Jurnal Kejuruteraan 37(3) 2025: 1581-1592
https://doi.org/10.17576/jkukm-2025-37(3)-39

Wavelet Energy Analysis of Random Road Load Data of Coil Spring for Fatigue Damage Characterisation

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Received 30 June 2024, Received in revised form 10 February 2025
Accepted 10 March 2025, Available online 30 May 2025

ABSTRACT

Suspension coil springs of ground vehicles are exposed to random excitations, leading to the complication of fatigue failure after a certain service period. Therefore, durability prediction is essential to prevent the failure of coil springs. However, random road excitations are highly complex data and often require a large sample of loading histories to statistically represent the actual loading conditions. Hence, advanced signal processing techniques are used to obtain useful information related to fatigue events in the loading histories, reducing the duration of analysis. This study aims to characterise the fatigue damage of coil spring through the wavelet energy parameter of vibration loading. In this study, wavelet transform was selected to process the random road load data collected from road tests. The car test was conducted on various roads to collect various loading data for the coil spring. Using wavelet transform, the time-frequency information of the signals was converted into wavelet coefficients in the form of a scalogram. Subsequently, wavelet energy was determined from the wavelet coefficients and correlated to the fatigue damage in the strain loading histories. Results showed that high wavelet energy are closely related to large-amplitude events, which eventually contribute to significant fatigue damage. Thus, it becomes possible to identify large-amplitude cycles due to strong road excitations, which have significant fatigue impact, using wavelet analysis. This approach can improve the efficiency of durability analysis by extracting the high-damaging sections from the loading histories.

Keywords: Durability; coil spring; road excitation; wavelet transform

INTRODUCTION

Suspension components of ground vehicles such as coil springs are susceptible to high risk of fatigue failure, primarily due to the continuous exposure to random vibration (Chin et al. 2023a; Kong et al. 2018; Pastorcic, Vukelic & Bozic 2019). Uneven road surfaces, speed bumps and potholes can result in vigorous excitations to the suspension system when the vehicle passes through the road surface. Catastrophic failure of coil springs can cause loss of control of the vehicle and jeopardise the safety of passengers. Therefore, it is important to consider the impact of randomness of loading data on the fatigue life of coil springs.

Fatigue failure analysis in coil springs is a critical aspect of automotive engineering, as these components are subjected to cyclic loading over extended periods, leading to material degradation and eventual failure. The fatigue life of a coil spring depends on several factors, including material properties, geometric characteristics, surface conditions, and loading conditions (Pastorcic, Vukelic & Bozic 2019). In general, fatigue failure in coil springs occurs due to the initiation and propagation of microcracks, which gradually expand under repeated loading cycles until catastrophic failure takes place. One of the primary causes of fatigue failure is stress concentration at specific locations, such as the inner surface of the coil or areas with manufacturing defects (Bergh et al. 2021). The presence of corrosive environments can further accelerate fatigue crack growth by weakening the material structure. Traditional fatigue life prediction methods involve S-N curves (stress-life approach) and strain-life methods, which estimate the number of cycles to failure based on stress or strain amplitudes. However, these methods have limitations when dealing with variable amplitude loading, which is common in real-world conditions. More advanced techniques, such as damage accumulation models and fracture mechanics-based approaches, provide better accuracy in predicting fatigue failure by considering crack initiation and propagation phases (Mroziński 2019).

In current industrial practice, the durability of coil springs is often examined experimentally with constant amplitude loading. Experimental tests require long testing time as well as high prototyping costs, and thus are very inefficient (Bergh et al. 2021; Chin et al. 2024). Recent advancements in numerical simulations, particularly finite element analysis (FEA), have enabled more precise fatigue life predictions by incorporating real-world loading data and material behaviour. By applying FEA, engineers can identify stress hotspots and optimize coil spring designs for enhanced durability. Additionally, experimental validation using strain gauges and high-speed cameras can complement numerical studies, providing insights into fatigue failure mechanisms. A main challenge in FEA-based durability analysis is the complexity of random loading data (Ren et al. 2025). Owing to the stochastic behaviours of the road load data, a large sample size is often needed to statistically represent the complex loading conditions (Ugras et al. 2019). This will inevitably increase the computational load of the FEA modelling and lower the efficiency of the analysis.

To tackle the problem of large sample size of loading histories for durability analysis, researchers begin to utilize signal processing tools, for example, the Fourier transform, the short-time Fourier transform (STFT), the wavelet transform and others to extract important information from the loading histories. Fourier transform, introduced by Joseph Fourier in 1822, is capable of identifying the frequencies contained in a time series in the form of frequency spectrum. STFT is the earliest time-frequency method to identify the time and frequency properties of a signal simultaneously. However, STFT has a constant resolution in time-frequency domain, leading to ineffective capture of transient properties. Unlike STFT, wavelet transform offers flexibility in time-frequency resolution and improved capabilities in processing of complex signals (Chin et al. 2024). In addition, wavelet transform also offers good capability in capturing transient events which are closely related to high amplitude events in road load data.

