CONTROLLING CONSERVATISM IN TRANSIENT VIBRATION TESTS

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BIOGRAPHY

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ABSTRACT

Transient vibration tests were performed on a typical aerospace flight component to demonstrate that a specific test conservatism could be obtained by simple amplitude tailoring of the transient test waveform. The absolute conservatism between a typical launch transient and the test environment responses was measured using alternative characterizations previously used in shock testing. The characterizations included peak ranking, and acceleration root mean square in both the frequency and time domains. Test responses were. also compared using their shock response spectra and shock intensity values. It was shown that a simple average of the overtest factors in the four characterizations could be used to adjust the achieved test conservatism.

KEYWORDS

Conservatism, overtest, vibration, test, tailoring.

INTRODUCTION

Vibration tests are normally carried out to demonstrate the ability of spacecraft components and assemblies to survive, the mechanical vibrations experienced during their launch vehicle flight. These tests are typically performed with a test vibration environment applied to a shaker table that is different from the actual environment. For example, a swept sine vibration test is carried out at some amplitude chosen to envelope the flight environment maxima over a prescribed frequency range. A common alternative to this is a random vibration test where the test environment is a random vibration whose amplitude, spectrum envelopes that of the flight environment. Force control of the shaker table may also be superimposed on these test methods to alleviate the extreme overtest[1] at the structural anti-resonances of the test component. This overtest needs to be controlled so that the spacecraft component is built to survive only the actual flight environment stresses plus a prescribed safety margin. Experiments were therefore made with a transient test method with the goal of achieving a predetermined level of test conservatism relative to the flight environment for a typical aerospace component. This transient test utilized a reproduction of the predicted flight transient waveform on the shaker table. The level of over-test measured for this transient test was used to modify, or tailor, the transient waveform amplitude to that needed to produce the predetermined level of conservatism. The tailored transient waveform was then applied to the test article and the resulting level of overtest compared to the unity value of overtest (no-overtest condition) for the predetermined level of conservatism.

CHARACTERIZATIONS

The conservatism of the test was measured using four characterizations. The traditional shock response spectrum (SRS) characterizes the test response waveform in terms of the maximum response of a single degree of freedom (SDOF) system, and is used here for comparison with the other characterizations. These other characterizations were developed [2] for shock time histories and describe. the salient features of the test waveform itself rather than it's effect on an elastic system.

The root mean square (rms) in time (TRMS) provides a measure of the response amplitude in time, and is described by the equation:

$$TRMS(\tau) = \left[\frac{1}{\tau}\int_{0}^{\tau}\ddot{x}^2(t)\,dt\right]^{1/2}, \quad 0 \le \tau \le TD \qquad (1)$$

The time interval τ, is less than the analysis time duration, TD.

The rms in frequency (FRMS) describes the frequency content of the response time history, and is given by:

$$FRMS(F) = \left[\frac{2}{TD}\int_0^F |X(f)|^2 \, df \right]^{1/2} \quad (2)$$

A plot of FRMS measures the contribution to the overall RMS acceleration by all frequencies below the frequency F, for the duration TD, of the. transient time history. $\ddot{X}(f)$ is the Fourier transform of the acceleration X(?).

The peak ranking (PKA) characterization provides a description of the actual peak values and their ranking distribution in a response. time history. This has the advantage of showing secondary peak magnitudes as well as the greatest response peak magnitude displayed in the SRS. These four characterizations provide useful descriptors of the. teat response in terns of overall response magnitude in both time and frequency.

CONSERVATISM INDEX

The test conservatism is quantified by the index of conservatism (IOC), see reference [2], which is defined by:

$$IOC = \frac{\overline{C}_T - \overline{C}_F}{\sqrt{\sigma_T^2 + \sigma_F^2}} = \frac{\overline{M}}{\sigma_M} \quad (3)$$

where $\overline{M}$ is the. mean margin of conservatism and $\overline{C}_T$ and $\overline{C}_F$ are the mean transient characterization values for the test (T) and flight (F) environments, and σ_M, σ_T, and σ_F are the corresponding standard deviations. In practice several teats would be run and characterized. An averaged characterization would then be generated together with the above statistics. The IOC measures the probability of achieving an overtest given the statistics of the test and flight environment characterizations. For instance IOC values of zero, one and two correspond to 50, 84.1 and 97.9 percent probability that an overtest will occur.

