EVALUATION OF CONSERVATISM IN LOW FREQUENCY VIBRATION TEST CONTROL

by M. J. Hine
Jet Propulsion Laboratory
Pasadena, California 91109

II1OGRAPHY

Dr. Hine received a B.Eng. degree in mechanical engineering from Sheffield University in 1963 and a Ph.D. in acoustics from the Institute of Sound and Vibration Research, Southampton University, England in 1971. He has worked primarily in machinery vibration control and signature analysis and is currently working on evaluating vibration test methods for the replacement of the swept-sine test.

ABSTRACT

Aerospace structures are typically qualified for low frequency flight environments by using a swept-sine vibration test method. However, this ground testing has a tendency to produce substantial overtesting at certain frequencies. This paper presents an evaluation of the response conservatism present with a typical swept-sine and two transient vibration tests when applied to a typical spacecraft component. The absolute conservatism between a typical launch transient response and the test environment responses is measured using alternative characterizations of transient vibrations previously used in shock testing. The characterizations used include the Shock Intensity Spectrum, Shock Response Spectrum, Acceleration Root Mean Square in both frequency and time domains, and Ranked Peaks. Control of the test/flight conservatism is shown to be possible through the over-test factor (OTF) parameter.

KEYWORDS

Conservatism, overtest, vibration, test, aerospace.

INTRODUCTION

Aerospace structures are typically qualified for low frequency flight vibration environments, which are usually transient in nature, by vibrating them on a shaker table with a swept-sine wave whose amplitude and frequency are varied within specified limits, These limits are typically determined from the Fourier spectrum of the measured or assumed flight vibration at the base of the structure. A typical swept-sine test specification is shown in Figure 1, for a spacecraft component, However, such tests are known to subject the structure at some frequencies to excessive vibration levels relative to the flight levels. An overtest is then said to occur and the test is conservative to some degree because the flight level has been exceeded. Structures tend therefore to be over designed to meet this excessive vibration environment. The studies reported in this paper were concerned with the quantification and control of such test conservatism. In particular, the relative conservatism was measured between three typical test methods. The test method names denominate the vibration waveform applied to the shaker table, and were: a swept sine test, a transient-test (exact-replica of the flight transient) and an SRS-test (transient having the same shock response. spectrum as the flight transient).

CONSERVATISM

A quantitative measure of test conservatism is the index of conservatism (1OC), [1] which is a statistical measure of the amount by which the average test level C_T, exceeds the desired average test (flight) level, C_F, see Figure 2. The curves represent statistical test data means. Two points on the figure are related at any frequency by the equation:

$$IOC = \frac{\bar{C}_T - \bar{C}_F}{\sqrt{\sigma_T^2 + \sigma_F^2}} = \frac{\bar{M}}{\sigma_M} \quad (1)$$

where $\bar{C}_T$, $\bar{C}_F$ = mean values
u = standard deviation
$\bar{M}$ = mean margin of conservatism

The IOC is the ratio of the expected value of the margin of conservatism $\bar{M}$ to the standard deviation of M, σ_M. This measure of test conservatism is dimensionless and does not require a statement of the probability density functions. It has the advantage of providing a measure of the test reliability without having to assume a probability distribution for the response characteristics and is applicable to any vibration characterization. The IOC value is related to the probability of a conservative test occurring, or test reliability level (TRL) as shown in Table 1.

TABLE 1

1OC		3.0	2,0	1.0	0.0
TRL	(%)	99.9	97.9	84.1	50.0

In planning a vibration test, the teat reliability level is chosen first (l), which yields a specific IOC. This IOC is then maintained during the teat by the use of another parameter, the overteat factor (OTF), discussed below. If the field data is nominal in nature then an IOC of greater than zero would be chosen. However, if the field data is extreme and already includes conservatism, as for example when enveloping is used, then an IOC of zero would be chosen. An example of such enveloping is shown in Figure 1. The coefficient of variation k, is now defined as the variance divided by the mean for a given curve:

$$k_T \cdot \frac{\sigma_T}{CT} \quad (2)$$

This coefficient is used to develop the OTF, which is used to tailor a test to yield a specific IOC. To describe the OTF, consider Figure 2, where the desired flight characterization mean is C_F. If an initial test produces the highest curve with a mean of C_T, and if C_T is related to C_F by a constant ratio factor R, then:

$$R = \frac{C_T}{\bar{C}_F} \quad (3)$$

If we desire the test to have an IOC of I, then the teat curve will be that shown as a dashed line and the teat mean will be represented by $C_{T,I}$. The corresponding ratio factor will be :

$$R_I \cdot \frac{C_{TJ}}{\bar{C}_F} \quad (4)$$

Dividing (3) by (4):