The integration of modern signal processing techniques, such as wavelet transform, further enhances the accuracy of fatigue failure analysis by identifying high-amplitude loading cycles that contribute significantly to fatigue damage. Understanding these high-amplitude events is essential for designing more resilient suspension systems and improving vehicle safety. Consequently, ongoing research in this field focuses on developing hybrid approaches that combine experimental data, numerical simulations, and advanced signal processing tools to achieve more reliable fatigue failure predictions and extend the service life of automotive coil springs. For example, Rahim et al. (2021) decomposed the strain loading histories of suspension coil spring with discrete wavelet transform to determine the fatigue damage in different frequency ranges. Putra et al. (2020) characterised the wavelet energy of strain loading signals of coil spring for fatigue damage correlation using continuous wavelet transform (CWT). Results showed that high amplitude cycles, which are associated with high fatigue damage, can be effectively identified using wavelet transform. Some studies also focus on statistical modelling of the loading distribution to explore the impact of loading statistical parameters on durability performance (Cianetti et al. 2018; Palmieri et al. 2017).

This study proposes to characterise the vibration loading data of a car suspension system operating under real-world conditions using CWT for fatigue damage determination. It is important to understand the characteristics of high-amplitude cycles in the loading histories, as these cycles contribute significantly to fatigue damage. Therefore, this research aims to aid in identifying high-amplitude events in the loading data that are associated with considerable fatigue damage.

METHODOLOGY

Figure 1 depicts the methodology flow chart. This study includes the loading signals acquisition, wavelet analysis of the signals and fatigue damage correlation to the wavelet parameters.

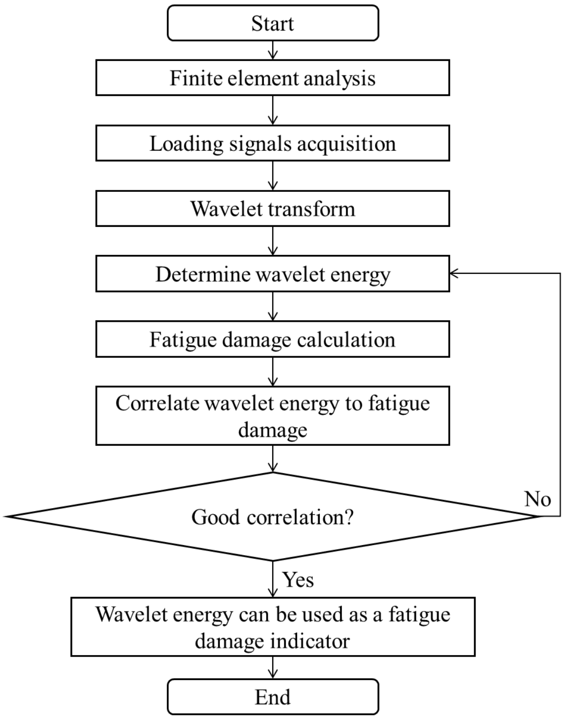


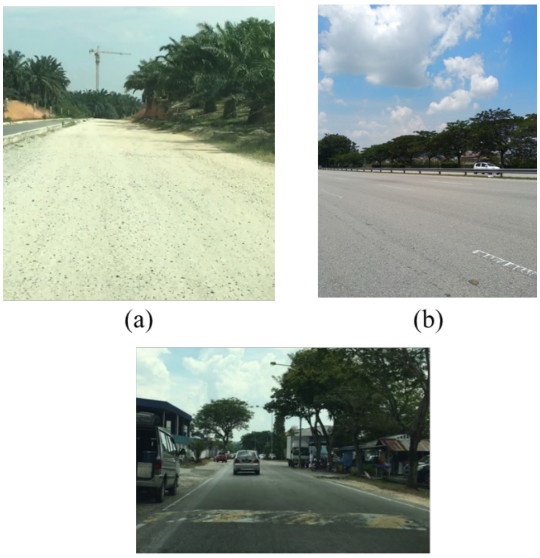
FIGURE 1. Methodology flowchart

FINITE ELEMENT ANALYSIS OF COIL SPRING

A static load analysis was performed to determine the hotspot location with the highest stress level. This was essential for identifying the optimal placement of the strain gauge to ensure that the critical strain most likely to contribute to fatigue failure was accurately measured. A geometric model of the coil spring was built based on actual measurement of the coil spring dimensions. The coil spring had five active coils with coil wire diameter of 12 mm and mean diameter of 120 mm. Next, the coil spring model was meshed with 2 mm octahedral elements. The upper part of the coil spring was fixed, while the lower part was subjected to a static load of 3600 N, representing a quarter of the vehicle's weight with three passengers, each assumed to weigh 70 kg (Chin et al. 2023b). The coil spring was made of SAE 5160 carbon steel, with a modulus of elasticity of 207 GPa and a Poisson's ratio of 0.3. From the analysis, the hotspot location was identified as the position with the highest Von Mises stress level.

