International Journal of Integrated Engineering: Special issue 2018:
Mechanical Engineering, Vol. 10 No. 5 (2018) p. 21-25
© Penerbit UTHM
DOI: https://doi.org/10.30880/ijie.2018.10.05.004

Strain Signal Characterisation Using the 4th Order of Daubechies Wavelet Transform for Fatigue Life Determination

A. A. A. Rahim, S. S. K. Singh*, S. Abdullah, M. Z. Nuawi

Centre for Integrated Design for Advanced Mechanical System (PRISMA), Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia.

Received 17 April 2018; accepted 6 August 2018, available online 30 August 2018

Abstract: This paper presents the significance of Discrete Wavelet Transform to provide more accuracy by using the Wavelet (Db4) Daubechies approach to analyse original signals obtained from the actual responses of an automotive suspension system. The time-frequency domain considers both time and frequency parameters, making this approach more efficient compared to the time domain and frequency domain approaches. An original signal was obtained from three road types: highway road, rural road and residential road. These signals were classified into 12 levels of decomposition where each level contained its own frequency range. The decomposed signals were then analysed using fatigue analysis to obtain the fatigue damage at each interval, which was then compared to the original signal. Results show that the decomposition signals from levels 1 to level 2 for highway and residential roads and level 1 to level 3 for rural roads gave a significant value of fatigue life located in the range of 2:1 and 1:2 in the fatigue life prediction graph. In summary, the Daubechies (Db4) Wavelet approach is capable of correlating the fatigue life of those components that contribute to the failure of a suspension system.

Keywords: Decomposition, discrete wavelet transform, fatigue analysis, time-frequency domain

1. Introduction

Fatigue is a regular cause of failure in mechanical structures which are subjected to time variable loadings. Fatigue failure can occur in any structure even if the structure receives only low amplitude cyclic loads [1]. The cycle obtained is the main characterising element for fatigue damage. Fatigue vibration is the vibration that shows non-stationary behaviour. This vibration occurs while the structure responds at the natural frequency of the structure [2]. The usual approach is a time domain-based analysis that evaluates time histories such as level crossings, range and rain flow. This approach allows the identification of cycles with different amplitudes and mean values. The time domain approach provides actual activities in time series, but has limited application for certainty in fatigue analysis.

Therefore, frequency domain analysis has been adopted to analyse the responses from a vibration fatigue signal [3]. Power spectral density is a common approach in frequency domain analysis to identify the dominant frequency obtained. Although the frequency domain approach can reveal the amplitude of the signal frequency, the disadvantage is that it cannot pinpoint information about when that particular dominant frequency occurred [4]. The time domain and frequency domain approaches adopt linear analysis, but the actual random loading conditions on structures are by nature non-linear, with a varying interaction between loadings, changes in road roughness and turbulence loads. Therefore, those significant activities that contribute to failure cannot be detected [5].

In this study, the strain signals obtained from the coil spring were characterised in the time-frequency domain based on different types of road conditions. The characteristics of the wavelet decomposition signals related to the fatigue analysis. By using the time-frequency domain, both elements - time and frequency - can be detected. Therefore, this approach is more efficient for vibration fatigue analysis.

2. Theory

2.1 Fatigue Analysis

In the time domain approach, fatigue life is predicted using strain-life approaches including the Coffin-Manson relationship, Smith-Watson-Topper (SWT) and Morrow models. Strain-life approaches are used with Palmgren-Miner's linear cumulative damage rule as shown in Equation (1) [6].

$$D=\sum_{i=1}^{k}\frac{n_i}{N} \tag{1}$$

where D is the damage value, N is total number of cycles and n_i is the number of applied cycles. The Coffin-

---

*Corresponding author: salvinder@ukm.edu.my

Manson relationship, SWT and Morrow models are expressed in Equation (2), (3) and (4), respectively.

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

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

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

where ε_a is the true strain amplitude, σ is the fatigue strength coefficient, b is the fatigue strength exponent, ε'_f is the fatigue ductility coefficient, c is the fatigue ductility exponent, E is the Young's modulus and $2N_f$ is the number of cycle to failure. The fatigue life in the Coffin-Manson relationship is calculated based on strain amplitude at zero mean stress. The SWT and Morrow models consider the mean stress effect in the calculation of fatigue life. Morrow's correction of the mean stress effect is more realistic. The fatigue damage can be calculated with Equation (5):

$$D = \frac{1}{N_f} \tag{5}$$

where D is fatigue damage and N_f is the number of cycle to failure.