$$\frac{R}{R_I} = \frac{\bar{C}_T}{\bar{C}_{TJ}} = OTF \quad (5)$$

Thus the OTF is the ratio of the test mean $\bar{C}_T$ to the desired test mean $C_{T,I}$ having an IOC of I. Using equation (3) the relationship for R_I from equation (1) becomes:

$$IOC = \frac{R_I - 1}{\sqrt{R_I^2 k_T^2 + k_F^2}} \quad (6)$$

where k_F and k_T are the coefficients of variation for the test and field environments. The solution for RI is thus:

$$R_I = \frac{1 \pm \sqrt{B}}{1 - Q_T^2} \quad (7)$$

where $B = (Q_F^2 + Q_T^2 - Q_F^2 . Q_T^2)$, $Q_I = k_T . I$ and $Q_F = k_T . I$

It is required that R_I assume only non-negative real numbers, therefore:

$$R_I = \frac{1 + \sqrt{B}}{1 - Q_T^2} \quad for\ Q_T^2 < 1\ for\ any\ (2_F^2\ value \tag{8}$$

$$R_T = \frac{1 - \sqrt{B}}{1 - Q_T^{2-}} \quad for\ Q_T^2 > 1\ ,\ Q_F^2 < 1 \tag{9}$$

The utility of R, is that it can be used to scale the test characterization to yield the desired OTF for a given IOC value.

Although designed for multiple test analysis in shock testing, the IOC formula can be used with singular tests without loss of generality [2]. In the tests reported herein k was assumed as 0.15 since singular tests were involved.

VIBRATION CHARACTERIZATIONS

In the application of the IOC to real test data it is necessary to choose a suitable vibration characterization for the test and flight vibration responses of the structure, The IOC is then determined for the characterization chosen. The most widely used vibration characterization has been the shock response spectrum (SRS). This is a plot of the maximum response, versus natural frequency, of a single degree of freedom damped oscillator, when subjected to a vibration waveform. Unfortunately, the SRS is not unique to its input, and tells us little about the nature of the input waveform. If one tries to replicate a flight waveform then the SRS would not be a suitable characterization to use. Other characterizations are available that more directly measure the flight waveform, as shown in references 1 and 2, that separately describe different features of the waveform, such as amplitude, frequency, energy and peak levels. Although developed and proven for shock testing, they are directly applicable to transient vibration testing due to the similarity of the waveforms. A brief description of these characterizations will be given, before they are used to compare the test methods in a later section.

The ranking of the acceleration peaks in a waveform (PKA) provides insight into the maximum peak level achieved and also the secondary peak levels achieved, Ranking means sorting and arranging in descending order of magnitude. A peak is defined as the maximum value of the waveform between zero crossings. The root mean square and average peak values may also be utilized in waveform comparisons.

The acceleration root-mean-square (RMS) in time (TRMS), provides an indication of the average signal level in time, and is defined [1] for a time duration τ:

$$TRMS(\tau) = [\ \frac{1}{\tau}\int_0^{\tau} \ddot{x}^2(t)\ \text{'d}\ ]^{1/2} \tag{10}$$

Since the TRMS is dependent on the time history length TD, it is important in comparing two test cases that they have the same time duration. When plotted against time, the TRMS amplitude represents the rms amplitude up to that instant in time,

The RMS acceleration as a function of frequency, FRMS, shows the amplitude changes occurring as a function of frequency and is defined [1] as:

$$FRMS(F)\ -\ [\ \frac{2}{TD}\int_0^{F} |\ddot{X}(f)|^2\ df\ ]^{1/2} \tag{11}$$

Where F is the frequency up to which the RMS is calculated. The FRM S graph shows the contribution to the overall RMS acceleration from all frequency components below the frequency at which the FRMS ordinate is plotted. As with the TRMS it is important to keep a consistent analysis time duration between test data when comparisons are made.

The final characterization used is the shock intensity spectrum, S1S, which for a frequency F_i is given [2] by:

$$SIS(F_i)\ =\ FRMS(F_i\ *\ \sqrt{r})\ -\ FRMS(\frac{F_i}{\sqrt{r}}) \tag{12}$$

where $F_{i+1} = F_i * r$

The constant, r is the ratio between adjacent frequency increments. The $SIS(F_i)$ ordinate value represents the contribution to the overall RMS of the transient time history by frequencies in the i-th. logarithmic frequency interval, Duration information is inherent from the calculation of FRMS for a specified time interval. As with the FRMS, similar time durations must be used when comparing S1S values for different time histories,

LABORATORY TESTING:

The objective of the laboratory testing was to measure the relative conservatism between the three test methods. The above vibration characterizations were used in this measurement for single-axis shaker tests on a dynamic mass model of a radioactive thermoelectric generator (RTG) used in recent spacecraft, Figure 3. This model has similar structural qualities to the real generator.

