

A Road Load Data Processing Technique for Durability Optimization of Automotive Products

Hong Su
Changan US R & D

ABSTRACT

Durability of a product is related to three major factors, the load, structure and material. The durability performance of an automotive product is, therefore, not only depended on the structure configuration, but also on the road load dynamic characteristics (profiles and frequency spectrum), and the material fatigue properties as well. Due to the dynamic nature of vehicle loads, one of the major technical challenges, to the durability design optimization of automotive products, is how to define a set of representative road loads, for fidelity and efficiency, based on the measured proving ground durability data of huge size.

This paper presents a procedure of processing the proving ground road loads, for vehicle durability design and optimization of automotive products, based on the statistical characteristics evaluation and fatigue damage equivalency techniques. A practical method for constructing a set of representative road load data, with much shorter time duration, is introduced, which satisfy all statistical property fidelity requirements with respect to the original measured load data.

The frequency spectrum and statistical characteristics of each road load event are first established from the measured proving ground data, by using the fast Fourier transform and power spectral density techniques. Based on the durability testing schedule and the fatigue damage level, the road load key life test events for lab tests and CAE are identified. For each selected road load event, a much shorter duration load data is then constructed, by iteratively searching and truncating a segment from the original measured load time history, based on the proposed technique. The resulted representative road load data, though is much shorter in time duration, maintains all statistical characteristics similar to that of the original measured dynamic proving ground data.

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INTRODUCTION

In automotive industry, computer aided engineering (CAE) simulation is increasingly employed to design a product for structural integrity and durability, by utilizing the same proving ground (PG) road load testing environments as in the test labs. It has been shown [1,2] that compared with physical tests, CAE simulation makes the product development faster and better at lower costs, especially at an early design stage before a prototype is built. CAE can not only evaluate product part stresses and fatigue life, but also provide a means to optimize the design in terms of durability, by employing the simulation iteration, design sensitivity, and optimization techniques [3].

However confidence in the CAE simulation, in an addition to fidelity of the structure model, is also dependent on the load representation of the proving ground road load testing environment. For a typical vehicle proving ground testing schedule, there are several road load events with different road surface profiles, traveling speeds, and durations. Even with

identified and selected the most damaging road load events, the total vehicle key life test (KLT) time duration is around several hundred hours. It is, therefore, not practical or necessary to simulate the entire key life test duration, due to the limited computational resources in terms of time, space and costs.

To reduce the simulation time and costs, many methods for simplified road load models have been proposed [4,5]. Most of the loading methods are, however, over simplified and based on a worst load case approach, which takes a segment of the most severe load event of the proving ground and disregards all other load events. The over simplified approaches may easily introduce significant errors and misleading results, as some frequency contents of the discarded load events could generate large stress responses in a product, which, in turn, could be the driving factors of the product failures.

Dynamic road loads, such as the proving ground durability road loads, to automotive structures are random in nature and can therefore be conveniently defined as random processes in terms of the power spectral density (PSD) functions and their statistic properties, respectively [6,7]. This paper presents a procedure of processing the proving ground road loads, for vehicle durability design and optimization of automotive products, based on the fatigue damage equivalency and statistic characteristics techniques. A practical method for constructing a set of representative road load data, with much shorter time duration, is introduced, which satisfy fidelity requirement based on all statistical properties similarity with respect to the original measured data.

The frequency spectrum and the statistic characteristics of each road load event are first established based on the measured proving ground data, by using the fast Fourier transform (FFT) and the power spectral density evaluation techniques. Based on the information of the durability test schedule and the established road load properties, the representative road events (key life events for lab tests and CAE) can be identified and selected. For each selected proving ground road load event, a segment of much shorter duration load data is then constructed, from truncating the original load time history, by employing the proposed technique and procedure.

Applications of the proposed proving ground road load processing procedure, as to establish a set of representative road loads for CAE analysis of automotive systems are illustrated. The constructed dynamic road data representative not only can generate the total fatigue damage equivalent to that of the original proving ground durability loads with the testing schedule, but also be well efficient and suitable for durability design optimizations and intensive CAE iterations, in terms of computer simulation time, space and costs.