ROAD LOAD DATA ACQUISITION

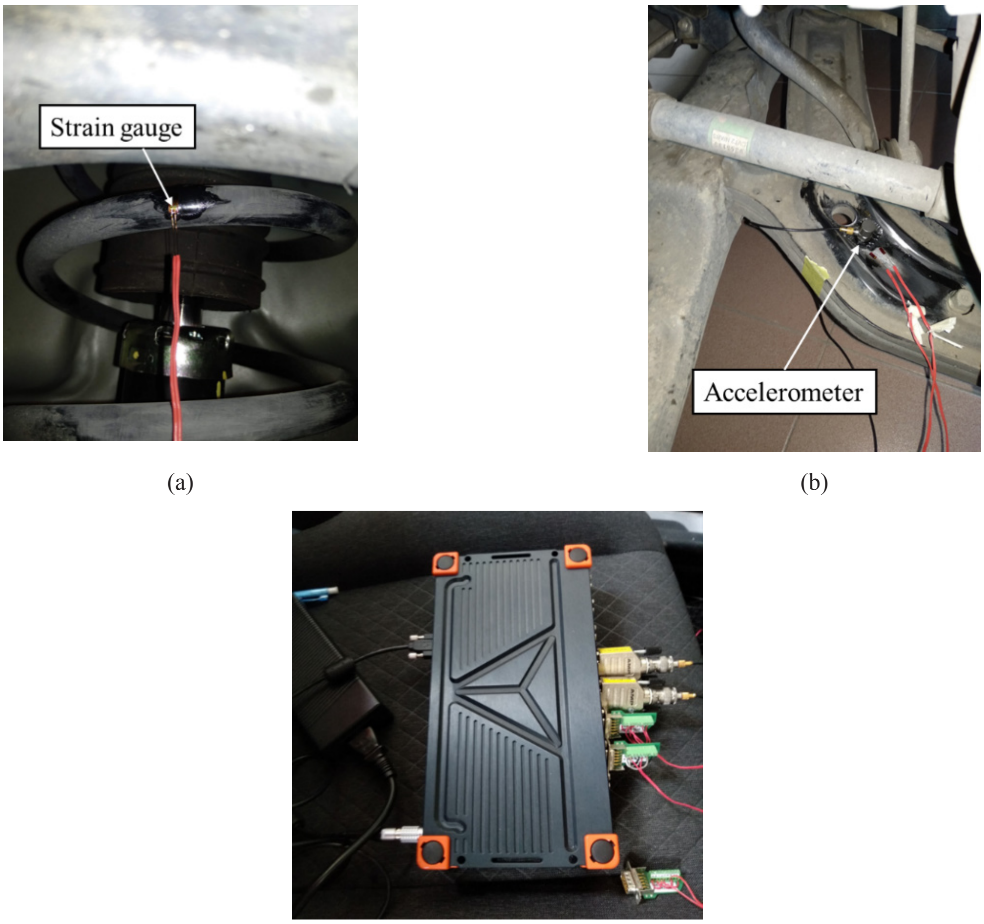
A road test was conducted to collect loading data from the car suspension system. A 1,500 cc sedan was driven on roads with varying conditions, including rural areas, highways, and industrial areas, as shown in Figure 2. The rural area had unpaved roads with highly irregular surfaces, causing intense vibrations as the vehicle traveled. Industrial roads featured numerous speed bumps designed to slow down vehicles, along with many potholes resulting from heavy truck traffic. In contrast, the highway had the smoothest surface profile due to regular maintenance. The vehicle speed was maintained at 30-40 km/h in rural and industrial areas, while on the highway, the average speed was 80-90 km/h. An accelerometer was mounted on the lower control arm to measure the wheel's vertical acceleration, as the wheel's vertical movement directly responded to road surface irregularities. Thus, measuring vertical acceleration provided valuable insights into road conditions. Simultaneously, a strain gauge was attached to the surface of the coil spring to record strain loading histories for fatigue life evaluation. The placement of the strain gauge was determined based on an FEA static load analysis, which identified the areas experiencing the highest stress levels in the coil spring. A data logger recorded the measurements at 500 samples per second. Figure 3 illustrates the location of the sensors during the car tests and the data acquisition equipment used.



(a) (b)

(c)

FIGURE 2. Tested road conditions: (a) Rural area, (b) Highway, (c) Industrial area



(a) (b)

(c)

FIGURE 3. Instruments for road load data acquisition: (a) Strain gauge, (b) Accelerometer, (c) Data logger

WAVELET TRANSFORM AND FATIGUE DAMAGE ESTIMATION

The acquired vibration and strain loading histories were processed using continuous wavelet transform (CWT). The CWT of time series *f(t)* will yield the wavelet coefficient $W_\psi(s,u)$, such that (ALTobi et al. 2019):

$$W_\psi(s,u) = \frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} f(t)\psi^*\left(\frac{t-u}{s}\right)dt \quad (1)$$

where ψ^* is the complex conjugate of mother wavelet function, u is the translation parameter and s is the scale parameter. The Morlet wavelet has exceptional capability in detecting transient events and thus it is used for the analysis (Le 2017). The wavelet energy (E_w) at particular time position u can be determined from the sum of the $W_\psi(s,u)$ at different scale s. E_w can also be mathematically express as:

$$\bar{E_w} = \int_0^{\infty} W_\psi(s,u)\,ds \quad (2)$$

Next, the fatigue damage assessment based on the strain loading data is conducted using the Morrow stain-life model. The Morrow model is given as:

$$\varepsilon = \frac{\sigma_f' - \sigma_m}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \quad (3)$$

where represents the total strain amplitude, $2N_f$ denotes the reversals to failure, σ_f is the fatigue strength coefficient, and b is the fatigue strength exponent, ε_f represents the fatigue ductility coefficient, c is the fatigue durability exponent, E is the modulus of elasticity and σ_m signifies the mean stress. The Morrow strain-life model is selected because it considers the mean-stress effects in the fatigue damage calculation (Aliyari, Miresmaeili & Azadi 2025).

