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Benefits of Force Limiting Vibration Testing

Mark E. McNelis
Glenn Research Center, Cleveland, Ohio

Terry D. Scharton
Jet Propulsion Laboratory, Pasadena, California

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BENEFITS OF FORCE LIMITING VIBRATION TESTING

Mark E. McNelis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Terry D. Scharton
Jet Propulsion Laboratory
Pasadena, California 91109

SUMMARY

Force limited random vibration testing is used at NASA John Glenn Research Center (formerly NASA Lewis Research Center) for qualifying aerospace hardware for flight. The benefit of force limiting testing is that it limits overtesting of flight hardware, by controlling input force and acceleration from the shaker (dual control) to the test article. The purpose of force limiting is to replicate the test article resonant response for the actual flight mounting condition.

The force limiting testing technology has been implemented at the Jet Propulsion Laboratory for the past 10 years on various spacecraft testing programs. The Cassini mission to Saturn, most notably, utilized force limiting vibration testing as part of the spacecraft system level vibration testing.

NASA John Glenn Research Center is responsible for microgravity combustion and fluid science research on the Shuttle and the International Space Station. Qualification testing of delicate and vibration sensitive science instrumentation is particularly challenging to successfully qualify for flight. In order to facilitate the testing process, force limiting has been implemented to minimize overtesting of flight hardware. This paper will address recent flight camera testing (qualification random vibration and strength testing) for the Combustion Module-2 mission and the impact of Semi-empirical Method force limits

INTRODUCTION

The force limiting technique of controlling both the input acceleration and force in vibration testing (dual control) has been implemented to reduce overtesting of aerospace hardware. The cause for overtesting in a mechanical shaker vibration test is the impedance mismatch between the flight boundary condition and the test configuration. The consequence of the impedance mismatch is the interface input force in the vibration test is higher than in flight, at the structural resonances. For lightly damped structures, the input acceleration spectral density overtest factor can be as high as ten thousand at resonance (ref. 1).

The application of force limiting has several benefits over traditional acceleration controlled vibration testing. Force limiting eliminates the interface impedance mismatch thereby limiting the test item response at resonance. Force limiting also provides a means to measure and limit the input force applied to the structure's center of gravity. Aerospace structural design load factors are defined at the center of gravity of the structure; the design load factors can be used as a constraint for the definition of maximum input force. In this way, force limiting can be implemented as a strength test.

FORCE LIMITING THEORY AND APPLICATION

NASA Glenn Research Center's Structural Dynamics Laboratory performs structural dynamic testing to qualify aerospace hardware for flight. The test results for the random vibration testing of the Combustion Module-2 (CM-2) Xybion camera package and the implementation of the force limiting technology is presented.

The advent of commercially available, economically priced, and miniaturized three axis piezoelectric force gages has facilitated the use of force limiting for practical application in the vibration test laboratory. Discussion of general force limiting criteria considering the force gage preload, calibration, fixturing, and control strategy may be found in reference 2. The force gages (washers) are installed in series between the test article and shaker table interface. Control accelerometers are installed in parallel with the test article. The shaker control system controls the force and acceleration signals independently using the algorithm:

$$F / F_o \quad \text{and} \quad A / A_o \le 1.0 \tag{1}$$

Where F is the measured base input force,
F_o is the reference force limiting specification,
A is the measured base input acceleration, and
A_o is the reference acceleration specification.

For the CM-2 Xybion camera package vibration testing, the Semi-empirical Method (Ref. 3) was used to define the force limits. The Semi-empirical Method theoretical equation is applied for random vibration:

$$\begin{aligned} S_{FF} &= C^2 M_o^2 S_{AA} && f \le f_o \\ S_{FF} &= C^2 M_o^2 S_{AA} / \left(f / f_o\right)^2 && f > f_o \end{aligned} \tag{2}$$

Where S_{FF} is the force spectral density,
C is a constant which depends on the test configuration,
M_o is the static mass of the test item,
S_{AA} is the acceleration spectral density,
f is the frequency in Hertz (Hz), and
f_o is the fundamental resonant frequency (Hz) of the test article.

