

Random Vibration Testing Development for Engine Mounted Products Considering Customer Usage

Liang Wang
Oakland University

Robert Burger and Yung-Li Lee
Chrysler Group LLC

Keyu Li
Oakland Univ

ABSTRACT

In this paper, the development of random vibration testing schedules for durability design verification of engine mounted products is presented, based on the equivalent fatigue damage concept and the 95th-percentile customer engine usage data for 150,000 miles. Development of the 95th-percentile customer usage profile is first discussed. Following that, the field engine excitation and engine duty cycle definition is introduced. By using a simplified transfer function of a single degree-of-freedom (SDOF) system subjected to a base excitation, the response acceleration and stress PSDs are related to the input excitation in PSD, which is the equivalent fatigue damage concept. Also, the narrow-band fatigue damage spectrum (FDS) is calculated in terms of the input excitation PSD based on the Miner linear damage rule, the Rayleigh statistical distribution for stress amplitude, a material's S-N curve, and the Miles approximate solution. Vice versa, the input excitation PSD is directly derived in terms of a given FDS and test duration. Finally, a random vibration test profile in PSD is obtained by varying the test duration such that the FDS calculated from the customer usage data equals the FDS from the test PSD. Two reliability demonstration test methods such as attribute testing and extended testing are introduced to ensure the tested parts will meet the required reliability and confidence target with a limited sample size.

CITATION: Wang, L., Burger, R., Lee, Y. and Li, K., "Random Vibration Testing Development for Engine Mounted Products Considering Customer Usage," *SAE Int. J. Mater. Manf.* 6(2):2013, doi:10.4271/2013-01-1007.

INTRODUCTION

Product development activities require some form of confirmation that the product being developed is moving in the correct direction. Product design must be evaluated for its effectiveness at meeting customer expectations and specifications. This verification and validation process has historically been associated with testing. Design Verification Plan (DVP) is a collection of tests and evaluation techniques to be followed that can provide confidence that the design is reliable. This paper presents a technique to define an accelerated test criterion or specification for engine mounted products and the test methods to demonstrate the reliability of this product to a specific confidence level.

The customer has always been the final verification phase of any design and development sequence. Therefore, if the earlier phases of testing and design are correlated to the customer, durability and reliability can be assured prior to

vehicle introduction. But, it is a major challenge for any engineer to develop an accelerated test procedure which will correlate to a certain percentile real world customer usage. This paper provides information and procedures necessary for an engineer to develop random vibration test specifications that correlate to the extreme customer's usage requirements for a given mission life.

A 95th-percentile customer usage profile for 150,000 miles is first obtained by a statistical analysis of an intensive customer market survey. Engine duty cycles are then defined for the field excitations experienced by the engine mounted components from a four-stroke four-cylinder internal combustion engine. By using a simplified transfer function of a single degree-of-freedom (SDOF) system subjected to a base excitation, the response acceleration and stress power spectrum density (PSD) for each engine duty cycle are related to the input excitation in PSD, which is the equivalent fatigue

damage concept [1,2,3,4,5,6,7,8,9]. Also, the narrow-band fatigue damage spectrum (FDS) is calculated in terms of the input excitation PSD based on the Miner linear damage rule [10], the Rayleigh statistical distribution for stress amplitude, a material's S-N curve, and the Miles approximate solution [11]. Vice versa, the input excitation PSD is directly derived in terms of a given FDS and test duration. At last, a random vibration test profile in PSD is obtained by varying the test duration such that the design test will produce same fatigue damage and comparable extreme response spectrum (ERS) as real world customer usage.

Finally, this paper also introduces the two non-repairable test plans to demonstrate durability and reliability of products due to engine firing excitations, where the pros and cons of each method are also addressed in detail.

RANDOM VIBRATION TEST DEVELOPMENT PROCEDURES

Described in the following sections is a method for specifying the random vibration test to correlate to customer usage. Development of the customer usage profile, definition of the engine excitations and engine duty cycle, fatigue damage and extreme response calculations for engine duty cycles, test synthesis for determining test duration and power spectral density are presented.