Subsequently, the computed fatigue damage was correlated with the wavelet energy E_w to determine the relationship between the wavelet energy and fatigue damage.

RESULTS AND DISCUSSION

VIBRATION AND STRAIN LOADING HISTORIES

Figure 4 shows the FEA results of the coil spring subjected to a static load. The results show that the highest Von Mises stress is 1136 MPa, located on the inner surface of the second coil from the bottom. The highest Von Mises stress is below the material's yield strength of 1487 MPa, indicating that the spring is safe under a static load of 3600 N. Additionally, the hotspot appeared on the inner surface of the coil due to the effects of spring curvature and the combined torsional and shear stresses (Chin et al. 2021). This result agrees with the findings of Putra, Husaini & Machmud (2020), which showed that coil spring hotspots are located on the inner coil surface. Hence, the hotspot with the highest stress level was selected as the placement location for the strain gauge during the car test.

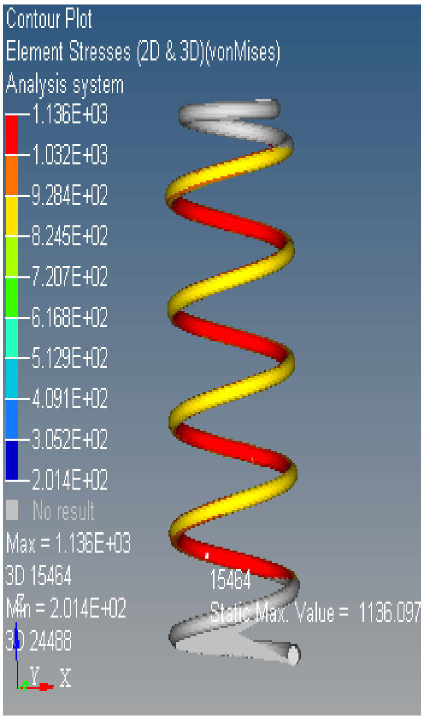


FIGURE 4. FEA analysis result of coil spring

VIBRATION AND STRAIN LOADING HISTORIES

Figures 5 and 6 shows the vibration and strain loading signals acquired in the road tests, respectively. There are many transients with high amplitudes in the rural and industrial road signals compared to the highway road. This is caused by the uneven surface in the areas, resulting in more intense excitations. The large amplitude fluctuations are mainly responsible for high fatigue damage (Manouchehrynia et al. 2023). Compare with the industrial signals which occasionally showed high amplitude fluctuations, the rural signals were consistently filled with high amplitude events. This can be related to the uneven road surfaces in the rural area and hence resulted in vigorous vibration and strain loading to the suspension components. It has been well known that fatigue damage is closely related to the amplitude of the loading histories. Therefore, signal processing technique must be able to capture the high amplitude events in a loading signal to characterise the fatigue damage.

