The Need to generate a Force Time History Towards Life Assessment of a Coil Spring

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ABSTRACT

This paper presents the generation of force time history for coil spring fatigue life predictions using cumulative trapezoidal numerical integration of acceleration time histories. Loading time history was a crucial element for fatigue life prediction but a suitable instrument for the data collection was not always available. Hence, the required force time histories were generated from two relative acceleration time histories. Acceleration time histories from vehicle sprung and un-sprung mass were collected and converted into displacement using cumulative trapezoidal numerical integration approach. Through regarding the spring as a linear component, the force time history was obtained. The force time history together with the spring finite element model were used as the input to fatigue life models for fatigue life prediction. The predicted fatigue lives for the coil spring were 3.12×10^{-6}, 5.67×10^{-6}, 6.97×10^{-6} blocks to failure using Coffin-Manson, Morrow, Smith-Watson-Topper model respectively. The results were validated using measured strain time history where the Morrow and Smith-Watson-Topper models' results were fitted perfectly using the conservative correlation approach.

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Introduction

Fatigue failure analysis was a part of the automotive suspension design process which was invariably important. One of the many steps in automotive suspension design process was analysing the loads in the suspension [1]. To analyse those loads, the most comprehensive way was through applying a wheel force transducer. However, wheel force transducer was a commercial product where it was extremely costly and not affordable for most of the research purpose [2]. For a smaller scale and single component measurement, a strain gauge setup with data acquisition system were usually used to obtain the strain time histories for fatigue analysis.

Due to the need of measurement of loading signals in fatigue life assessment, sample loadings for suspension, bracket and gear have been proposed by SAE, i.e. SAESUS, SUSBRAKT and SAETRN [3]. Savkin et al. [4] have utilised the SAE loadings to quantify the fatigue characteristic of a steel. These loadings were also used to predict fatigue life of a vehicle knuckle and compared with the results of a multibody simulation [5]. For a more realistic analysis, the service strain time histories of the automotive component were needed to be collected and it involved experiment setup efforts. Kong et al. [6] used several strain gauges to collect strain time histories and predicted the fatigue life of a leaf spring associated to different road profiles. The vehicle was applied with dummy loads to simulate vehicle fully loaded condition.

During a strain measurement, a data acquisition system setup was needed. Even though the setup of strain measurement was not as complicated as wheel transducer, it required a few strain gauges which were disposed after used. Padzi et al. [7] associated the fatigue life of steel using integrated kurtosis-based algorithm for Z-filter which served as an alternative for fatigue strain analysis. Understanding the needs for signal generation, Putra et al. [8] proposed a conversion of acceleration to strain time histories using a mathematical suspension model. However, the construction of the mathematical model required lots of effort. Hence, it was significant to have a more direct and simple method of measurement which could be immediate used for suspension fatigue life prediction.

Based on understanding of the overview of the case studies, this work proposed a generation method of force time history from two reference acceleration time histories for coil spring fatigue life assessment. Hence, the prediction of spring fatigue lives was achieved without strain measurement setup. This serves to reduce the experimental work that required for spring fatigue design. The acceleration signals were converted into relative displacement and subsequently, force time history through a linear Hooke's law. When nonlinear state of analysis, Ramberg-Osgood relationship was applied to convert the strain into stress. This analysis involved two accelerometers and a data acquisition where no mathematical model was required for force conversion.

Methodology

The method of this analysis could be divided into four steps which were real-time road data collection, acceleration-displacement time history conversion using cumulative trapezoidal numerical integration, finite element analysis (FEA) of coil spring and fatigue life prediction of the spring. The acceleration time histories of the vehicle front Macpherson suspension were measured using two single axis accelerometers. One of the accelerometers was attached at the lower arm of the vehicle to measure un-spring mass vibration signal as shown in Figure 1(a). Another accelerometer was attached at the top mount of the suspension strut to collect vibration signal of sprung mass as shown in Figure 1(b). A uniaxial strain gauge was attached at the critical region of the coil spring for strain data collection as shown in Figure 1(c). The accelerometers and uniaxial strain gauge were then connected to a data acquisition system as shown in Figure 1(d) to record the time histories. The sampling rate was determined to be 1000 Hz to include all dynamic characteristics of the road [9] were 1000 Hz was sufficient for spring fatigue analysis, as reported by Putra et al. [8].

