# FORCE LIMITS MEASURED ON A SPACE SHUTTLE FLIGHT

T. Scharton

*Jet Propulsion Laboratory,*
*California Institute of Technology, Pasadena, CA, USA*
Tel: +01 818 354-8368, fax: +01 818 393 1156
terry.d.scharton@jpl.nasa.gov

ABSTRACT

The random vibration forces between a payload and the sidewall of the space shuttle have been measured in flight and compared with the force specifications used in ground vibration tests. The flight data are in agreement with a semi-empirical method, which is widely used to predict vibration test force limits. The flight measurements are less than one-half of the random vibration loads specified in the shuttle payload design guide. These data are consistent with published data and have been previously disseminated within NASA and the aerospace community in the USA [1].

## INTRODUCTION

It is becoming standard practice in NASA aerospace programs to measure and limit the input forces in vibration tests of structure-like hardware [2, 3]. Force limiting makes vibration tests more realistic by simulating the impedance characteristics of the flight mounting structure.

The most straight forward method of defining force limits is based on the interpretation of the quasi-static limit loads, which are defined early in the design process, as the accelerations at the center-of-gravity (CG) of the test item [2, 4]. Then, by Newton's second law, the force limit is equal to the limit load times the weight of the test item. For random vibration tests, it is common to multiply the measured rms force by a peak factor of 3 for comparison with the limit loads. In addition to these limits on the overall or peak force, it is often desirable to have frequency dependent force limits in order to facilitate notching of the input acceleration at the fixed base resonance frequencies of the test item. A number of techniques are available for deriving spectral force limits. The simplest method is semi-empirical and requires only the acceleration specification and the test item mass [2, 5]. More complicated methods require the effective modal masses and/or the residual masses of the test item and of the flight mounting structure [2, 6]. Another paper, presented at this conference, discusses the interrelationship of overall and spectral force limits [7]. Only two previous in-flight measurements of random vibration forces are available [8, 9].

This paper presents force data measured in two experiments, the Shuttle Vibration Forces payloads 1 and 2 (SVF-1 and SVF-2), which flew on two Space Transportation System (STS) missions, STS-90 in April 1998 and STS-96 in May 1999, respectively. The flight force data are compared with: 1) loads criteria used in the design of the SVF experiment, 2) force limits used for vibration testing of SVF, and 3) flight force data obtained previously on an expendable launch vehicle [8].

## DESCRIPTION OF SVF EXPERIMENT

Figure 1 and 2 are photographs of the SVF-1 and SVF-2 experiments mounted in the space shuttle cargo bay. In each case, the SVF experiment involved a Hitchhiker (HH) canister attached to the shuttle sidewall via an adapter beam. (Each adapter beam also held a second HH experiment; the SVF-1 experiment is the HH canister on the left in figure 1, and SVF-2 is the HH canister on the right in figure 2.) The Hitchhiker payload support was provided by NASA GSFC. Four tri-axial force gages were located between the SVF canisters and the adapter beam, and two accelerometers along with the signal processing and recorders were located inside the canister, as shown in figure 3. The "stand alone" recorders (WBSAAMD's) were provided by NASA JSC.

The only data recovered from the SVF-1 experiment were data from the accelerometer located at the canister CG. Data from the other accelerometer and from the force gages were not obtained on SVF-1 because of problems with the recorders, which were reworked before SVF-2. Data from the top accelerometer and, most importantly from the force gages, were obtained on SVF-2.