The predicted RTG flight lateral accelerations at the base and free end are shown in Figures 4 and 5 for one axis. It is assumed here that the flight vibration occurs predominantly in one axis and that the cross axis force and moment inputs do not significantly affect the response in the test axis. However, exact flight representation is not the primary concern here. If the RTG base is subjected to the flight transient acceleration waveform of Figure 4, it should respond at the free end as in flight, and provide an exact duplication of the flight acceleration waveform.

The three test methods used to shake the RTG on a shaker table, were a flight-transient, a swept sine and an SRS-test method. These methods provided the following controlled motions at the base of the RTG:

1. Transient flight waveform
2. Swept frequency sine waveform
3. Synthesized waveform
   (with the same SRS as the flight waveform)

The transient flight base motion is an exact replica of the flight motion shown in Figure 4, The swept sine waveform followed the profile of Figure 1, at a two-octave per minute sweep rate. The synthesized waveform is shown in Figure 6 and was derived from the vibration controller to yield the same SRS as the flight base motion of Figure 4. The IOC for each of the test methods was derived from the test response at the RTG free end relative to the predicted flight end response of Figure 5. The IOC was calculated for each of the characterizations as described below. All the plots apply to the free end response of the RTG unless otherwise stated.

PEAK RANKING

The nature of the swept sine test prevents it being compared with the other methods except by the peak ranking characterization, due to the large disparity in test times. This was caused by the two-octaves per minute sweep rate, lasting about 3 minutes. The flight transient, however is only 1 second long, as were both the transient inputs used. In fact even the PKA characterization was too unwieldy in this case for the sine sweep test so another characterization was utilized, namely the peaks-exceeded curve [3] which displays the number of peaks exceeding a specific amplitude, as in Figure 7, for all peaks. The sine sweep test predictably exhibits extremely large peaks-exceeded numbers relative to the flight data, and is therefore an extreme overtest. The peak magnitudes are also excessive with the sine sweep test, with about 400 peaks over 5.0 G's , greater than the flight maximum of 4.4 G's. The transient test characteristics are similar to those of flight, whereas the SRS-test data shows a lower number of peaks-exceeded at amplitudes below 4 G's. The corresponding IOC and OTF curves for Figure 7 are shown in Figures 8 and 9. These latter two plots are distorted at the higher amplitude-exceeded values by a zero occurrence for the flight data. In summary the transient test provides similar peak amplitude characteristics to the flight response. For flight similarity the sine sweep test needs the number of peaks exceeded to be reduced by a factor of 200. The sweep rate therefore needs to be increased to limit the number of peaks occurring. The PKA ranking and OTF for the two transient test methods are compared in Figure-s 10 and 11. As above, the SRS-test needs adjustment to increase the number of lower amplitude (low ranking) peaks.

The maximum peak amplitudes experienced during the tests are shown in table 2.

TABLE 2

Condition	Maximum Peak (G)
Flight	4.4
Transient test	5.5
SRS test	5.25
Sine sweep test	12.6

TRMS: The RTG responses for the SRS and transient tests are. compared to the flight response in Figure 12. The transient test provides undertest for the total test duration, and only provides a reasonable representation of the flight transient after 0.4 seconds. This is reflecting in the IOC and OTF plots of Figures 13 and 14. A doubling of the transient-test amplitude is required to meet the IOC of 1 during the first half of the test period, The SRS test however, provides both overtest and under-test during the test duration. An overtest occurs from 0.1 -0.4 seconds with a noticeable peak at 0.2 seconds. The SRS test input waveform therefore needs reshaping for a good flight representation.

SRS: The SRS characterization plots are shown in Figure 15, where both the SRS and transient test show undertest relative to the transient test, at the lower frequencies. The 10C and OTF plots of Figures 16 and 17 show how both tests require increased amplitudes in the lower frequency region. Both the transient and SRS-test require an approximate. doubling of amplitude at the lower frequencies, and a 30% reduction at the higher frequencies.

FRMS: The FRMS characterization plots are compared in Figure 18. The corresponding IOC and OTF plots are shown in Figures 19 and 20. Both the transient and SRS-test provide undertest through most of the frequency range and require corresponding amplitude increases. Both tests need about a doubling in amplitude in the lower frequency regions. Neither test method supplies the large amplitude increase needed at around 35 Hz. to duplicate the flight data. This frequency disparity is clearly shown in the Fourier spectrum (FFT) of the test methods in Figure21,

S1S: The undertest occurring with the test methods in the 35 Hz, region is also clearly visible in the S1S characterization plot of Figure 22. A lot more energy is required with the SRS and transient test in the lower frequency ranges. The IOC and OTF plots are shown in Figures 23 and 24. It should be noted here that there is an apparent overtest in the 90-100 Hz. region in the IOC and OTF plots, in direct contrast to the S1S spectrum, Figure 22. This appears to be due to the minimal flight amplitudes in the same frequency range, which substantially distort the IOC and OTF plots, It would therefore, appear desirable to place a limit on the IOC and OTF plot values when the originating characterization drops below some threshold, to prevent excessive adjustment of the test waveform.