The force limit, S_{FF}, is proportional to the acceleration control spectrum $S_{AA.}$ The acceleration control spectrum is derived based on the envelope of test data, flight data or analysis at the interface between the test article and its flight mounting location. Any inherent error in the acceleration control spectrum will also adversely affect the force limiting spectrum.

Some engineering judgement and reference data for similar test configurations must be used to estimate the value of C used in the equation (2). The validation of equation (2) has been shown for the Cassini spacecraft and component force limiting testing (ref. 3).

CM-2 XYBION CAMERA PACKAGE TESTING

The CM-2 Xybion camera package was random vibration tested in three mutually perpendicular axes (normal, radial, and tangential) to evaluate the benefits of force limiting. The Xybion camera package is a cantilevered test configuration composed of a base mounting bracket and the Xybion camera. The test configuration, instrumentation locations and axes coordinate system is defined in figure 1. Six force gages were mounted between the Xybion mounting bracket and the test fixture to measure the base input force. Two control accelerometers (not shown) were mounted on the fixture. Only the control accelerometers, not the force gages, were used to control the Xybion camera package test. Control to the nominal acceleration test specification was excellent in all three axes. The base input force was monitored but not used in the shaker control algorithm due to test schedule constraints.

Calculation of the force limiting specification requires an estimate of the structural dynamic response of the test article. An example of the force limit calculation for the normal axis is given in table I.

The first step in calculating the force limit is to estimate the fundamental frequency, f_o and the total mass, M_o, of the test article. Because the CM-2 mission is a reflight of CM-1 hardware, qualification test data existed for the estimation of f_o. The total mass, M_o, of the CM-2 Xybion camera package is 9.6 pounds (lbs).

The second step in computing the force limiting specification is to develop the interface acceleration control spectrum specification using previous test data, flight data or by analysis. The CM-2 Xybion camera package interface acceleration control specification is based on the envelope of previous CM-1 Xybion camera package test data from 20 to 2000 Hz.

The final step in calculating the force limit is to estimate the constant C. Selection of the C value can be based on the desired notch depth. The C factor can also be chosen such that the force limit is constrained to the test article structural design limit load factor.

The force limiting criteria developed for the Xybion camera package was to constrain the root mean square (rms) force limit to be 95 percent of 1.1 times the limit load factor. This ensures that the force limit and the testing control tolerances would not allow the test to exceed the limit load factor (defined at the center of gravity of the structure) for the Xybion camera package. By constraining the force limit by the structural design limit load factor, the test article is effectively exposed to a pseudo strength test during the execution of the random vibration test.

The apparent mass is defined as the magnitude of the structural impedance of the test article (ref. 3). The apparent mass, or dynamic mass, is a measure of the ratio of the reaction force to the prescribed acceleration. At frequencies below the fundamental resonance, the apparent mass is the static mass. At resonance, the apparent mass is the static mass multiplied by the dynamic magnification factor, Q. Beyond the fundamental resonance, the apparent mass is reduced below the static mass value. For the Xybion camera package, the static mass is 9.6 pounds (lbs). The apparent mass for the normal, radial, and tangential excitation directions are illustrated by figures 3, 5, and 7, respectively.

Due to schedule limitations in the Structural Dynamics Laboratory, force limiting was not implemented for the Xybion camera package test. However, pretest force limiting specifications were developed as a benchmark to compare with the measure base input force without force limiting.

In the normal axis (fig. 2), the benefit of force limiting would have been a 4.4 dB reduction in the measured overall base input force (no force limiting) from 206 to 123.6 lbs rms. The reduction was exhibited over a broadband frequency range. Force limiting would have also provided a reduction of 6.7 dB at the measured fundamental resonance (1172 Hz) in the normal axis.

In the radial axis (fig. 4) the benefit of force limiting would have been obtained just at the fundamental resonance (3.7 dB reduction at 364 Hz), with no impact elsewhere.