OVERTEST FACTORS

The IOC quantifies the. probability of an over-test but not the amount of overtest. This quantitative information is provided by the over-test factor (OTF) described in reference [3]:

$$OTF = \frac{\overline{C}_T}{\overline{C}_{T,I}} \quad (4)$$

where $\overline{C}_{T,I}$, is the mean characterization of the test data which produces the desired IOC value of I. The OTF defines how many times greater the actual mean teat characterization, $\overline{C}_T$, is than the mean test characterization, $\overline{C}_{T,I}$, having an index of conservatism of I. If one assumes a constant ratio between the test and flight environments them:

$$R = \frac{\overline{C}_T}{\overline{C}_F} \quad (5)$$

and:

$$R_I = \frac{\overline{C}_{T,I}}{\overline{C}_F} \quad (6)$$

The IOC is then expressed as:

$$I = \frac{R_I \overline{C}_F - \overline{C}_F}{\sqrt{\sigma_F^2 + \sigma_T^2}} = \frac{(R_I - 1)}{\sqrt{k_F^2 + R_I^2 k_T^2}} \quad (7)$$

where k_F and k_T are the coefficients of variation for the flight and test environments, respectively. Equation (7) can be solved for R_I, and the OTF is found using equations (5) and (4). The utility of the OTF is seen by the. following logic. Assuming the test response, $\overline{C}_T$ is linearly proportional to the waveform amplitude applied to the shaker table, $\overline{A}_T$, one may write:

$$OTF = \frac{\overline{C}_T}{\overline{C}_{T,I}} = \frac{\overline{A}_T}{\overline{A}_{T,I}} \quad (8)$$

or:

$$\overline{A}_{T,I} = \frac{\overline{A}_T}{OTF} \quad (9)$$

The initially applied shaker waveform amplitude can therefore be adjusted or tailored to provide. the desired test conservatism by dividing it by the OTF. This is a simple ratio applied to the characterization amplitude throughout it's abscissa range. The initial shaker amplitude is thus treated like a calibration run providing the test response sensitivity coefficients. in this manner the applied transient waveform can be tailored for the originally specified conservatism I.

TESTING

Tests were run in order to assess the efficiency of equation (9) in tailoring a transient test waveform on a typical aerospace component. The test component used was a component evaluation test, radioisotope thermoelectric generator (CET-RTG), which was mounted on a shaker slip table as shown schematically in Figure 1. The CET-RTG is a dynamic mass model of a complex structure with internally clamped heat sources and multi-foil insulation, with a natural trending, frequency near 45 Hz. A real RTG would experience the predicted transient flight vibration waveform of Figure 2, which was applied laterally to the CET-RTG base by the shaker slip table.. The test conservatism was calculated for the free end lateral response of the CET-RTG relative to that of the flight response of Figure 3, The test data were analyzed with a time duration of 1,0 second. The digital sampling rate for all test response measurements was 512 samples per second. This provided a reasonable compromise between the need to obtain frequency resolution up to 100 Hz,. and the need for reasonable peak descriptions of the data. The test data was bandpass filtered between 10 and 100 Hz before the characterizations were made.

TEST TAILORING

Equation (9) is in a strict sense a function of the characterization abscissa. For example if a characterization is a function of frequency, F, then equation (9) would be written as:

$$\overline{A(F)_{T,I}} = \frac{\overline{A(F)_T}}{OTF(F)} \tag{10}$$

This would require modification of the frequency content of the original transient. The required transient test input could be obtained by adjustment of the response. characterization and transformation thereof back into the time domain. The resulting transient however, would not resemble the flight transient waveform. in order to retain the physical significance of the test transient test input waveform, the variation of OTF with the characterization's abscissa is eliminated by simple averaging over the abscissa range of interest. Equation (9) is then applicable by simple adjustment of the test input waveform magnitude. The flight transient waveform is therefore retained in it's original time history format. For this work, further liberties were taken with equation (9), wherein the average OTF value used was the average. of the PKA, TRMS, SRS and FRMS characterizations. This was an attempt to obtain a tailored test waveform that maintains a reasonable OTF for all of the. test response characterizations.