The IOC and OTF values vary significantly for the different characterizations. The tester must decide which aspect of the flight waveform needs to be reproduced in test. The appropriate characterization would then be used to adjust the input test amplitude to obtain the desired IOC and OTF values.

CONCLUSIONS

The relative conservatism achieved between the transient, SRS-test and sine sweep test methods has been compared using the peaks-exceeded characterization, The sine sweep test has been shown to provide excessive overtest relative to the number of response peaks above specified levels.

The relative conservatism achieved between the transient and SRS test methods has been compared using the following characterizations: time and frequency RMS (TRMS and FRMS), shock intensity spectrum (S1S), shock response spectrum, and ranked peaks. An index of conservatism (IOC) and an overtest factor (OTF) plot has been created for each transient characterization.

It has been indicated how the test method amplitudes can be tailored to provide. desired amounts of overtest by using the IOC and OTF parameters.

ACKNOWLEDGEMENTS

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3. C. M, Harris and C. E. Creole, 'Shock and Vibration Handbook", McGraw-Hill, Inc. 1961, Volume 2, p23-21.

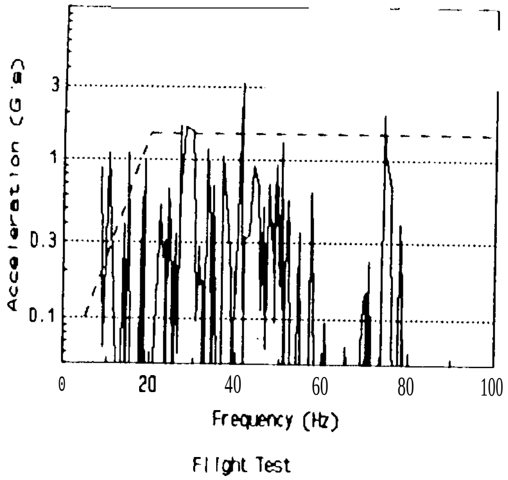


Figure 1 - Swept Sine Test/Flight Levels

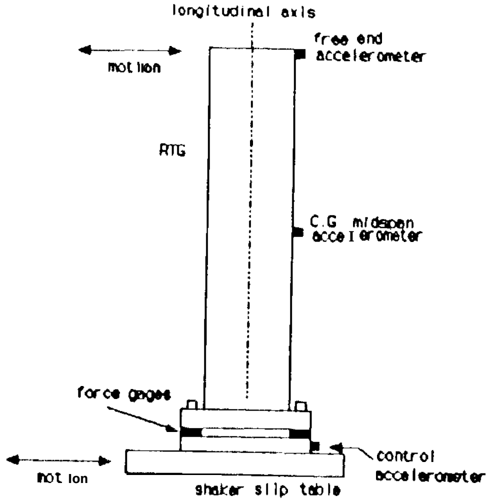


Figure 3 - CET RTG Installation on Shaker Slip Table

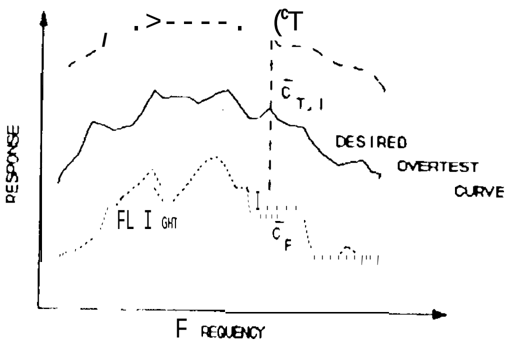


Figure 2 - IOC and OTF from Test/Flight Data

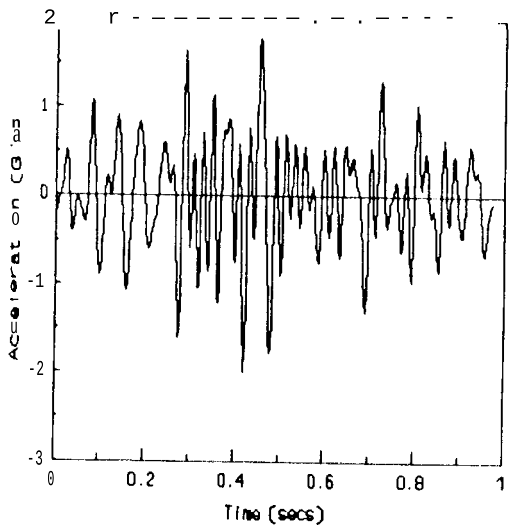


Figure 4- RTG Base Flight Motion

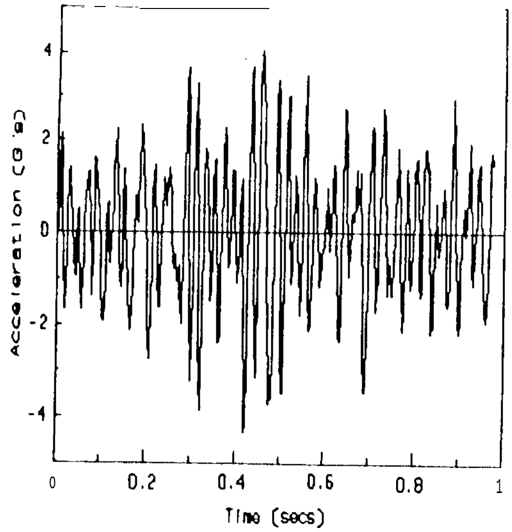


Figure 5- RIG Free End Flight Response

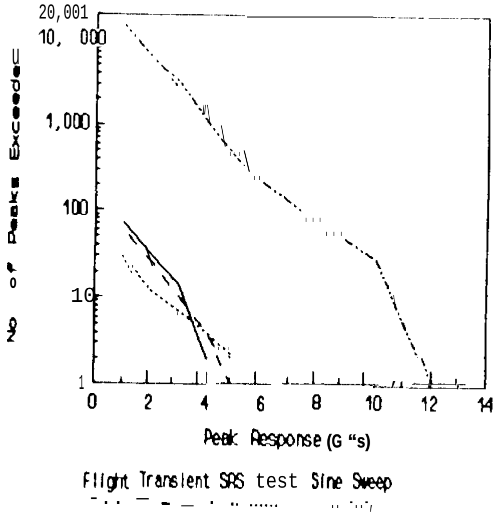


Figure 7- Peaks Exceeded Plot (All peaks)

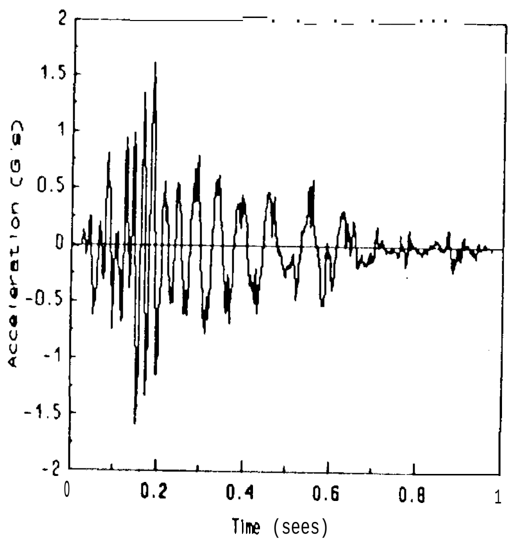


Figure 6- RIG Base Input - SRS-test

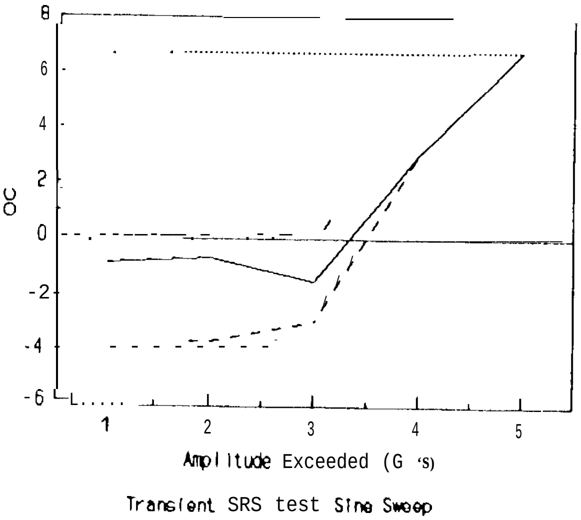
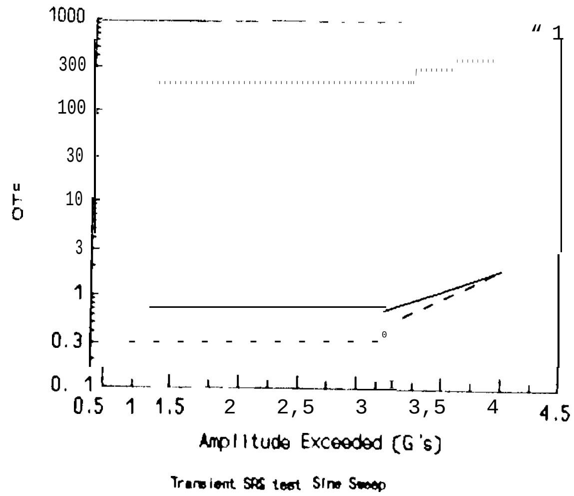
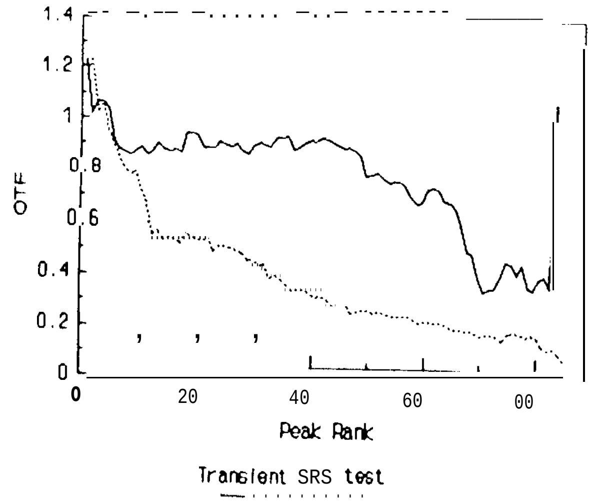


