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SENSITIVITY OF FORCE SPECIFICATIONS TO THE ERRORS IN MEASURING THE INTERFACE FORCE

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Abstract

Force-Limited Random Vibration Testing has been applied in the last several years at the NASA Goddard Space Flight Center (GSFC) and other NASA centers for various programs at the instrument and spacecraft level. Different techniques have been developed over the last few decades to estimate the dynamic forces that the test article under consideration will encounter in the flight environment. Some of these techniques are described in the handbook, NASA-HDBK-7004, and the monograph, NASA-RP-1403.

This paper will show the effects of some measurement and calibration errors in force gauges. In some cases, the notches in the acceleration spectrum when a random vibration test is performed with measurement errors are the same as the notches produced during a test that has no measurement errors. The paper will also present the results of tests that were used to validate this effect. Knowing the effect of measurement errors can allow tests to continue after force gauge failures or allow dummy gauges to be used in places that are inaccessible to a force gage.

INTRODUCTION

There have been instances in the recent past where connections to force gages have failed or a force gage could not be located at a particular bolt location. Since the effects of a failure are unknown then the test item would have to be removed and the failed gage or wiring replaced. In the instance where a force gage could not be fit at a bolt location, either an interface adapter would need to be fabricated, which changes the dynamic characteristics of the test item, or force limited vibration testing would not be performed.

In this paper, I have attempted to discover the effects of various gage failures through the use of a mass model left over from the development of the Composite Infrared Spectrometer (CIRS) instrument that was flown on CASSINI. At first, eight force gages were used to measure the interface force for various failure modes and then the experiments were repeated with four gages. For each set of experiments, a baseline test with all of the gages working was run using two different force-limiting specification methods: semi-empirical; and the maximum of the simple and complex two-degree-of-freedom-system (TDFS) methods. The force-limited tests were run again with each

Figure 1. Photograph of CIRS Mass Model

force gage disconnected to simulate a gage failure or a dummy gage. In addition, a series of tests was conducted with the sensitivity of the force sum set to the incorrect value.

TEST CONFIGURATION

Figure (1) is photograph of the CIRS mass model used for the experiments. It consists of four different weights attached with pipes of various lengths to a central weight. This results in the center-of-gravity not being centered over the force gages. Table (1) shows the mass of each weight and pipe and the length from the center of the central weight to the center of each weight. The total weight of the model is 58 lbs (26.4 kg). The mass model was bolted to the shaker table using either four or eight attachment bolts. Four Kistler model 9251A force gages were used when testing with four attachment bolts and eight Kistler 9101A gages were used when testing with eight attachment bolts (due to availability of gages). In both instances, the outputs of the force gages were connected together to measure the total interface force. The force gage locations and their designators are shown in Figure (2).

Endevco 2221D Accelerometers were located on each mass and Endevco 7704-50 accelerometers were used in two locations on the shaker table to control the input acceleration.

All of the signals from the various gages were sent to the m+p Model VCX9000 controller that calculated the Power Spectral Densities and the Frequency Response Functions from each gage. The

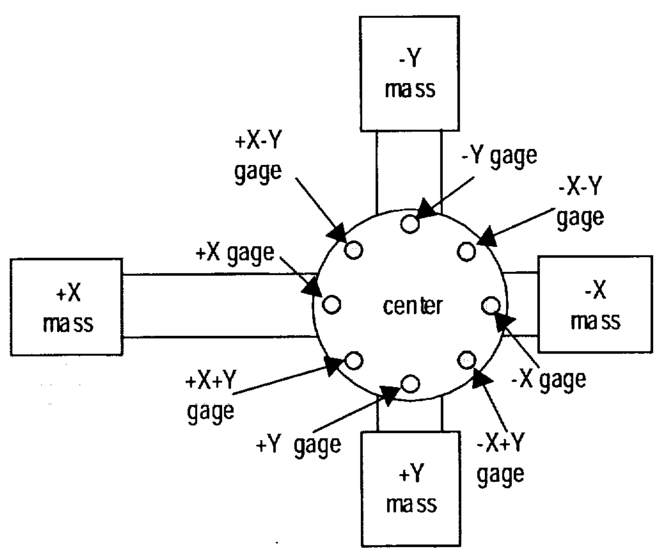

Figure 2. Sketch of masses, pipes, and force gage locations

controller also performed the force-limited random vibration tests using extremal control.