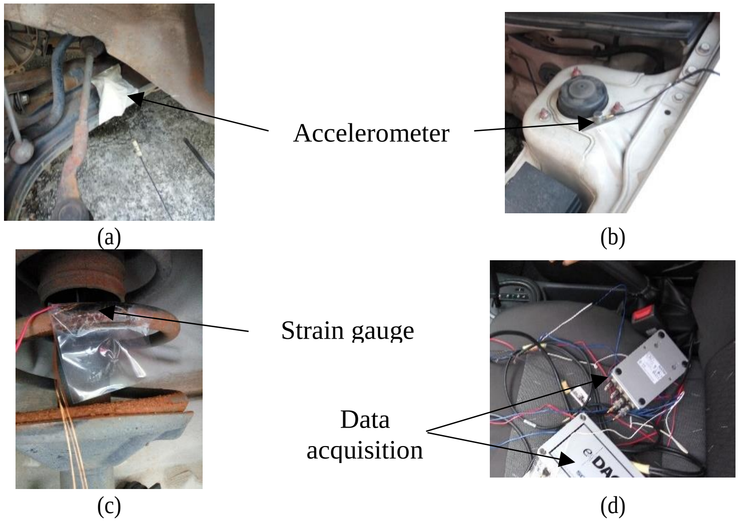


Figure 1: Experimental setup of road data collection, (a) accelerometer at lower arm (b) accelerometer at upper body, (c) strain gauge at coil spring, (d) data acquisition system

The process flow for force signal generation is shown in Figure 2. Initially, the vehicle was driven across a standard road for acceleration data measurement. The procedures to obtain the spring force time histories were shown in Figure 3 where the spring displacement was difference of u_2 and u_1. After the acceleration time histories were obtained, the time histories were then converted into velocity time histories using cumulative trapezoidal numerical integration. To obtain the displacement time histories, the velocity time histories were again integrated. In this dynamic case, the vehicle wheel was moved relatively to the vehicle body as shown in Figure 3. Therefore, the relative displacement between the displacement time histories of the wheel and vehicle body was obtained through a subtraction. Nevertheless, drift of integration point existed which caused deviation of the outcome.

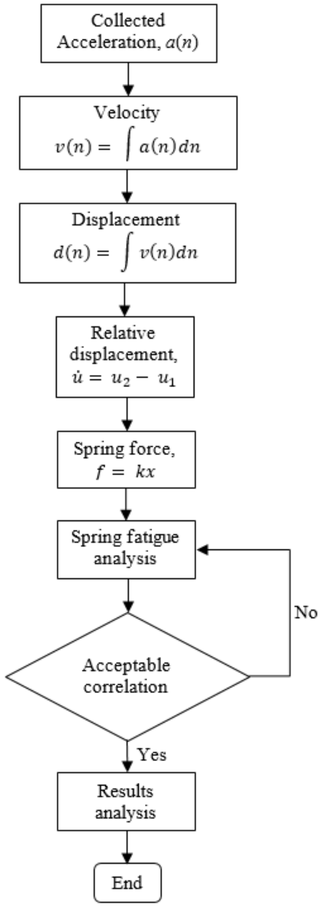


Figure 2: Process flow of signal generation for fatigue analysis

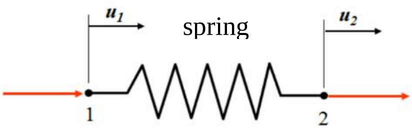


Figure 3: Relative movement of spring

where u_2 is the movement of sprung mass and u_1 is the movement of un-sprung mass, $\dot{u}$ is the relative displacement. With the known spring stiffness, the relative displacement time history was further converted into force time histories based on Hooke's law as below:

