

Vibration Test Specification Design and Reliability Analysis

2011-01-0491

Published
04/12/2011Wei-Lun Chang, Ken-Yuan Lin, Chin-Duo Hsueh and Jung-Ming Chang
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doi:10.4271/2011-01-0491

ABSTRACT

The purpose of this paper is to apply the concept of the frequency spectrum as derived from a Single Degree of Freedom (SDOF) system, establish the accelerated vibration specification, and investigate the specification under customer usage with reliability analysis. The main technique is to convert a time domain signal, which is derived from a Proving Ground or customer usage, to the frequency domain. An automotive headlamp was used in our research. The input signal from the Proving Ground was converted into an eight-hour bench test that is equivalent to a five-year/100,000 km field usage through the theory of Fatigue Damage Equivalence. The fatigue parameters of the materials were then estimated from various vibration conditions with the MIL-STD-810F standard. The benefit of this approach is that we could quickly obtain the material parameters of a complex structure made of composite plastics. Our research correlates customer usage with the Proving Ground and compresses the 100,000 km time domain history into an eight-hour laboratory bench test specification to accelerate the effect. In the end, life tests of eight headlamp pieces were conducted, and the Weibull distribution was used to perform reliability analysis. The results showed that the reliability is about 99.25% after the eight-hour bench test (or equivalently, after 100,000 km of field usage). At a 90% confidence level, the reliability becomes about 90%.

INTRODUCTION

Generally, the vehicle components or electrical devices used during transportation are easily affected by temperature, humidity, vibration, and/or shock. Therefore, environmental testing is important for validating the components. During the product development phase, environmental testing methods can be used to increase reliability. It is very important for

manufactures and users to assess and improve reliability through the use of a life test. Accelerated Life Testing (ALT) is the most widely adopted method for environmental testing to assess product reliability.

Accelerated testing is required for vehicle components to quickly assess the life of a component and to meet the market demand. Therefore, market usage research must be conducted to determine the correlation between the Proving Ground and market research usage, and the parts must be tested in an accelerated environment. Considering this correlation, Haq et al. [1] investigated a suspension system with rainflow cycle counting and optimization methods and took 5 tracks of public roads that added up to 100 miles and extrapolated them to 150,000 miles of equivalent customer miles. It was these 150,000 miles that were reduced to 24,000 proving ground miles. Gosavi and Chavan [2] discussed powertrain systems under customer correlated and accelerated life testing. Lin et al. [3] investigated the correlation between the Automotive Research & Testing Center's (ARTC) proving ground in Taiwan and 5,000 km in the Taiwan market to assess a new type of scooter durability testing. In addition to life analysis in laboratory accelerated testing, the test load specifications for products have begun to be developed in recent years. In 2006, Su [4] used the Fast Fourier Transform (FFT) technique to convert time domain road load data to frequency domain data and established an engine-mounted product vibration test specification with equivalent fatigue damage theory. In 2006, Halfpenny [5] proposed the concept of the Shock Response Spectrum (SRS) to calculate the Fatigue Damage Spectrum (FDS) and, furthermore, established a vibration specification to reduce the testing time.

Traditionally, the load specifications of vehicle components or electrical devices are directly given by OEMs and often are

treated as confidential information. The reasonableness of the test specifications is unknown. Therefore, developing appropriate specifications is an important issue.

In the design and development stage for automotive products, it is important to determine the test specifications to discover defects early and improve reliability. In this paper, the accelerated testing methods, which include time and frequency domain methods, the frequency response, and other parameters of the materials, are presented. Furthermore, we construct a vibration specification from the time domain to the frequency domain. In the end, a life test of eight pieces of headlamps was conducted and the Weibull distribution was used to perform the reliability analysis.

THEORY

ACCELERATED LIFE TESTING (ALT)

The purpose of accelerated life testing is to use higher stresses than would normally be encountered to quickly determine the life of products and their reliability under normal operating conditions. There are many kinds of accelerated test methods, such as frequency accelerated methods, compressed signal methods, increased stress methods, etc. Frequency accelerated methods apply higher than normal frequencies to achieve accelerated effects. Compressed signal methods edit the original signals and neglect the small amplitude signals to shorten the original signal histories. Increased stress methods enhance the environmental stresses to cause the products to fail within a short time.

