6DOF machine characteristics and methods of measuring effectiveness

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With the evolution of six-degree-of-freedom (6DOF) machines used for Highly Accelerated Stress Testing (HALT), it has been suggested that traditional Power Spectral Density (PSD) and RMS analysis methods do not provide a relevant measurement of 6DOF machine effectiveness.[1,2] These machines are considered to be very effective in reducing the time needed to precipitate product defects during vibration screening as compared to typical uniaxial shakers.

No specific analysis of why PSD and RMS methods do not work for 6DOF machines has been published. Nor has a description of a method that does. This paper discusses the PSD/RMS problem and introduces a new method that gives a quantitative measure of how a 6DOF machine accelerates the screening process. This method is based on accepted principles of measuring the accumulation of stress fatigue.

The 6DOF machine has found an important role in areas such as HALT or HASS (Highly Accelerated Stress Screens) as proposed by Hobbs.[3,4] There has been little published on successful applications of these processes until recently.[5] This does not mean that successful applications of HALT and HASS do not exist; recent presentations prove otherwise.[6,7]

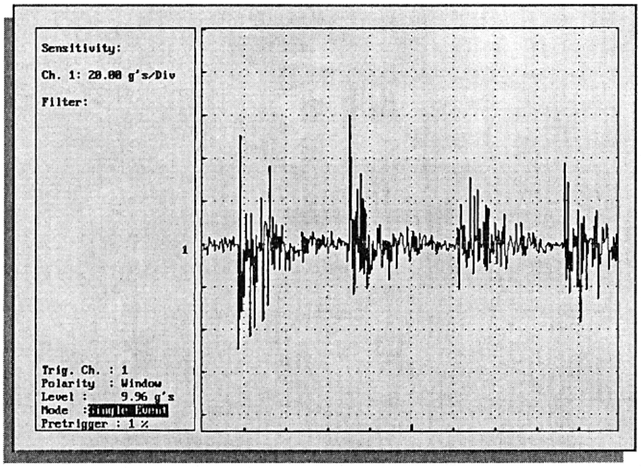
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FIG. 1—Expanded time domain history of 6DOF machine showing individual hammer impacts. Only two of nine hammers were running for this figure.

6DOF machine description

Some knowledge of the operation of 6DOF machines is necessary in order to understand why contemporary spectral analysis techniques do not work. 6DOF machines are not random shakers in the classical sense. They are high-repetition-rate, damped-sine, shock-producing machines with mode-rich tables. The shocks are produced by multiple impact hammers attached to the table. The table may be solid or laminated, depending on the manufacturer. In either case, complex interactions between transmitted shock waves within the table produce 6DOF accelerations with zero net velocities and displacements.

Transmissibility/coherence studies have shown that between two locations on a 6DOF table, very low coherence between acceleration spectra phase exists, giving validity to the claim that 6DOF machines also produce three-degrees-of-freedom in addition to the translational X, Y, and Z coordinates. These are rotational accelerations about the principal axes X_r, Y_r, and Z_r. Piersol points out that multi-axis excitations need to be considered since the real-world environment is not uniaxial.[8] In addition, multi-degrees-of-freedom excitation is not easily produced by uniaxial shakers.

The unique abilities of 6DOF machines, plus a major factor to be described below, set them apart from uniaxial shakers. Single- or multi-axis electrodynamic (E-D) or servohydraulic (S-H) shakers used for ESS testing do not possess the properties of 6DOF machines and vise versa. For one thing, 6DOF machines produce very-low-velocity and displacement excitation. These characteristics are in contrast to the larger displacements available on E-D or S-H machines. Some environmental tests require large low-frequency displacements at high Gs, and for these, E-D and in particular S-H shakers excel.

Figure 1, a greatly expanded acceleration time history of a nine-hammer 6DOF machine with a only two of nine hammers running, illustrates the damped sine oscillations produced by single-hammer impacts. Over a time period of seconds, this excitation appears to be near random vibration. 6DOF machine manufacturers' proprietary features cause the repetition rate and intensity of the individual hammers to vary in a non-systematic manner, giving rise to more complex wave interactions. This is called "spectrum smearing," and gives rise to a richer, more random-like overall excitation. Smearing is also probably responsible for reducing the maximum number of high σ events per unit time through phase cancellations. This has been seen on certain 6DOF machines.

The probability density of 6DOF acceleration peaks does not conform to a normal Gaussian 3σ distribution (1σ is the standard deviation of the amplitutde distribution and is also the RMS value).

Figure 2 is a probability peak acceleration density distribution of a 6DOF machine. From this illustration, 6DOF machines are seen to have Gaussian-like distributions with extended σ tails. Some have been measured at up to 10σ or more. Compare this distribution to that of a typical uniaxial random shaker limited to 3σ, as seen in Figure 3.

Autospectral density analysis, ASD or PSD, works well with 3σ limited distributions for E-D or S-H shakers, but it fails to quantify 6DOF machines because of their high kurtosis. Kurtosis is the fourth moment about the mean and relates to the "wild" or extreme peaks that exceed a normal distribution. The process of estimating PSDs averages out the wild peak amplitudes in the data and gives only a measure of the average power density of the excitation.