$$F = kx \tag{2}$$

where F is the spring force, k is the spring stiffness and x is the spring displacement. The damping effects were small as reported in [10] and therefore neglected in this analysis. There is a relationship between strain and displacement which is defined as follows:

$$\varepsilon = \frac{\Delta L}{L} \tag{3}$$

where ε is the strain, L is the displacement.

For FE analysis, a geometry of the spring model was constructed using a commercial CAD software, as shown in Figure 4. The spring model was pre-processed with meshing of tetra elements with 9227 nodes and 7170 elements. This spring model has considered the 3D stress including shear effects. For applied material, the most common used spring SAE 5160 with heat treatment and the mechanical properties of the spring steel are listed in Table 1. The top of the spring was fixed with a constraint while a load of 2000 N was applied at the bottom. Linear static analysis was performed to obtain the stress strain results of this spring design. In terms of fatigue life prediction, the FE model with stress strain information, the force time histories and material cyclic properties were used as input to three common used strain life fatigue model.

In general, fatigue analysis of spring could be divided into stress-life (*S-N*) or strain-life (ε-*N*) approach. *S-N* approach provides nominal fatigue results while ε-*N* approach gives the localised fatigue results [11]. ε-*N* approach considered also the low cycle fatigue where the crack initiation occurs. Hence, ε-*N* approach was more suitable for automotive fatigue analysis. For automotive application, uniaxial strain life approach was used to predict the fatigue life of a wheel rim [12]. Peiklo et al. [13] utilised the uniaxial ε-*N* approach to predict fatigue life of a toothed segment of an automotive gear. Three widely adopted ε-*N* models were applied in their analysis.

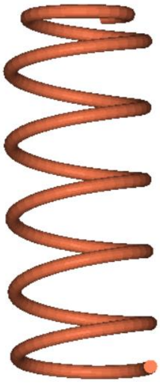


Figure 4: CAD model of the coil spring

The three strain life fatigue models were Coffin-Manson, Morrow and Smith-Watson-Topper (SWT) approach. These three models were widely used and providing different results of estimation based on mean stress effects [10]. The Coffin-Manson model is derived as follows [14]:

$$\varepsilon = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{3}$$

where σ'_f is the fatigue strength coefficient, N_f is the number of cycles to failure for a particular stress range, b is the fatigue strength exponent, ε'_f is the fatigue ductility coefficient and c is the fatigue ductility exponent. The Morrow strain life model is defined as follows:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f - \sigma_m}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{4}$$

The SWT model is mathematically defined as below:

$$\sigma_{\max}\varepsilon_a E = (\sigma'_f)^2(2N_f)^b + \sigma'_f\varepsilon'_f E(2N_f)^{b+c} \tag{5}$$

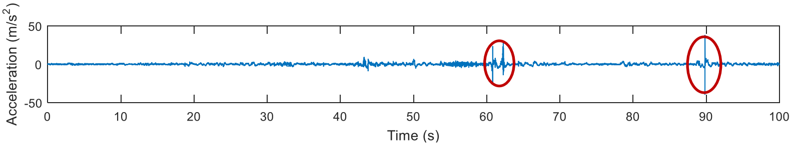
Table 1: Properties of carbon steel SAE 5160 [15]

Properties	Value
Yield strength (MPa)	1,487
Ultimate tensile strength (MPa)	1,584
Material modulus of elasticity (GPa)	207
Fatigue strength coefficient	2,063