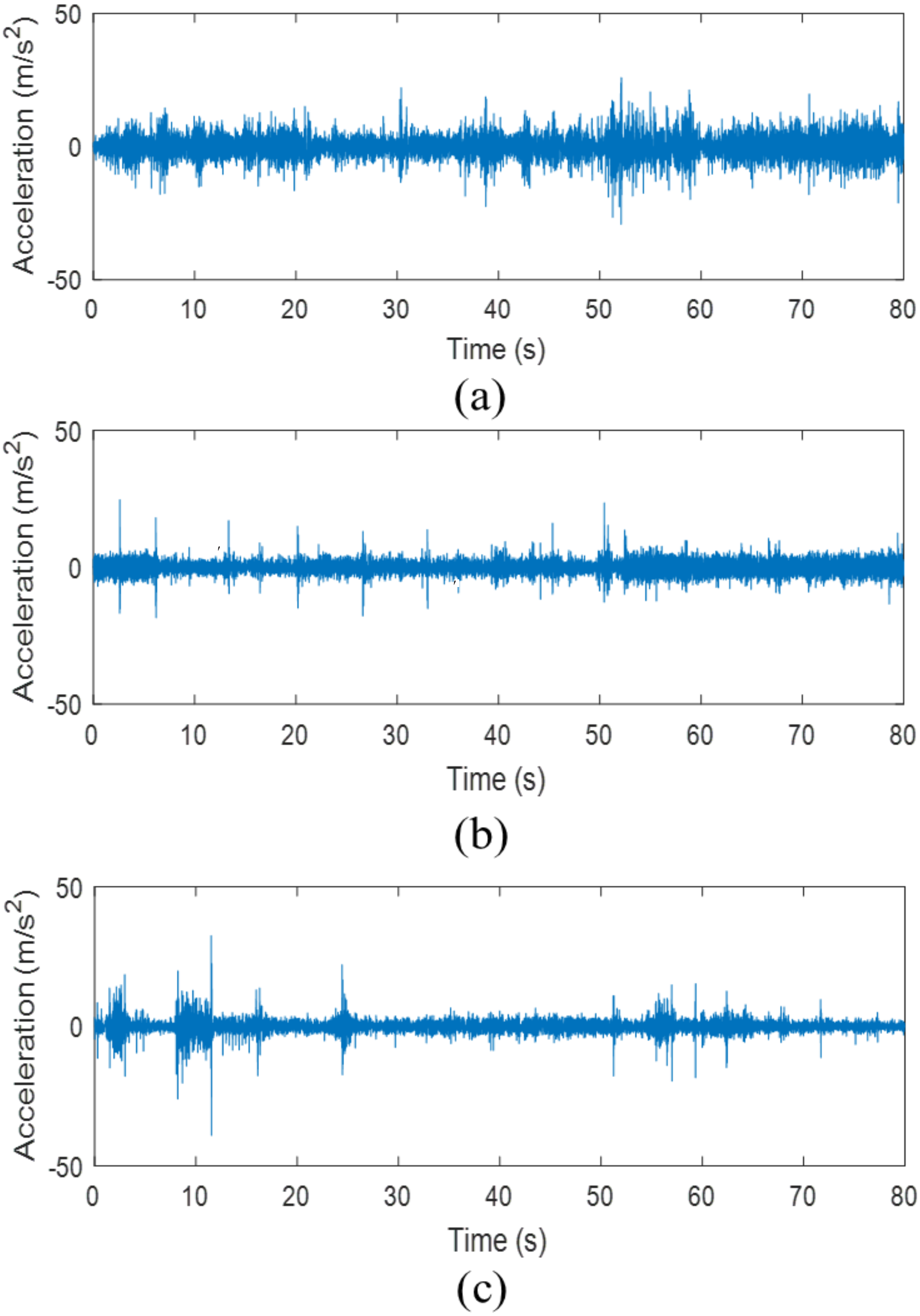


FIGURE 5. Vibration loading histories measured in (a) rural road, (b) highway and (c) industrial road

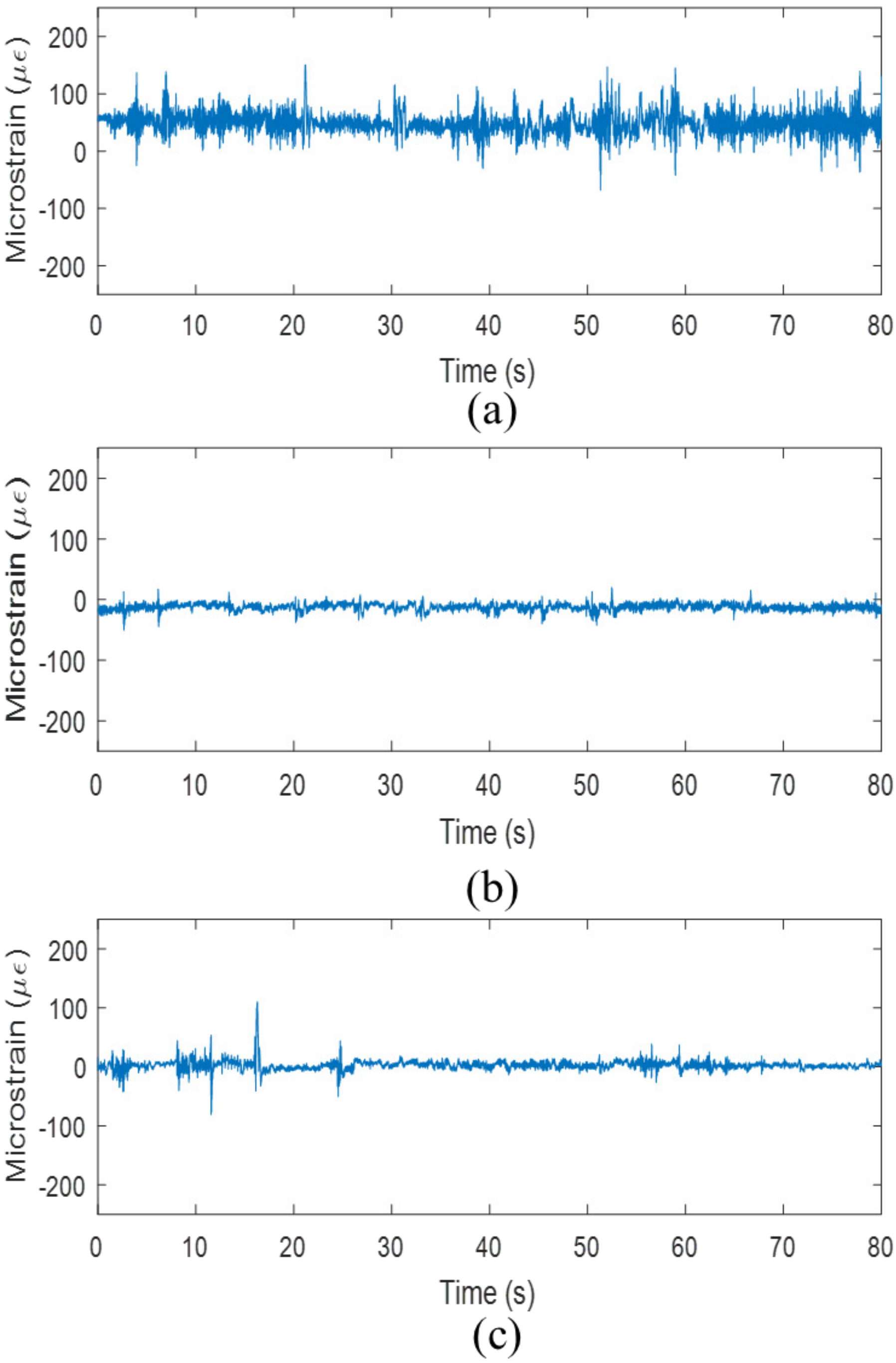


FIGURE 6. Strain loading histories measured in (a) rural road, (b) highway and (c) industrial road