Table 1. Masses and weights of CIRS mass model

Designator	Mass of Weight (grams)	Mass of Pipe (grams)	Distance (cm)
Center	8319	-------	-------
-X	3930	321	20.3
+Y	3935	415	24.0
+X	3930	898	44.0
-Y	3935	681	35.0

Force limited tests were conducted using either the semi-empirical method, with the constant 'C' set to 1.414, or the maximum envelope of the Simple TDFS and the Complex TDFS methods as described in the handbook NASA-HDBK-7004 (P011) and the monograph NASA-RP-1403. Both of these documents are available on the worldwide web at http://standards.jpl.nasa.gov/jpl-nasa/.

A spreadsheet was used to calculate the residual masses needed for the TDFS methods based upon the measured modal mass. The Q was calculated by measuring the peak and 3dB bandwidth of each mode. The residual mass for each mode was then calculated by measuring the peak force, modal mass, and Q using the equation:

$$M_n = (F_n - m_n * A)/Q_n$$

where: M_n = Residual Mass at a particular mode n
F_n = Peak Force at mode n
m_n = Modal Mass at mode n
A = input acceleration (1 g in this case)
Q_n = Q at mode n

Another spreadsheet base upon NASA-HDBK-7004 (P011) was used to calculate the force limits based upon this information and source residual masses that were measured for the CASSINI program. When using either the semi-empirical or the TDFS methods, no modifications to the force specification were performed to reduce notches that appeared unreasonable. Also, no smoothing was performed on the resulting force specification.

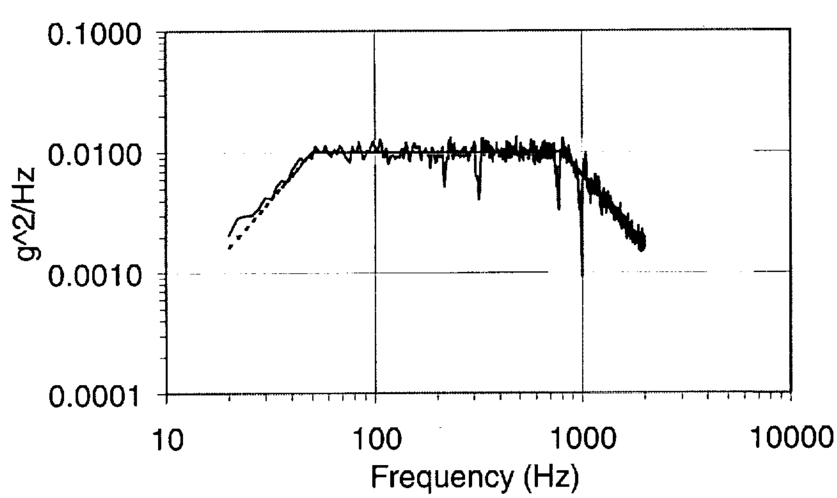

Figure 3. Notches with eight gages good using maximum of Simple and Complex TDFS methods

TESTS CONDUCTED WITH EIGHT FORCE GAGES

The first set of experiments was conducted with eight force gages measuring the interface force. The results with all of the gages working and using the maximum of the simple and complex TDFS methods is shown in Figure (3). This resulted in notches at 216, 312, and 771 Hz. The results with all of the gages working and using the semi-empirical method is shown in Figure (4). This resulted in notches at 82, 131 and 855 Hz in addition to deeper notches at 216, 312, and 771 Hz