TRANSIENT OTF

The transient of Figure 2 was applied five times to the CET-RTG and the free end response characterized, for each application, using the four characterizations mentioned above. Since the original flight test transient had a maximum acceleration of -2g, it is referred to as the 2g transient test, to distinguish it from the. tailored transient test having a maximum amplitude of -2.9g. The flight response characterizations were assumed to have a constant coefficient of variation of 0.15, which would represent a reasonable distribution of measurement errors. Figures 4, 5, 6, and 7 show the averaged. PKA, TRMS, SRS and FRMS characterizations for the test transient response alongside those of the. flight response. The corresponding OTF's for an IOC of 1,0, are shown in Figures 8, 9, 10, and 11. This IOC value represents a reasonable, degree of conservatism that would be sought in a component vibration test. The abscissa-averaged OTF's for these characterizations are. shown in Table 1, together with the overall 4-characterization-averaged OTF values. Although the prescribed test transient duplicates a flight environment, waveform reproduction errors in the vibration control system caused considerable undertest.

TABLE 1 - Average Over-test Factors
2g Transient Test

	Characterization			Overall
PKA	TRMS	SRS	FRMS	Average.
0.78	0.61	0.79	0.69	0.72

TAILORED OTF

The tailored test amplitude input to the CET-RTG base, to achieve an ideal OTF of 1.0, was calculated by dividing the. test input amplitude of 2g by the characterization averaged OTF of Table 1. To better represent the measurement errors present this overall average should be quoted to only one significant figure and was therefore reduced to 0.7 for calculating the tailored transient test input amplitude of -2.9g (-2g/0.7). The resulting tailored test waveform is that shown in Figure 12, an amplified version of Figure 2, over the same time duration. Further tests were conducted using this tailored amplitude waveform and the responses referred to by the expression: 2.9g transient test. The CET-RTG was therefore retested with the. waveform of Figure 12. applied to it's base five times. The averaged characterizations for the tailored CET-RTG responses are shown in Figures 4 through 7 together with the original 2g transient characterizations. The. corresponding OTF plots are shown in Figures 8 through 11 for an IOC of 1.0. The time averaged achieved test responses for the CET-RTG base and free end are shown in Figures 13 and 14 for comparison with the prescribed flight responses of Figures 2 and 3. It should be noted that these achieved waveforms differ from the. prescribed waveforms due to reproduction errors (about 9%) in the vibration controller system.

PEAK RANKING

The peak ranking of the test responses (Figure 4) shows how the original flight transient undervests for the higher ranked peaks and provides a reasonable simulation for the lower ranked peaks. This is reflected in the OTF of Figure 8 where the data statistics reveal undertest for most of the peak ranks and an abscissa-average of 0.78. The tailored 2.9g test produces a generally conservative. response and has an abscissa averaged OTF of 1.1. The tailored test therefore produces on average a 10% overtest over all peak ranks.

TRMS

The TRMS characterization is shown in Figure 5, where the 2g transient provides undertest throughout the transient test time.. The corresponding OTF curve of Figure 9 shows an average, OTF of 0.61 representing considerable undertest. The tailored test overtests initially and provides a time. averaged OTF of 0.91. The tailored test therefore provides a more accurate representation of the flight time history amplitude environment.

SRS

The SRS for the. 2g test is shown in Figure 6, where under-test is evident at all frequencies apart from the resonant frequency around 45 Hz. The OTF curve of Figure 10, shows undertest below 60117., and an averaged OTF of 0.79 is produced. The tailored 2.9g test produces an SRS slightly larger in amplitude than the 2g test, with an averaged OTF of 0.99, an almost perfect test.

s]

The shock intensity (S1) characterization represents the area under the SRS curve and the S1 values are indicated for each test response in the SRS characterizations of Figure 6. Conservatism has not been applied to this characterization but it can be used as an absolute gage of test to flight shock intensity equivalence, without any statistical significance. If one takes the ratio of test S1 to flight S1 then one has a crude measure of the test to flight shock intensity ratio as in table 2 below.

TABLE 2 - Test and Flight Shock Intensity (S1)

		Test /Flight
Flight	850	
2g Transient	72.3	0.85
2 .9g Transient	893	1.05

Thus the tailored transient better replicates the flight response shock intensity, than the original 2g transient test response, and comes within 5 % of duplicating the flight shock intensity.

FRMS

The FRMS characterization is shown in Figure 7, where the 2g transient undertests for the complete frequency range. The OTF curve of Figure 11 reflects this with an averaged OTF of 0.69. The tailored 2.9g test provided a comparable FRMS to that of flight with an averaged OTF of 0.89. The. tailored test therefore produced on average a closer replication of the flight environment in the frequency domain than the original transient test.