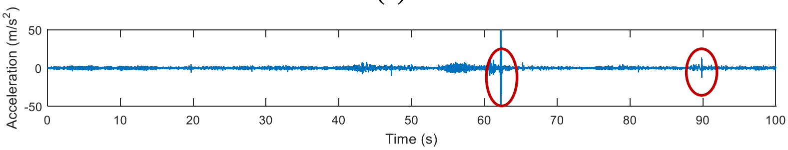
Fatigue strength exponent	-0.08
Fatigue ductility coefficient	9.56
Fatigue ductility exponent	-1.05
Cyclic strain hardening exponent	0.05
Poisson ratio	0.27

Results

The measured acceleration time histories from the vehicle is shown in Figure 5. As observed from Figure 5, most of the portion of the signals were in stationary condition. The signals have showed some transient response in time 60 to 63 s and 89 s as highlighted because the vehicle has passed through a pothole. When the vehicle travelled across the pothole, the wheel and body of the vehicle experience extra response and peaks were produced. Through applying the first cumulative trapezoidal numerical integration, the velocities of the lower arm and suspension top mount was obtained. The velocity time histories were plotted into Figure 6. Figure 6(a) shows the velocity time history for sprung mass while Figure 6(b) shows data for un-sprung mass. The velocity time histories were indicating some similar peaks at time 60 to 63 s and 89 s. The velocity time histories were then integrated for a second time to obtain the reference displacement as illustrated in Figure 7. Based on the observation, the time histories of sprung and un-sprung mass possess very similar pattern and trend because of the excitation sources were the same but with phase shift.

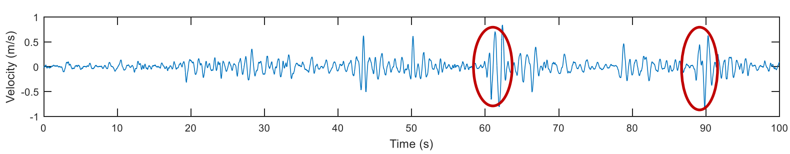


(a)

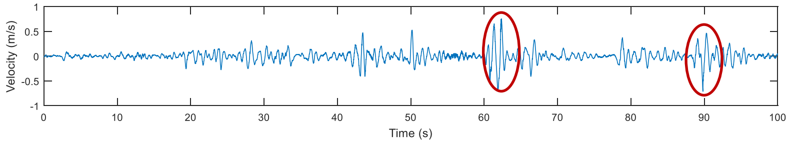


(b)

Figure 5: Measured acceleration time histories, (a) sprung, (b) un-sprung mass

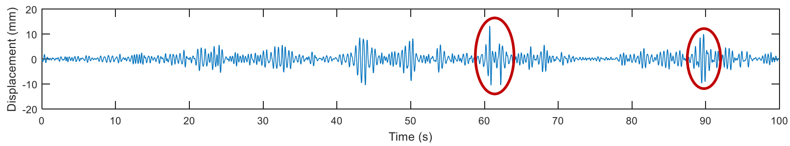


(a)

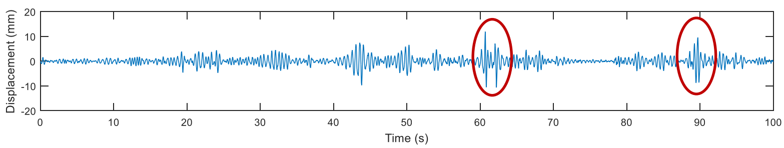


(b)

Figure 6: Velocity time history, (a) sprung mass, (b) un-sprung mass



(a)



(b)

Figure 7: Displacement time history, (a) sprung mass, (b) un-sprung mass

The relative displacement time history was obtained and plotted into Figure 8. The relative displacement was converted into force time history through multiplication of spring stiffness of 20 N/mm and shown in Figure 9. Due to linearity assumption of the spring, the force time history had the same trend as displacement time history but different in scale. The measured strain time history is shown in Figure 10. Strain time history was used for the standard fatigue life estimation and validation purpose. Based on the durability theory, the prerequisite to perform fatigue life estimation were loadings, material cyclic properties and the component geometry. Hence, the structure of the spring was analysed using FEA and the stress contour is plotted into Figure 11. Higher stress was observed at the inner surface of the spring and maximum von Mises stress as high as 1208 MPa was obtained. According to the material properties, the stress level was below yield strength and this indicated that the design of spring was good in terms of static strength.