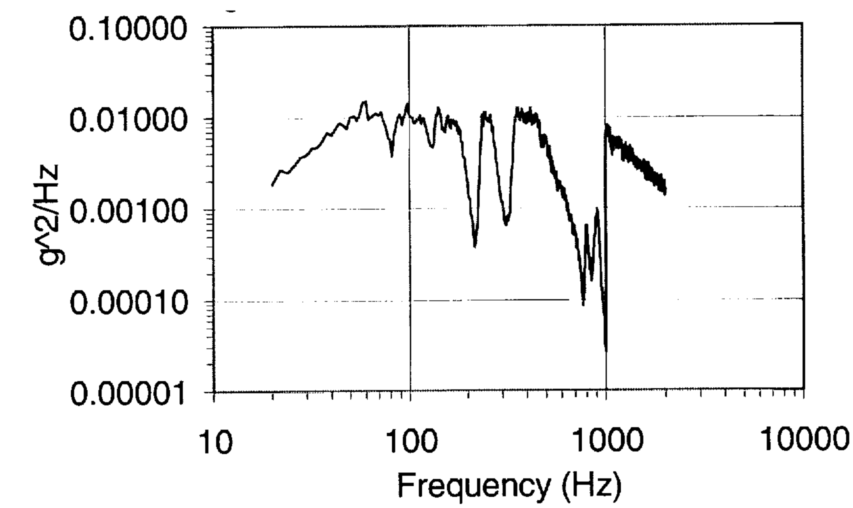

Figure 4. Notches with eight gages good using semi-empirical method

Incorrect Sensitivity Tests

The sensitivity of force gages changes with preload; however, the manufacturer's sensitivity is given with a preload that is unobtainable unless special pre-loading hardware is used. Usually, the gage sensitivity is calculated with the known weight of the test item during a low-frequency sine sweep or a sine dwell. What happens if you do not do this correctly is the purpose of the first set of experiments. I simulated the effect of using the incorrect sensitivity by adjusting the gain of the amplifier until the gain is either twice or half of the correct reading. This results in a weight measurement error of +100% or -50% (or ± 3dB) -- a much greater error then one might get in any real test.

Table (2) summarizes the results of this sequence of experiments. For each mode, the change in depth of the resulting notch is shown and the worst-case change in notch for each mode is shaded. The TDFS methods indicate some sensitivity to incorrect weight measurements, with the worst case being the disappearance of the 2.9 dB notch at 216 Hz when the amplifier is adjusted for the over-weight condition. This result was better then expected since the TDFS methods rely upon the ratio of the load and source weights to determine the force specification. On the other hand, the semi-empirical method indicates almost no sensitivity to incorrect weight measurement.

Table 2. Change in notch depth with incorrect weight measurement - eight gages

	Change in Notch Depth (dB)			
	Max of TDFS		Semi-Empirical	
Fn	Under Weight	Over Weight	Under Weight	Over Weight
82		-1.9	-0.4	
95				
131			-0.7	
152				
216	2.9	-1.2	-0.9	
312	0.6	0.3	-0.8	-0.4
771	1.8	-1.4	-0.1	
855			-0.5	-0.7

Table 3. Compensated Sensitivities for various failure modes - eight gages

	Good	-X Bad	-X+Y	+Y Bad	+X+Y	+X Bad	+X-Y	-Y Bad	-X-Y
Sensitivity (pC/lb)	14.8	14.5	14.4	13.1	12.3	12.1	11.3	12.4	13.7
Error (%)	0.0	-2.0	-2.7	-11.5	-16.9	-18.2	-23.6	-16.2	-7.4
Error (dB)		-0.2	-0.2	-1.1	-1.6	-1.7	-2.3	-1.5	-0.7

Gage Failure Simulation Tests

There have been cases where a connecting cable has failed or loosened after the test item has been installed. There has also been instances where projects have wanted to perform a force-limited vibration test, but some bolt locations did not have enough clearance for force gage. In these instances, a spacer could have been fabricated to take the place of a force gage. Both the failed and dummy gage situations were simulated by disconnecting each of the eight gages one at a time.

Sine sweeps were run with each gage disconnected and the sensitivity of the charge amplifier adjusted so the weight is correct at low frequency. The sensitivities and resulting errors in both percent and dB are shown in Table (3). The worst sensitivity error (-2.3dB) occurred at +X/-Y location which happens to be located nearest to the center of gravity.

