vertical Vibration Test



Force Measured in RTG 0.5 g Sine-Sweep Test

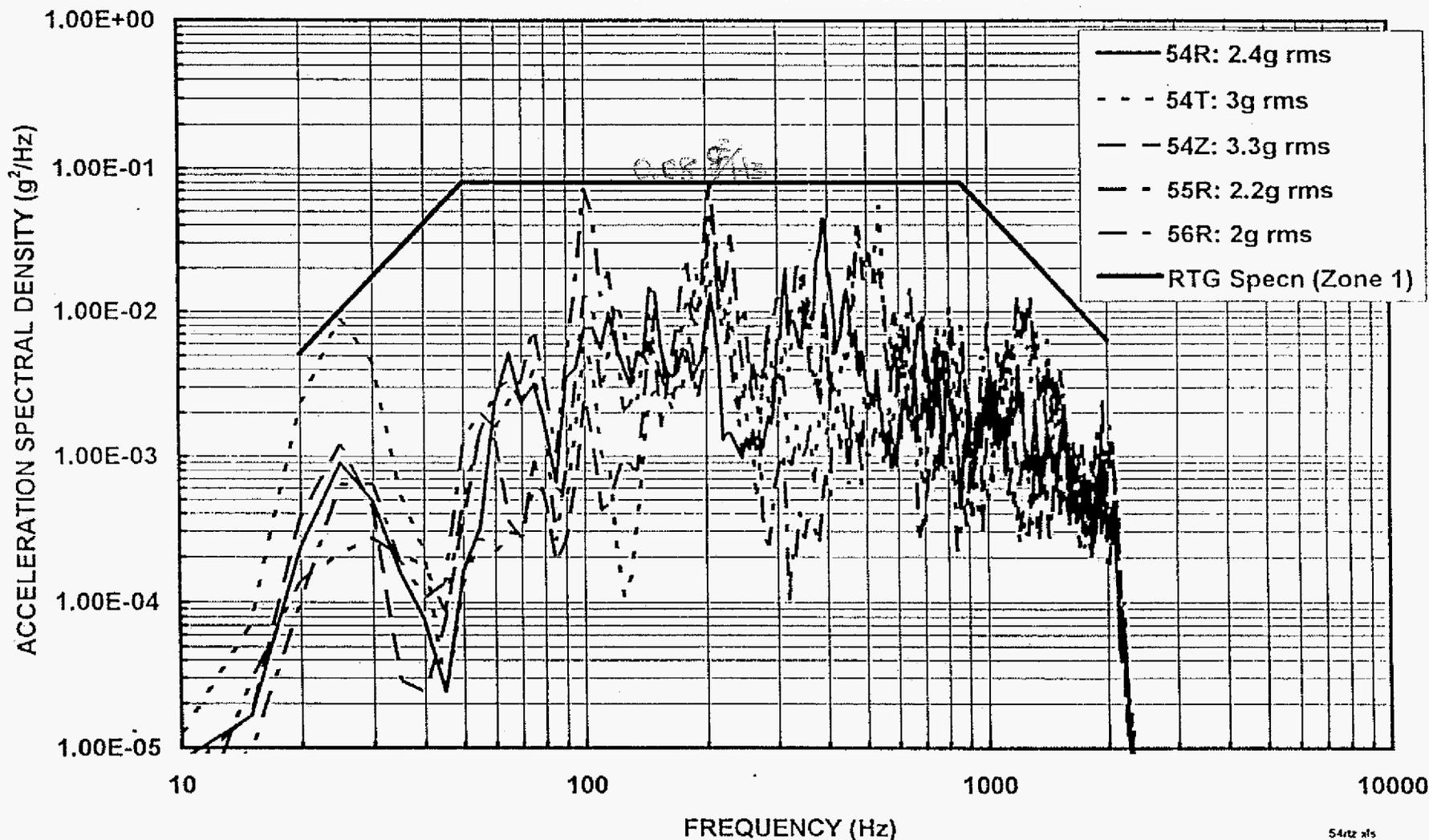


Shaker Measurement of the Apparent Mass of the RTG Equipment in 0.5 g Sine-Sweep Test (Multiply ordinate by two to obtain apparent mass.)

