

Proving Ground Optimization and Damage Correlation with Customer Usage

2011-01-0484

Published
04/12/2011Andrew Halfpenny and Mark Pompetzki
HBM - nCode Products

Copyright © 2011 SAE International

doi:10.4271/2011-01-0484

ABSTRACT

Proving grounds are an extremely efficient means of qualifying the durability of vehicle components. They accelerate damage accumulation rates so failures are detectable in a very short period of time. It is important that proving ground damage is correlated with target customer usage. It is also important to determine the most efficient use of the proving ground in order to meet project targets and minimize overall development costs. This paper describes the latest techniques for proving ground correlation and optimization.

Acceleration, strain, wheel force and other types of data are collected on a vehicle as it traverses different proving ground surfaces. Comparable data are also collected from instrumented 'customer' vehicles. The objective of the analysis is to determine which mixture of proving ground surfaces offers the best representation of customer usage while minimizing the total test time.

Prior to the optimization stage, time series data must be characterized and reduced to an efficient format. Techniques such as rainflow cycle counting and level crossing are discussed and recommendations are made on the merits of each approach. A new technique based on a damage-weighted frequency spectrum is introduced. This offers significant improvements in damage-based optimization when used with acceleration measurements.

The proving ground schedule will tend to be more severely damaging in some components than others. The paper discusses the choice of measurement location in optimizing overall vehicle damage. It also describes how to establish which components are under-tested (i.e. not expected to fail)

and which are over-tested (i.e. fail early) in the proving ground schedule.

INTRODUCTION

Proving grounds are often used for durability qualification as well as ride and handling assessments. They accelerate damage accumulation by concentrating on the most extreme loading events and then concatenating them one after the other. A typical proving ground is divided into several track surfaces, for example: highway, washboard, gravel, Belgian block, potholes, off-road, cross-country, etc. Each surface represents a portion of the real road; however, the surface 'roughness' is generally increased so damage can be accumulated much more quickly than under ordinary usage.

The engineer must determine the optimal mix of track surfaces and vehicle conditions that approximate to real usage by the target customer. An analysis technique known as 'proving ground optimization' (or 'end-customer correlation') uses advanced optimization routines to determine this optimal mix. The same analysis can also be used to improve the efficiency of existing proving ground schedules or to correlate one proving ground with another. The optimal proving ground mix usually considers a range of factors listed below:

- Proving ground surface
- Vehicle weight / trailer configuration
- Road speed
- Steering maneuvers

The paper describes two optimization algorithms that are suitable for proving ground analysis, these are:

- Best fit optimization
- Track optimization

The Best fit optimization technique is used to establish what track surfaces and vehicle conditions should be used to obtain the closest relationship to the target user; whereas, Track optimization establishes the most economical test schedule that meets the target usage spectrum in the most efficient manner. This might include either minimizing the total number of track repeats, the total track miles or the total track time.

The most common question arising from proving ground optimization is: “what is the acceleration factor of the proving ground schedule”, or “what’s the ratio of proving ground miles to equivalent road miles?” This is not an easy question to answer because the rate of damage accumulation is different for different components. Therefore, some components are under-tested by the proving ground while others are over-tested. The question therefore demanded is: to what extent is any particular component over- or under-tested by the proving ground test?

Proving ground optimization could be considered using any number of measurement locations on the vehicle. For example, the strain response on a particular component will lead to excellent proving ground correlation for that particular component; however, it is unlikely to result in a good representation on other components. In most cases engineers prefer to use generic vehicle measurements for the purpose of optimization. The idea is to characterize vehicle input data rather than output response. The paper reviews the following measurements as a source of input for optimization:

- Centre of gravity (C of G) acceleration (with optional roll, pitch and yaw rates)
- Wheel force transducer measurements
- Wheel displacements and steering angle
- Tri-axial acceleration at the spindle
- Strain gage measurements or load transducers at multiple locations
- CAN bus channels and GPS

Measured data is initially recorded in a time series format. This is not suitable for optimization because optimization is performed on characteristics of the data that describe the parameters of interest and not the data itself. Data characterization techniques are used to reduce data into a simple histogram format. The histogram retains the important characteristics of the data and leads to more efficient

optimization analysis. The choice of characterization techniques will depend on the source of the measured data (i.e. accelerometer, displacement, strain, force, etc.) and the required target (i.e. damage-retention or maneuver-retention). The paper describes and considers the advantages of several characterizations methods listed below:

- Level crossing analysis
- Time at level histogram
- Rainflow cycle counting
- Pseudo damage indices
- Relative Damage Spectrum (RDS)
- Fatigue Damage Spectrum (FDS)
- Power Spectral Density (PSD)

The paper concludes by describing several experiments which demonstrate the use of these techniques on real proving ground data. A simple test is considered where the target measurements are taken as linear combinations of several proving ground surfaces. This is used to demonstrate the ‘orthogonality’ of the optimization algorithms - i.e. the ability of the algorithm to determine the original target composition. A full analysis is then documented which uses much more extensive target data to derive an optimized proving ground schedule. A study is made to consider the damage retention on various instrumented components on the vehicle.