Table (4) summarizes the results of this sequence of experiments. Once again, the change in depth of the notch for each mode is shown and the worst-case change in notches for are shaded grey. The TDFS method appears to be less sensitive to gage failures then the Semi-Empirical method.

Table 4. Change in notch depth with various failure modes - eight gages

	Change in Notch Depth (dB)							
	Max of Simple and Complex							
Fn	-X Bad	-X/+Y Bad	+Y Bad	+X/+Y Bac	+X Bad	+X/-Y Bad	-Y Bad	-X/-Y Bad
82	-2.6	-2.9						-1.9
95								
131								
152								
216	0.5	2.9	2.9	2.9	0.5	-2.8	-3.2	-0.7
312	0.4	3.9		-3.2	3.9	-1.0	1.4	3.9
771	-0.3	0.3	0.1	1.6	0.5	0.6	-0.9	0.2
855					-4.4	-3.3		
	Semi-Empirical							
Fn	-X Bad	-X/+Y Bad	+Y Bad	+X/+Y Bac	+X Bad	+X/-Y Bad	-Y Bad	-X/-Y Bad
82	-5.1	-3.6	-1.7	4.3	4.3	3.1	1.1	-3.8
95					-2.0	-1.9		-1.6
131	1.3	-2.2	-5.5	-4.6	-2.1	1.0	-1.1	3.3
152					-4.1	-5.8	-4.8	
216	0.4	2.5	5.6	2.1	-1.0	-3.6	-3.9	-3.0
312	6.5	2.1	-0.1	-4.1	-4.6	-4.0	-0.8	3.7
771	-0.7	-0.8	0.6	2.3	1.3	0.6	-0.1	-1.0
855	1.3	0.8	0.1	-1.6	-1.9	-2.8	-1.6	-0.1

The worst change in notches for the TDFS methods is the case where the +X gage is bad with a change of +3.9 dB occurring at 312 Hz and a change of –4.4 dB occurring at 855 Hz with a change of input sensitivity of –1.7 dB. The Semi-Empirical shows the worst change when the –X gage is bad with a change of –5.1 dB occurring at 82 Hz and a change of +6.5 dB occurring at 312 Hz with a change of input sensitivity of only –0.2 dB. Still, there are enough missing and new notches with either method to recommend against conducting a force-limited test under these conditions.

GAGE FAILURE SIMULATION TESTS - FOUR FORCE GAGES

Another series of tests was conducted with only four mounting bolts and force gages to see if there was any change in the notch sensitivity. The results with all of the gages working and using the maximum of the simple and complex TDFS methods is shown in Figure (5). This resulted in notches at 211, 308, 710, 812, 934 and 984 Hz. The results with all of the gages working and using the semi-empirical method is shown in Figure (6). This resulted in notches at 80, 128, 149 and 479 Hz in addition to deeper notches at 211, 308, 710, 812, 934 and 984 Hz.

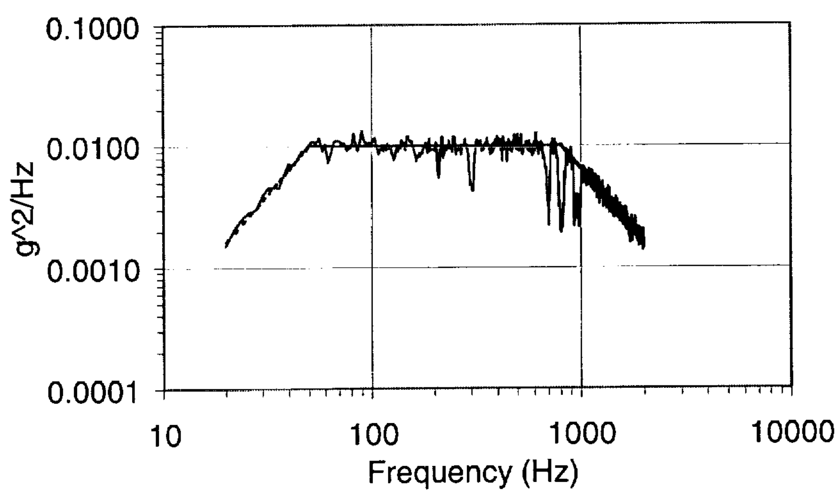

Figure 5. Notches with four gages good using maximum of Simple and Complex TDFS methods