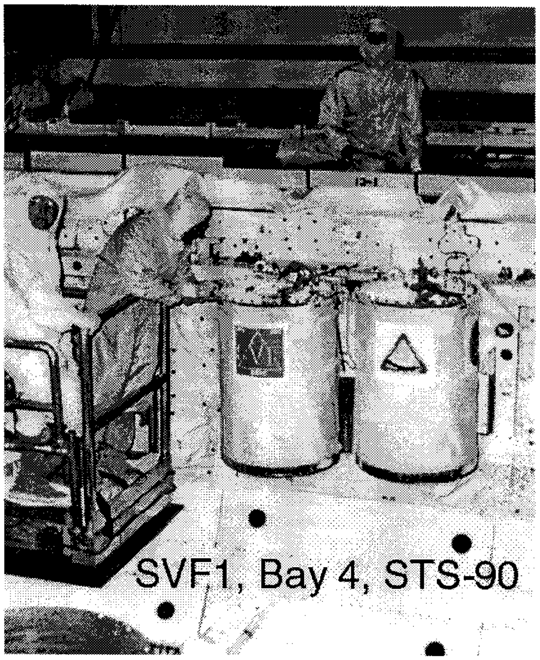


Figure 1: SVF1 Experiment on STS-90

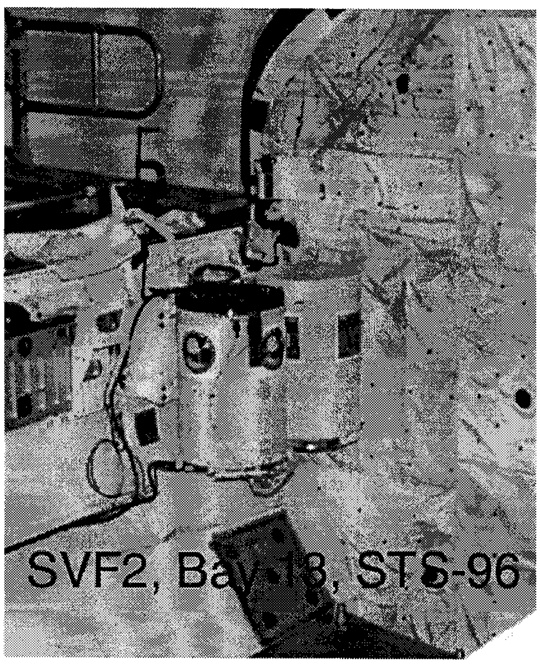


Figure 2: SVF2 Experiment on STS-96

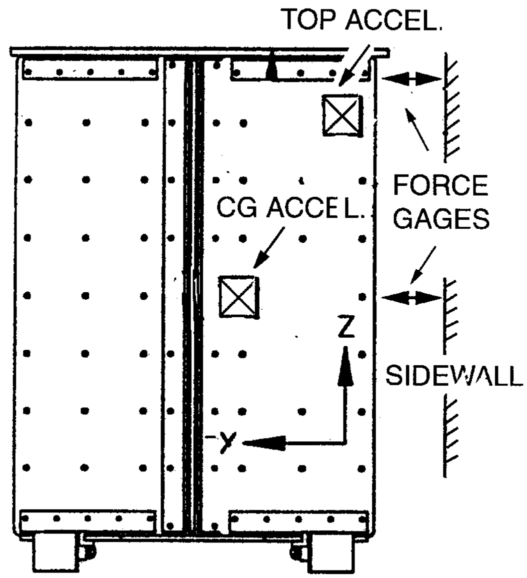


Figure 3: Hitchhiker Canister with Force Gages in Mounting Brackets and with Electronics Inside

DATA

For brevity, only the acceleration and force data measured in the Y-axis, which is normal to the shuttle sidewall is discussed. (See coordinate system in figure 3.) The Y-axis random vibration is generally larger than that in-plane, because acoustic excitation is the primary source of random vibration of the sidewall. The data are power spectral densities calculated during the time interval $6.5 < T < 9.0$ seconds after main engine ignition. This interval corresponds to the lift-off portion of the flight, which exhibited the maximum acoustic and random vibration responses. The spectral analyses were conducted using MATLAB with a bandwidth of 5 Hz.

Figure 4 shows the Y-axis acceleration measured in flight by the CG accelerometer on SVF-1, and figure 5 shows the Y-axis acceleration measured by the top accelerometer on SVF-2. (See location of accelerometers in figure 3.) Data at the same locations on the two flights were not obtained because of equipment malfunctions. Both measured spectra are about a factor of two below the 0.04 $G^2$/Hz acceleration specified for vibration qualification tests of HH canisters, which is compatible with the NASA standard 3 dB margin [10]. Since the specification is for the input and the data are responses, the measurements support the thesis that there is little amplification between the vibration input and response in actual flight configurations [5].

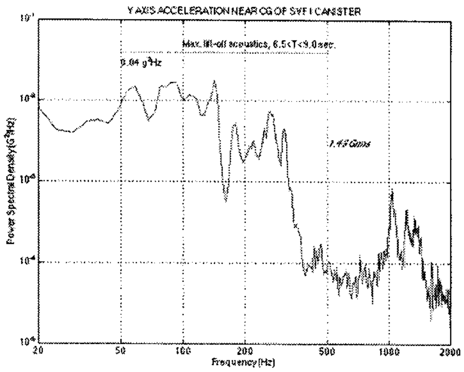


Figure 4: Y-Axis Acceleration at CG of SVF-1

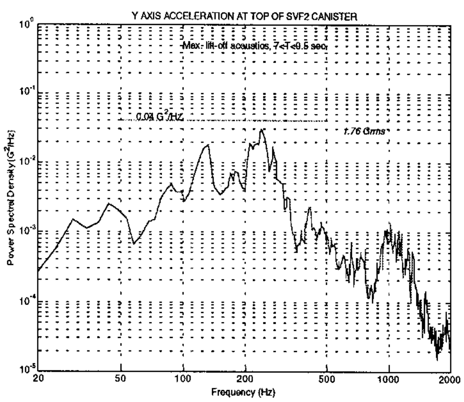


Figure 5: Y-Axis Acceleration at Top of SVF-2

Figure 6 shows the total Y-axis force measured in flight between the sidewall and the canister. The total force was obtained by summing the Y-axis outputs of the four force gages in real time. The measured rms force of 233 lb divided by the total canister weight of 230 lb gives a CG acceleration of 1.0 grms or a 3 sigma of 3 G, which is considerably less than the 8 G shuttle sidewall design limit for the Y-axis.