MEASUREMENT LOCATIONS AND DATA CHARACTERIZATION METHODS

The choice of both measurement location and data characterization method will influence the quality of the proving ground optimization study. This section reviews the most popular characterization methods and the suitable measurement locations.

DATA CHARACTERIZATION METHODS

Level Crossing Analysis

Level crossing analysis is concerned with recording the number of times the measured time signal crosses a certain amplitude threshold. A different threshold is associated with each bin of the histogram. The histogram bin is incremented by 1 point every time the time signal crosses its associated threshold. It is usually only recorded on the upward crossing for positive amplitude values and downward crossing for negative amplitude values. The level crossing count offers an efficient way of representing the variability of a time signal using relatively few coefficients. It offers a proportional

relationship with fatigue damage when used with strain or load measurements. If acceleration is used as an input then the resulting histogram is not proportional to the fatigue damage; however, it does offer a good correlation for ride and handling studies. An explanation of level crossing analysis is given by Lee, et al.(1).

Time at Level Histogram

The Time at level histogram is based on the amplitude probability function covered by most statistical text books such as Chatfield (2). It records the duration (in terms of time, distance, revolutions, etc.), that a signal falls in a particular amplitude range. It is commonly used for optimizing driveline components where measurements of engine RPM, torque and temperature are often considered. The histogram is proportional to damage in driveline systems but is not directly applicable to road surface-induced damage. It is still useful for track optimization however, as a means of ensuring that the final track schedule encompasses all the conditions the driveline components see under operational usage. Additional dynamometer tests can be used to cover any short-fall.

Rainflow Cycle Counting

The Rainflow cycle counting method was originally developed by Matsuishi (3) as a means of quantifying fatigue cycles and is generally considered better than Level crossing analysis in this regard. An overview of the principles involved in fatigue cycle counting is given by Halfpenny (4) and a more detailed reference on the rainflow algorithm is given by Downing (5). Rainflow cycle counting offers a proportional relationship with fatigue damage when used with strain or load measurements. If acceleration is used as an input then the resulting histogram is not proportional to the fatigue damage; however, it does offer a good correlation for ride and handling studies.

Pseudo Damage Indices

A Pseudo damage coefficient represents the cumulative damage seen by a single component. Strain gage measurements are most commonly used for this type of analysis; however, load and displacement are also suitable. The signal is first of all rainflow cycle counted and then the fatigue damage is estimated using a SN fatigue curve such as that illustrated in Figure 1. The SN curve is often idealized by a single slope with Basquin slope (b) in the range 3 - 6, where $b=3$ is representative of fatigue in a welded joint and $b=5$ is more representative of fatigue in a notched component. The term 'Pseudo' damage is used to indicate that the SN curve has not been calibrated to failure on a particular component. The Pseudo damage coefficient increases proportionally with fatigue damage.

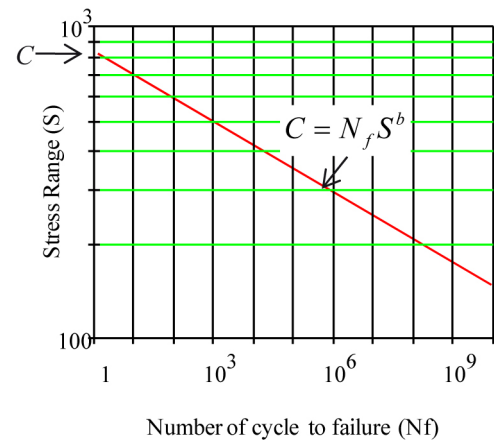


Figure 1. Typical SN fatigue curve

Relative Damage Spectrum (RDS) and Fatigue Damage Spectrum (FDS)

Both RDS and FDS methods return a histogram of fatigue damage vs. frequency. Input can be given in terms of acceleration or displacement measurements. When acceleration inputs are used, both methods effectively double-integrate the input to create a 'derived' displacement value which is proportional to the applied load and hence fatigue damage.

Damage and frequency are both important for durability correlation because different components will be more or less sensitive to different frequencies of loading. This is due to vehicle dynamics and component resonance. The loading frequency in turn is dependent on the terrain profile and the speed the vehicle is travelling.