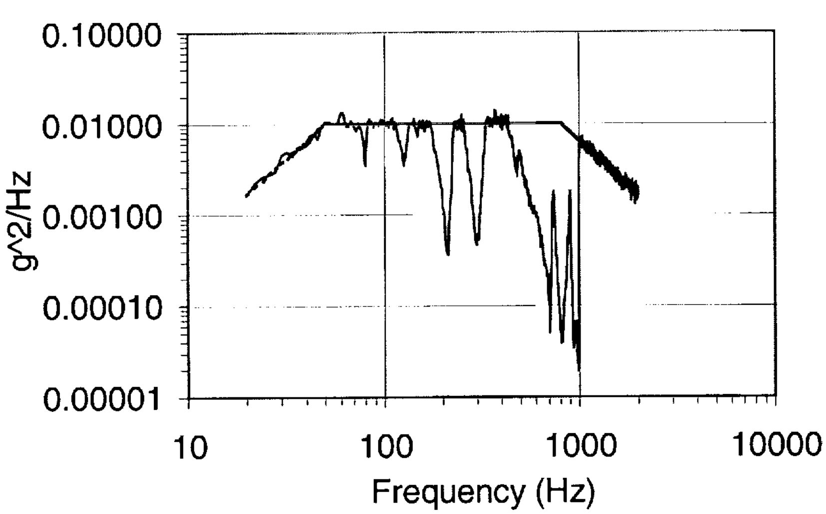

Figure 6. Notches with four gages good using semi-empirical method

Table (5) summarizes the results of these tests with the worst-case change in notches shaded grey. The results of sine sweeps run when the +X and –Y gages were disconnected generated outrageous effective mass values and could not be used to generate a force-limited specification, so these tests were not run.

With fewer gages, the effect of a gage failure is more pronounced. Once again, the TDFS methods do a better of job of compensat-

Table 5. Change in notch depth with various failure modes - four gages

Fn	Change in Notch Depth (dB)			
	Max of TDFS		Semi-Empirical	
	-X Bad	+Y Bad	-X Bad	+Y Bad
80	-6.5		-8.6	-1.7
95				-1.9
128		-2.2	4.6	-5.4
149			1.4	1.4
211	1.7	2.6	1.4	14.4
308	3.6	0.2	13.4	1.2
479			-1.4	0.9
574				
710	-1.5	1.5	-0.6	3.0
812	3.6	1.1	3.4	1.1
934	0.1	-0.4	1.3	
984	2.5	-0.2	2.8	1.3

ing for gage failure with the worst case being the appearance of a -6.5 dB notch at 80 Hz when the -X gage is bad. The Semi-Empirical method had the -13.4 dB notch 308 Hz disappear when the -X gage is bad and a -14.4 dB notch disappear when the +Y gage was bad. Once again, there are enough missing and new notches with either method to recommend against running a test.

CONCLUSIONS

The set of experiments described in this paper demonstrate that the semi-empirical method was insensitive to an incorrect gage sensitivity or weight measurement. However, the TDFS methods were less sensitive to a simulated missing or failed gage. How can a failed gage be detected without measuring each force gage separately? It looks like it is worthwhile to calculate the modal and effective masses, even if the semi-empirical is used. When the modal masses are calculated for each of the eight simulated failed gages, as shown in Table (6), there are cases where the modal masses