RTG Random Vibration Test Requirements



RTG BASE ACCELERATIONS CASSINI DTM PROTOFLIGHT ACOUSTIC TEST

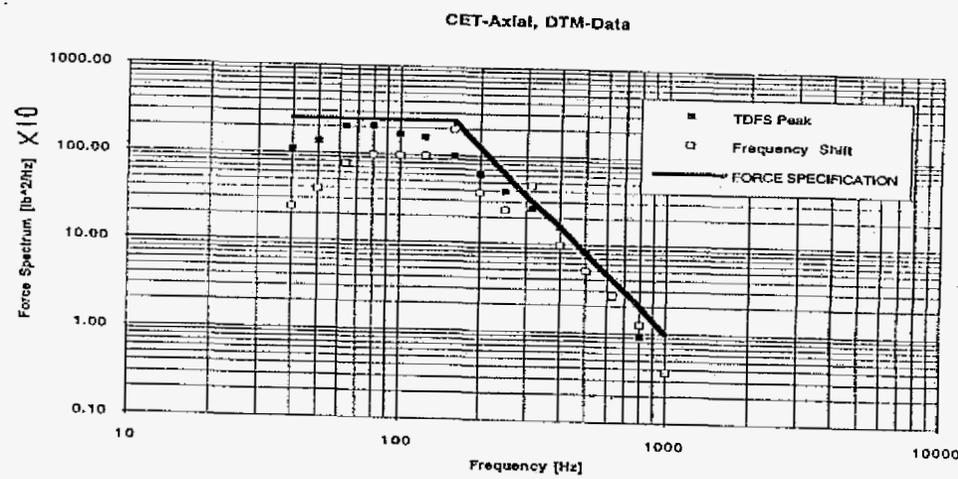


Force Predictions Based on TDFS Methods



Example of Spread Sheet for Calculating Force Limits – Cassini RTG Equipment

Rootz 3/1/95		FORCE SPECIFICATION CET-Axial, DTM-Data														
Damping (Q = 50/20 for 5)	5.00	ζ = 0.100														
Frequency (f)	Hz	40	50	63	80	100	125	160	200	250	315	400	500	630	800	1000
(ω)	rad/sec	251	314	396	503	628	785	1005	1257	1571	1979	2513	3142	3958	5027	6283
Acceleration: PSD	(G ² /Hz)	0.0020	0.0032	0.0064	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0064	0.0032	0.0020	0.0012
SOURCE Eff. Weight (lbs)	Total	300.00	data													
Cumulative Weight Fraction	NOTE 1	data	data	data	data	data	data	data	data	data	data	data	data	data	data	data
Residual Weight (M)	NOTE 2	300.00	200.00	120.00	80.00	50.00	40.00	31.00	25.00	20.00	16.00	12.00	10.00	8.00	6.00	5.00
Total Modal Weight in Band		100.00	100.00	80.00	40.00	30.00	10.00	9.00	6.00	5.00	4.00	4.00	2.00	2.00	2.00	1.00
Number of Modes in Band (N)		1	1	0	0	1	2	2	2	2	2	2	2	2	2	2
Band Aver. Modal Weight (m1)		100.00	100.00	0.00	0.00	30.00	5.00	4.80	3.00	2.50	2.00	2.00	1.00	1.00	1.00	0.50
Ratio of Modal to Residual Weight (a1)		0.33	0.50	0.00	0.00	0.60	0.13	0.15	0.12	0.13	0.17	0.10	0.13	0.17	0.10	0.10
LOAD Eff. Weight (lbs)	Total	110.00	data													
Cumulative Weight Fraction	NOTE 1	data	data	data	data	data	data	data	data	data	data	data	data	data	data	data
Residual Weight (M2)	NOTE 2	110.00	110.00	110.00	110.00	110.00	110.00	87.00	69.00	55.00	44.00	35.00	28.00	22.00	17.00	14.00
Total Modal Weight in Band		0.00	0.00	0.00	0.00	0.00	0.00	23.00	18.00	14.00	11.00	9.00	7.00	6.00	5.00	3.00
Number of Modes in Band (N2)		0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
Band Aver. Modal Weight (m2)		0.00	0.00	0.00	0.00	0.00	0.00	23.00	0.00	0.00	11.00	0.00	0.00	2.00	2.50	1.00
Ratio of Modal to Residual Weight (a2)		0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.25	0.00	0.00	0.03	0.15	0.07
M2/M1 (Residual)		0.37	0.55	0.92	1.38	2.20	2.75	2.81	2.76	2.75	2.75	2.82	2.80	2.75	2.83	2.80
MAX NORM FORCE (TDFS Peak)	NOTE 3	5	4	3	2	2	2	2	2	2	2	2	2	2	2	2
MAX NORM FORCE (Freq Shift)	NOTE 3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
TDFS Peak Force PSD	(lb ² /Hz)	110.45	138.21	207.21	211.17	172.28	158.53	98.46	62.30	39.63	25.36	15.72	8.17	2.54	0.94	0.38
Freq Shift Force PSD	(lb ² /Hz)	24.20	38.72	77.44	96.80	96.80	96.80	199.06	36.09	24.20	48.48	9.00	5.02	2.68	1.28	0.37
FORCE SPEC (lb ² /Hz)	NOTE 4	250.00	250.00	250.00	250.00	250.00	250.00	250.00	125.00	63.00	31.00	16.00	8.00	4.00	2.00	1.00
NOTE 1. Cumulative fraction includes weight of subject mode and all lower modes (You may choose to ignore cumulative fraction and enter residual weights directly.)																
NOTE 2. Residual weight of all higher frequency modes.																
NOTE 3. Normalized by load residual mass squared and by acceleration spectrum.																
NOTE 4. SMOOTHED ENVELOPE OF TDFS PEAK AND FREQUENCY SHIFT METHOD.																



Force Prediction Based on Simi-Empirical Method



Example for Computing Semi-Empirical Force Values

The fundamental resonance of the RTG mounted in a shaker vertical test,

$$f_0 \approx 150 \text{ Hz}$$

The input acceleration spectrum value at the frequency, $f_0 = 150 \text{ Hz}$

$$S_{AA} = 0.08 \text{ g}^2/\text{Hz}$$

The RTG apparent mass (measured in 0.5 g sine-sweep vertical test),

$$M = 110 \text{ lbs.}$$

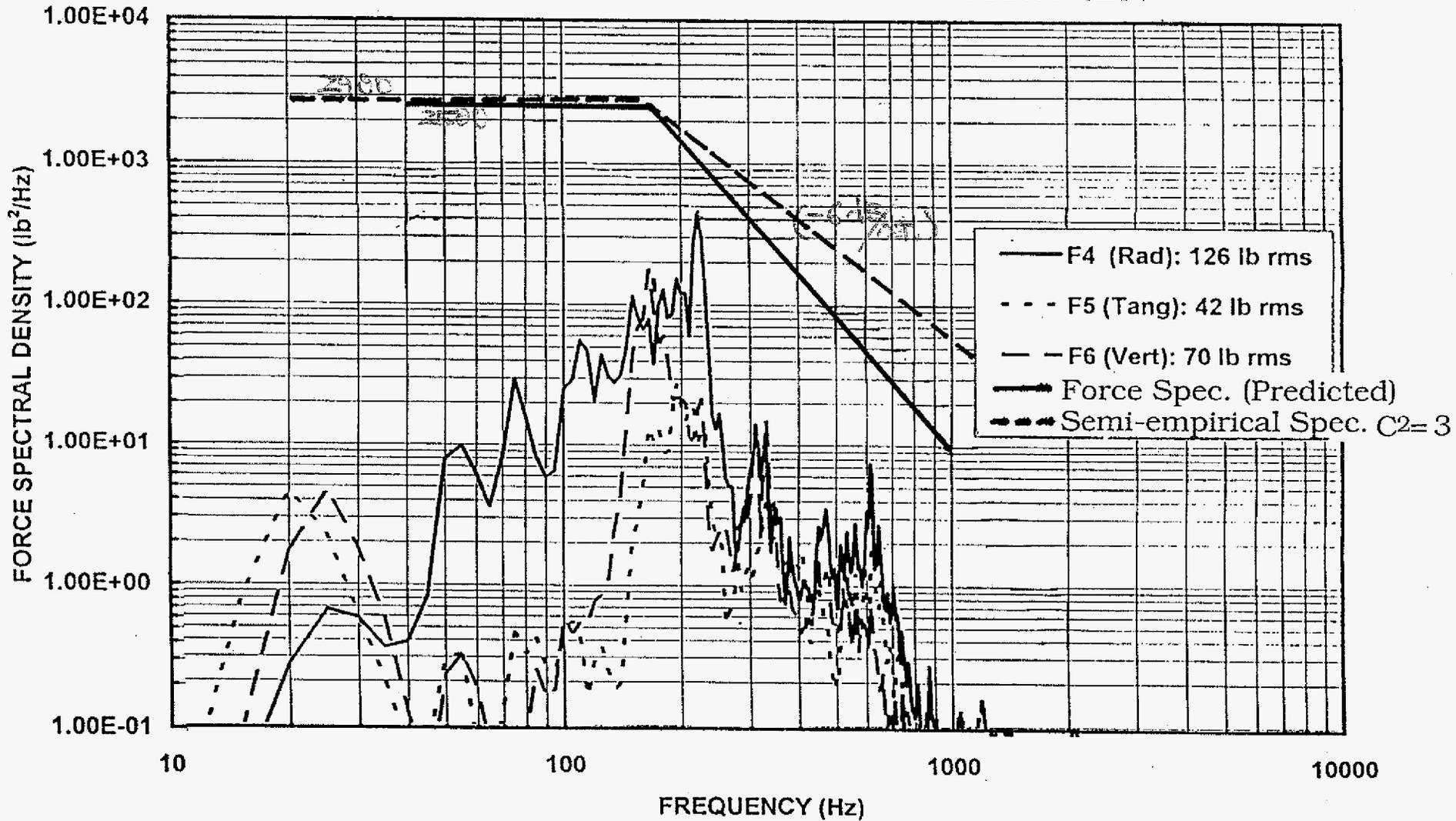
The semi-empirical vertical force limit with $C^2 = 3$,