Tables 1 and 2 present the statistical properties of the loading histories recorded using the accelerometer and strain gauge, respectively. The vibration signals exhibited zero mean properties due to the inherent characteristics of the sensor; therefore, their mean values are not included. In contrast, for strain histories, the mean values represent the overall loading characteristics. A negative mean value indicates compressive loading, whereas a positive mean value corresponds to tensile loading. The analysis of the rural strain loading histories showed a mean strain of 48.96 με, indicating a predominantly tensile loading condition. Tensile loading is known to contribute to higher fatigue damage compared to compressive loading, as reported by Chin et al. (2023a). This is because tensile stresses promote crack initiation and propagation more effectively than compressive stresses, making tensile loading more detrimental to fatigue failure.

TABLE 1. Statistical properties of vibration signals

Signal type	RMS (m/s^2)	Skewness	Kurtosis
Rural	3.77	-0.02	5.76
Highway	2.22	0.11	8.63
Industrial	2.24	-0.43	30.83

TABLE 2. Statistical properties of strain signals

Signal type	Mean (με)	RMS (με)	Skewness	Kurtosis
Rural	48.96	52.55	0.29	6.41
Highway	-12.37	14.50	0.14	3.32
Industrial	2.77	19.87	0.85	12.49

The root-mean-square (RMS) value, which is an amplitude-related parameter, is commonly used as an indicator of signal energy in fatigue analysis. Higher RMS values generally suggest more intense excitations. In both vibration and strain histories, the rural signals exhibited the highest RMS values among all the measured signals. This suggests that the excitation forces experienced on rural roads are more intense compared to industrial and highway conditions.

Skewness and kurtosis, which are the third and fourth statistical moments, respectively, provide insights into the distribution of extreme values within the signals. Higher kurtosis indicates the presence of more frequent or extreme peaks in the data. According to Kihm et al. (2015), signals with higher kurtosis values tend to result in greater fatigue damage. The rural strain data exhibited numerous high-amplitude events, leading to a kurtosis value of 6.41—higher than that observed in the highway strain histories. However, the industrial vibration and strain histories recorded the highest kurtosis values of 30.83 and 12.49, respectively. This is primarily due to the occasional occurrence of high-amplitude events, creating an extremely sharp data distribution. These findings suggest that kurtosis is an effective parameter for detecting transient events associated with high fatigue damage. The ability to identify such events is crucial for improving durability assessment and predictive maintenance strategies, as it enables a better understanding of how extreme loading conditions affect structural integrity over time.

WAVELET TRANSFORM AND FATIGUE DAMAGE CHARACTERISATION

Using wavelet transform, the wavelet scalogram of the vibration and strain loading histories were obtained. Subsequently, the wavelet energy E_w was also computed. Fatigue damage was also calculated with the Morrow model. Figure 7 depicts the time-frequency properties and wavelet energy of the vibration signals. Figure 8 illustrates the time-frequency scalogram, wavelet energy and running fatigue damage of the strain signals.