BASIC BACKGROUND OF ROAD LOAD TECHNIQUES

Structural Model in Time Domain

For a general nonlinear dynamic system of an automotive product, for example, such as a suspension structure with rubber mounts and bushings, under the dynamic proving ground road loads, the mathematical model can be established as a system of nonlinear differential equations in the time domain [8, 9].

$$[M]\{\ddot{x}(t)\} + [C(x, \dot{x}, T)]\{\dot{x}(t)\} + [K(x, \dot{x}, T)]\{x(t)\} = \{P_s(t)\} \quad (1)$$

Where $[M]$ is the mass matrix of the dynamic system; $\{x(t)\}$ is the generalized coordinate vector, as a function of time, t . $[C]$ is the damping matrix, as a function of response $\{x\}$, time t and temperature T . $[K]$ is the stiffness matrix, as a function of response $\{x\}$, time t and temperature T . $\{P_s(t)\}$ is the dynamic

force vector due to the vehicle loads. The solution $\{x(t)\}$ to the above system of equations is generally obtained by using the finite element integration simulation technique, corresponding to each time step.

Vehicle dynamic loads to automotive structures are mainly interface reactions between wheel tires and road surfaces from proving grounds, which are in general constructed based on statistics of vehicle customer usage, loading conditions, reliability target, and confidence level for the designed vehicle life [5]. A typical set of vehicle proving ground load tests are usually defined in the reliability test schedule, which includes several road load events, with different road surface profiles, travelling speeds and durations.

The advantage of the computer virtual tests, as compared with the vehicle proving ground tests and the simulated lab tests, is simply due to the fact that its structure model is generated based on the design geometry data, loading data and material information, not any physically built parts are required. It employs the same measured proving ground loadings as the test lab, but without expensive test equipment and fixtures. In addition, it is much more efficient to make changes to the design and to run numerous what if study cases, as to find the best design solution under the given load conditions, using the simulation, iteration and optimization technique.

Fatigue Evaluation in Time Domain

All stress results of each component are first ranked and sorted out for the elements with the highest stress levels. The selected element dynamic stress time history is the result of the component under the given proving ground road loads. The representative stress time history is then further evaluated, along with the material fatigue data and damage model, for prediction of durability life of the component.

The material fatigue properties are usually measured as S-N curves, which define the relationship between the stress amplitude level, S_A , versus the mean cycles to failure, N . For most high cycle fatigue durability problems ($N \geq 10^4$), the S-N curves can be expressed as a simplified form [10]:

$$B = NS_A^m \quad (2)$$

Where B and m are the material properties varying with material type, and its loading and environment conditions, such as mean stress, surface finishing, and temperature.

In the time domain, the expected value of accumulated damage, $E[AD]$, due to dynamic fatigue stress loading on an automotive structure component, is evaluated based on the Palmgren-Miner's rule, and expressed as [11]:

$$E[AD] = \sum_i \frac{n_i(S_A)}{N_i(S_A)} \quad (3)$$

Where $n_i(S_A)$ is the number of cycles applied at stress amplitude level S_A , which is related to the simulated stress time history response; while $N_i(S_A)$ is the number of cycles to failure at stress amplitude S_A , which is based on the material fatigue properties, such as S-N curves, and i is the stress load case number. The geometrical and surface conditions of all critical components will be also considered for the modified material damage model.

Dynamic Random Load Description

Road surfaces traversed by ground vehicles are random in nature [12]. It has been established that most road surface irregularities, such as the proving ground durability roads of long durations (not short duration transient events for yield or ultimate strength), are normally distributed and may be accurately described by a stationary random process [7, 13]. For a stationary ergodic random phenomenon, the ensemble averages are equal to the time averages. The statistical properties of a stationary ergodic process can then be computed from a single time history of sufficiently long period. The time average of a random variable $x(t)$ is equal to the expected value of $x(t)$, as defined as:

$$E[x(t)] = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t) dt \quad (4)$$

The mean square value of $x(t)$ is found by applying average operation to variable $x^2(t)$ over a time interval T .

$$E[x^2(t)] = \overline{x^2} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x^2(t) dt \quad (5)$$

