

Rainflow Counting Based Block Cycle Development for Fatigue Analysis using Nonlinear Stress Approach

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ABSTRACT

An accurate representation of proving ground loading is essential for nonlinear Finite Element analysis and component fatigue test. In this paper, a rainflow counting based multiple blocks loading development procedure is described. The procedure includes: (1) Rainflow counting analysis to obtain the relationship between load range and cumulative repeats and the statistical relationship between load range and mean load; (2) Formation of preliminary multiple loading blocks with specified load range, mean load, and the approximate cycle repeats, and construction of the preliminary multiple loading blocks; (3) Calibration and finalization of the repeats for preliminary multiple loading blocks according to the equivalent damage rule, meaning that the damage value due to the block loads is equivalent to that from a PG loading. The multiple loading blocks simplifies the original PG loading into several typical load cases, which could be conveniently implemented in nonlinear stress approach based fatigue life estimations.

An example study is made on a tie-down hook joint in a pickup truck cargo box. Several typical tie-down load cases are obtained after block cycle extraction. These blocking loads are then exploited to conduct the nonlinear analysis on a local joint assembly model, which includes contact interference and nonlinear material property. Fatigue lives are estimated based on nonlinear stresses/strains using linear damage accumulation rule.

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INTRODUCTION

In the past, automotive industry durability was determined through prototype field testing. Results from the field test would then be used by the engineer for future improvement. With technology advancement, the laboratory test and CAE simulation play a more and more important role in automotive development and validation today. However, the results of the laboratory test and CAE simulation are highly dependent on the input from proving ground loading (PG loading), which is collected from all instrumented vehicle when it runs over a series of predefined road profiles. Generally, PG loading varies with time and is complicated, random, dynamic and varies in amplitude.

There are two types of durability lab testing, which are system level fatigue test and component level fatigue test. The system level test, such as a road test simulator (RTS) or four post test, is conducted by applying PG inputs from tire or tire spindles. System level testing is time consuming. It requires very sophisticated hydraulic control systems. Unlike a system level test, a component test is normally conducted on a component or a local assembly using a simplified

loading format, which could be implemented easily and does not lose the characteristics from its original PG loading.

As computer hardware and software technology advance, CAE simulation is becoming a more and more important validation tool in automotive development. Similar to lab testing, there are two types of simulation based on PG loading, which are system level simulation approach and component level simulation approach. Vehicle system durability simulations highly depend on the proving ground (PG) loading. In order to exploit the multiple-channeled sophisticated time series loads, a normal durability simulation practice initiates linear pseudo stress analysis based on multiple unit load cases using inertia relief algorithm. The fatigue solvers could construct structural stress history results by superimposing PG loads with the corresponding pseudo stress results. But, the fatigue results based on linear FEA pseudo stress approach over contact area do not have much fidelity [1]. In order to increase confidence, nonlinear FEA analysis must be carried out to fully obtain the stress strain behavior over this area. However, it is not practical to apply PG time series loading directly in nonlinear FEA analysis. The problem becomes how to simplify the complicated PG

loading history into a simple loading format, which is not only suitable for nonlinear FEA analysis, but also capable of correctly representing the characteristics of the original PG loading.

An accurate representation of PG loading is critical for component level nonlinear structure FEA analysis and component fatigue tests. There are two ways to simplify a complicated PG loading history. The first one is the equivalent constant amplitude fatigue load, and another one is the equivalent multi-block fatigue load. As its name implies, the equivalent constant amplitude fatigue load approach is to represent the original dynamic and variable amplitude PG loading by using one constant amplitude loading block. But, equivalent constant amplitude loading block approach is too simple to precisely cover all the characteristics of a variable amplitude PG loading history. From this perspective, the equivalent multi-block fatigue load becomes a more favorable load representation for sophisticated PG loading.

