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Development of multiple linear regression-based models for fatigue life evaluation of automotive coil springs

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ABSTRACT

This paper discusses the establishment of multiple linear regression (MLR)-based spring durability models for predicting the fatigue life of automotive coil springs based on the vertical vibrations of the vehicle and natural frequencies of the vehicle suspension system. These models were developed in order to simplify the design and development process of vehicle suspension systems, which is both time-intensive and cost-intensive. The simulated force-time histories were processed to obtain the fatigue life of the automotive coil spring based on the strain-life models whereas the acceleration-time histories were weighted according to the ISO-2631-1:1997 standard to determine the vertical vibrations of the vehicle. MLR was used to establish the spring durability models and the goodness of fit, linearity, normality, and homoscedasticity of the models were assessed. The highest coefficient of determination at 0.8820 was obtained for the Morrow MLR-based spring durability model, with the mean square error of 0.5855. The models were validated by comparing the fatigue life values predicted by the models with those predicted from strain measurements. The results show a good agreement between the predicted and experimental values, indicating the suitability of these models in predicting the fatigue life of automotive coil springs.

1. Introduction

Fatigue analysis of automotive coil springs is crucial because these components are constantly exposed to dynamic loads as the vehicle travels across different terrains. Coil springs are also among the critical components in an automotive chassis because they affect passenger comfort and vehicle aerodynamics. The spring durability and vehicle ride quality are dependent on the design of the coil spring-damper pairs in order to handle different road profiles [1]. Many studies have been carried out to examine the vertical vibrations of the vehicle excited by realistic road profiles [1,2,3]. Reza-Kashyzadeh et al. [1] studied the effects of road surface roughness on the vibrations of the vehicle suspension system. The road profiles were regarded as random road excitations in order to estimate the fatigue life values of the suspension system components such as the wheel hub, Pitman arm, suspension arm, and joints. González et al. [2] used vehicle acceleration

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measurements instead of random road profiles to estimate the road surface roughness, where a transfer function was used to establish the relationship between the power spectral densities of the road surface and the vehicle acceleration measurements.

Under certain road excitations, the components of the vehicle suspension system will eventually fail due to crack initiation and propagation as the suspension system is subjected to high-amplitude dynamic cyclic loads. This type of failure is known as fatigue failure. Among all of the components in the vehicle suspension system, coil springs typically fail because of fatigue. Zhu et al. [3] investigated the fatigue failure of coil spring and suggested that fatigue crack initiation typically occurs in the contact zone of the coil spring. Improper design of the coil spring will lead to premature fatigue failure. According to Das et al. [4], premature fatigue failure of the coil spring occurs in the presence of inclusions. Even though the coil spring was designed to have a high-cycle fatigue life, the presence of inclusions significantly reduced the fatigue life, especially when the coil spring was subjected to variable amplitude loadings. Fatigue failure induced by variable amplitude loadings is more complex to predict compared with fatigue failure induced by constant amplitude loadings [5]. However, advances in computing technology has greatly facilitated fatigue analysis of various coil spring designs [6]. Gaikwad and Kachare [7] conducted fatigue analysis and explained the overdesign of a helical compression spring by means of simulations. However, their fatigue analysis was limited to constant amplitude loadings because the actual road profiles were not known.

Harsh road profiles do not only affect the fatigue life of automotive coil springs but also the vehicle ride quality [8]. Spring design plays a vital role in determining the vehicle response towards road excitations, which will affect the vehicle ride quality. The vehicle ride quality is defined in terms of the vehicle body acceleration [9]. Seifi et al. [10] used random road excitations as the inputs for simulations of a ground vehicle in order to improve ride comfort by minimizing the vehicle body acceleration. Based on the findings of existing studies, both the fatigue life of automotive coil springs and vertical vibrations of the vehicle are determined by a common source: road excitations. This is further supported by the durability transfer concept, which posits that damage or severity of usage at various points of interest on a vehicle can be predicted by measuring the vehicle acceleration at nominal points [11]. Since vehicle ride quality is influenced by ground excitations, it is possible to correlate the fatigue life of automotive coil spring with vehicle ride quality. Pawar Prasant and Saraf [12] assessed the vehicle ride quality and durability of an automotive coil spring based on the road profile measurement method. The results showed that it is possible to develop models that can simultaneously predict the fatigue life of the automotive coil spring and vehicle ride characteristics. Kong et al. [8] proposed a linear model to express the relationship between spring durability and vehicle ride quality based on power regression. However, it shall be noted that the model was limited to a predefined set of parameters for the vehicle suspension system.

In general, there is a need for a more complex modelling approach to establish the relationship between numerous parameters. In this regard, MLR is a suitable approach to establish the relationship between the dependent variable (response variable) and multiple independent variables (predictor variables) [13]. MLR has been used to model ride comfort and vehicle handling contributed by the suspension system. Mitra et al. [14] optimized a vehicle suspension system using the data collected from a test rig of a quarter car model. MLR has also been used to model the international roughness index (IRI), where wheel acceleration was used as the independent variable [15]. MLR has also been used for fatigue analysis in order to model the stress amplitude, crack length, and number of cycles for Al 6061-T6 alloy [16]. In addition, MLR has been used to model the damping ratio of a disc brake with different parameters such as slot angle, chamfer, and Young's modulus [17]. According to Garg et al. [18], MLR modelling yields varying degrees of accuracy because of its linear representation of a non-linear system. Based on the findings of these studies, it can be deduced that MLR is commonly used to model the relationship between various parameters for automotive systems and components.

MLR is capable of providing immediate predictions of the dependent variable by fitting a best fit line to the observation data, which will reduce the need for repeated analyses. It is known that fatigue analysis of automotive coil springs and vehicle ride quality analysis are time-consuming and therefore, there is a need to develop models that are capable of predicting the fatigue life of automotive coil springs based on MLR, which will greatly facilitate the design and development process of vehicle suspension systems.

Thus, the objective of this study is to develop MLR-based spring durability models in order to predict the fatigue life of automotive coil springs. It is hypothesized that the fatigue life of the automotive coil spring is correlated with the vertical vibrations of the vehicle and natural frequencies of the vehicle suspension system because both of these parameters are related to road excitations. To the best of the authors' knowledge, there are no detailed models currently available that are capable of predicting the spring durability and vehicle ride quality. Even though many studies have been carried out to analyse spring durability and vehicle ride quality, none of these studies are focused on modelling the relationship between spring durability, vehicle ride quality, and natural frequencies of the vehicle suspension system. In this study, MLR-based models are established to predict the fatigue life of automotive coil springs and it is believed that the findings presented in this paper will extend the current body of knowledge on the applicability of MLR in fatigue analysis.

2. Methodology

The methodology adopted in this study consists of five major steps: (1) data acquisition, (2) finite element analysis (FEA) of the automotive coil spring, (3) simulations of the quarter car model, (4) signal processing, and (5) development and validation of the MLR-based spring durability models. Fig. 1 shows the flow chart of the methodology adopted in this study.