Correlation function is a measure of the similarity between two random quantities in a time domain τ . For a single record $x(t)$, the autocorrelation $R(\tau)$ of $x(t)$ is the expected value of the product $x(t)x(t+\tau)$:

$$R(\tau) = E[x(t)x(t+\tau)] = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t)x(t+\tau) dt \quad (6)$$

When $\tau=0$, the above definition reduces to the mean square value.

$$R(0) = \overline{x^2} = E[x^2(t)] \quad (7)$$

A random process can be described in frequency domain in terms of power spectral density (PSD) functions. It can be shown that PSD functions are related to the correlation functions by Fourier transform pairs. For a single random record $x(t)$, the relationship can be shown in the following equations:

$$S(\omega) = \int_{-\infty}^{\infty} R(\tau) e^{-i\omega\tau} d\tau \quad (8)$$

and

$$R(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) e^{i\omega\tau} d\omega \quad (9)$$

where $\omega=2\pi f$. From equations (6) and (8) it is clear that auto-correlation $R(\tau)$ is an even function of τ , and the auto PSD $S(\omega)$ is real. When $\tau=0$, the mean square value is related to PSD $S(\omega)$ from (7) and (9) by

$$\overline{x^2} = R(0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) d\omega \quad (10)$$

Fatigue Evaluation in Frequency Domain

Corresponding to the time domain fatigue damage method in (3), the expected value of accumulated damage, $E[AD]$, in the frequency domain, due to fatigue random loading is also evaluated based on the Palmgren-Miner's rule, and expressed as [9, 14]:

$$E[AD] = \sum_i \frac{n_i(S_A)}{N_i(S_A)} = \int_0^{\infty} \frac{p(S_A)}{N(S_A)} dS_A \quad (11)$$

Where $n(S_A)$ is the number of cycles applied at stress amplitude level S_A , $p(S_A)$ is the probability density function of the stress amplitude, while N is the mean cycles to failure, $N(S_A)$ is the number of cycles to failure at stress amplitude S_A .

Basic Load Spectral Properties

Under random vibration loads, the fatigue damage of a structure is estimated based on the statistical properties of the response stress PSD function. The statistical characteristics of the random vibration response stress can be obtained through the moments of the PSD function. The n^{th} spectral moment, m_n of the stress PSD function $S(f)$, frequency f in unit of Hz, is defined by the following equation [14]:

$$m_n = \int_0^{\infty} f^n S(f) df$$

Properties of a continuous stationary Gaussian process can be related to the above n^{th} moments, m_n of the PSD function. The root mean square (RMS) value, σ of the stress PSD function is

$$\sigma = (m_0)^{1/2} = \left[\int_0^\infty S(f) df \right]^{1/2} \quad (13)$$

The average rate of the zero crossing with positive slope, $E[0]$, which is also called as equivalent frequency in unit time, is expressed as:

$$E[0] = [m_2/m_0]^{1/2} \quad (14)$$

The average rate of peaks, $E[p]$ in unit time, is expressed as:

$$E[p] = [m_4/m_2]^{1/2} \quad (15)$$

The irregularity factor, α of PSD function, is defined as:

$$\alpha = E[0]/E[p], \quad 0 \leq \alpha \leq 1 \quad (16)$$

PROCEDURE FOR PG ROAD LOAD PROCESSING

Based upon the dynamic characteristics of the product and the statistical properties of the proving ground road loads, a procedure for constructing a set of representative road load data is proposed in the following. The resulted road loads will satisfy the statistical properties fidelity requirements, and are also much shorter in time duration that is practically suitable for durability design iterations and optimizations.

1. Input the measured proving ground load data and the PG testing schedule with time durations of the load events.
2. For each road surface event, perform a fast Fourier transform (FFT) on the time domain road load data, so as to obtain the corresponding power spectral density function PSD, respectively, as shown in [equation \(8\)](#).
3. Based on the material damage evaluation models, as shown in either [equation \(3\)](#) time domain or [\(11\)](#) frequency domain, identify the most damaging road load events of all the PG surface events, and establish the equivalent durability key life test (KLT) schedule, each with a duration for the selected events.
4. For each selected KLT road load event, establish the statistical properties by calculating its moments and parameters of each PSD function in the frequency domain, as presented in equations from [\(12\)](#), [\(13\)](#), [\(14\)](#), [\(15\)](#), [\(16\)](#).
5. Determine the basic dynamic characteristics of the product structure, in terms of the natural frequency f_{n1} and the equivalent damping coefficient ζ_{n1} of the first major mode,

based on the product model shown in [equation \(1\)](#).