In order to obtain a precise description about the PG loading, a statistic at analysis or counting process is necessary to extract the cycle distribution of an original PG loading. Several cycle counting techniques have been developed to perform this task [2]. These approaches include level crossing cycle counting, peak-valley cycle counting, range-pair counting, range-mean, and rainflow counting. The above techniques convert a complicated variable amplitude loading history into a number of discrete simple constant amplitude loading events. Level crossing cycle counting, peak-valley cycle counting, and range-pair counting are categorized into one parameter counting techniques. As the name implies, one parameter counting only conduct the cycle counts based on one parameter. However, the one parameter counting method is unsatisfactory for the purpose of accurately depicting PG loading properties. Unlike one parameter counting, two-parameter counting technique counts the cycles according to two parameters, which have range-mean format, max-min format or from-to format. The rainflow counting is a well known two parameters' counting technique, initially proposed by M. Matsuiski and T. Endo in 1968 to count the cycles or the half cycles of strain-time signals. There are two types of rainflow cycle extraction approaches. The first one is a three point counting method, which determines an inner cycle using three consecutive points in a load-time history. Another one is four point counting method, which uses four consecutive points to define an inner cycle. The stress amplitude and mean stress are two key parameters to determine the fatigue life. Accordingly, the load range and mean load together with their distribution, which directly affect the stress amplitude and mean stress, become indispensable parameters for forming the equivalent multi-block fatigue loads. From this perspective, the rainflow counting technique is the most ideal counting technique for such purposes.

This paper develops a procedure to construct an equivalent multi-block fatigue load based on the rainflow cycle counting technique. The first step in this procedure is to

construct a preliminary multiple-block loading cycle based on the rainflow statistical analysis. The relationship between the loading range and exceedance cumulative cycles is first obtained from rainflow analysis on a PG loading history. Based on such relationship, preliminary multiple load range blocks and corresponding repeats could be approximated. Preliminary multi-blocks loading is then generated after pairing the load range with a corresponding mean load, which is determined from a statistical analysis on mean load distribution at the corresponding load range. The corresponding preliminary block cycle is then constructed. The second step is to calibrate the preliminary block loading using the equivalent damage rule, meaning that the damage value due to block loading should be equivalent to that from PG loading. The calibration process is carried out on the same linear global stress results to finalize the repeats for equivalent multi-block fatigue loading.

The equivalent multi-block loading simplifies a complex variable loading time history into a series of constant amplitude load blocks, which could be implemented easily in nonlinear FEA analysis. Unlike linear methodology, nonlinear FEA analysis could consider contact interference, material plasticity with hardening, loading sequence, and nonlinear geometry thoroughly. Therefore, more accurate stress and strain behavior could be achieved on the interference zone. These results could then be directly used to estimate the damage and life without any plastic strain manipulation. So, the fatigue analysis based on the true strain and stress could eliminate the potential errors caused by the plasticity correction used in the linear FEA approach. This paper demonstrates a nonlinear FEA analysis example on a tie-down joint in a pickup truck cargo box. Two loading sequences, ascending loading sequence and descending loading sequence, are studied in this paper to investigate the fatigue influence from the loading sequence as well.

FATIGUE ANALYSIS USING LINEAR PSEUDO STRESS APPROACH

In order to predict the structure life behavior using PG loading, a linear FEA approach is widely adopted to obtain pseudo stress for every single unit load case which locates in the corresponding position of PG loading channel by using inertia relief algorithm. As mentioned earlier, a linear FEA model and analysis could not include contact interference, nonlinear geometry, and nonlinear material property. These limitations result in low confidence around contact area. Fig. 1 is a cargo box with gross vehicle weight (GVW) FEA model. In this figure, (A), (B), (C), and (D) are four upper attachments to the payload from tie-down straps. A tie-down strap is used to hold and stabilize the payload on the floor bed of a cargo box. On the lower side of each strap, the strap is tied to the tie-down hook wire as shown in Fig. 2. When vehicle moves, the strap is subjected to a dynamic pulling force caused by the payload inertia, whose loading time history data is recorded in a load cell attached to tie down

strap from proving ground. In the global FEA model, the tie-down strap is removed, and replaced with a pair of equal but opposite directional forces as shown in Fig. 2. Generally, the tie-down hook wire is subjected to the dynamic pulling force $P(t)$ from the strap during the vehicle moving as shown in Fig. 3.