AVERAGE OTF

The average OTF values achieved for the two transient tests are shown in Figure 15, for the characterizations used. These averages are pure arithmetic averages over the abscissa range of the characterizations. They are also shown in Table 3 below. The average OTF for the tailored 2.9g test response over the four characterizations shown is 0.97. The tailored transient test therefore. came very close to providing an ideal test (OTF = 1.0) for an 10C of unity. The 2g transient test values are shown to have an average OTF of 0.72. The original transient test may be considered as a calibration test, since it was used to establish the increased magnitude transient waveform from the originally specified transient test results.

TABLE 3 - Average Overtest Factors
2g and 2.9g Transient Tests

	--------- Characterization ---------				Overall
TEST	PKA	TRMS	SRS	FRMS	Average
2.9g	1.1	0.91	0.99	0.89	0.97
2g	0.78	0.61	0.79	0.69	0.72

Another approach to the data analysis involved the use of a time averaged version of the test response together with a constant value of0015 for the test coefficient of variation. The OTF curves were not significantly altered as evidenced by the average OTF plot of Figure 16. A good approximation of test conservatism could therefore be obtained with only one test response time history compared to the singular flight time history, as in reference [3].

CONCLUSIONS

It has been successfully demonstrated that by using average values of the overtest factor (OTF), a transient test waveform can be tailored in amplitude to achieve a specific index of conservatism (IOC), with controlled overtest in the test response characterizations of ranked peaks (PKA), time and frequency root mean square (TRMS and FRMS), and shock response spectrum (SRS).

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3. T. J. Baca and 'T'. D. Blacker, "Relative Conservatism of Drop Table. and Shaker Shock Tests". The Shock and Vibration Bulletin 56 (part 1 of 3), pp.289-298, August 1986.