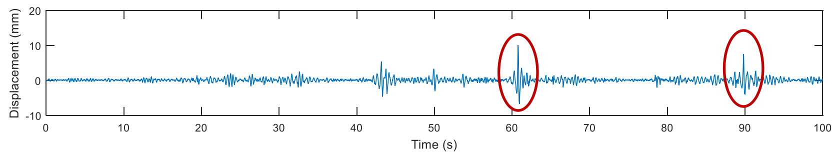


Figure 8: Relative displacement time history

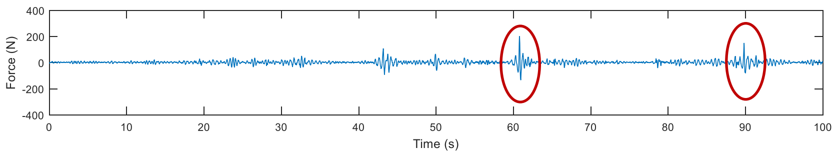


Figure 9: Force time history

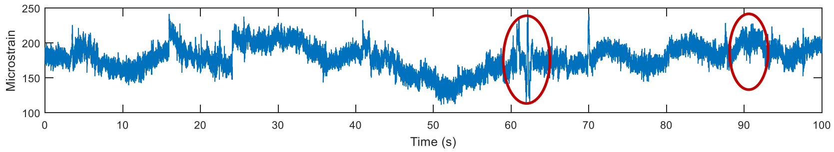


Figure 10: Measured strain time history

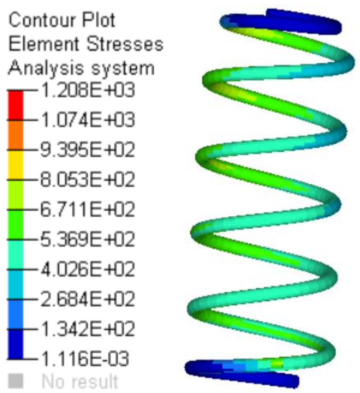
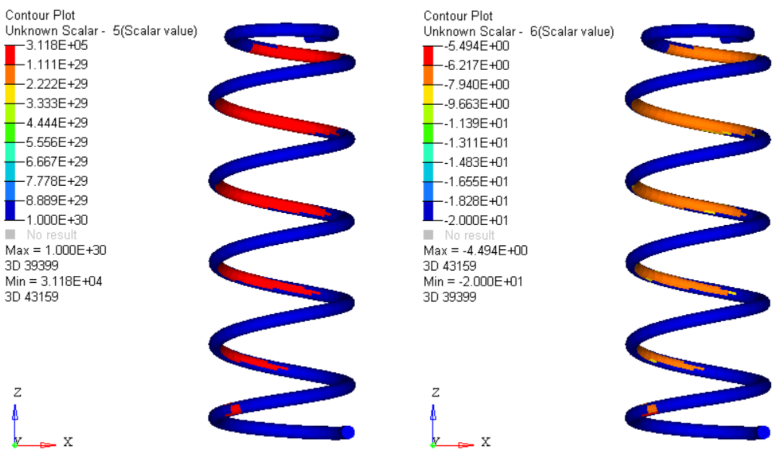