6. Based on the product dynamic characteristics, determine the allowable simulation time constant (as related to the response settling time constant), as the shortest road load simulation duration time T_{si} .
7. For each KLT road load event, construct a representative road load by selecting a segment with duration T_{si} from the original measures proving ground road load data.
8. For each selected road load segment, perform FFT on the time domain road load data, to obtain the corresponding power spectral density function PSD, as shown in [equation \(8\)](#).
9. Based on the results of step 8, establish the statistical properties of each selected road load segment, by calculating its moments and parameters of each PSD function in the frequency domain, as presented in equations from [\(12\)](#), [\(13\)](#), [\(14\)](#), [\(15\)](#), [\(16\)](#).
10. Compare the statistical property similarity of each selected road load segment with the original proving ground data of the KLT event, by computing the relative error index of their moments and parameters.
11. If the error index is within a selected threshold, then accept the segment as the representative load for the KLT simulation, and go to construct the next KLT load event. If not, the process repeats steps 7 to 11, to construct a new load segment. If the constructing trial repeats more than a preset number, increase the duration time T_{si} by 10%, and then go to step 7, with updated T_{si} .
12. This process continues until a complete acceptable road load model for the whole KLT simulation is constructed.

This programmed search process will select a segment of the dynamic load data from a measured road load event of full time history, which meets the requirements for their statistical similarity, in terms of the dynamic road load PSD function characteristics.

EXAMPLES OF ROAD LOAD PROCESS AND TECHNIQUES

In the following sections, application examples of the proposed road load processing procedure to establish a set of representative road loads, for vehicle durability design and optimization of automotive products, are illustrated. The measured proving ground road loads are processed based on the statistic characteristics evaluation and equivalency techniques, both in time and frequency domains, as outlined in the previous sections.

In the given examples, the statistical properties of the road load data are first computed by using the FFT technique, in terms of PSD functions. The FFT parameters, such as the window, buffer size, frequency resolution, are selected to be the same for all processed data. The dynamic characteristics of each road load data are established, in terms of their respect PSD parameters. The relative statistical similarity between deferent

road loads are quantified in terms of their relative error index, which is a function of the PSD parameters of the road load data compared. The statistical similarity between different loads, such as different locations, different data acquisition repeats, and different truncated segments from a same original PG load, are also demonstrated. Finally, based on the durability key life test schedule, a set of representative road loads of short duration are constructed from an original PG load data, which are also practically suitable for computational durability design iterations and optimizations.

Properties of A PG road load event

A road load time history from a typical proving ground durability testing event is shown in Figure 1a. The road loads are measured by using the wheel force transducer (WFT), which usually picks six load components (three forces and three moments) of a wheel spindle. Here the road load is from the right front (rf) wheel spindle center of the vehicle, in the vertical direction, from a particular test run pass (p1), through a durability road surface route event (e1), and for easy identification marked as road load (e1p1rf).

The time history road load data (e1p1rf) is first processed by using the FFT technique, and converted into a frequency domain function, in terms of power spectral density curve, as shown in Figure 1b. The corresponding statistical characteristics of the road load data (e1p1rf) are then identified and listed in Table 1, in terms of nine PSD parameters. There, the root mean square (RMS) value is computed based on equation (13). The maximum peak value PSDm and the corresponding frequency fmax are directly identified from the PSD curve. The moments of the PSD function are computed based on equation (12). The equivalent frequency E[0], the rate of peaks E[p], and the irregularity factor α , are computed from equations (14), (15), (16), respectively.