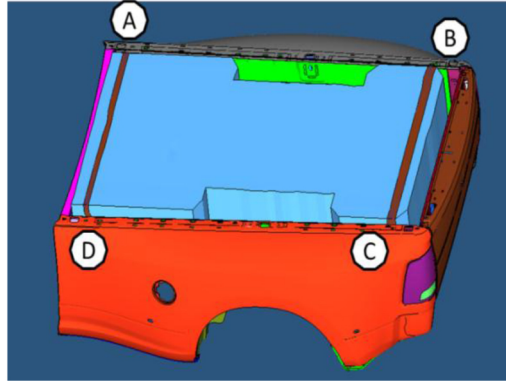


Figure 1. Linear Cargo Box GVW FEA Model

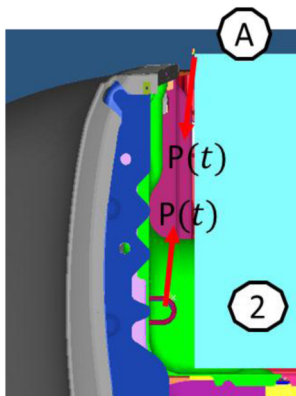


Figure 2. Tie-down strap model

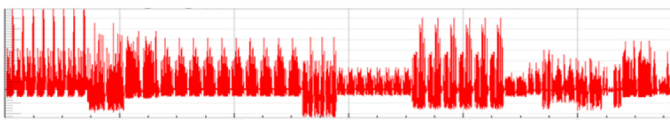
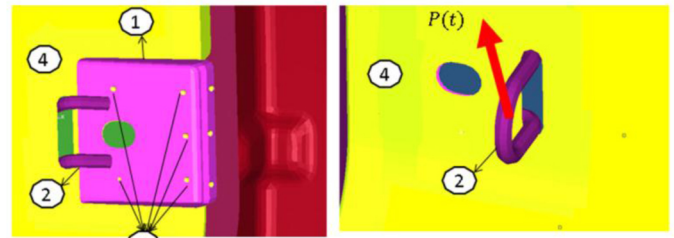


Figure 3. An example of tie down PG loading history $P(t)$

The tie-down pulling force $P(t)$ is then distributed to a typical tie-down hook joint as shown in the Fig. 4. In Fig. 4, (1) is a tie-down bracket, (2) is a hook wire, (3) are spot weld connections, and (4) is a box inner panel. The tie-down hook wire passes the tie-down force $P(t)$ to the tie-down bracket and then tie down bracket distributes the tie down load to the surrounding parts through spot weld connections and contact bearing. However, the pseudo stress approach could only consider loading path through weld connections, and does not have a good way to include the contact bearing interference in the system analysis approach.



(2) Tie down bracket connection (b) Tie down hook wire

Figure 4. A typical tie-down hook joint

Since correct stress results cannot be guaranteed over contact region from the linear pseudo stress analysis, the fatigue results over this region are also hardly dependable and trustworthy. In Fig. 5, very low fatigue lives for spot welds as shown are obtained from linear stress approach. However, such results have no correlation with the experimental results, which do not have issues in this area. Questions are frequently raised about including the contact interference in FEA analysis.

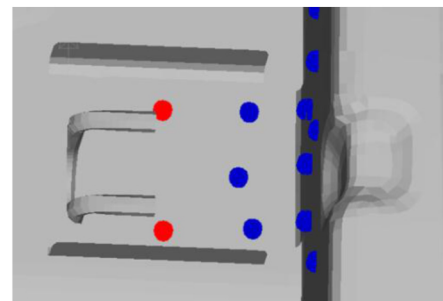


Figure 5. The tie-down joint fatigue results using linear stress approach

PG LOADING RAINFLOW COUNTING AND PRELIMINARY BLOCK CYCLE DEFINITION

Before deriving a multi-block fatigue loading, the rainflow counting technique is used to identify the statistical properties from the PG loading history. Fig. 6 is an illustration about a rainflow counting for a simple fluctuating loading history and its equivalent stress strain history.

The four points' counting method is normally used to count an inner cycle and a residual cycle. For example, in Fig. 6, 1, 2, 3 and 4 are four consecutive loading turning points that include a close cycle (2, 3) and a residual cycle (1, 4). In this way, one inner cycle (2, 3), with the corresponding max load point and min load point, is identified. The (2, 3) loading cycle can also be described as the format of range-mean pair or from-to format. In the range-mean format, load range and mean load are two parameters. In from-to format, the loading sequences from "from" to "to" are two parameters. After an inner cycle is identified, this inner cycle