Figure 8 - IOC Peaks Exceeded



IOC = 1

Figure 9- OTF Peaks Exceeded



IOC = 1

Figure 11 - OTF - for PKA (All peaks)

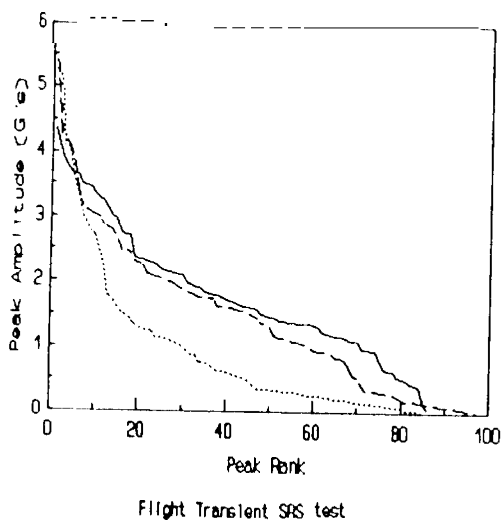


Figure 10 - PKA (All peaks)

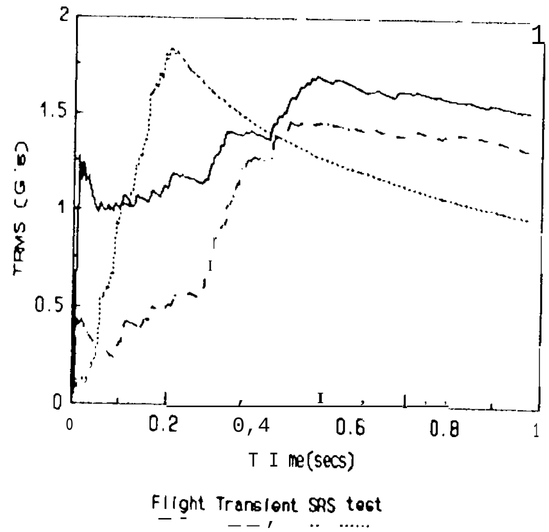
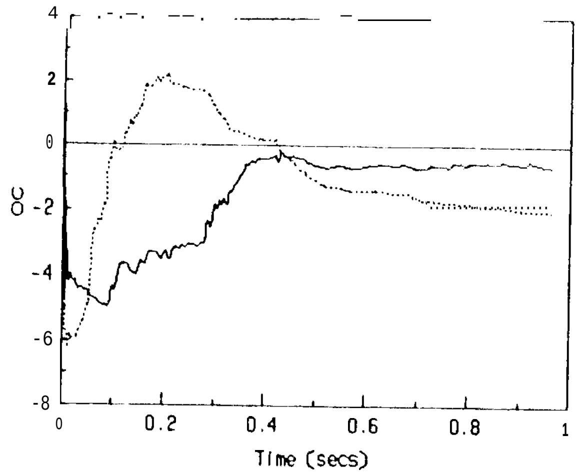
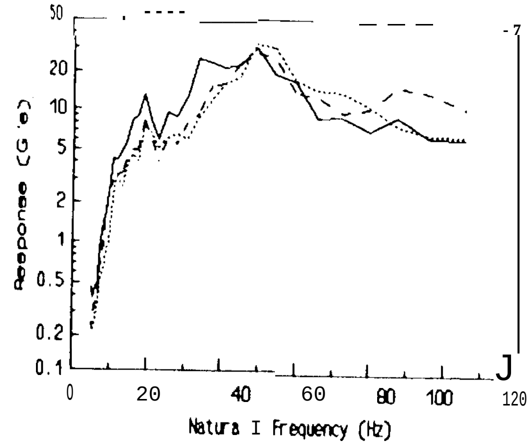


