MULTIAXIAL VERSUS UNIAXIAL VIBRATION TESTING: A RESEARCH PLAN FOR COMPARISON

Wayne E. Whiteman

Department of Civil and Mechanical Engineering
United States Military Academy
West Point, New York 10996

ABSTRACT

Traditionally, vibration tests of hardware and equipment have been conducted by sequentially applying uniaxial excitation to test articles along three orthogonal axes. Simultaneous multiaxial excitation is an advanced method of vibration testing with the goal of more closely approximating real-world operating conditions. Multiaxial testing achieves the synergistic effect of exciting all resonant modes concurrently and induces a more realistic vibrational stress loading condition. The differences in fatigue failure potential and prediction between sequentially applied uniaxial and simultaneous multiaxial tests has been the subject of great debate. This paper describes a research plan to systematically investigate these differences. It starts with simple cantilever beam structures. Once these initial results are complete, more complex and typical components of hardware and equipment will be tested. This paper provides preliminary results that reveal inadequacies in traditional uniaxial test methods. It is shown that the order in which orthogonal uniaxial excitation is applied has a significant effect on fatigue failure.

NOMENCLATURE

x, y, z translational degrees of freedom/coordinates

1 INTRODUCTION AND BACKGROUND

Validating the design and reliability of hardware and equipment prior to fielding is a critical step in the material development and manufacturing process. Success of new equipment requires that it undergo and survive testing that replicates true operating environments. The reliability of on-board computers and electronics, along with other components that can endure a high level of vibration stress over an extended period, will allow systems to avoid the potential cost and consequences of catastrophic failure under real world conditions. There are numerous examples of items that have malfunctioned as a result of shipping, handling, and operating stresses. Unfortunately, this same equipment may have passed prior vibration qualification tests. There is some evidence to conclude that these failures may have stemmed from the vibration testing methods applied to the test article.

Stress screen vibration testing is product-dependent and attempts to detect defective parts that might fail in a field environment, rather than simulate the characteristics of actual field conditions[1]. The purpose of stress screen vibration is to identify flaws that escape detection by other forms of testing. These flaws are often intermittent or latent potential defects in soldering, mounting, or wiring that appear only after certain thresholds of stress are crossed. The goal is to detect these problems during testing before a product goes out and experiences a failure in the real world[2].

Traditionally, vibration tests have been conducted by sequentially applying uniaxial excitation to test articles along three orthogonal axes. In other words, the object is first vibrated up and down in the vertical axis. It is then removed from the fixture, rotated 90°, remounted, and tested in one horizontal axis. Finally, it is removed, rotated, and tested along the third remaining axis. Both MIL-STD-810E, 14 July 1989, and NAVMAT P-9492, May 1979, provide guidance and specifications for the conduct of these tests.

There are two major shortcomings of this sequential, uniaxial method. First, the time to mount, remount, set-up, and test articles multiple times can be excessive. A second, more important, shortcoming with this method is that the sensitive directions of many of the internal components of equipment being tested may not be aligned with the three orthogonal directions chosen for the test. The result is items that may pass uniaxial testing procedures but fail under operating conditions[2-5].

Ideally, laboratory tests should replicate three dimensional service environments by duplicating three dimensional time histories. This duplication is almost never achieved in practice due mainly to the variability of the service environment and differences between the test and the service installation[1]. Simultaneous multiaxial excitation is an advanced method of vibration testing with the goal of more closely approximating real-world operating conditions. Multiaxial testing achieves the synergistic effect of exciting all resonant modes concurrently and induces a more realistic vibrational stress loading condition. While MIL-STD-810E allows for tests applied along two or three axes simultaneously, to date there are no published or recognized standards.

The U.S. Army Research Laboratory at Adelphi, Maryland has a triaxial vibration test system. This system utilizes specially developed hydrostatic bearings to achieve maximum drive stiffness in each of three orthogonal directions, with minimal cross-coupling between orthogonal directions. Using specialized mechanical constraints, the test platform can generate translational motions while all uncontrolled rotations are suppressed. This system was developed to address the shortcomings in uniaxial test methods and provide a test system that more closely approximates the life cycle environment of most Army materiel. The ultimate objective of the triaxial system involves redefining vibration screening and testing procedures to properly validate the safety level of equipment, increase the efficiency of the test method, more effectively precipitate design and manufacturing flaws, and ensure the proper operation of critical components under operating conditions[3].

The problems of realistic simulation of field environments fall into two main categories: (1) properly defining the test environment to represent the expected service condition, and (2) simulating the desired environment under laboratory conditions. Defining the proper input energy spectrum is one of the most important issues in any test program. The test spectrum is selected to envelope the service spectra and the duration is selected based on an expected service life at that level. With traditional uniaxial tests, this practice typically results in conservative input levels and excessive test time due to the sequential axial test requirements as described earlier[1].