Figure 11: Stress contour of spring model

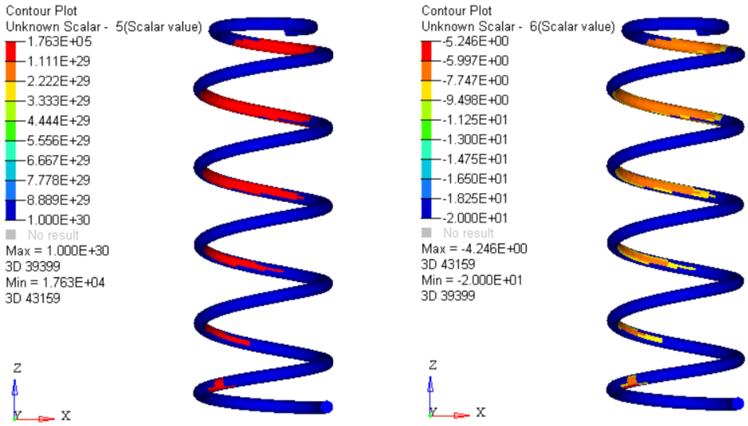
The force time history and spring model were used as input for fatigue life prediction. The fatigue contour of the spring using Coffin-Manson model was plotted into Figure 12 while the the fatigue behaviour of the spring using Morrow model is plotted into Figure 13. Meanwhile, the results of SWT model is plotted into Figure 14. The red and yellow region indicated the area where the crack was initiated. As observed from the fatigue damage distribution, the fatigue failure shall occur in the inner surface of the spring which the FEA stress results of the spring suggested the same distributions. The high stress region of spring inner surface was also reported in [16] where crack of coil spring was usually initiated from inner surface to outer surface. The fatigue life and damage results are tabulated into Table 2. Morrow and SWT model consider the mean stress effects and hence, the mean value of the loading time history was obtained. Based on a statistical calculation, the force loading time history consisted of approximate zero mean value.

When studied the fatigue results from Table 2, it was showing that the Coffin-Manson gives the highest fatigue life results when compared to Morrow and SWT model. As proposed by Al-Asady et al. [17], when the loading was tensile predominant, SWT model provided a more realistic prediction for carbon steel. When the load was compressive in nature, Morrow model was the suitable model for fatigue life prediction. In addition, the research has also suggested that when the mean loading was zero, all three models provided acceptable results. In this research, the simulated fatigue life using all three models were lied within a close range. The fatigue life analysis of the same spring using strain measurement was performed by Putra et al. [18] and the fatigue life of 1.53×10^5 was reported. The difference between force simulated fatigue life and proposed fatigue life are listed in Table 3. Based on the percentage differences, the acceleration-force fatigue life predictions have yielded a quite good accuracy.



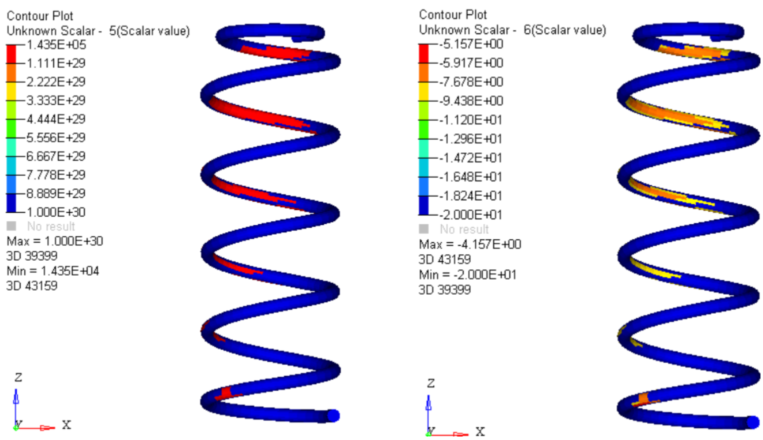
(a) (b)

Figure 12: Fatigue contour of spring using Coffin-Manson model, (a) fatigue life, (b) fatigue damage



(a) (b)

Figure 13: Fatigue contour of spring using Morrow model, (a) fatigue life, (b) fatigue damage



(a) (b)

Figure 14: Fatigue contour of spring using SWT model, (a) fatigue life, (b) fatigue damage