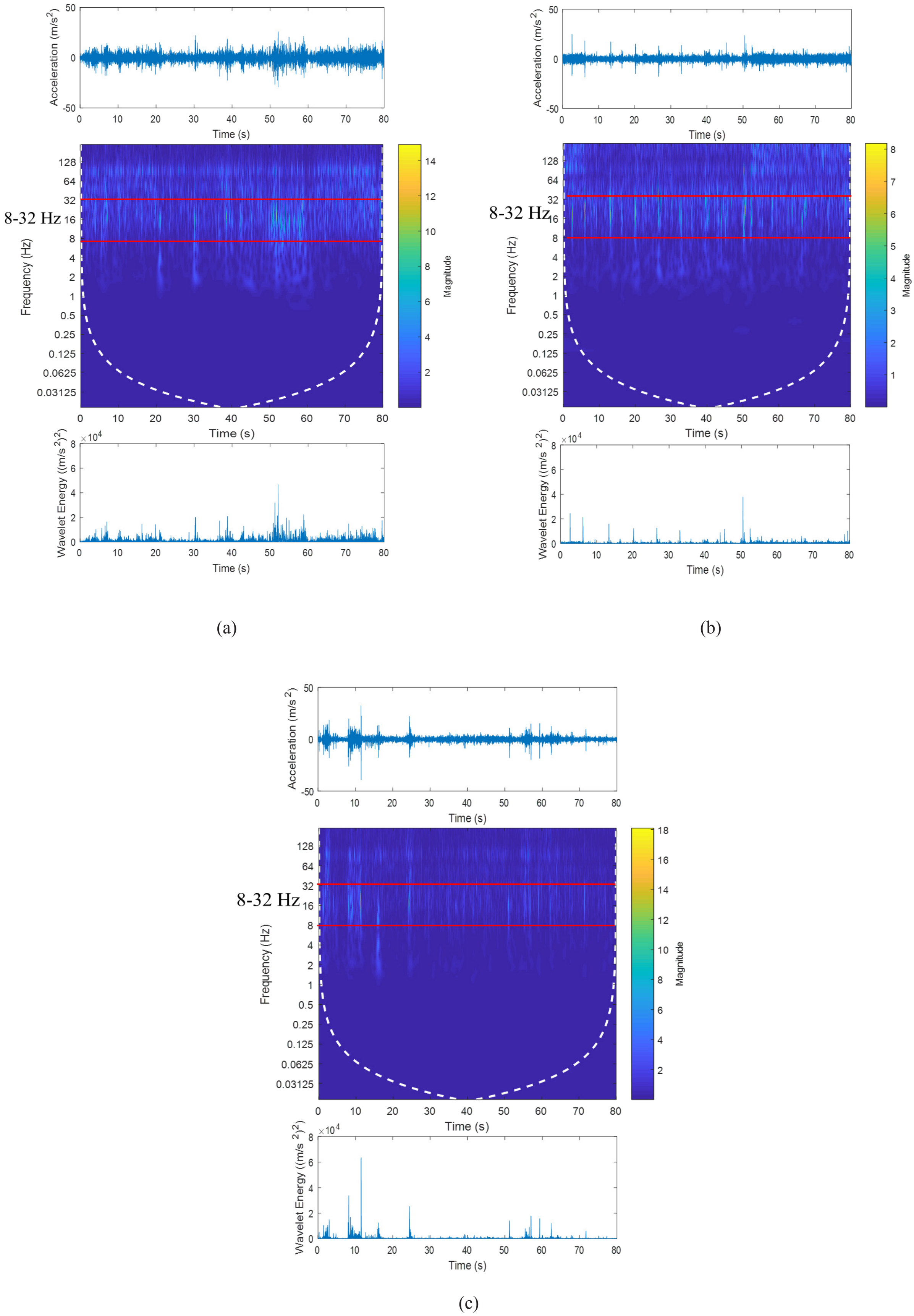
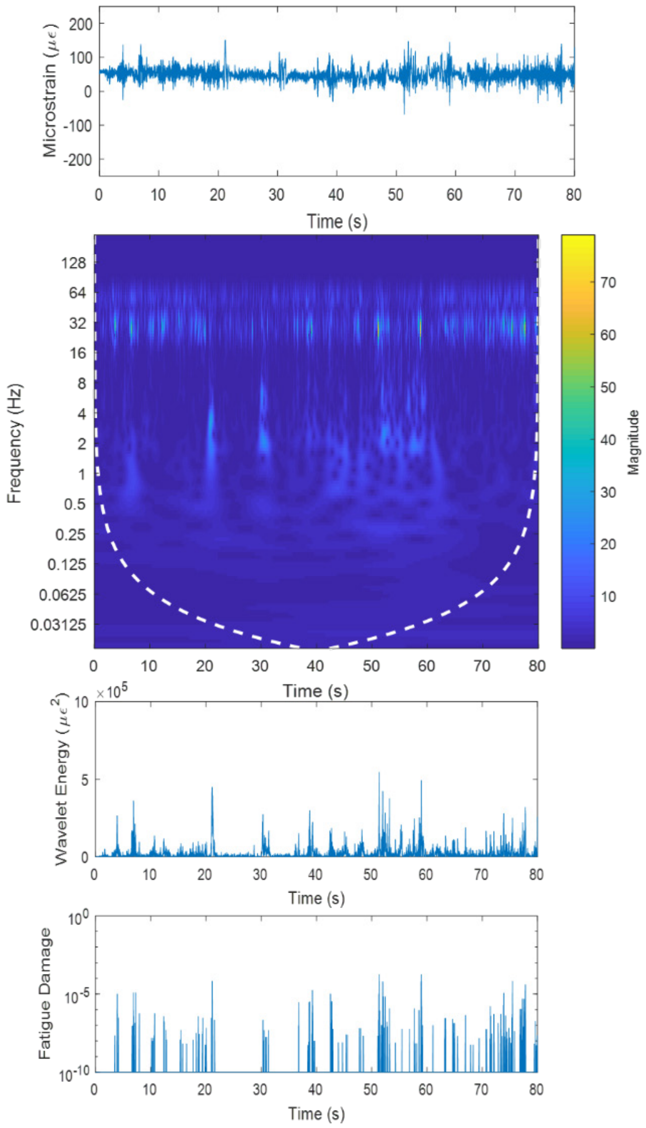