Little research has been done in systematically studying the differences between multiaxial vibration testing and single axis methods. In terms of problems defined in the previous paragraph, it is expected that multiaxial techniques may have significant advantages in defining a realistic test environment and simulating that environment in the laboratory. This current research begins an effort to explore the difference in predicting fatigue failure between sequentially applied uniaxial and simultaneous triaxial tests.

Some fatigue specialists maintain that the levels of stress caused by vibration are usually too low to contribute to fatigue damage, and that fatigue cracks start because of higher stresses present in the loading history. It is generally recognized, however, that large number of stress cycles generated by high-frequency vibration can substantially contribute to fatigue damage and in some circumstances cause failure without needing the occasional high load. Special analysis is often needed in these circumstances because the basic information about vibration is not in a form which can be used directly in a conventional Miner-type fatigue cumulative damage calculation. In spite of the fact that fatigue itself is not known to be very sensitive to frequency, tests using Power Spectral Density (PSD) to control the loading have shown a strong link between life and the PSD. Assuming a Guassian amplitude probability density distribution, the PSD fixes the peak and trough distribution of the vibration, thereby fixing the number and amplitude of motion reversals in a time-domain description of the stress history. This fact allows general fatigue life prediction from frequency-domain data[6]. The method of fatigue failure prediction in this current research effort takes advantage of these observations.

The research plan starts with simple cantilever beam structures and experimentally determines the observed differences in fatigue failure prediction. Once these initial results are complete, more complex and typical components will be tested. This report provides preliminary results that reveal inadequacies in traditional uniaxial test procedures. It is shown that the order in which orthogonal uniaxial excitation is applied has a significant effect on fatigue failure prediction.

This paper begins with a brief description of the test set-up. Procedures, results, and discussion follow. The final section contains conclusions and recommendations for future work.

2 TEST SET-UP

To begin this research effort, uniaxial random vibration excitation was applied to simple cantilever beam structures to establish a baseline for future triaxial tests. The test specimens were manufactured from 2024-T4 Aluminum. A typical specimen is shown in Figure 1. Dimensions are provided in Figure 2. A Cartesian coordinate system was introduced to denote the direction of base excitation. Aluminum was chosen since, as a nonferrous alloy, it would not exhibit an endurance limit and eventually fail in each test due to fatigue. A notch was introduced around the entire circumference of the beams to facilitate the formation of the fatigue damage mechanism under repeated loads in a consistent manner.

