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Real time high cycle fatigue estimation algorithm and load history monitoring for vehicles by the use of frequency domain methods

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ABSTRACT

Real time high cycle fatigue estimation problem for vehicles is examined by the use of frequency domain methods. The purpose was twofold: monitoring of fatigue damage and tracking of load history in real time. Firstly, power spectral density functions (PSDs) of acceleration measurement at a selected location are calculated in a piecewise manner by dividing the acceleration-time history into pieces. Following, Frequency Response Functions (FRF's), whose outputs are the absolute maximum principal stress values at selected components, are calculated by finite element methods to account for multiaxial stress state in fatigue life estimations. Then, fatigue damage intensity at selected output locations is estimated using the FRF results. To this end, the following frequency domain fatigue estimation methods (FDFEMs) proposed for Gaussian and stationary data sets are applied to the selected components of a heavy duty truck: narrow-band approximation, Tovo and Benasciutti, Zhao and Baker, Dirlik and Tovo's $\alpha_{0.75}$ methods. Gaussianity and stationarity of acceleration-time data set used to estimate fatigue life of a component is checked to ensure the validity of FDFEMs. Numerical results are compared with experimental fatigue lives and damage calculations in time domain made by the combination of rainflow counting and Miner-Palmgren rules. There are two difficulties in implementing this approach using on-board equipment in real time such as overcoming the limited memory to store data sets and completing the computations sufficiently fast. To overcome them, the proposed approach is implemented in a piecewise manner and associated normalized PSDs are updated accordingly. Then, spectral moments and damage intensities are calculated in frequency domain. Implementation of the proposed approach is described in detail and numerical results are presented. It is shown that the proposed approach is able to predict the fatigue damage accurately and can keep track of loading conditions in real time.

1. Introduction

Fatigue is the main reason for the failure of mechanical components in vehicles. There are numerous studies in literature to predict the fatigue failure and calculate the fatigue life of mechanical components, e.g., see [1] for an overview. In automotive industry, fatigue damage mainly occurs by two main types of forces; periodic forces originating from cyclic engine

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combustion and random forces acting on tires generated by irregular road surface. In general, engine components are designed considering infinite fatigue life [2]. Thus, the main focus of this study is selected as the fatigue damage due to random loading of vehicle components.

In the past, many studies were undertaken about fatigue life estimation due to random vibrations that can be classified into two groups such as time-domain and frequency domain studies. In time domain approaches, a counting method (e.g., range-mean stress, rain flow counting and range-pair methods [3–5]) and a damage accumulation rule (e.g., Miner-Palmgren rule and Haibach rule [6–8]) are employed for fatigue damage prediction. The counting methods are used to convert irregular stress-time history data into equivalent stress cycles having a constant range and mean stress. Following, the damage accumulation rule is implemented to calculate the total damage by summing the contributions of each stress cycle found by the counting method. Among the other alternatives, rainflow counting method and Miner-Palmgren rule are widely used in fatigue damage prediction studies due to their accuracy [9–14]. Since the rainflow counting method is accepted as the most accurate method by the scientific community, capturing the cycle distributions of rainflow counting method is the aim of some frequency domain methods [9].

Frequency domain fatigue estimation methods (FDFEMs) considered in this study are based on stationary Gaussian processes such as narrow band and wide band stress cycle distributions. In narrow band stress cycle distributions, the distribution of cycles is obtained directly [9,15]. For wide band stress cycle distributions, proposed mathematical models are more complicated that can be classified as empirical (e.g., Dirlik [16], Zhao and Baker [13] and Tovo and Benasciutti [17]) and theoretical (e.g., Bishop [18]). To guarantee that the stress-time history is Gaussian and stationary, related stochastic parameters of stress-time history must be checked [19–23]. Non-Gaussian and non-stationary distributions [24] are not considered in this study.

In FDFEMs, firstly power spectral density (PSD) of stress time history is calculated; then, necessary spectral moments required by the selected FDFEM [12,13,15–17] are computed. According to the selected FDFEM, associated coefficients of the mathematical model are computed by using the spectral moments. Then, total fatigue damage is computed by using these computed coefficients, material S-N curve and spectral moments. As mentioned above, the most accurate damage estimations can be acquired by using time domain methods; however, burden of time domain implementations is significantly higher than that of the frequency domain methods. Thus, fatigue damage estimation in frequency domain is much faster than that of time domain. In addition, fatigue damage estimation could be needed at multiple locations at which PSDs of stresses are required. On the other hand, these PSDs can be calculated by strain gauge measurements in time domain or by using frequency response analysis on finite element (FE) model of the vehicle. In contrary to the frequency response analysis, computational cost of transient dynamic analysis required in time domain implementations is high that is followed with experimental strain gauge measurements [11]. This is one of the reasons that frequency domain methods are preferred in this study.

Note that multi-axial stress state exists in our analyses. Even though the structure is excited in only one direction, the corresponding stress tensor may be multi-axial and assumption of uniaxial stress-time history may lead to unacceptable errors in fatigue life estimation [25]. Thus, the FRFs are calculated such that the outputs are absolute maximum principle stress at selected components.

Technological developments enabled that even an electronic control unit (ECU) on a vehicle is capable of making some vehicle dynamics and engine control calculations effectively. As a result, the ECU of a vehicle can be used for estimating the fatigue life of vulnerable parts of the vehicle in real time. On the other hand, vehicles are subjected to different load spectrums depending on their usages; consequently, their maintenance schedules should be based on their loading conditions and maintenance periods can be scheduled by a fatigue damage estimation algorithm. In particular, having a significant economic impact for truck fleets, such a monitoring algorithm for fatigue damage can be used to determine the service intervals of vehicles and predict fatigue failure of components, that reduces the operational costs and increases the reliability of vehicles; moreover, it can also be used to keep track of load history in real time that can be used for maintenance and statistical purposes.

Motivated by these facts, a real time monitoring algorithm for high cycle fatigue failures in vehicles is developed in this paper. The computational difficulty of this algorithm is to process the random loads to calculate fatigue damage accumulation and estimate fatigue failures at critical locations in real time. While fatigue damage is estimated, computational time is the most important parameter affecting the feasibility of damage prognosis. If elapsed time of an algorithm is not smaller than the real-time stress-time history interval, the fatigue damage estimation could not be in real time. To overcome this difficulty, FDFEMs are implemented that have an advantage over time domain methods in terms of CPU time. Developed methodology depends on piecewise updating of normalized PSDs in time by dividing the stress time history into pieces. Following, how to estimate the fatigue life at selected components by using frequency response functions (FRFs) is examined. Main concerns are updating the PSDs, and computing the spectral moments and FRF's in real time, whose solutions are presented in the paper. The proposed real-time high cycle fatigue estimation algorithm is implemented into a heavy duty truck frame. Numerical results are compared with experimental fatigue lives and calculations made in time domain. It is shown that the proposed approach can be used for real time fatigue damage monitoring of vehicles and FDFEMs yield accurate predictions for fatigue damage.