The force limiting benefit would have been minimal in the tangential (fig. 6) testing axis.

CONCLUSIONS

The application of force limiting to random vibration testing is straight forward and beneficial for minimizing overtesting of the test article. Force limiting can be used to measure the center of gravity response of the test article. The force limit can be constrained to the design load factor for the test article enabling a pseudo strength test while performing the random vibration test. For the CM-2 Xybion camera package testing, the impact of force limiting would have been greatest in the normal axis where a 4.4 dB reduction in the broadband spectrum and a 6.7 dB reduction at the fundamental resonance could be realized. In the radial axis, a 3.7 dB reduction due to force limiting could be realized at the fundamental resonance. The apparent mass can be accurately measured using force limiting to characterize the Xybion camera package structural dynamic response.

REFERENCES

1. Scharton, T.D., Boatman, D.J., Kern, D.L.: “Dual Control Vibration Testing,” Jet Propulsion Laboratory, presented at the 60th Shock and Vibration Symposium, Virginia Beach, Virginia USA, November 14–16, 1989.
2. Scharton, T.D.: “Force Limited Vibration Testing,” NASA Technical Handbook, April 1997.
3. Scharton, T.D.: “Force Limited Vibration Testing Monograph,” NASA RP–1403, May 1997.

TABLE I.—EXAMPLE FORCE LIMIT CALCULATION
(Normal Axis)

Estimation of the Structural Parameters:
Estimated Fundamental Frequency, f_o = 1300.0 Hz
Test Article Mass, M_o = 9.6 lbs
Constant, C = 0.81

Calculation of Force Specification (Normal Axis):
$S_{FF} = C^2\ Mo^2\ S_{AA}$
$S_{FF} = C^2\ Mo^2\ S_{AA}/(f/f_o)^2 \quad f > f_o$

Frequency, Hz	Acceleration specification, S_{AA}, g^2/Hz	Force limit specification, SFF, lb^2/Hz
20.0	0.002	0.1
75.0	0.059	3.6
100.0	0.432	26.1
140.0	0.856	51.7
185.0	0.360	21.8
545.0	0.353	21.3
2000.0	0.006	0.2
Composite	16.5 g rms	123.6 lbs rms

Comparison of 1.1 x Limit Load with Predicted Test Load:

Load Case	
Predicted Test Load = 123.6 lbs rms/9.6 lbs	12.9 g's
1.1 x Limit Load	13.5 g's
Predicted Test Load/1.1 x Limit Load	95 percent