2.2 Discrete Wavelet Transform

The main idea of the Discrete Wavelet Transform (DWT) analysis is to decompose a signal into different levels of resolution, a process known as multi-resolution [6]. This process provides a simple hierarchical framework to represent the information in a time series. At different resolutions, the details of a signal usually characterise different physical structures of themselves. These detail at each decomposed signals contains the different information obtained from the original signal [7].

Decomposition of the signals was performed using Daubechies (Db4) Wavelet order with 12 levels of decompositions, which are the optimal levels to remove most noise. Wavelet decomposition calculates the group index known as the wavelet coefficient [8]. The coefficients are obtained from the signal regression generated at different frequency scales in a wavelet. The generated signal establishes the correlation between the wavelet and the section of the signal being analysed. The Daubechies (Db4) Wavelet of class is defined in the following equation:

$$\varphi(x) = \sqrt{2}\sum_{k=0}^{2N-1}(-1)^k h_{2N-1-k}\,\varphi(2x-k) \tag{6}$$

where $h_0, \ldots, h_{2N-1} \in \Re$ and N is the order.

3. Methodology

Fig. 1 shows the location of strain gauges located on the coil spring of the car suspension system. The strain gauge was attached to the structure based on the ASTM E1237-93 (2009): Standard Guide for Installing Bonded Resistance Strain Gauges. The car was driven on different road profiles such as highway with speed 70-80 km/h, rural with speed 40-50 km/h and residential with speed 20-30 km/h types, to obtain the strain signals. The duration for all signals collected was 120 seconds with a 500 Hz sampling frequency. For each strain signal, a fatigue analysis was performed to obtain the fatigue damage and fatigue life of the structure. This method is essential to determine the suspension damage incurred on each of the different road types.

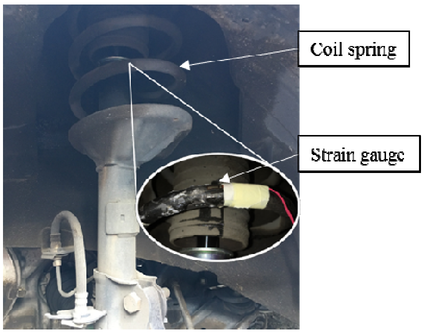


Fig. 1 Position of strain gauge attached at car coil spring.

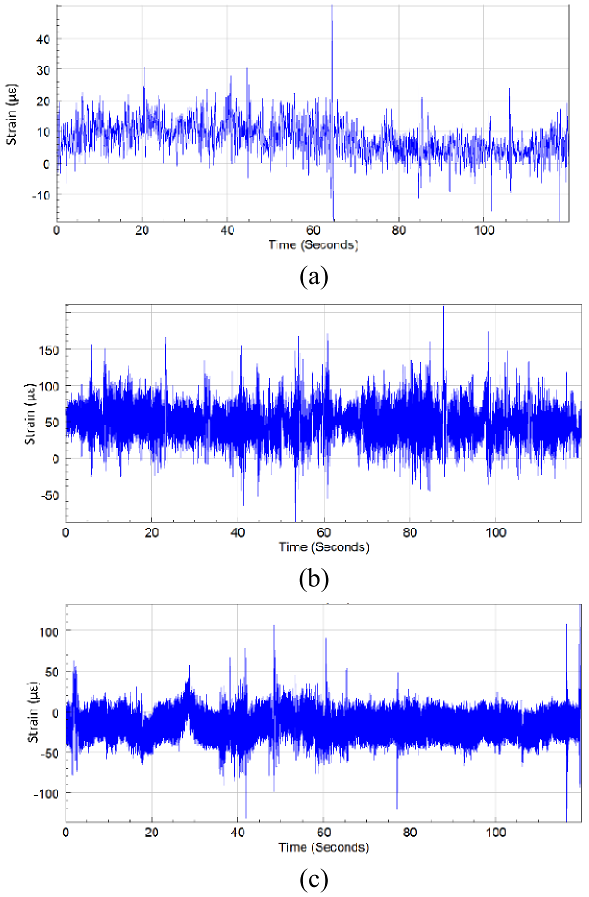
Next, the signals underwent DWT into 12 levels of decomposition. A transformation decomposes a signal into basic functions known as wavelets [9]. This process was done separately for different segments of the time domain signal, and at different frequencies. This approach allows the usually non-stationary signal to be analysed [10]. Another advantage to this approach is that DWT also allow the construction of filters for stationary and non-stationary signals.