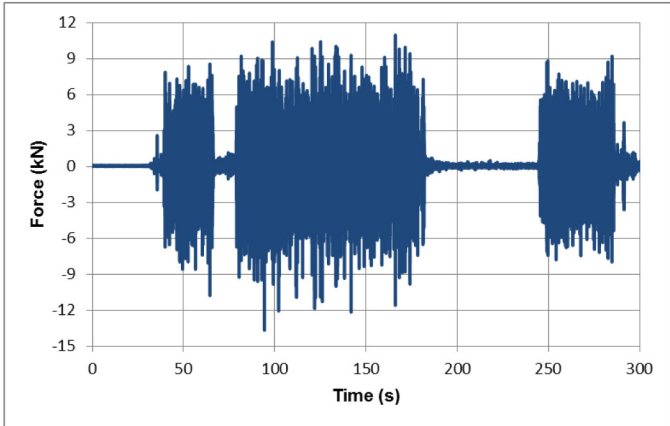


Figure 1a. A time history of a PG road load e1p1rf

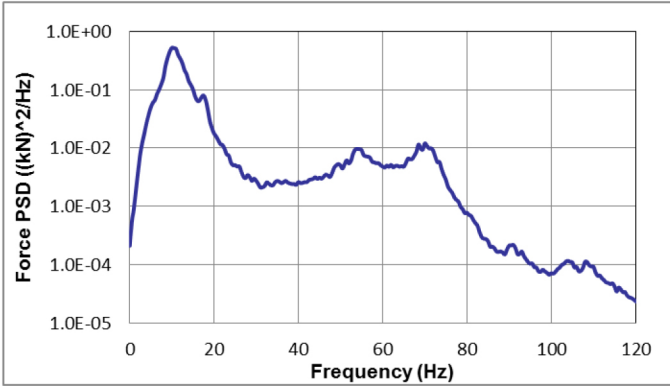


Figure 1b. A PSD profile of a PG road load e1p1rf

Table 1. PSD parameters of a PG road load e1p1rf

RMS =	1.77	M0 =	3.13E+00	E[0] (Hz)	20.36
PSDm =	0.52	M2 =	1.30E+03	E[p] (Hz)	58.52
fmax (Hz)	10	M4 =	4.45E+06	α =	0.348

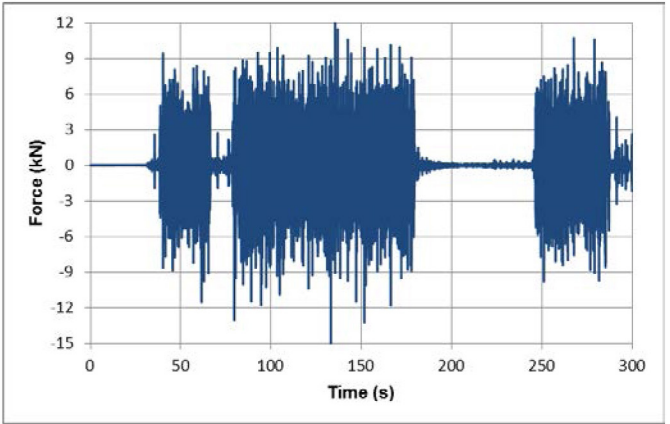


Figure 2a. A time history of a PG road load e1p1lf

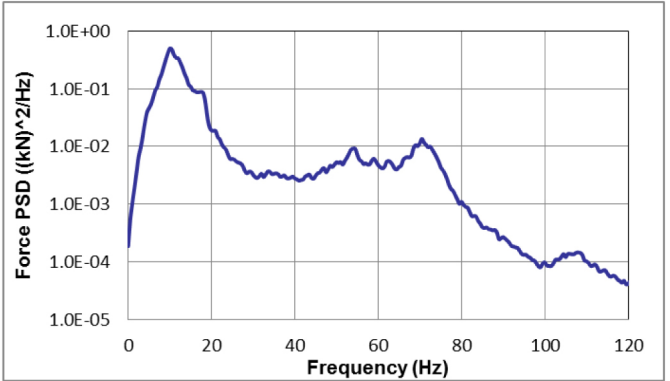


Figure 2b. A PSD profile of a PG road load e1p1lf

A second road load time history of the same PG road surface event (e1), from the same test drive run pass (p1), but measured at different location, the left front (lf) wheel spindle center of the vehicle, identified as road load (e1p1lf), is shown