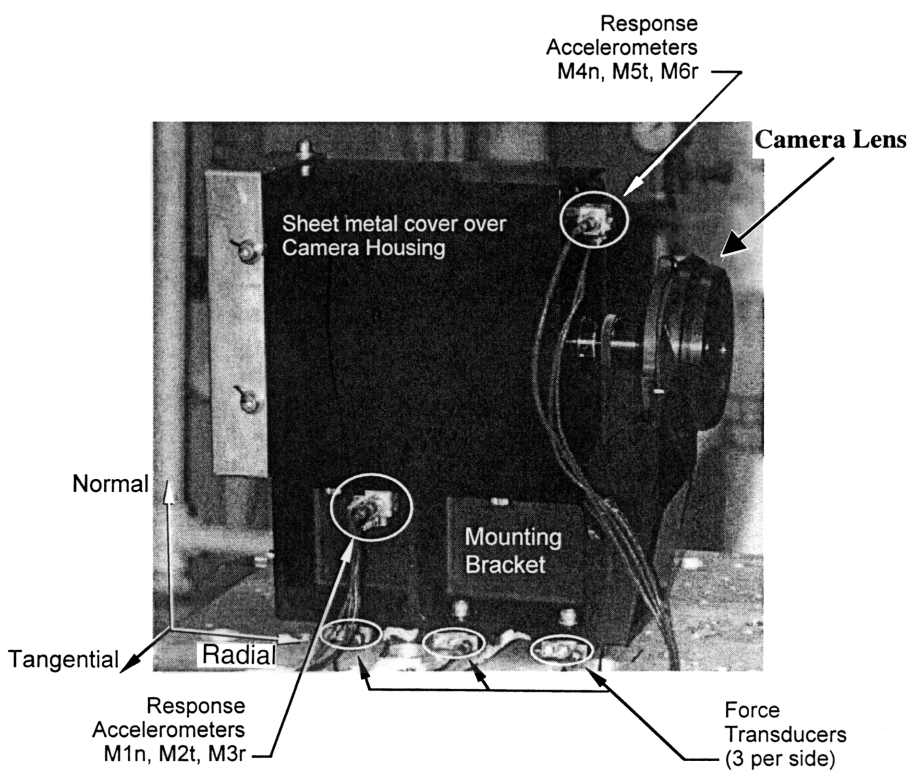

Figure 1.—CM-2 Xybion camera coordinate system and test instrumentation.

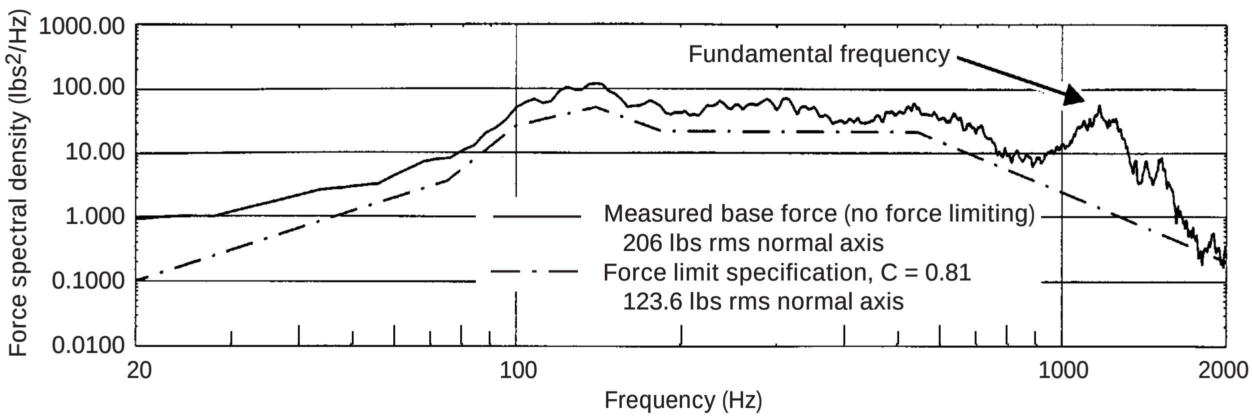

Figure 2.—Comparison of normal axis measured base input force (no force limiting) and force limit specification.

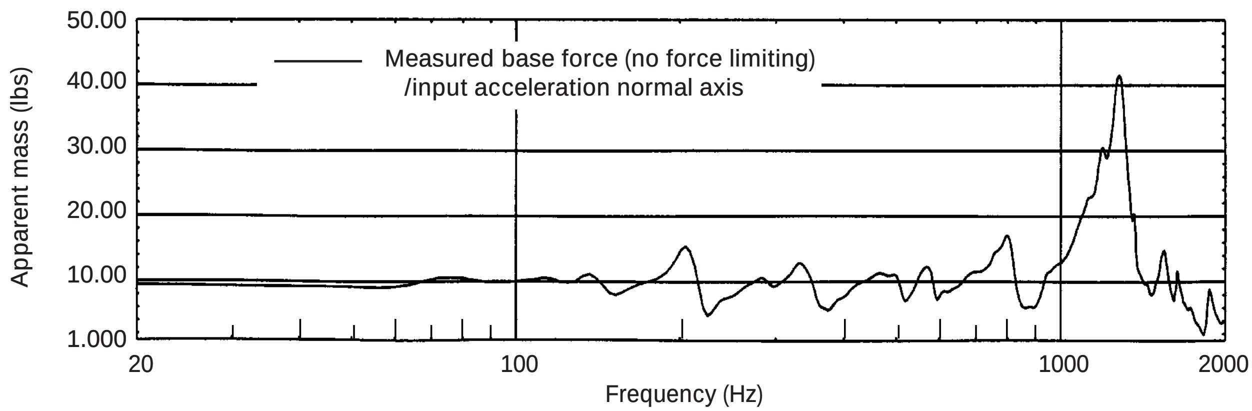

Figure 3.—Normal axis apparent mass.