$$S_{FF} = 3 \times 110^2 \times 0.08 = 2900 \text{ lb}^2/\text{Hz}$$

Comparison of Force Predictions for RTG Test



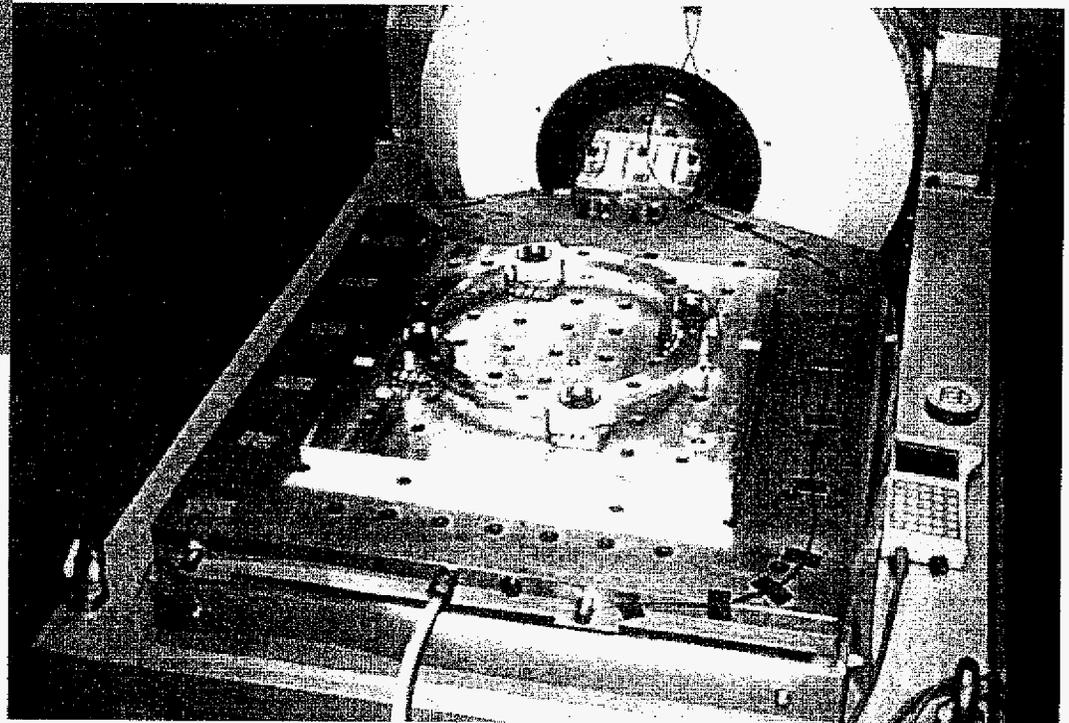
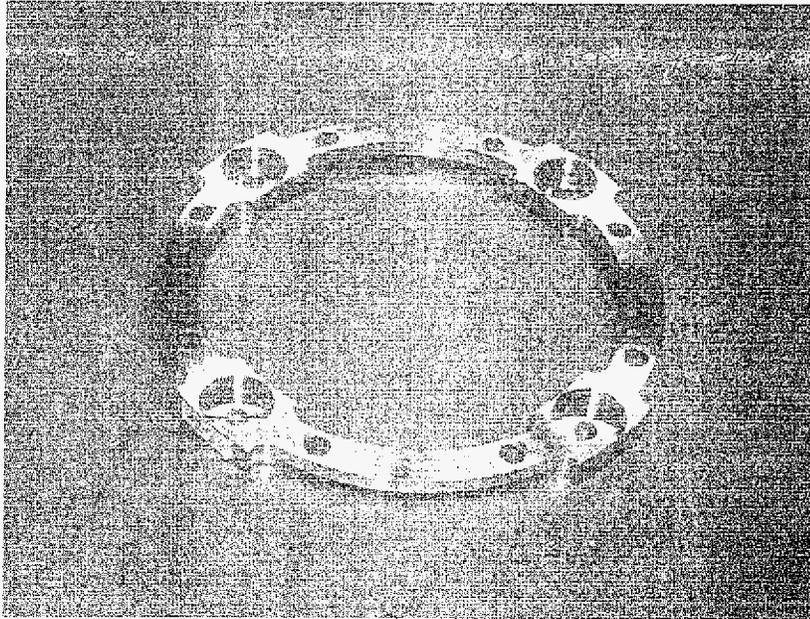
RTG INTERFACE FORCE SUMS CASSINI DTM FOLLOW-UP PROTOFLIGHT ACOUSTIC TEST