Classical ESS as practiced on E-D or S-H shakers is based on Gaussian random excitation with maximum stress peak distributions of 3σ max. For these machines RMS can be directly correlated with defect precipitation results since one knows the maximum stress (from the known probability density) that will be applied. 6DOF machines, on the other hand, can produce variable magnitude probability density distributions of 10σ or more. Since these distributions are non-Gaussian, having extended σ tails, RMS as a measure will not correlate to the resulting screen failures.

The problem of RMS analysis for 6DOF machines comes down to the fact that two vibrations can have the same RMS value; for example, a pure sine wave and one with non-Gaussian high σ peaks.

As shown by Lambert, most cumulative fatigue damage is produced by stress peaks above the 2σ level.[9] Therefore, the high σ peak amplitude probability distribution of the 6DOF machine, far in excess of 2σ, have the ability to accelerate the precipitation of product defects. 6DOF machines also need a different technique to measure their effectiveness.

Analysis of 6DOF machine excitation

There are two methods that can be used for 6DOF machine analysis. The first is shock response spectrum (SRS) which has its roots in high kurtosis seismic vibration analysis, as explored by Biot, and proposed for 6DOF machines by Smithson.[10, 11] The second method is not a new concept, but has not been previously reduced to practice for 6DOF machines.

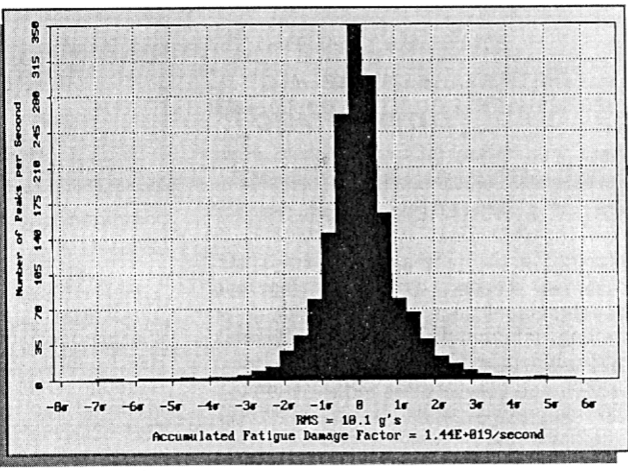

FIG. 2—Probability density distribution of acceleration peaks of 6DOF machine.

This latter method is to estimate the magnitude of an accumulated fatigue factor (AFF) per unit time of machine operation. This estimate is based on a special implementation of Miner's Rule as defined below.[12]

$$AFF=n\sigma^{b}\ (1)$$

where AFF is the accumulated fatigue factor, n is number of stress event peaks which relate to closed hysteresis loop cycles of stress, σ is the magnitude of stress and b is the negative reciprocal slope of a materials logarithmic S-N diagram, and usually has a value of from 5 to 25. For this special implementation where the goal is to compare different excitations (or machines), an assumption is made that peak mechanical stress will be proportional to peak acceleration, $f=ma$, and that for equivalency purposes, the b value will be arbitrarily chosen in the low range of 8 to 10.

This paper ... introduces a new method that gives a quantitative measure of how a 6DOF machine accelerates the screening process.

In order to implement Equation 1, it is necessary to count the stresses per unit time and their magnitudes. To do this, a form of rain-flow analysis is used.

Rain-flow analysis counts stress peaks that correlate with fully closed stress-strain hysteresis loops as defined by Dowling.[13] This count produces the probability density distributions shown in Figure 2 and 3, from the distribution, the accumulated fatigue factor, AFF, is estimated from Equation 2:

$$AFF=\sum_{n=1}^{x}(n_1\sigma_1^{b}+n_2\sigma_2^{b}+.\,.\,.\,.\,.\,n_x\sigma_x^{b})\ (2)$$

Example of AFF analysis

A walk-through of an AFF analysis comparing a 6DOF machine to a uniaxial E-D machine will show how the method is applied using real data. The first task is to obtain an acceleration history of the excitations of the machines. The monitoring point should be comparable for the two. Once the data is recorded, then the algorithm described above is used.

Figure 2 illustrates the peak acceleration (stress) probability density distribution of the 6DOF machine. The plot is scaled in peaks per second, n, as a function of increments of stress σ. The estimated value of AFF for this machine, 1.48E+19/second, is shown immediately below the distribution plot.

Figure 3 shows the results of the same analysis applied to a uniaxial random E-D shaker, again normalized to 10 Gs RMS. Note the lower values of both n, σ, and AFF of 7.00E+15/second, even though the two machines are producing the same Gs RMS. The comparative ratio of screen time reduction by one 6DOF machine as compared to another specific uniaxial E-D machine is given by the inverse of the ratios of their AFF values.