Figure 12 - TRMS Response Characterization



Transient SRS test

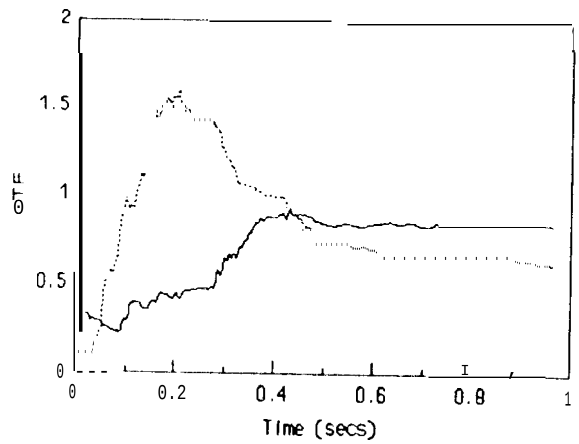
Figure 13 - IOC for TRMS Characterization



Flight Transient SRS test

DR = 003

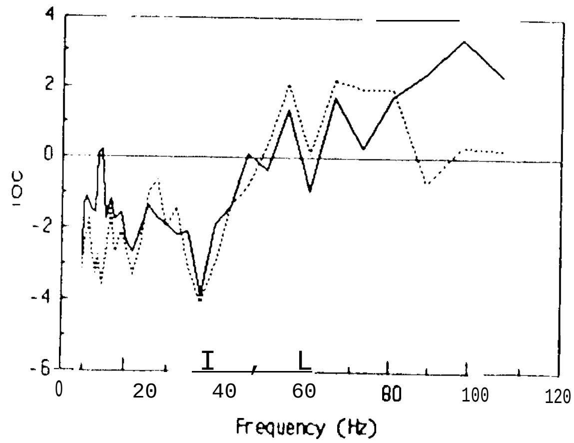
Figure 15- SRS Response Characterization



Transient SRS test

IOC = 1 td= 1.0

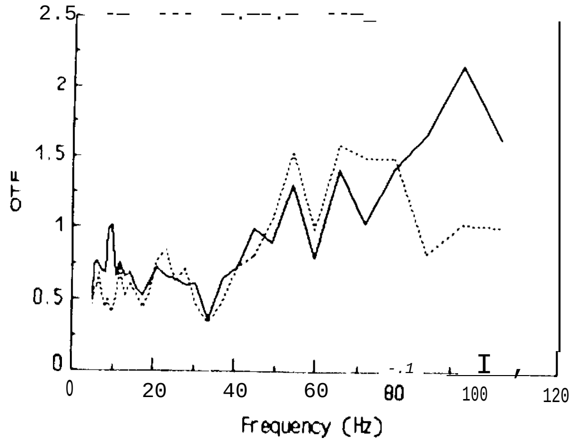
Figure 14 - OTF for TRMS Characterization



Transient SRS test

DR = 0.03

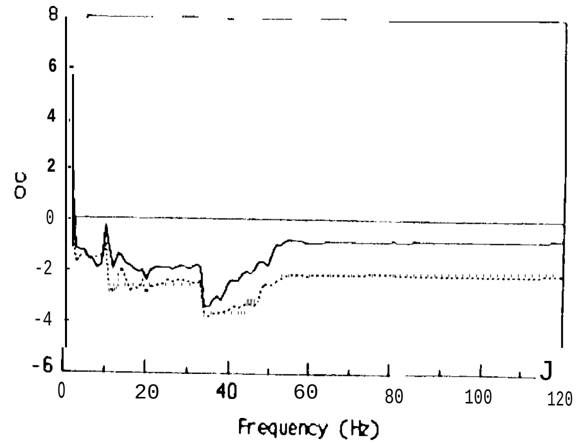
Figure 16 - IOC for SRS Characterization



Transient SRS test

IOC = 1

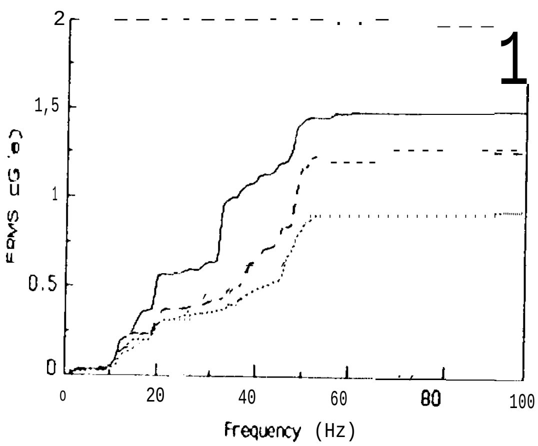
Figure 17 - OTF for SRS Characterization