Cassini CDA on Shaker for Lateral (X-Axis) Test

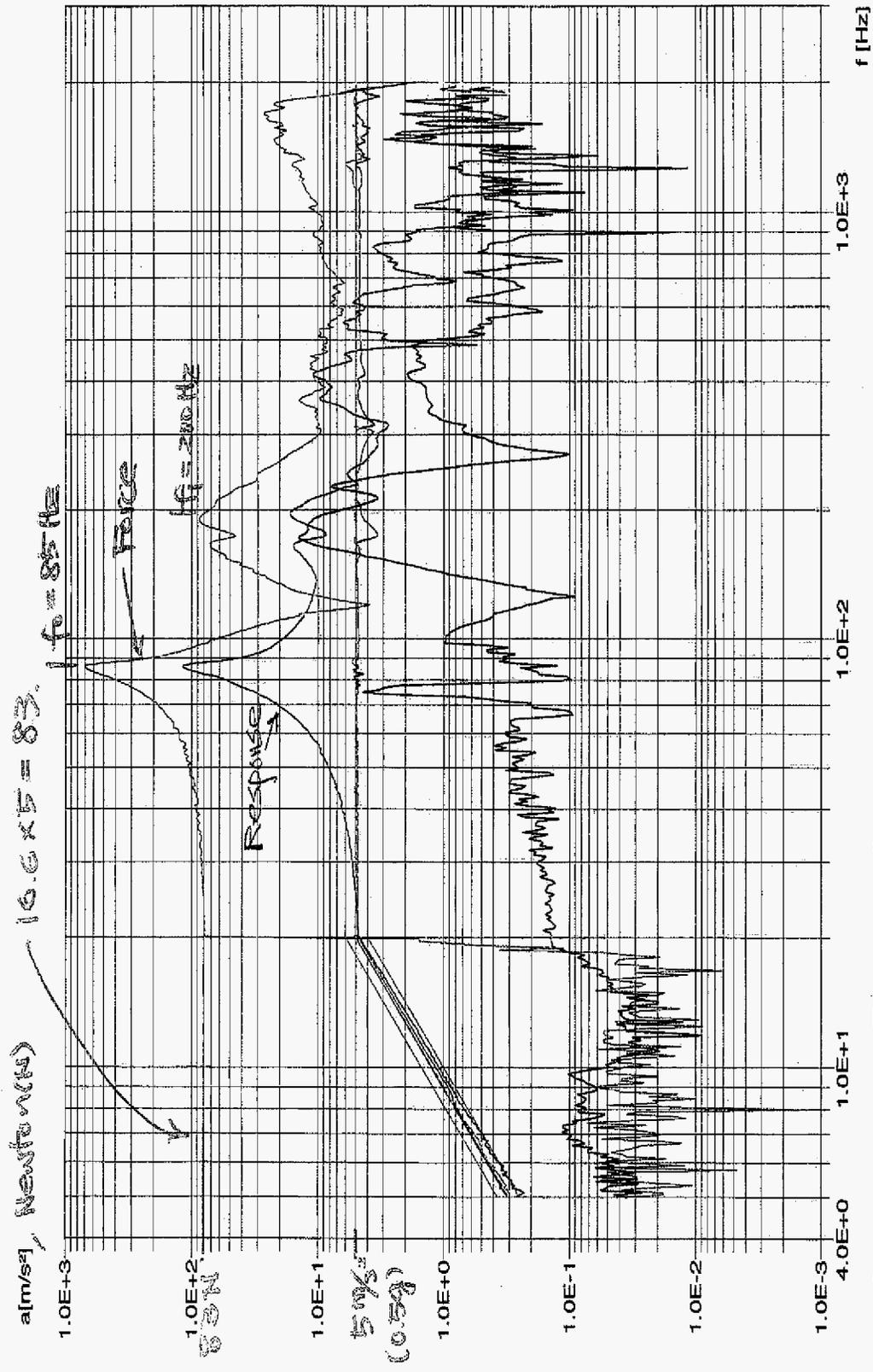


CDA Adapter Ring and Test Fixture for Force Measurement





Cassini CDA Resonance Survey (0.5 g Sine-Sweep) Test

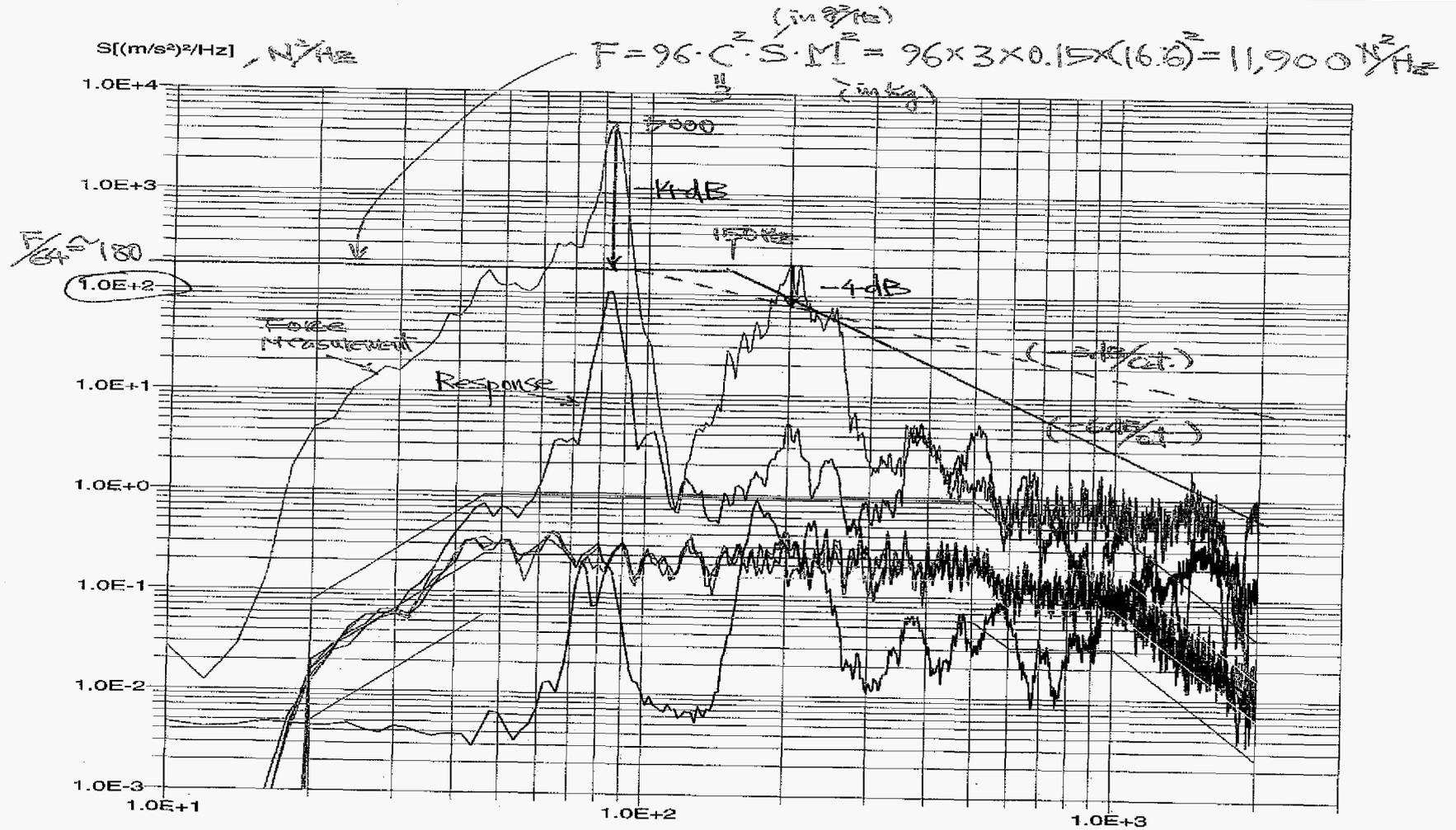


(Total Weight = 16.6 + 0.6 = 16.6 kg)

Status : Test stopped!
Cause :
Date : 10.11.1998
Time : 09:31:09
Elapsed test time : 0:4:22

Actual amplitude : 0.00 m/s²
Actual frequency : 1853.98 Hz

CDA Low-Level (-18 dB) Test Without Force Limiting



Status : Stopped by user!