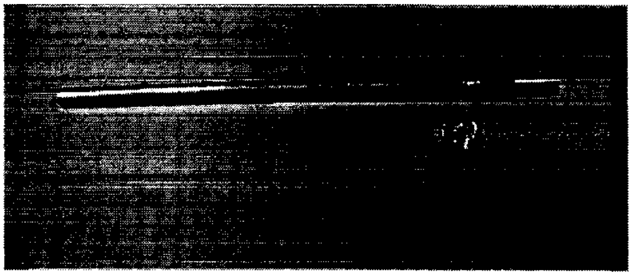

Figure 1: Typical Specimen

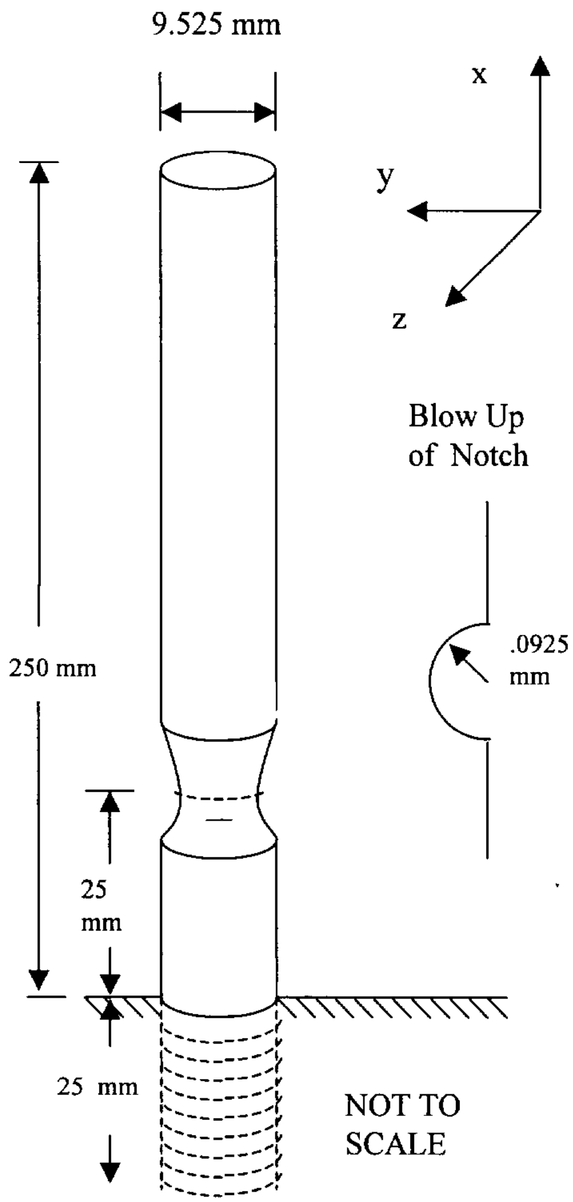

Figure 2: Specimen Dimensions

Uniaxial tests were conducted on a Model PM75C-B, MB Dynamics Shaker. The test specimens were mounted with a simple plate fixture. The excitation was controlled by a Data Physics Corporation Controller. The test set-up is depicted in Figure 3.

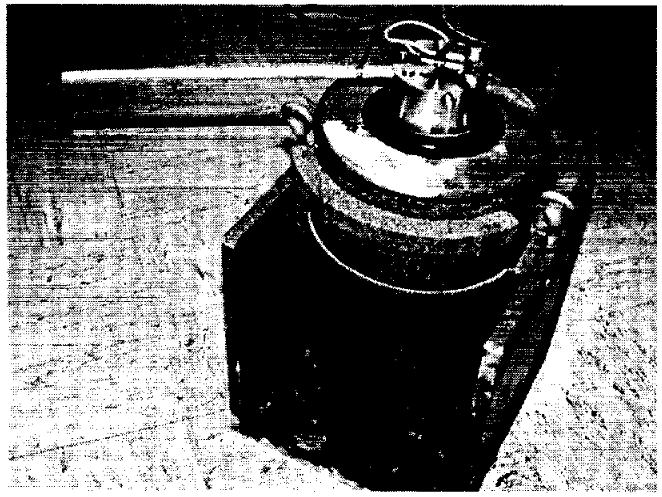

Figure 3: Test Set-Up

To enable comparisons of uniaxial test results, the same random vibration input spectrum was applied at specified input energy levels for each of the tests. Figure 4 shows the random vibration acceleration spectrum at the 4 gRMS input level.

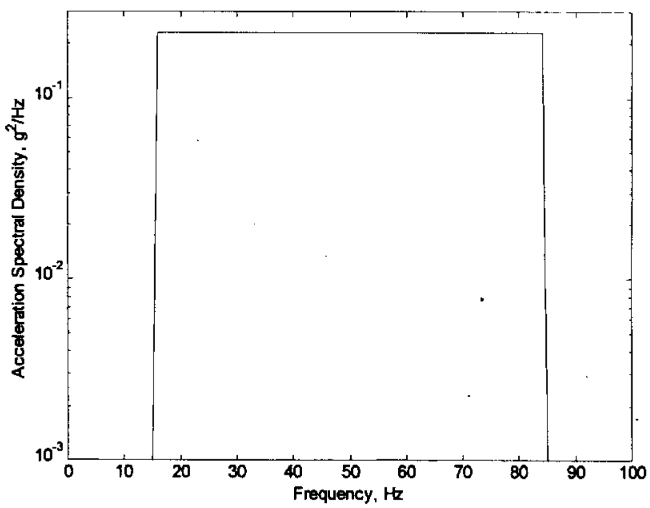

Figure 4: Random Vibration Input Acceleration Spectrum

Preliminary transverse uniaxial vibration was applied to the samples to properly scale this input spectrum so that the specimens broke in a reasonable amount of time. The fundamental natural frequency for transverse vibration was observed to shift dramatically from the onset of the tests through the formation of fatigue damage until final failure. At the beginning of the shaking sequence, the first resonant frequency was about 80 Hz. By the time complete fatigue failure occurred, the first resonant frequency had dropped to around 20 to 30 Hz. This observation motivated the decision to apply a random vibration input spectrum from 15 to 85 Hz, vice a simple sinusoidal input at a particular frequency.

3 PROCEDURES, RESULTS, AND DISCUSSION

Initial tests were completed for transverse uniaxial vibration. Base excitation was identical in the y or z direction as shown in Figure 2. For the first set of tests, specimens were excited until complete fatigue failure in the transverse, or y (or z) direction. Results were plotted to show the input spectrum gRMS level on the ordinate axis and time to failure on the abscissa. The resulting plots are analogous to typical fatigue strength life diagrams or S-N curves. It has been proven that the stress response of a structure under dynamic loading is directly proportional to the velocity response[7-9]. Likewise, under random vibration, it can be shown that the stress spectrum is directly proportional to the velocity, and hence acceleration, spectrum[10]. The time to failure under random excitation is directly proportional to the number of cycles to failure[6].