Table 6. Modal masses for various failure modes - eight gages

Fn	Modal Mass (lbs)								
	Good	-X Bad	-X+Y	+Y Bad	+X+Y	+X Bad	+X-Y	-Y Bad	-X-Y
81.89	6.12	8.31	6.63	6.40	0.00	0.00	0.00	9.12	6.34
94.67	0.48	0.01	0.30	1.20	2.61	3.56	0.00	0.12	-0.19
130.51	3.03	1.24	3.42	5.90	5.95	5.52	0.00	0.00	0.00
152.45	0.51	-0.79	-0.31	-0.04	0.54	1.90	0.00	0.00	0.00
217.94	6.41	5.13	4.04	2.12	3.89	6.94	9.89	10.24	7.29
314.80	4.85	-0.62	1.92	4.58	8.59	10.26	9.66	5.13	0.87
771.19	1.95	2.41	2.14	1.89	1.95	2.32	2.10	2.50	2.23
855.35	1.43	0.33	0.58	1.14	1.95	2.90	2.30	1.71	0.68

turn out to be negative. These cases are shown are shaded in the table. Table (6) also shows cases where the low frequency modes are missing completely (0.00 values). Figure (7) is a plot of the sweep data used to calculate all of the modal masses for the "-X-Y bad" case. One can see the questionable results at low frequency, especially when there is an anti-resonance without a corresponding resonance at a lower frequency.

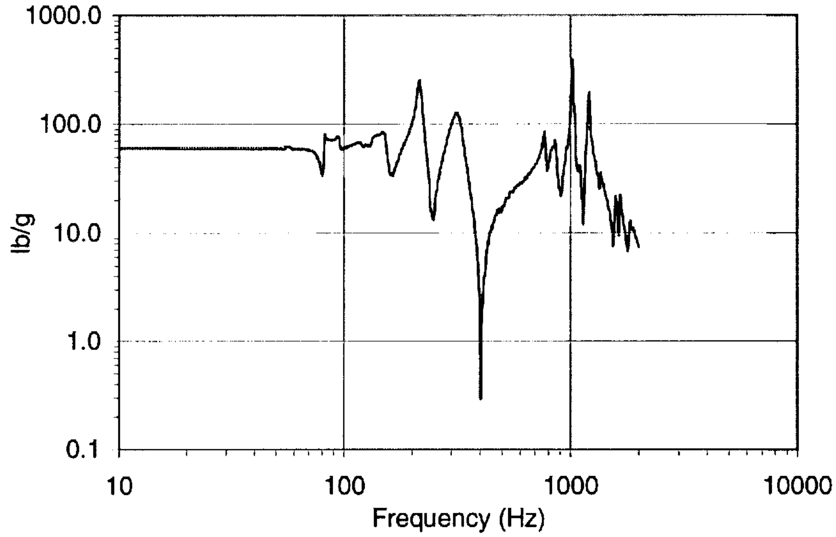

Figure 7. Example of questionable sweep data when +X-Y gage is bad

Another technique to detected failed force gages is to calculate effective mass. When this calculation is performed for each of the four simulated failed gages, as shown in Table (7), there is a case where the effective mass becomes negative. This case (+X bad) is shaded in the table. Use of these three techniques will help to insure that all of the force gages are working without resorting to the cumbersome technique of monitoring each gage individually.

Table 7. Effective masses for various failure modes - four gages

	Residual Mass (lbs)				
Fn	Good	-X Bad	+Y Bad	+X Bad	-Y Bad
80.21	51.69	44.74	50.92	31.36	58.00
94.67	50.67	44.31	48.66	31.36	58.00
127.84	47.51	43.65	40.28	10.44	49.35
149.33	46.48	43.65	39.99	1.80	49.35
211.27	40.67	39.09	40.76	-8.31	33.62
300.46	35.73	39.09	35.43	-33.60	27.13
478.88	35.73	39.09	35.43	-33.60	27.13
574.05	35.73	39.09	35.43	-33.60	27.13
709.86	33.54	36.63	33.87	-38.38	24.31
812.18	28.65	34.35	30.17	-48.03	19.09
934.08	25.51	32.47	29.02	-48.84	15.46
983.73	23.08	31.09	27.28	-52.95	13.25

The set of experiments also shows that a measurement with fewer gages is more sensitive to error when one of them fails; therefore, it is better to use more gages then to try to use adapters to reduce the gage count.

Knowing that the force limiting technique can correct for some measurement errors allows tests to continue after force gauge failures or allows dummy gauges to be used in places that are inaccessible. There still might be instances where one could run a force-limited test with failed or missing force gages, but some analysis of mode shapes would be required beforehand to see which modes would not be measured correctly.