Table 2: Fatigue simulation results

	Coffin-Manson	Morrow	SWT
Fatigue life (blocks to failure)	3.12×10^5	1.76×10^5	1.44×10^5
Fatigue damage (damage / block)	3.12×10^{-6}	5.67×10^{-6}	6.97×10^{-6}

Table 3: Comparison between generated force and proposed fatigue life

Generated force fatigue life (blocks to failure)	Proposed fatigue life (blocks to failure) [18]	Difference (%)
3.12×10^5	1.53×10^5	104
1.76×10^5	1.53×10^5	15
1.44×10^5	1.53×10^5	6

To further validate the fatigue prediction results, the measured strain life time histories were used to predict the fatigue life and compared with the acceleration-force fatigue lives. The results of generated force and strain predicted fatigue life are tabulated into Table 4. A 1:2 or 2:1 correlation curve was used to determine the correlation between the acceleration-force converted fatigue life and strain measurement predicted fatigue life as shown in Figure 13. The results shown that the Morrow and the SWT method fitted well into the correlation curve. However, the Coffin-Manson prediction result was not fitted into this correlation curve. In this analysis, the Coffin-Manson relationship has shown a non-conservative prediction for this acceleration-force fatigue analysis. Abdullah et al. [19] has also reported that the Coffin-Manson relationship provided the most non-conservative results when compared to Morrow and SWT method in a steel lower arm fatigue analysis. In this analysis, the Coffin-Manson model has shown the result that distributed far away from the acceptable region. The results have also indicated that the accelerated-force fatigue life gave more consistent analysis results.

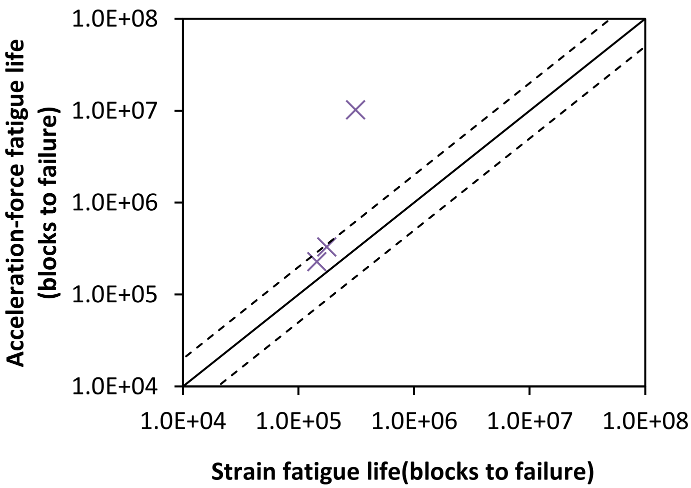


Figure 13: The correlation between acceleration-force and strain fatigue life

Table 4: Comparison between generated force and strain fatigue life

Generated force fatigue life (blocks to failure)	Strain fatigue life (blocks to failure)
3.12×10^5	1.02×10^7
1.76×10^5	3.28×10^5
1.44×10^5	2.27×10^5

Conclusions

The fatigue life prediction of coil spring has been presented using two measured acceleration signal and cumulative trapezoidal numerical integration. The displacement time histories of the spring were obtained through the integration and converted into force time histories. In order to validate the usability of the generated force signal, the generated force signal was used to predict fatigue life of the spring. The fatigue results have shown an acceptable correlation with proposed fatigue life prediction where the fatigue lives of the spring were 3.12×10^5, 1.76×10^5 and 1.44×10^5 blocks to failure using Coffin-Manson, Morrow and SWT model, respectively. The generated force fatigue lives were then validated with measured strain signal using a conservative approach. Both the validations have revealed that Coffin-Manson fatigue life prediction were deviated from acceptable the range. However, this method could provide an acceptable fatigue life prediction method of a coil spring without using any strain measurement data acquisition system.

Acknowledgement

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