Figures 7 and 8 show the force and acceleration spectra from the force limited vibration qualification test of the HH canister. The force spectrum measured in flight (see figure 6) is about 10 dB less than the 10,000 $lb^2/Hz$ force limit used in the random vibration test

The force limit for the vibration test was derived using the semi-empirical method [2, 3]:

$$S_{ff} = C^2 * M_o^2 * S_{aa} * (f/f_o)^2 \qquad \text{Eq. 1}$$

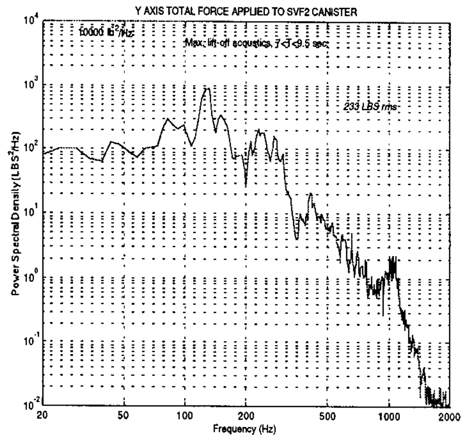


Figure 6: Total Y-Axis Force in SVF-2 Flight

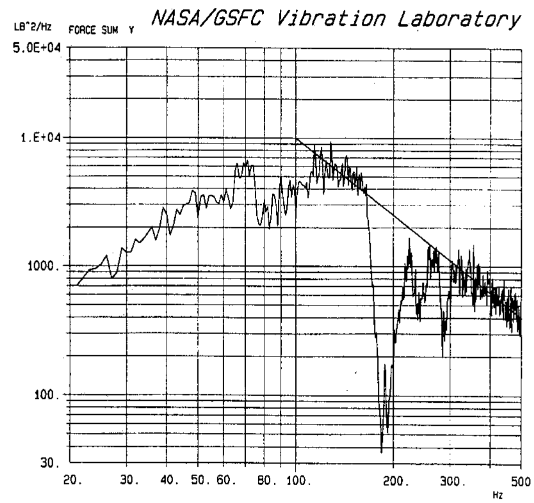


Figure 7: Force Limit in Vibration Test

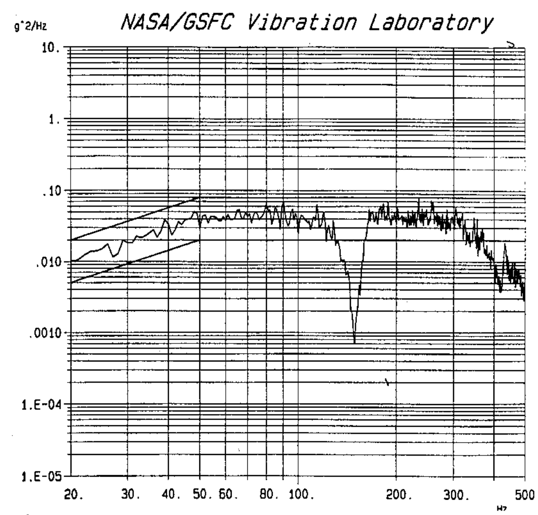


Figure 8: Acceleration Input in Vibration Test

In Eq. 1, $S_{ff}$ is the force limit spectrum (8,500, which was rounded up to 10,000 $lb^2/Hz$); C is an adjustable coefficient (in this case $C^2 = 4$); $M_o$ is the test item weight (230 lb); $S_{aa}$ is the acceleration spectrum (0.04 $G^2/Hz$); and $f_o$ is the break frequency ($f_o = 100$ Hz) taken equal to, or a bit less than, the fundamental resonance frequency of the test item on the shaker.

If the flight input acceleration is assumed to be 0.01 $G^2/Hz$, which is consistent with previous measurements of shuttle sidewall vibration and with the response measurements in figures 4 and 5, then Eq. 1 with $S_{ff} = 1000$ $lb^2/Hz$ yields $C^2 \sim 2$. This is the same value exhibited by the force data for a 60 lb instrument located on the ACE spacecraft that flew on an expendable launch vehicle [8]. The results of these two experiments indicate that force limited vibration tests of comparable payloads are conservative for $C^2 > 2$. Note that even with the relatively high force limit ($C^2 = 4$) used for the SVF vibration test, about 16 dB of notching was obtained (Figure 8).

## CONCLUSIONS

The SVF-2 experiment was successful since valid data on the vibration forces were obtained. The in-flight forces measured on SVF-2 provide validation of the methods currently being used to derive force limits for NASA aerospace programs. The SVF-2 force data indicate 3 G maximum CG acceleration in the Y-axis, which is considerably less than the current shuttle sidewall mounted payload design limit of 8 G. An additional SVF experiment (WSVFM) is manifested on STS-102 in February 2001 and it is anticipated that these measurements will be continued as part of the shuttle HH program. It is hoped that the SVF data, together with that from future flights, will result in reduced design loads for shuttle sidewall mounted payloads.

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