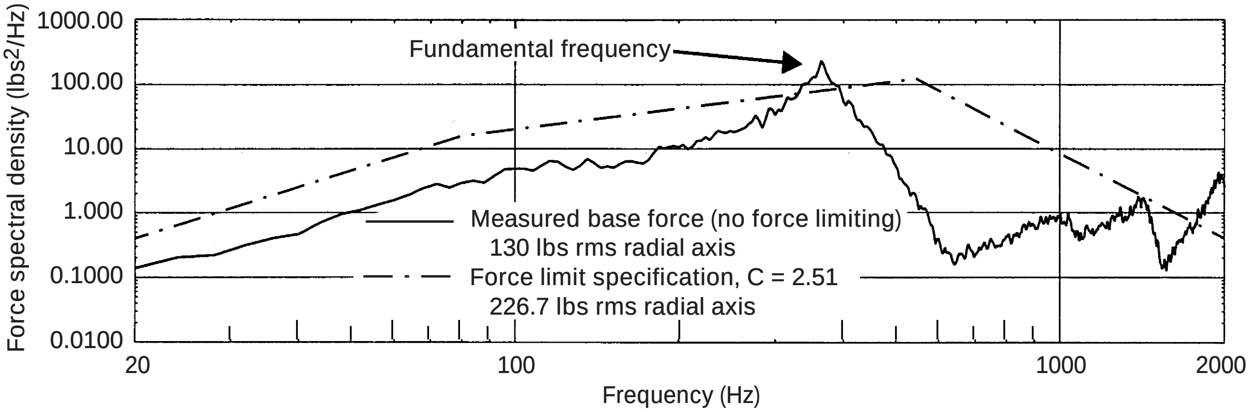

Figure 4.—Comparison of radial axis measured base input force (no force limiting) and force limit specification.

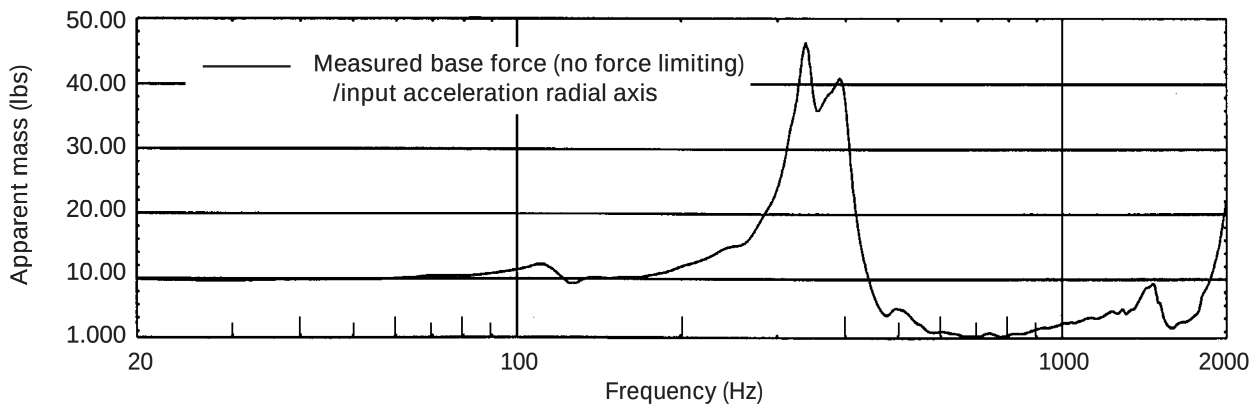

Figure 5.—Radial axis apparent mass.