The parameters that can usually be used to control environmental stress are the temperature, humidity, voltage, acceleration, stress, etc. The common temperature accelerated model is the Arrhenius Model, which, when combined into a temperature-humidity mode, is known as Peck's Model. The accelerated testing method for acceleration and stress is the Inverse Power Law [6]. This paper uses the Inverse Power Law to conduct a life test of headlamps to verify the damage between the time domain and frequency domain. The Inverse Power Law is given as follows :

$$AF = \frac{N_{use}}{N_{test}} = \left(\frac{G_{test}}{G_{use}} \right)^b \quad (1)$$

where

AF : accelerated factor

N_{use} : life under normal operating

N_{test} : life under accelerated testing

G : the RMS value of the acceleration

b : material parameter

The vibration tests conducted in laboratories typically use shakers, which means that the tests are performed in the frequency domain. For the frequency domain, the MIL-STD-810F standard offers the vibration accelerated formula given below :

$$\frac{T_{use}}{T_{test}} = \left(\sqrt{\frac{W_{test}}{W_{use}}} \right)^b \quad (2)$$

where

T : vibration test time

W : vibration PSD level (g^2/Hz)

b : material parameter

RAINFLOW CYCLE COUNTING AND THE LINEAR DAMAGE RULE

Signals, such as stress, strain, force or acceleration, when measured over a long period of time can result in an unmanageably large amount of data. Therefore, rainflow cycle counting is used in the analysis of fatigue data to reduce the spectrum of varying stress into a set of simple stress reversals. This method also allows the application of the Linear Miner's Rule to assess the fatigue life of a structure subject to complex loading. In a rainflow cycle counting chart, the time-history axis points downward, and one can imagine the rain flow flowing along pagoda roofs, as shown in Figure 1. According to the ASTM E 1049 standard [7], the rainflow cycle counting algorithm for any set of four consecutive turning points is defined as three steps :

Step 1. Compute the three corresponding ranges. If the amplitude changes from small to large, take half cycles.

Step 2. If the middle range is smaller than the two, extract a cycle of that range from the signal and proceed with the new signal.

Step 3. For the remaining ranges, when no more cycles can be extracted, give a few additional half cycles.

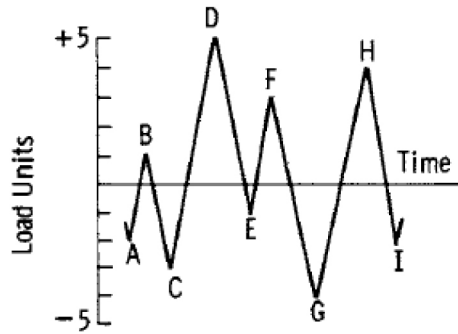


Figure 1. Rainflow cycle counting[7]

Fatigue breakage is an important failure mode in the vehicle field. When vehicles are subjected to a random vibration environment, fatigue damage may accumulate. If the accumulated fatigue damage reaches the limit of the material, failure will occur. The Linear Miner's Rule is the most common method used to calculate damage. A damage fraction D is defined as the fraction of the life used up by an event or a series of events. Failure is predicted to occur when $D \geq 1$.

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \quad (3)$$

where

D : damage criterion (a constant).

I : index of each set of applied load cycles at constant stress level S_i

n_i : number of applied load cycles at constant stress level S_i

N_i : fatigue life at constant stress level S_i , obtained from the S-N curve

SHOCK RESPONSE SPECTRUM AND VIBRATION SPECIFICATION

The SRS is a method used to estimate the response of an item to an input shock, with the information presented as a frequency spectrum. The principle is that the shock signals enter into a serial Single Degree of Freedom filter system (SDOF), as shown in Figure 2. Each filter has a specific frequency range and specific system damping values. The SRS is composed of the maximum response values in each frequency. The mathematical formula is

$$M\ddot{x} + C(\dot{x} - \dot{u}) + K(x - u) = 0 \quad (4)$$

where

$x(t)$: the absolute displacement of the mass M

$u(t)$: the displacement of the base

C : damping coefficient

K : spring stiffness coefficient

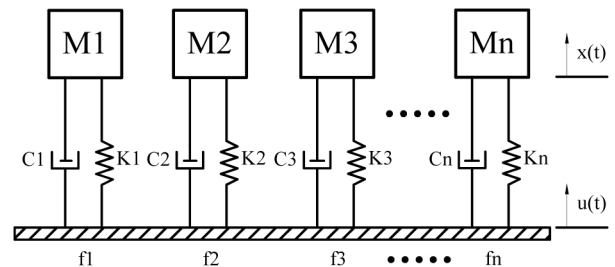


Figure 2. Shock Response Spectrum model

Using the Laplace Transform and assuming that the initial values of $x(t)$ and $u(t)$ are equal to zero, we can obtain another mathematical form

$$\frac{X(s)}{U(s)} = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (5)$$

where

$X(s)$ and $U(s)$: Laplace Transform of $x(t)$ and $u(t)$

ζ : damping ratio ($\zeta=0.05$)

ω_n : natural frequency

The Extreme Response Spectrum (ERS) is another response spectrum, which is similar to the SRS. The difference between the ERS and SRS is that the ERS is applicable to stationary processes, but the SRS is used to represent only non-stationary processes. Therefore, the test ERS must be smaller than the lifetime SRS to ensure that we do not accelerate the test too much and that we apply loads reasonably. The mathematical formula for the ERS is presented as follows [5] :

$$ERS(f_n) = \sqrt{\pi \cdot f_n \cdot Q \cdot PSD(f_n) \cdot \ln(f_n \cdot T)} \quad (6)$$