Customer Usage Profile Development

A customer usage profile is a statistically significant distribution of the time duration or frequency at a measured engine speed in rpm, which represents the customers' expectations over the mission life (ten years or 150,000 miles) of the engine. It is developed from intensive customer surveys, which include external parameters such as driving styles, road type, loading conditions and internal parameters such as speed, torque, and temperature [12]. For this paper, customer surveys were conducted in the greater Detroit area, and the annual engine speed distribution for each customer was calculated from Road Torque Data Collection (RTDC) data in the customer survey and listed in Table 1. For each customer, there will be a customer usage profile which is duration versus engine speed. At each discrete engine speed, there will be substantial durations (N durations, usually more than 100) from each customer. A statistical analysis using a cumulative frequency distribution on a Weibull plot is conducted on the N durations to estimate the 95th-percentile customer usage at each engine speed. Connecting the discrete value at each engine speed, the overall customer profile is obtained. The 95th-percentile customer usage is the value which is higher than 95 percent of the usages among the N samples. Thus, it represents the most extreme rpm durations. For a ten years mission profile, the obtained annual customer profile is multiplied by ten. When a 150,000 miles mission profile is required, the annual customer profile is multiplied by the ratio of mission profile to the annual mileage.

The 95th-percentile customer usage profile for a 150,000 mile service life of the four-stroke, four-cylinder engine where the engine components are mounted is depicted in Figure 1. Since exact testing following this customer usage would take a long time to complete, an accelerated testing strategy based on the equivalent damage concept is always required.

Table 1. Annual engine excitation durations at each engine speed from customer survey

Customer Engine Speed (rpm)	Customer 1	Customer 2	...	Customer N
1400	130 hours	120 hours	...	137 hours
1700	300 hours	295 hours	...	280 hours
...	...	...	...	...
6500	0.2 hours	0.3 hours	...	0.1 hours

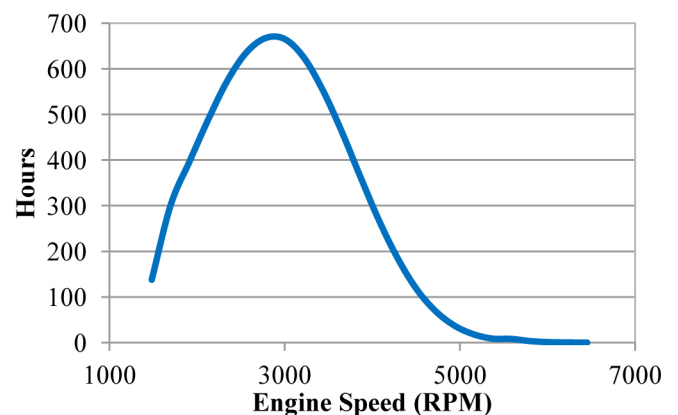


Figure 1. 95th-percentile customer usage profile of an engine for 150,000 miles

Engine Excitations

For developing a realistic and reliable random vibration reliability test, vibration profiles are carefully developed from the loading inputs, which are in the format of PSDs for random vibration testing. When designing a test for a whole vehicle, the loading inputs are usually determined from proving ground load inputs or road load data, which offers the best representation of customer usage [13, 14]. However, for the engine mounted components in this paper, the engine excitations are the main loading input. Therefore, the engine excitation PSDs, which can be determined from the real world engine excitations, for engine mounted components are required.

To collect the field engine excitations experienced by the engine mounted components, a tri-axial engine dynamometer test was conducted running from idle speed to the maximum engine speed on the four-stroke four-cylinder engine. Engine block and cylinder head are the two general places where accelerometers are installed during the dynamometer test. The vibration measured at the engine block indicates the generic engine excitations. However, for some engine mounted components, such as throttle body and exhaust gas recirculation valves which are often cantilevered, the engine excitations are usually measured at the cylinder head. In addition, installation of the accelerometer is critical when engine excitation for specific engine mounted component is required. The Z axis of the accelerometer should be installed parallel to the dominant vibration direction of the component. For demonstration purpose, engine excitation measured at the engine block is used in this paper. The engine speed and engine excitations in vertical, lateral and longitudinal directions versus time are shown in Figure 2.

