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Title: ACCELERATED VIBRATION TESTING—*Proceed with Caution*

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With the increasing pressure for improved reliability in all manufactured hardware items that are exposed to dynamic loads during their service life, the interest in accurate and effective vibration testing procedures to verify the durability of such items is also growing. Durability vibration tests (sometimes called qualification or design verification tests) are intended to establish that the item has a minimum desired wear-out life when exposed to the anticipated vibration environment during its service life. For many hardware items, including transportation vehicles and their components, this service vibration environment may be many thousands of hours in duration. Since vibration tests of this duration are not feasible, it is common to accelerate durability vibration tests by trading off an increased vibration level against a reduced test duration in accordance with a specific analytical damage model for the item being tested.

The most common damage model assumed to design accelerated durability vibration tests is a fatigue damage model. Metal fatigue is a complex subject that is best treated using the principles of fracture mechanics [1], but in simple terms, it can be approached using an “S-N curve” for the material in question. Specifically, if a stress load of sufficient magnitude is repeatedly applied to a structural material, a crack will ultimately form and propagate until failure occurs. An S-N curve defines the number of cycles N required to cause a failure for repeated loads producing a peak stress S. The S-N curves for many metals can be approximated by straight lines when plotted on a log-log scale, as illustrated for a typical steel alloy in Figure 1, below.

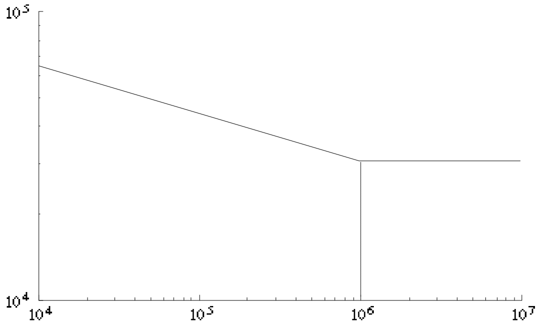

Figure 1. Idealized S-N Curve for Typical Steel Alloy.

The break to a horizontal line at N - 10^6 cycles in Figure 1 indicates there is a stress level S_e, called the endurance or fatigue limit of the material, where stress cycles with peak values below this limit will not cause damage. Many steel alloys show a well-defined endurance limit, but S-N curves for aluminum alloys generally break more gradually as N increases. Representative S-N curves for various materials are widely published; e.g., [2]. For random vibrations, S-N curves can be established in terms of the rms stress level versus number of stress maxima to failure, independent of the power spectral density (PSD) function (sometimes called the autospectral density function) of the random vibration [3]. However, the S-N curve for a given material subjected to random vibration may be different in shape from that for a constant amplitude vibration [4]. Also, a specific technique must be established to determine what constitutes a damaging stress maximum in a random vibration [5].

The above principles are the basis for designing accelerated durability vibration tests. Specifically, five assumptions are made, as follows:

(1) All wear-out failures of the test item will be due to straightforward fatigue damage mechanisms. Hence, a fatigue damage model will accurately predict the wear-out life.

(2) The test item materials have no endurance limit. Hence, the idealized S-N curve in Figure 1 can be expressed as $N = c\ S^{-b}$ where b and c are material dependent constants.

(3) The fatigue damage accumulates in a linear manner as hypothesized by Miner [6]. Hence, the damage to the test item is $D = n/N = (1/c)\ n\ S^b$ where n is the number of stress cycles applied with a peak stress S.

(4) The stress response of the test item is a linear function of the input vibration rms value, σ. Hence, the peak stress is proportional to the rms vibration, meaning $D\ \mu\ n\ \sigma^b$.

(5) The number of stress cycles per unit time during a vibration test is the same as during the service vibration environment. Hence, the number of stress cycles accumulated during the vibration test and the service vibration environment is proportional to the exposure duration T, meaning $D\ \mu\ T\ s^b$.

It follows that if a test is performed with an input vibration level of σ_t on a test item that experiences an input vibration level of σ_e in its service environment, the test duration T_t needed to produce the same damage as a service vibration environment of duration T_e is

$$T_t = T_e \, (\sigma_e/\sigma_t)^b \tag{1}$$

For random vibration tests where the test and service vibration environments have the same PSD shape [i.e., $G_t(f)/G_e(f)$ is a constant] and the same probability density function (PDF), the number of maxima per unit time will be the same. Also, PSD μ σ^2, so

$$T_t = T_e \, [G_e(f)/G_t(f)]^{b/2} \tag{2}$$

For example, given a structure with a fatigue parameter b = 8, if a sinusoidal vibration test is used to simulate a sinusoidal vibration environment with the same frequency, but the rms value of test vibration is made twice as high as the rms value of the service vibration ($\sigma_t = 2\,\sigma_e$), the test duration needed to produce the same damage as the service environment is $T_t = T_e/256$. For the same structure, if a random vibration test is used to simulate a random vibration environment with the same spectral shape and PDF, but the PSD value of the test vibration at each frequency is made twice as high as the PSD value of the service vibration [$G_t(f) = 2\,G_e(f)$], the test duration needed to produce the same damage as the service environment is $T_t = T_e/16$.

The design of accelerated vibration tests based upon Equation (1) or (2) is vulnerable to errors from a number of sources, as follows:

(1) The failure mechanism for the test item may not be fatigue related.

(2) The test item may be assembled from a number of different materials that have different values of the fatigue parameter b.

(3) Even if the test item is fabricated from a single material, the selected value of the fatigue parameter b may be inaccurate.

(4) The test vibration applied to the item may not produce the same number of stress maxima per unit time as the service vibration environment.

(5) The relationship between the input vibration level and the stress response of the test item may not be linear.

(6) For items fabricated from steel alloys, the test vibration levels may produce stresses above the endurance limit of the material, while the service vibration induced stresses are below the endurance limit.

(7) For random vibration tests simulating random vibration environments, the PDF for the test and service vibrations may not be the same; i.e., the test vibration generally is Gaussian, but the service vibration may not be Gaussian.

Problems (1) through (3) above constitute the most serious limits on the accuracy of accelerated vibration tests. The values of the fatigue parameter b for various structural materials range from 5 to 25. MIL-STD-810E [7] recommends a value of b = 6 for sinusoidal vibration tests, and b = 8 (b/2 = M = 4) for random vibration tests. Although these values are reasonable approximations for the fatigue properties of aluminum and steel alloys commonly used for structural members in transportation vehicles, they may be in substantial error for some materials in more complex test items. **In such cases, the accelerated test may produce failures that are unlikely to occur in the service environment, and/or miss failures that will occur in the service environment [8].**

For long service life transportation vehicles and their components, the service vibration environment is highly nonstationary with a brief portion of the total service life spent at extreme vibration levels, and the remainder of the service life at somewhat lower vibration levels. **In this case, the potential errors in an accelerated vibration test can be suppressed by limiting the test level to the highest vibration level experienced in the service environment,** and then adjusting the test duration to accelerate those portions of the service environment that produce vibration levels below the maximum level [9]. If this does not reduce the test duration sufficiently, then some increase in the test level beyond the highest level anticipated in the service vibration environment may be necessary, but any such increase will produce substantial uncertainties in the validity of the test results, particularly for more complex hardware items.

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