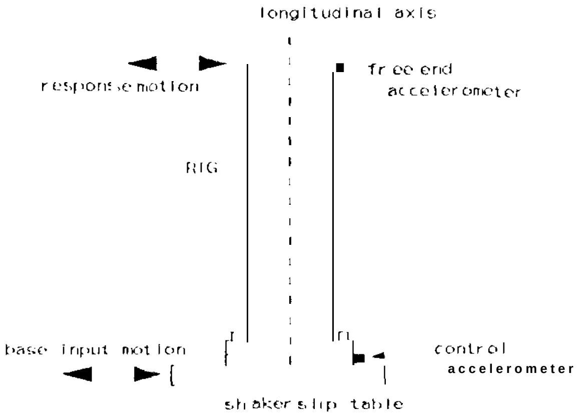

Figure 1 - CET-RTG on Shaker Table

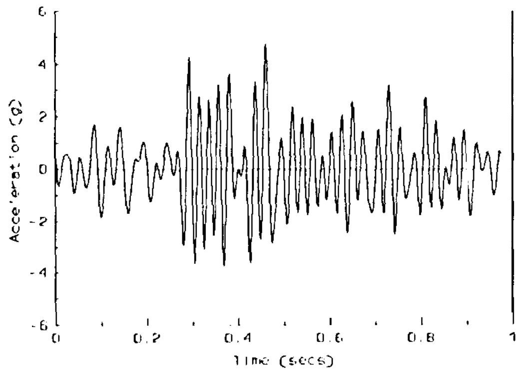

Figure 3- Predicted RTG Flight End Response

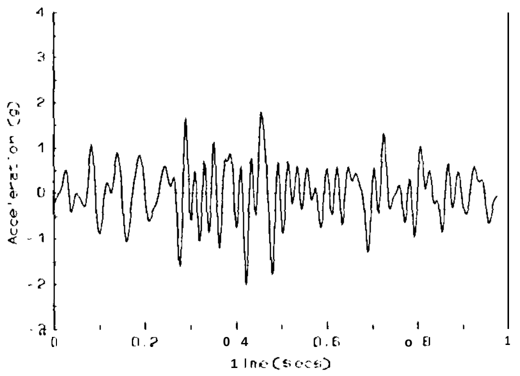

Figure 2- Predicted RTG Flight Base Response

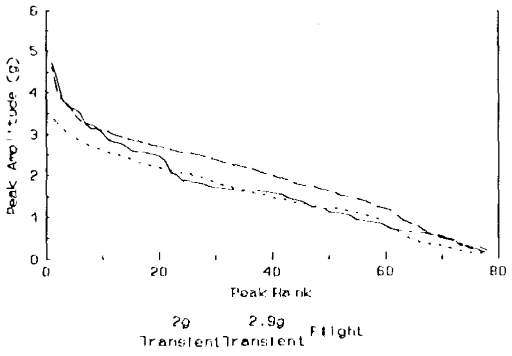

Figure 4- PKA(-1 /-) of End Response

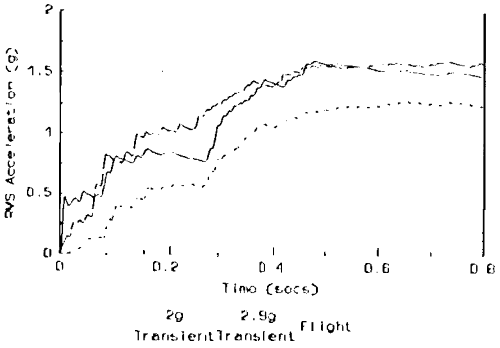

Figure 5- TRMS of End Response

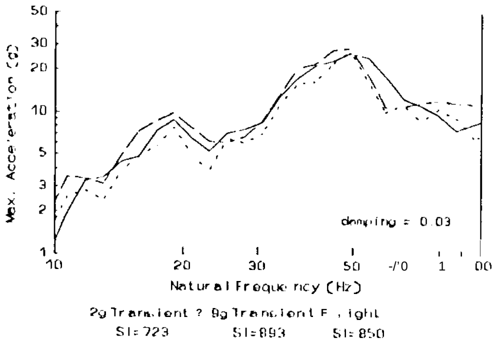

Figure 6- SRS of End Response

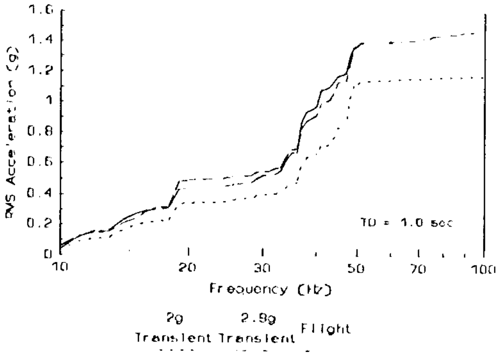

Figure 7 - FRMS of End Response

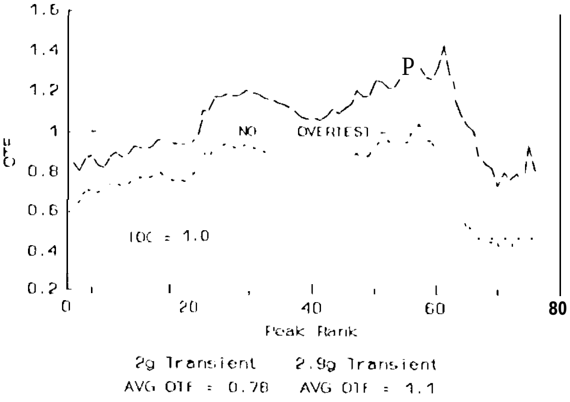

Figure 8 - OTF (PKA +/-) End Response

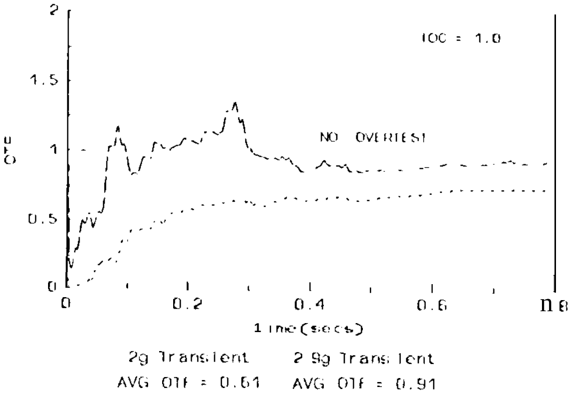