Transient SRS test

td= 1.0

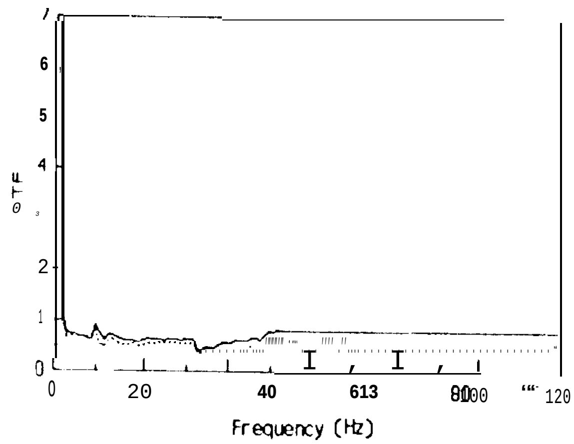
Figure 19 - IOC for FRMS Characterization



Flight Transient SRS test

td = 1.0

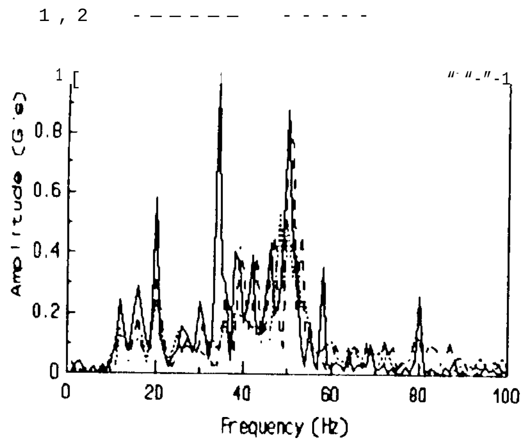
Figure 18 - FRMS Response Characterization



Transient SRS test

IOC = 1 td= 1.0

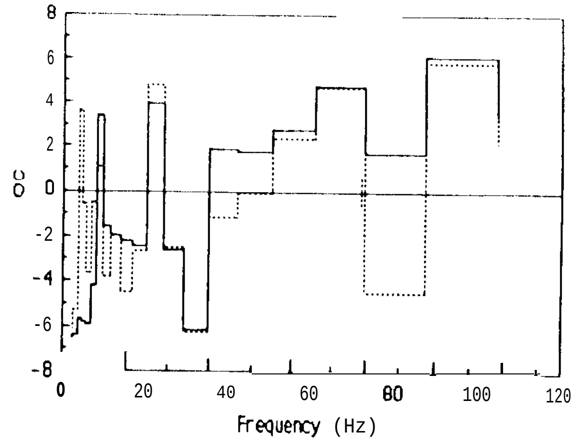
Figure 20 - OTF for FRMS Characterization



Flight Transient SRS test

td = 1.0

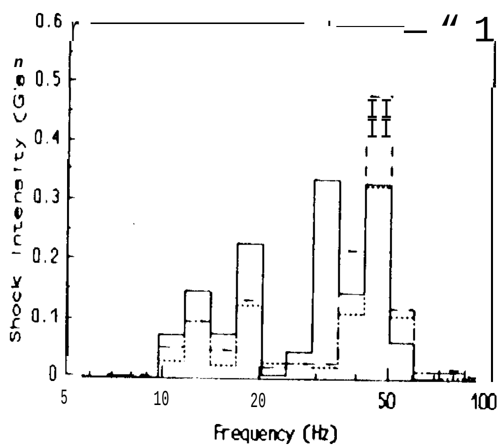
Figure 21 - FFT of Response



Transient SRS test

td = 1.0

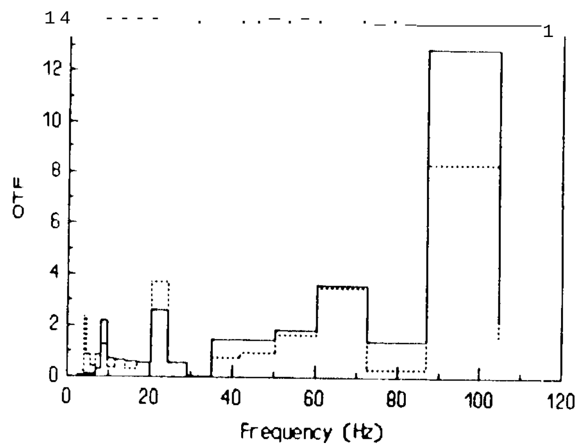
Figure 23 - IOC for SIS Characterization



Flight Transient SRS test

td= 1,0

Figure 22- SIS Response Characterization



Transient SRS test

IOC = 1 td = 1.0

Figure 24 - oTF for SIS Characterization