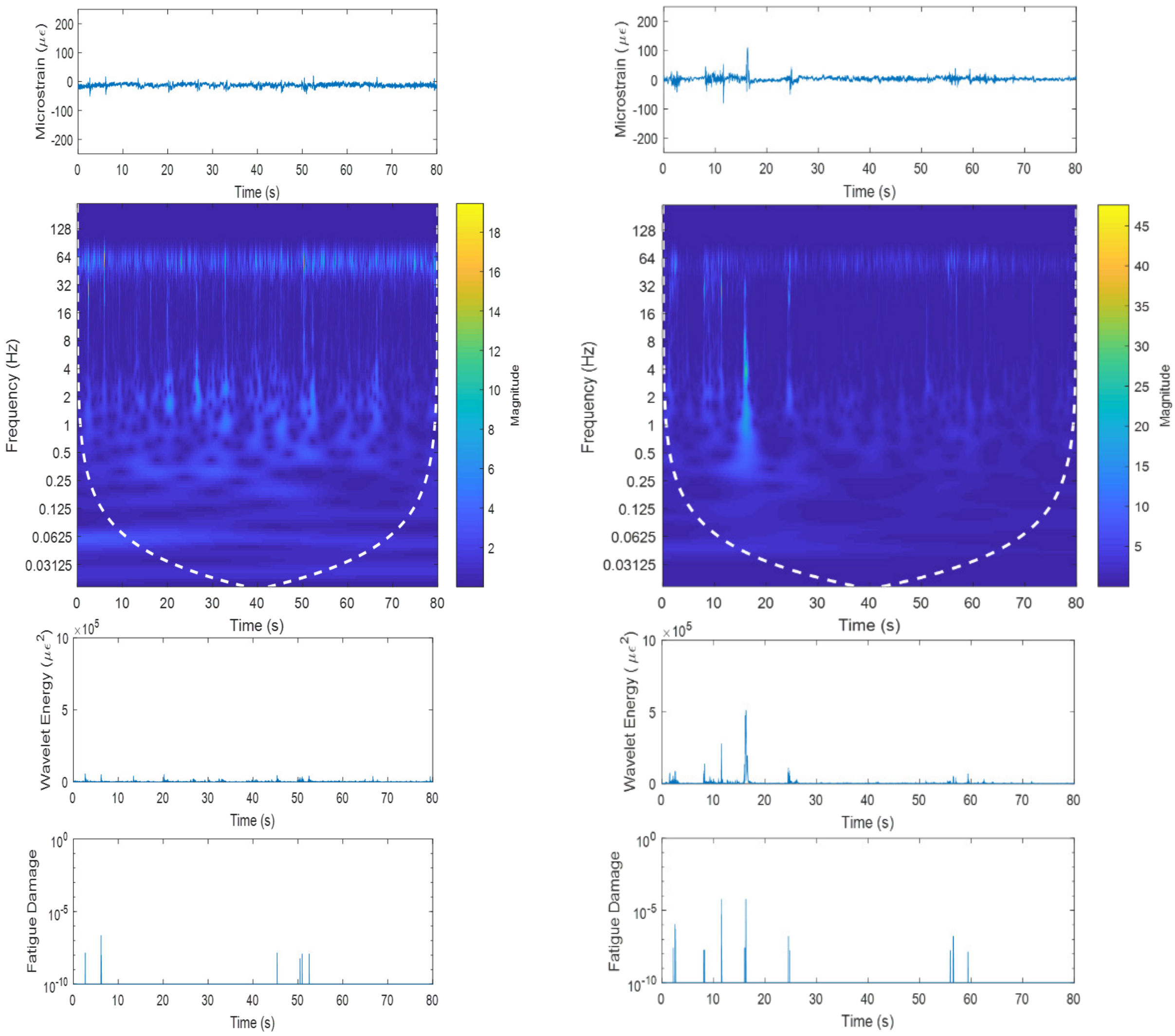
FIGURE 7. Time-frequency scalogram and energy content of the (a) rural road, (b) highway and (c) industrial road vibration signals

From Figure 7, the wavelet transform revealed that large amplitude fluctuations were observed as high-magnitude coefficients between 8 and 32 Hz. Minaker & Yao (2017) found that road excitations are low-frequency signals below 20 Hz. Furthermore, high wavelet energy was produced in response to high amplitude fluctuations. In particular, the highest wavelet coefficient magnitude was recorded in the industrial signal at 13s, within the 8–32 Hz range. This corresponds to the highest amplitude changes in the vibration signal due to a bump event. Therefore, it is shown that wavelet analysis can effectively recognise transient high-amplitude events, which provide important information for durability analysis. The rural vibration data consistently exhibited large amplitude changes, resulting in high wavelet energy throughout the signal. Meanwhile, the wavelet energy was also able to reflect high-amplitude events that occasionally occurred in the industrial and highway signals.

In Figure 8, the strain loading histories displayed a similar trend to the vibration signals. High wavelet energy was observed in the rural signal, while the highway signal exhibited lower wavelet energy. Additionally, the running damage analysis identified high fatigue damage at high-amplitude events associated with high wavelet energy. Unlike the rural signal, the highway strain signal showed limited fatigue damage because its strain histories contained only low-amplitude cycles. Thus, wavelet analysis is proven to be an effective tool for characterising fatigue damage in coil springs by determining the wavelet energy parameter.



(a)



(b) (c)

FIGURE 8. Time-frequency scalogram, wavelet energy and running fatigue damage of the (a) rural road, (b) highway and (c) industrial strain signals

CONCLUSION

This research highlights the effectiveness of wavelet transform as a powerful signal processing technique for detecting high-amplitude variations in loading patterns, which are strongly correlated with high fatigue damage in mechanical components. Unlike traditional analysis methods, wavelet transform enables the identification of transient and localized fluctuations within the signal, making it particularly valuable for assessing fatigue in complex, real-world conditions. The study demonstrated that wavelet energy serves as a reliable indicator for detecting and quantifying these high-impact events, offering a more precise and data-driven approach to fatigue analysis.

Furthermore, these findings are important for improving durability assessment, as they help engineers and researchers better understand how coil springs respond to different road conditions. Using wavelet-based analysis allows for a more accurate evaluation of fatigue life while reducing the need for extensive physical testing. This approach lowers computational costs and saves time and resources. In the long run, applying wavelet transform to fatigue analysis can help improve the design and maintenance of automotive suspension systems.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Kebangsaan Malaysia for their financial support under the grant GGPM-2024-031 and the European Unions's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 730888.

DECLARATION OF COMPETING INTEREST

None.

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