Date : 10.11.1998

Time : 09:33:40

Elapsed test time : 0:0:0

Acceleration rms : 14.7 m/s²

Test level : -18 dB *w/o Force Limiting*

Drive : 10 %

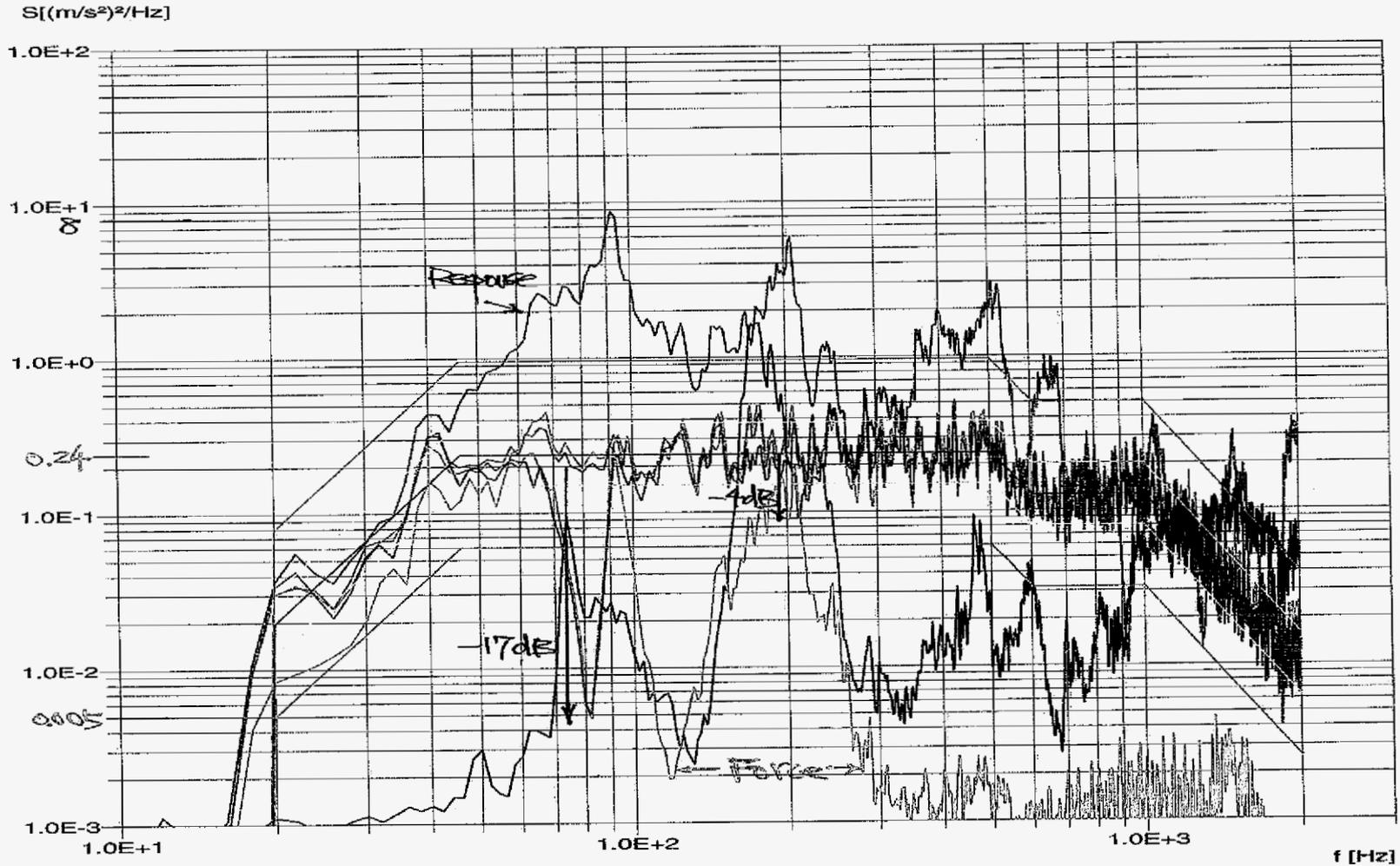
DOF : 92 DOF

Warn limits : enabled

Abort limits : disabled

Abort level : disabled

CDA Low-Level (-18 dB) Test With Force Limiting



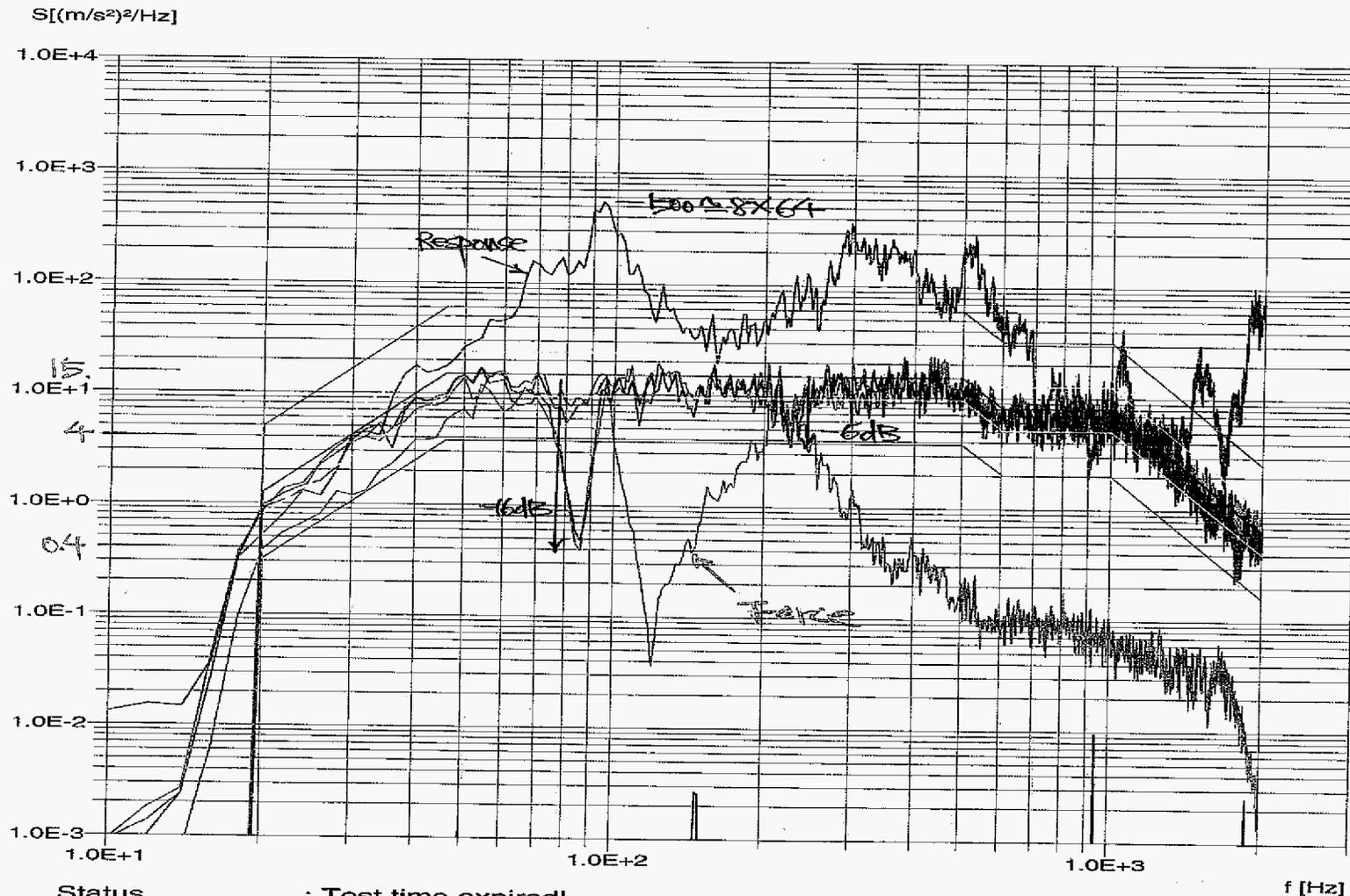
Status : Stopped by user!

Date : 10.11.1998
 Time : 09:38:50
 Elapsed test time : 0:0:0
 Acceleration rms : 15.4 m/s²
 Test level : -18 dB

Drive : 10 %
 DOF : 96 DOF
 Warn limits : enabled
 Abort limits : disabled
 Abort level : disabled