Figure 9 - OTF (TRMS) End Response

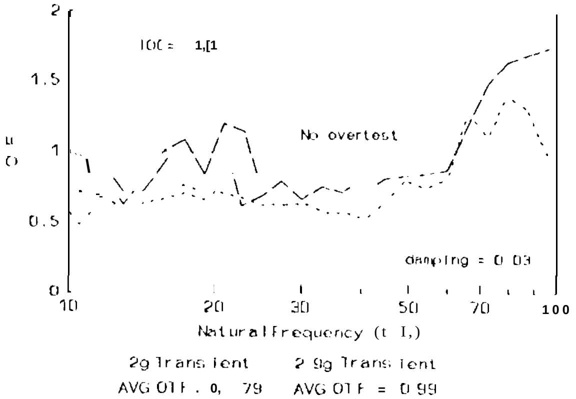

Figure 10- OTF (SRS) End Response,

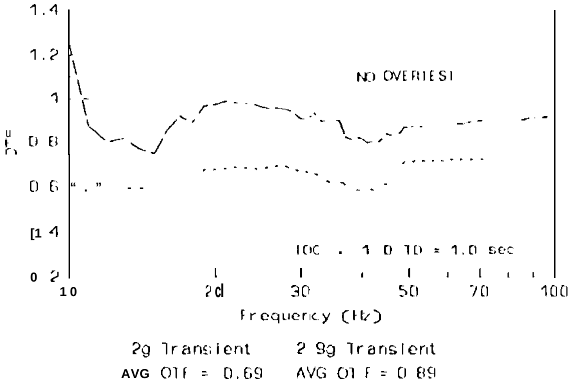

Figure 11 - OTF (PRMS) End Response.

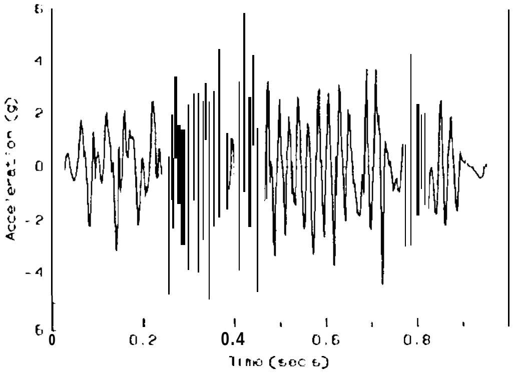

Figure 14- Averaged 2g Transient End Response

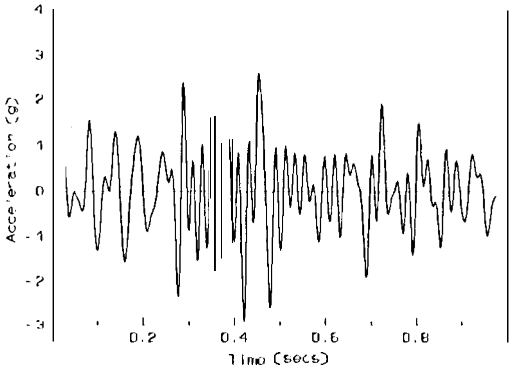

Figure 12 - Tailored 2.9g Transient Test Base input

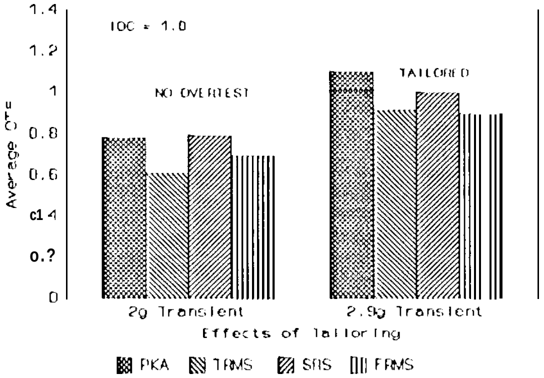

Figure 15- Tailoring Effects

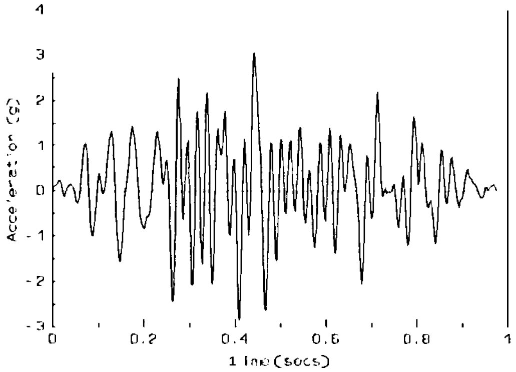

Figure 13 - Averaged 2.9g Transient Base Response

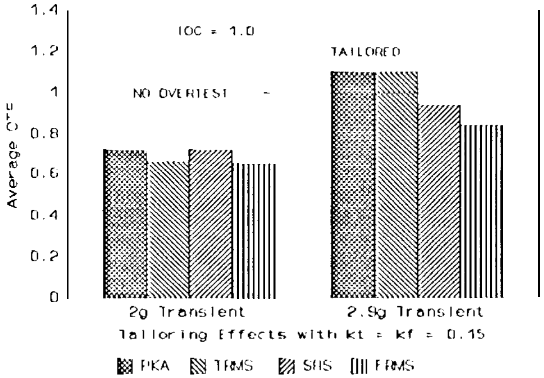

Figure 16- Constant Coefficient of Variation Assumption