The RDS approach was originally proposed by Rupp(6) as a means of correlating road profile to in-service health monitoring of vehicles. Extensive development of this has been undertaken and is documented in Halfpenny (7). A typical RDS plot is shown in Figure 4. The FDS approach was first proposed in the French defense standard GAM-EG-13 (8) and is based on the pioneering work of Lalanne (9). Further information on this approach is given by Halfpenny (10). A typical FDS plot is shown in Figure 7.

The RDS offers an efficient approach for low frequency ground-induced vibration. It is able to characterize track surface-induced damage using only 5-6 histogram bins. Over the same frequency range, the FDS will require many more calculation points to provide the same levels of accuracy. At higher frequencies, the RDS approach suffers from poor frequency resolution and is surpassed by the FDS. This makes the RDS approach ideally suited for road surface-induced damage while the FDS is best suited for driveline.

Power Spectral Density (PSD)

The PSD represents a plot of vibration amplitude vs. frequency. An introduction to the PSD is given by Halfpenny (11). Input can be in terms of acceleration, displacement or load. PSDs are not commonly used as a track optimization parameter; however, they are used to check that the final mix encompasses the range of frequencies seen by the customer.

Note: PSDs are commonly used to create accelerated vibration tests for vehicle components and these are often based on proving ground measurements. This topic is beyond the scope of this paper and the reader is referred to Halfpenny (10) and Halfpenny (12) for more details.

MEASUREMENT LOCATIONS

Centre of Gravity (C of G) Measurements

Acceleration measurements at the vehicle centre of gravity are a most affordable and durable approach to proving ground optimization; however, they may not be representative of the road-induced damage. Acceleration measurements are recorded in the fore-aft, transverse and vertical planes, along with the roll, pitch and yaw rates. This six degree of freedom motion can then be used as a basis for ride and handling optimization.

Although C of G measurements are used for optimization, they do not provide the best correlation with vehicle durability. The measurement point is too far removed from the road surface to offer a good correlation with the surface effect. These parameters measure the response of the vehicle to the road surface but do not closely represent the road surface itself. For the purpose of durability correlation it is preferable to turn the vehicle into a transducer for measuring the road surface profile. This implies that measurements should be performed on the suspension system itself. Notwithstanding this argument, C of G measurements are useful in ensuring that the final proving ground schedule encompasses the range of handling maneuvers seen during operation. If the engineer is limited only to C of G acceleration, then the RDS characterization method yields a proportional relationship with damage.

Wheel Force Transducer (WFT) Measurements

The WFT offers the best correlation between road surface profile and the loads entering the vehicle. These offer excellent means for a durability optimization; however, the cost and complexity of using WFT on a large number of customer vehicles is often prohibitive and so many engineers are forced to consider other options. Level crossing and Rainflow characterization methods are usually preferred when using WFT.

Wheel Displacement and Steering Angle

Wheel displacement offers a very good indication of road surface roughness. It is relatively inexpensive to measure although the durability of the measurement installation can hamper long-term customer deployment tests. Level crossing or Rainflow analysis are the preferred characterization methods. These analyses do not implicitly account for the loading frequency but errors can be mitigated by including the road speed in the optimization analysis. It is also common practice to measure steering angle to capture maneuver information.

Tri-Axial Acceleration at the Spindle

This solution is affordable, durable and representative. The triaxial acceleration is measured on the unsprung mass (spindle) and represents the profile of the ground. Acceleration by itself would offer a poor indicator of load and so the frequency of the applied acceleration is also very important. The frequency will change with respect to road speed and terrain roughness. In most cases the derived displacement (double integral of acceleration) offers a much better parameter as this is proportional to load. An efficient means of characterizing both damage and frequency is provided by the Relative Damage Spectrum (RDS).

Strain Gage Measurements or Load Transducers at Multiple Locations

A single strain gauged component could theoretically be used as an optimization parameter; however, the optimized result is unlikely to correlate well with other components in general. This occurs because most structural components are designed to resist certain types of load and are relatively unaffected by others. They therefore favor one load event over any other. This 'bias' problem can be overcome by using several instrumented components so the ensemble is not unduly biased. This approach is very useful if strain gages or load transducers can be positioned in reliable locations without excessive signal noise and risk of damage. Pseudo damage indices work best for this type of analysis.

CAN Bus Channels and GPS

CAN bus and GPS data offer a very economical means of acquiring data for optimization analysis. Data exist for driveline and vehicle handling characteristics but little data is available for road-induced loading at the moment. CAN bus and GPS data is often characterized using the Time at level approach.

OPTIMIZATION TECHNIQUES

The paper considers two optimization strategies; these are:

1. Best fit optimization
2. Track optimization