Figure 5 is a plot of seven samples tested with transverse uniaxial excitation in the y (or z) direction at both the 3.5 and 4.0 gRMS input level. The data is consistent with expected simple fatigue tests. The time to failure increases at lower input energy levels.

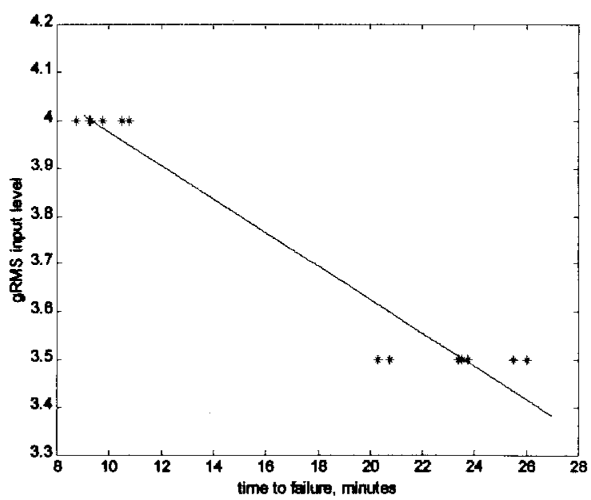

Figure 5: Uniaxial Results for Excitation in the Transverse Direction Only

A similar procedure was repeated for the second set of tests except, in this series, the specimens were excited first in the axial, or x direction for the previously determined time to failure followed by excitation in the transverse, or y (or z) direction until complete failure. This allowed comparison to the previous uniaxial results for excitation in the transverse direction only.

Based on the results shown in Figure 5, the initial excitation in the axial, or x direction for this second series of tests was chosen to last 10 minutes at the 4.0 gRMS level and 20 minutes at the 3.5 gRMS level. As expected, the specimens did not fail since they were excited well below the natural frequency in the axial direction.

Now, using these same specimens, the tests were applied in the transverse, or y (or z) direction until complete fatigue failure. Figure 6 shows the results for excitation in the axial, or x direction followed by the transverse, or y (or z) direction as compared to the previous series of tests for excitation to failure in the transverse, or y (or z) direction only.

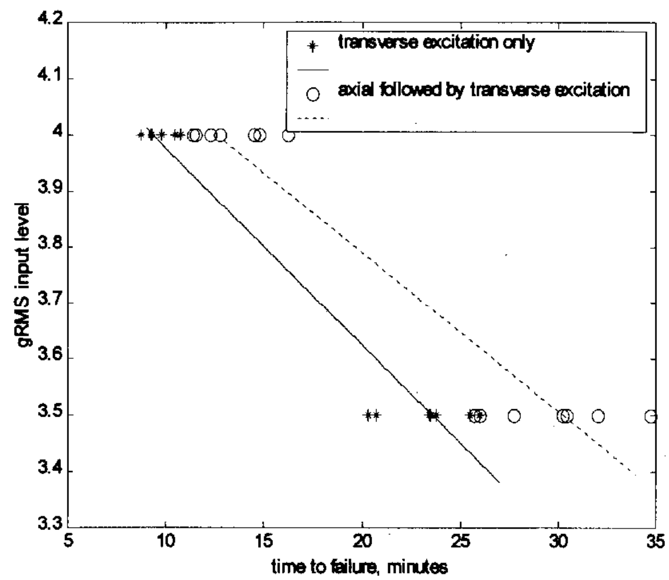

Figure 6: Uniaxial Results for Excitation in the Axial followed by Transverse Direction

These results were quite surprising and unexpected. It was expected that the preliminary excitation in the axial direction would weaken the specimens and cause more rapid failure when the transverse excitation was applied. Exactly the opposite occurred. It is apparent that work or strain hardening took place during the axial excitation portion of the second set of tests and the specimens were actually more resistant to fatigue failure in the transverse direction as a result.

4 CONCLUSIONS AND RECOMMENDATIONS

The results in this report confirm the inadequacy of sequentially applied uniaxial test methods for this simple cantilever beam structure. The order in which the uniaxial excitation is applied during the test caused up to a 40% variance in the results. It is reasonable to expect that the same variances occur with more complex items of hardware and equipment undergoing current uniaxial vibration screening and testing procedures.

Future triaxial tests are planned on the same specimens to directly compare results. This will allow significant conclusions to be made regarding the ability of multiaxial tests to more realistically replicate actual service conditions. Following this, more complex and typical components in vehicles will be tested to extend these results even further.

The preliminary results in this report also motivate the development of new methodologies addressing environmental definition and simulation for multiaxial shaker systems. This includes translating the one dimensional test requirements used in current vibration tests into equivalent three dimensional test requirements. Some initial work has been done in this area, but the need remains for better developed three dimensional test approaches[1].

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