with Force Limiting

CDA Full-Level (0 dB) Test With Force Limiting

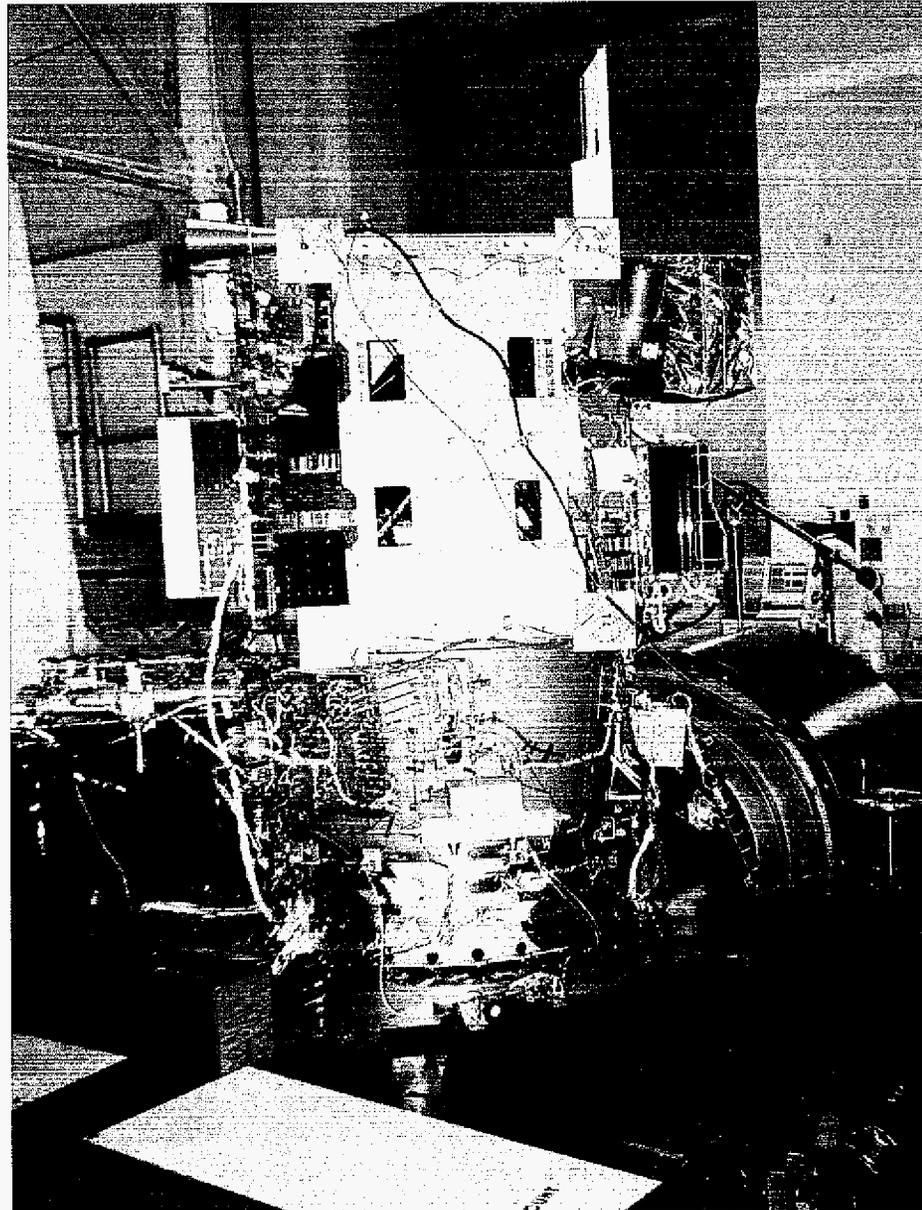


Status : Test time expired!

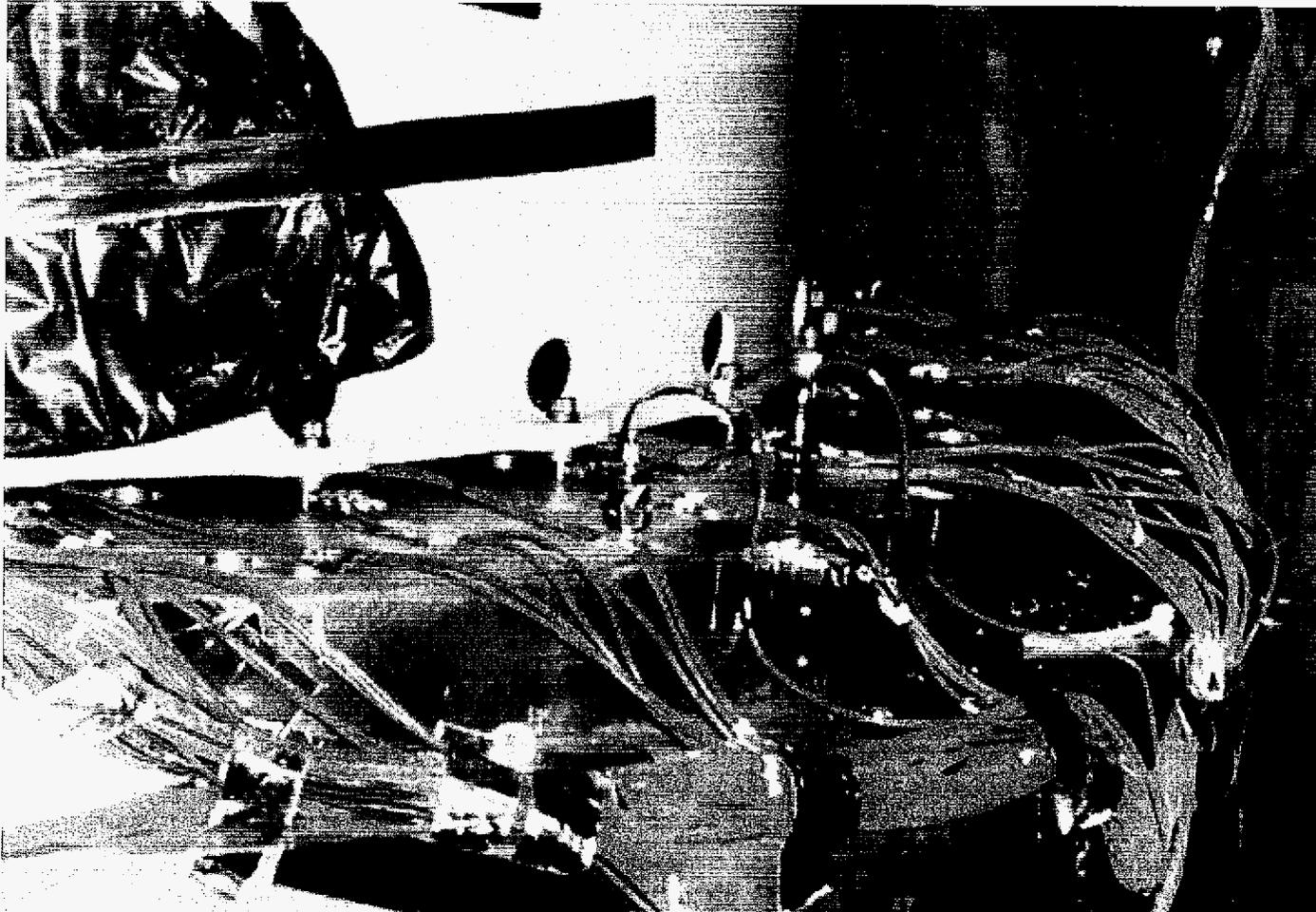
Date : 10.11.1998
 Time : 09:35:32
 Elapsed test time : 0:1:0
 Acceleration rms : 110. m/s²
 Test level : 0 dB

Drive : 72 %
 DOF : 42 DOF
 Warn limits : enabled
 Abort limits : disabled
 Abort level : disabled