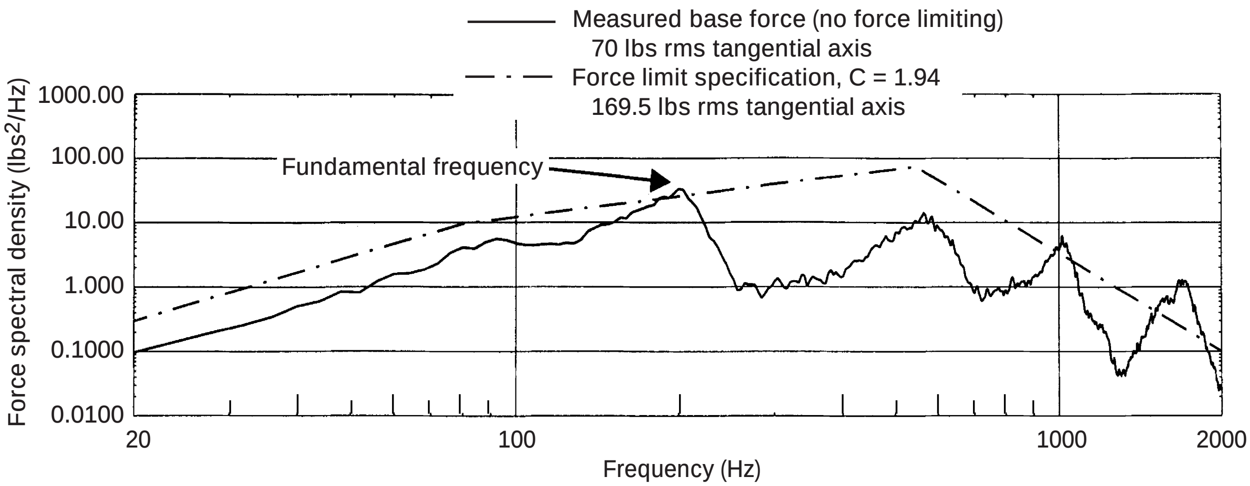

Figure 6.—Comparison of tangential axis measured base input force (no force limiting) and force limit specification.

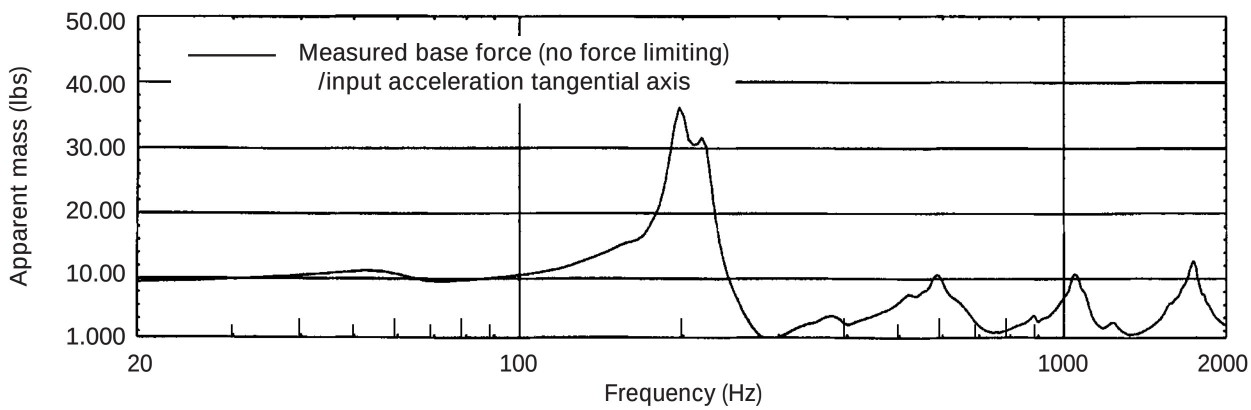

Figure 7.—Tangential axis apparent mass.

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