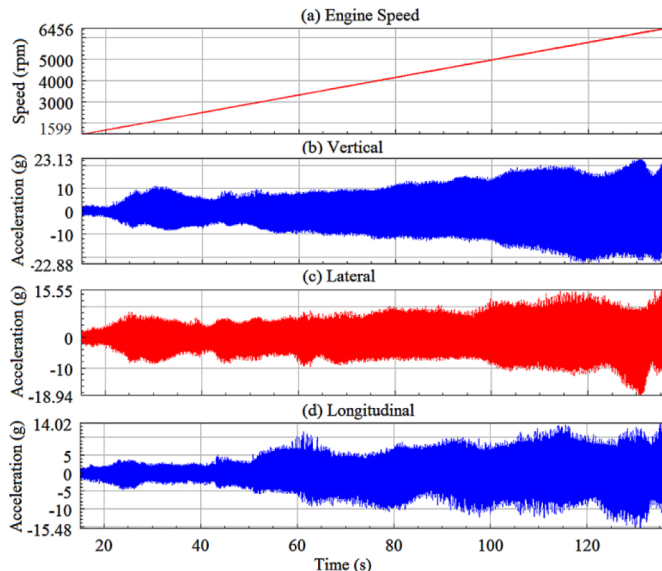


Figure 2. Engine speed (a) and engine vibrations in vertical (b), lateral (c) and longitudinal directions (d)

Engine Duty Cycle Definition

For random vibration test development, the FDS and the ERS are usually calculated based on the vibration theory for a SDOF linear system under random base excitations in acceleration. The base excitation of an engine mounted product for an entire frequency domain or engine speed range can be obtained by the measured tri-axial accelerometers' responses as shown in Figure 2. Combining Figures 1 and 2 would reveal the duty cycle of the time duration of a base excitation or engine response at each engine speed or frequency. Subsequently, both FDS and ERS from customers' expectations can be estimated by the dynamic response of the SDOF linear model subjected to the duty cycle data. In this paper the FDS and ERS derived from the engine duty cycle

data are referred to as the global FDS and ERS. For demonstration of the global FDS and ERS calculation, the engine speed and dynamic responses are divided into four descriptive customer usage zones, as shown in Table 2. For each zone, the duration and duration percentage can be obtained by summing the durations at the speed range in this zone from the customer usage profiles.

Table 2. Engine duty cycle definition

Duty Cycles	Speed Range	Duration (hours)	Duration Percentage
1	Idle to 25% of redline	2660	38%
2	25% to 50% of redline	3570	51%
3	50% to 75% of redline	700	10%
4	75% of redline to red line	70	1%

Fatigue Damage and Extreme Response Calculations

To calculate the FDS and ERS for each engine duty cycle, the model which correlates engine base excitation and dynamic response is selected first. Engine mounted component systems usually include many electronic sensors coupled with structural components. It would be very challenging to model a multi degree-of-freedom (MDOF) system. Therefore, a SDOF system is traditionally utilized. Assuming the engine mounted product is a SDOF linear system with a mass m attached to a base with a spring rate k and a damping coefficient c , the equation of motion can be represented as

$$m\ddot{x} = c(\dot{y} - \dot{x}) + k(y - x) \quad (1)$$

where x is displacement of the mass, y is input base displacement, $\dot{x}$ is velocity of the mass, $\dot{y}$ is velocity of the base, and $\ddot{x}$ is acceleration of the mass. Following Miles' solutions [11] with a given PSD of base input acceleration $W_{\ddot{y}}$, the RMS of the absolute acceleration of the mass $\ddot{x}_{RMS}$ can be estimated. Based on the relationship between absolute acceleration and absolute displacement, the RMS of the relative displacement z_{RMS} is estimated as

$$z_{RMS} \approx x_{RMS} = \frac{\ddot{x}_{RMS}}{(2\pi f_n)^2} = \sqrt{\frac{QW_{\ddot{y}}}{4 \cdot (2\pi f_n)^3}} \quad (2)$$

where f_n is natural frequency, and Q is dynamic amplification factor, which can be determined by the damping coefficient. Selection of the damping coefficient is critical and it depends on the application and experience. For a system which