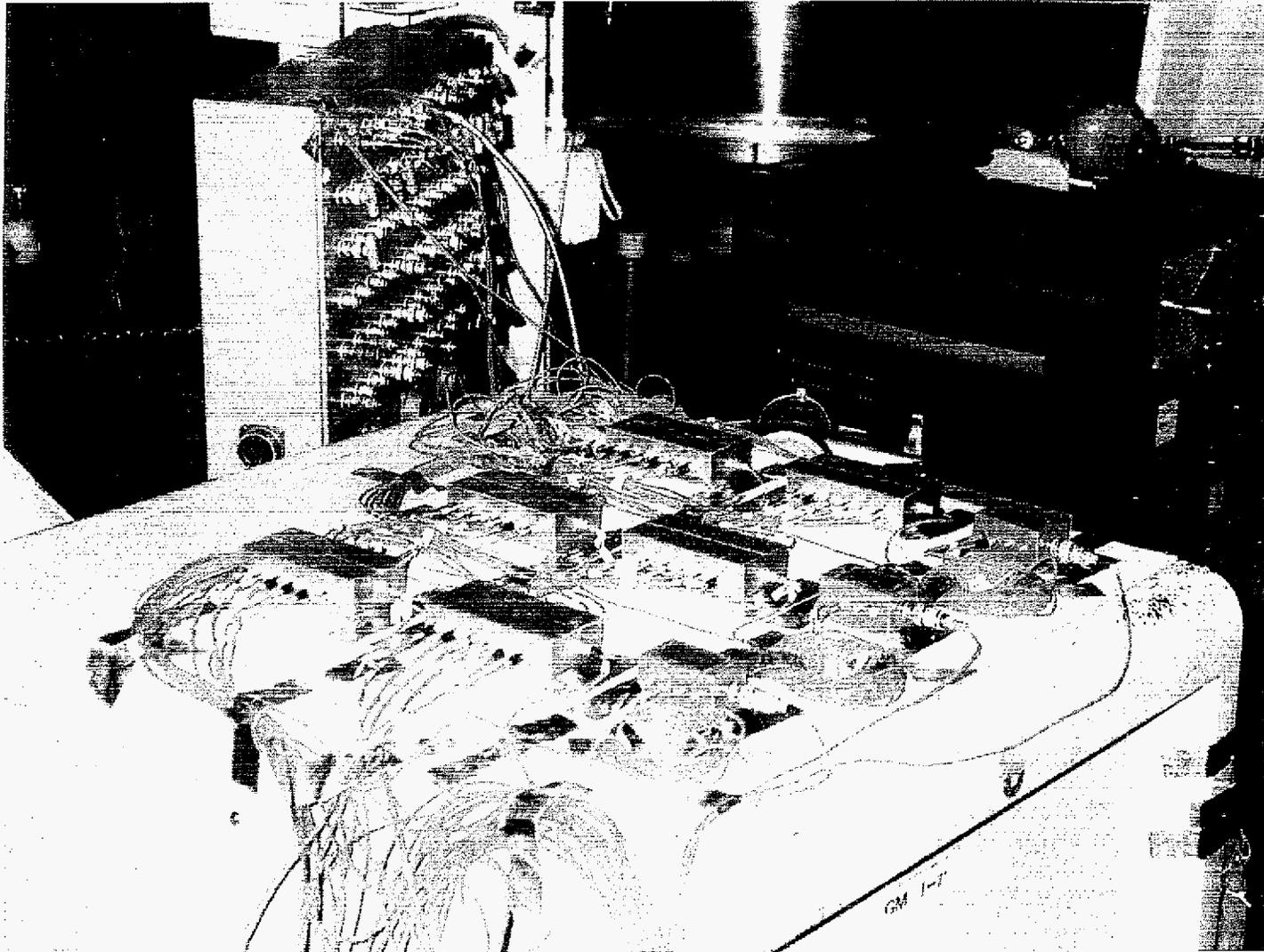
DS1 Spacecraft Installation for Lateral Vibration Test



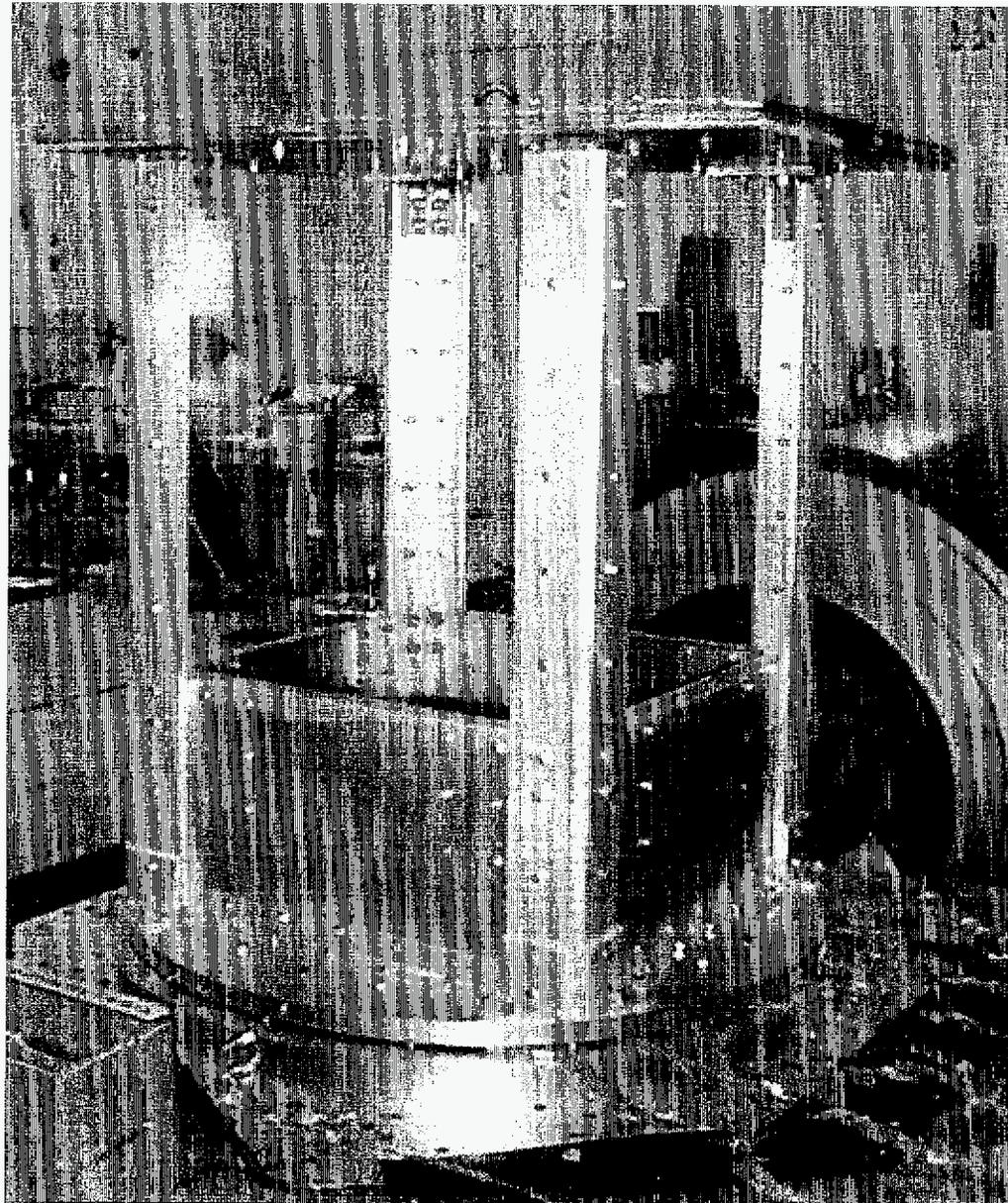
Force Transducers and Control Accelerometers for DS1 S/C Vertical Vibration Test