The last step is to use the AFF values taken from Figures 2 and 3, and calculate the ratio of AFFs. For this specific example, a ratio of 2,114 to 1 is obtained. Both higher and lower ratios have been measured between different 6DOF machines and between 6DOF machines and uniaxial shakers by this author.

To aid the comparison, all shaker time domain data was normalized to 10 Gs RMS. Normalization does not affect the probability distribution range, but it affects the magnitude of AFF.

With the AFF estimate, a quantitative measure of the effectiveness of excitation can be made. As stated above, one key use is estimating time reduction when performing HALT or HASS on one machine as compared to another. But more importantly, the amount and rate of stress producing excitation reaching fixture/product attachment points—or best, reaching the product itself—can be made. Because the primary spectral characteristics of 6DOF machines are the result of wave and modal interaction in the machine table, variations in excitation can be caused by loading, thermal mode shifting, or damping. By measuring AFF on the product, these changes plus damping due to intervening product structure can be quantified and taken into account.

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The SRS method, discussed by Smithson (referenced earlier), provides a *qualitative* analysis of excitation, giving us plots of static acceleration peak values as functions of excitation frequency. This is more or less a spectral peak amplitude "fingerprint" of the screen excitation. AFF gives a *quantitative* measure of the stress related accumulated fatigue rate of an excitation. Together, they are the means to develop, analyze, and later duplicate a screen, something that cannot be done with PSD or RMS analysis.

The ESS-versus-6DOF Issue

This author has noticed a large disparity in opinion between users of HALT and HASS and ESS practitioners from the military/aerospace school of thought. In the case of the latter, the term ESS has a specific definition that doesn't include intentionally taking a product to levels of stress far beyond specification or design limits. Conventional ESS is concerned primarily with failures caused by stresses in the environment in which the product must operate, regardless of its design weaknesses (hence the practice of noting ESS PSD profiles to protect weak components or to simulate a specific field environment).

In contrast, HALT and HASS's goal is to induce failures as soon as possible in the design-to-distribution cycle. This shortens time-to-market. The motivation here is purely financial. Less test time; more profit from getting to the market first with a more robust product; a higher quality product with fewer failures in the field; increased customer satisfaction and a more competitive market position. Perhaps industry can be better served if the acronym ESS is not applied to the roles of HALT, HASS, or STRIFE.

Relevance of AFF to process defects

The basis for AFF is accumulated fatigue failure of materials due to mechanical stress. The relationship of AFF to process problems such as workership is not clear. However, it has been reported by McLean that major →

assembly process, IC process, and raw board defects such as "no solder, poor wetting, intermittent solder shorts, weak parts and assembly, delamination, open traces, no plating and copper flakes," manifest themselves during high accelerated screening.[14] Intuition would say that over-stressing will cause process defects to precipitate from purely mechanical causes, as they also do in lower σ level ESS testing. But since they are not strictly related to material strain-stress failures, more study is needed to be able to quantify AFF with these types of defects.

Conclusions

6DOF machines have unique properties requiring analysis techniques other than tradition PSD or RMS. A method directly correlating stress-producing excitation with machine run time, named "accumulated fatigue factor," AFF, was developed and tested on both 6DOF and uniaxial machines. Differences in effectiveness between 6DOF machines and uniaxial shakers for accelerating stress related failures were shown to be as high as 2,114 to 1 in favor of the 6DOF machine, based on AFF analysis.

AFF analysis has direct application to shakers or exciters for HALT and HASS. Although not explored in detail for normal ESS-based testing on random 3σ limited shakers, AFF may also have application in this field. When AFF rate analysis is combined with SRS analysis, the user has a complete tool set to characterize machines, product response and screen spectral characteristics.

Acknowledgements

The author is indebted to various owners of 6DOF and random E-D and S-H shakers for the use of their equipment in the development of the AFF estimate method; to Allan Piersol for his technical advice and suggested references; to Steve Smithson and Harry McLean for their comments and editorial assistance. All analysis was performed on GHI CAT 6DOF controller and analyzer systems.

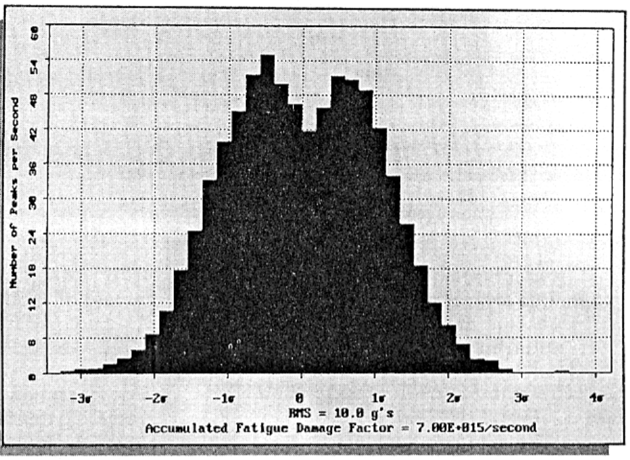

FIG. 3—Probability density distribution of acceleration peaks typical of 3X limited uniaxial shaker.

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