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Fatigue life prediction of parabolic leaf spring under various road conditions

Y.S. Kong [a,b], M.Z. Omar [a,c,*], L.B. Chua [b], S. Abdullah [a,c]

[a] *Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*
[b] *APM Engineering & Research Sdn Bhd, Level 4, Bangunan B, Peremba Square, Saujana Resort, Seksyen U2, 40150 Shah Alam, Selangor, Malaysia*
[c] *Centre for Automotive Research, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

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ABSTRACT

Parabolic leaf spring experiences repeated cyclic loading during operating condition. Fatigue life assessment of the parabolic leaf spring is a significant aspect during the component design stage. This paper serves to simulate the fatigue life of a parabolic leaf spring design under variable amplitude loading (VAL). VALs carry the road signal that provokes fatigue failure on leaf spring. In order to seek for comprehensive leaf spring fatigue assessment, VALs signal were gathered through measurements from various road conditions such as highway, curve mountain road and rough rural area road. Subsequently, fatigue life of particular leaf spring design was predicted using finite element (FE) stress–strain model together with VALs signal as load input. For more conservative way, Morrow and Smith Watson Topper (SWT) mean stress correction methods were also applied. The results indicate that fatigue life of leaf spring is lowest during rough road mission, followed by curve mountain road and smooth highway road respectively. Additional design modification to prolong the fatigue life of the parabolic leaf spring is compulsory. The road VALs has provided even more realistic fatigue life estimation of parabolic leaf spring design when compared to traditional controlled laboratory method.

1. Introduction

In the fast pace automotive technology era, automotive engineers facing challenge in rapid development of complex automotive which can be considered as a compound structure made with many mechanical components subjected to complex cyclic loading. In the design stage, durability evaluation of the vehicle components is one of the major concerns to be considered, however the experimental assessment is time consuming and expensive. Hence, finite element (FE) method which is known as state of art technology in design is widely applied in automotive industry to assist in assessing the stress level of automotive components, especially the suspension system, such as leaf springs [1]. With the enhanced computing power and advance finite element software nowadays, accessibility of automotive components durability has become more convenient and possible.

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[*] Corresponding author at: Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia. Tel.: +60 3 8911 8010; fax: +60 3 8925 2546.

E-mail address: zaidi@eng.ukm.my (M.Z. Omar).

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In automotive part manufacturing industry such as spring maker, fatigue analysis procedures for the design of products rely on the techniques that follow relatively simple procedures, apply single phase repeated loading on products until the components fail. Lab experimental fatigue life prediction has poor description on the real life road condition whereby the actual condition could be much more severe. Currently, strain–life fatigue analysis calculations could be performed base on time series data, rainflow matrix, or multi-column list of cycles. A complete schedule of multiple time series events can also be summed to give overall damage. Currently, strain life fatigue analysis is also available with finite element (FE) method. Instead of strain life analysis, others fatigue analysis approach such as stress–life, crack propagation, creep analysis, vibration fatigue and multi-axial fatigue also widely adopted in FE method fatigue analysis. For the strain–life method, three of the most popular strain–life models are Coffin–Manson, Morrow and Smith–Watson–Topper (SWT). Coffin–Manson is performed without mean stress effects while Morrow and SWT consider the mean stress effects [2].

Recently, another strain–life approach known as effective strain damage method (ESD) which is based on crack growth and crack closure mechanisms was developed. The algorithm is used to account for the cycles sequence effect [3]. In fatigue analysis, strain–life model combined together with VAL are extensively used. Characterisation of load sequence effect on fatigue crack propagation under VAL has been conducted and proved [4]. Loading sequence is affecting the fatigue level of the component. Fatigue crack growth test under constant amplitude loading (CAL) and VAL in different environment to find the combined effect of load history and environment is emphasised [5]. VAL with imposing multiple overload-underload cycles is developed to predict fatigue crack growth through probabilistic approach [6]. Multi-axial fatigue with VAL correlation has been developed to predict fatigue life of rubbers [7]. Probability distribution of fatigue life of steel notched elements under VAL directly from tensile properties is predicted by using probabilistic stress life (*P*–*S*–*N*) curves [8]. All the research in VAL has proven its significance towards fatigue research where the traditional laboratory experiment unable to understand.

Numerous researchers have proposed methods for fatigue life prediction for automotive components subjected to variable amplitude loadings (VAL). Automotive components require high cycle fatigue life especially the suspension system. Fatigue life of vehicle suspension components such as parabolic springs [9], lower suspension arm [10–12] has been analysed under VALs. Modified stress–life and strain–life method in predicting automotive components that are exposed to VAL have been suggested [13]. In their research, CAL with random overloads was converted into VAL to predict fatigue crack propagation of steel. Damage tolerance reliability analysis methodology for spot-welded joints on automotive under VAL history has also been performed [14]. Research on fatigue assessment presents that wavelet bump extraction to summarise load history and obtain fatigue lives under VAL has shown a high correlation to the experiment data [15,16]. Based on these publications, it is obvious that researches are intended to create VAL according to CAL. The reason for this is due to VAL is always provide the more accurate results.

In this analysis, VAL data of a parabolic leaf spring was collected from three different road conditions which are highway, curvy and rough road. VALs were then used as the load input for FE fatigue analysis. Previous CAL fatigue test is widely used to determine the strain–life or stress–life curve for metal products. However, most automotive components especially suspension components are subjected to random loading conditions in which stress–strain cycles fluctuate with time. Life estimation of components with CAL is not sufficient to describe the actual loading conditions where the actual conditions are more damaging. VAL includes occasional severe event which may happen during driving condition. Severe conditions were not considered during CAL fatigue prediction. Therefore, strain life approaches with road VAL were applied to evaluate the fatigue life of the parabolic leaf spring for realistic environment fatigue estimation. Other than different road conditions, effects of Morrow and SWT strain life model were also performed to seek for the difference between fatigue results.

2. Fatigue strain–life approach

Fatigue life of automotive components under service loadings is commonly evaluated by strain–life damage approach [9–11,16]. The early stage of fatigue formula was explored about a century ago where Basquin observed the linear relationship between stress and fatigue life in log scale when the stress is limited [2]. The preliminary fatigue formula controlled by stress is listed in Eq. (1):

$$\sigma_a = \sigma'_f (2N_f)^b \tag{1}$$

where σ_a is the stress amplitude, σ'_f is the fatigue strength coefficient, N_f or $2N_f$ is the number of cycles or reversals to failure, *b* is fatigue strength exponent. Later, Coffin and Manson proposed that plastic strain may also be related with fatigue life by simple power law. Subsequently, Morrow combined the work of Basquin, Coffin and Manson whereby the elastic and plastic strain devotes to fatigue life as well [17]. Nowadays, among the strain life method, Coffin–Manson, Morrow, and SWT are the most well-known approaches in finite element model for life assessments. The Coffin–Manson strain–life is mathematically defined as in Eq. (2):

$$\varepsilon_a = \frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f (2N_f)^c \tag{2}$$

where ε_a and $\frac{\Delta\varepsilon}{2}$ is the total strain amplitude, ε'_f is the fatigue ductility coefficient, *c* is the fatigue ductility exponent, *E* is the modulus of elasticity.