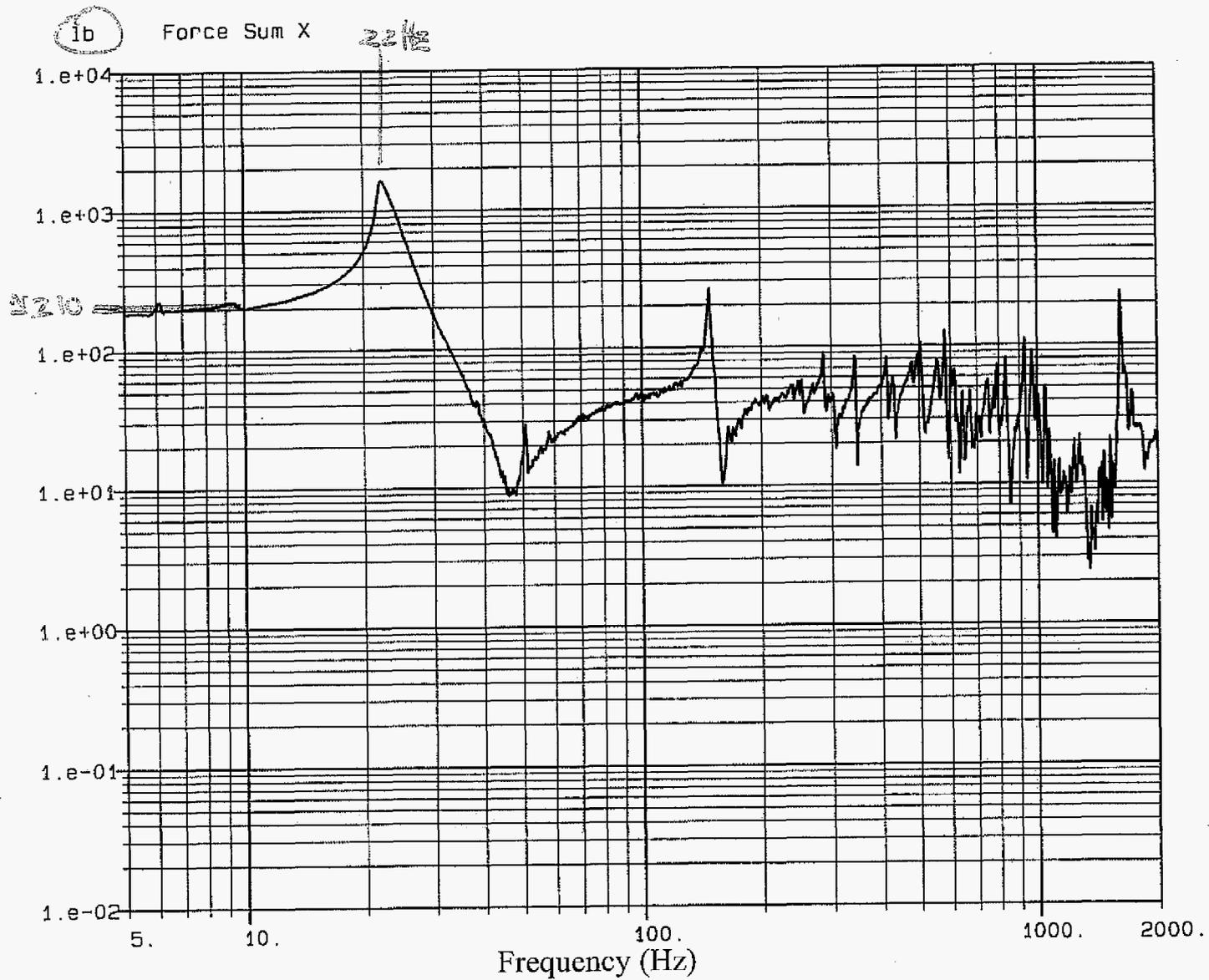
Sums of 24 Force Measurements in X, Y, and Z Directions



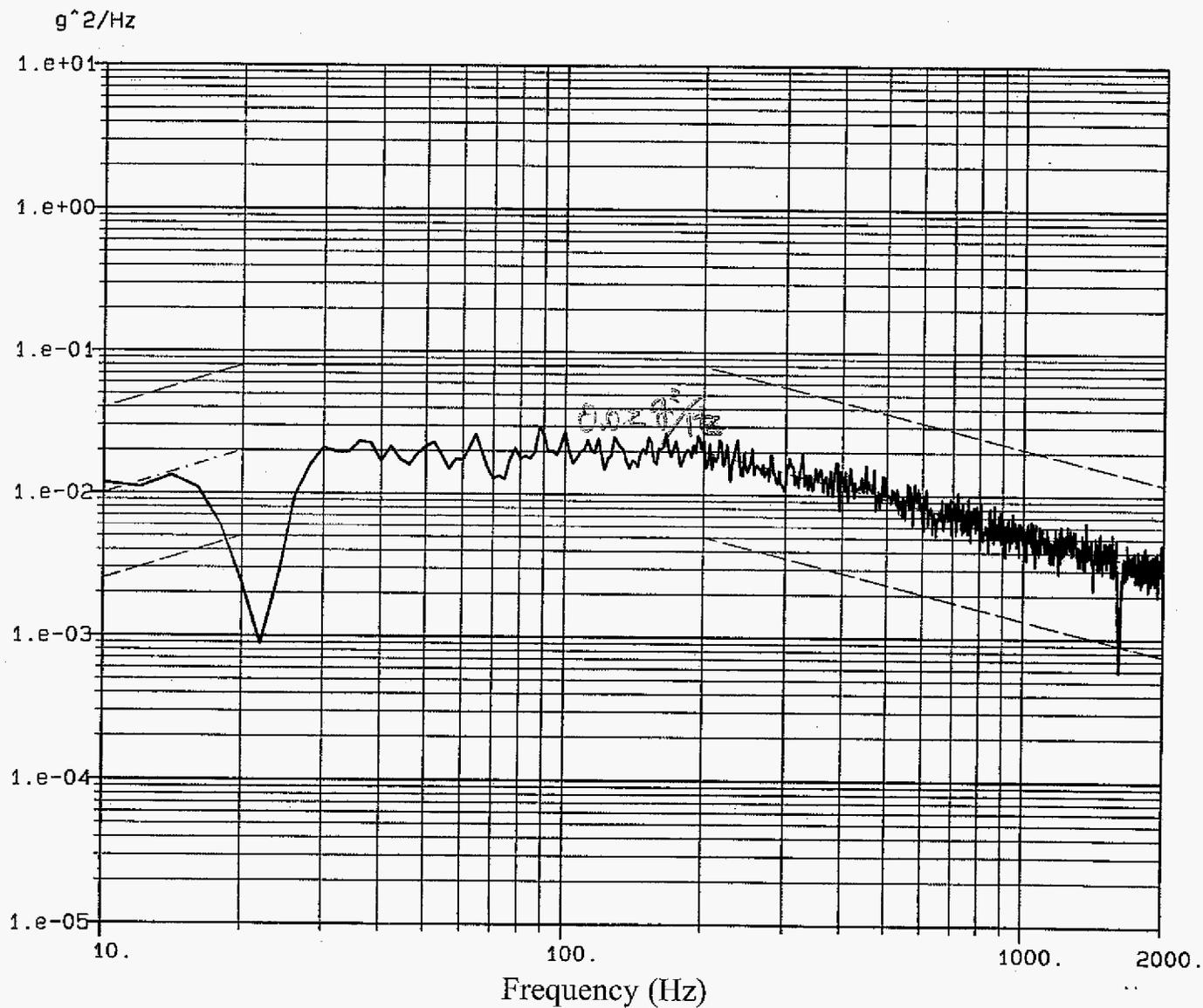
DS1 Safety Mass Simulator Vibration Test



Force Measured in Safety Mass 0.25 g Sine-Sweep Test



Full Level Acceleration Input for Safety Mass Lateral Test



Force Measured in Full Level Input Safety Mass Test