4. Results and Discussion

The selected road profile is considered a variable amplitude type, which can be regarded as the representative common road type in Malaysia. All signals were collected considering different vehicle speeds, which are dependent on the road condition. Fig. 2 shows the time domain signal obtained for all types of road; highway, rural and residential roads. From Fig. 2(a), the time domain signal for a highway is smoother and shows fewer peaks. This is due to the road surface being smoother compared to the other types of road which are bumpy with the existence of potholes and uneven road surfaces. The strain amplitude range and mean for the highway road is the lowest, between -20 με until 50 με with mean value 15 με compared to rural and residential roads which are -100 με until 200 με with mean value 50 με and -100 με until 150 με with mean value 25 με, respectively. This can be proven by referring to Table 1. In Table 1, the fatigue life of the highway is the highest compared to other road surfaces, with total fatigue life 5.51×10^5 cycles (highway road), 8.61×10^4 cycles (rural road) and 4.99×10^5 cycles (residential road). All these fatigue life values been calculated by using SWT model. This is due to this model is suitable for positive mean value. Hence, it can be concluded that the type of road surface provides a crucial pattern on the time domain signals for suspension systems.

Table 1 Fatigue analysis of four type of roads selected.

Type of road	Highway Road	Rural road	Residential road
Damage	1.81×10^{-6}	1.16×10^{-5}	2.00×10^{-6}
Life	5.51×10^{5}	8.61×10^{4}	4.99×10^{5}



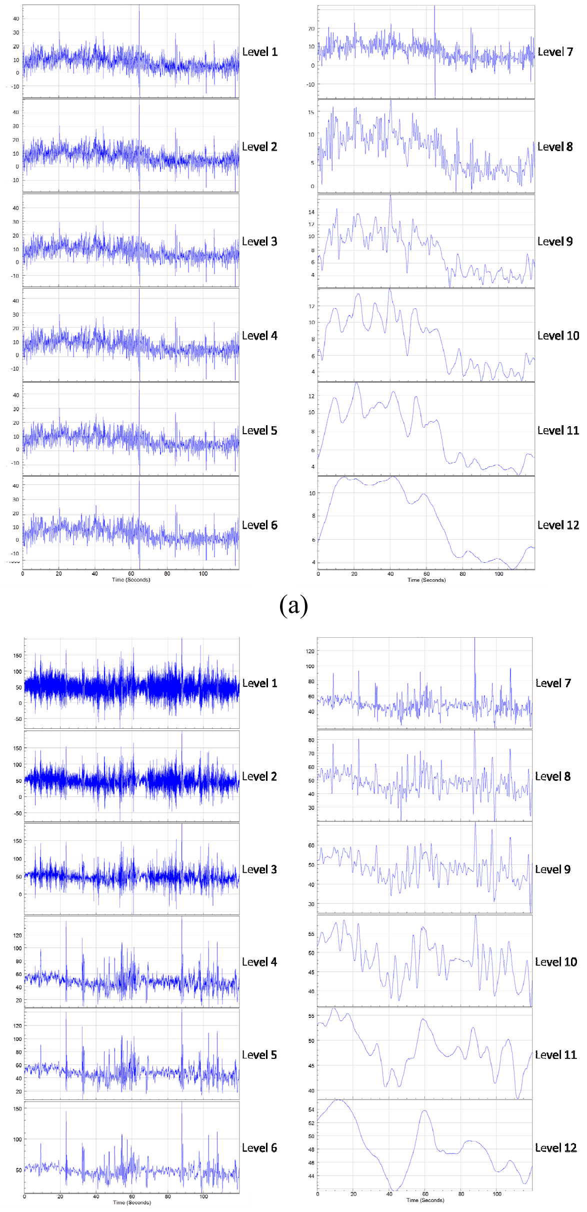
(a)

(b)

(c)

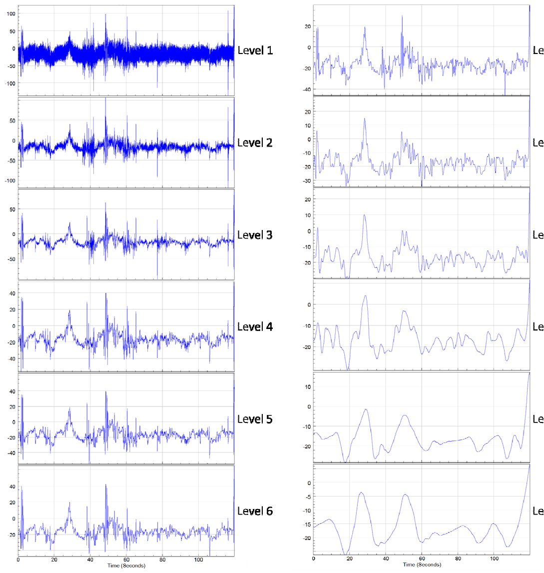
Fig. 2 The original signals for: (a) Highway road, (b) Rural road and (c) Residential road

Fig. 3 presents the decomposition of the signals using the 4th order of Daubechies Wavelet Transform sampled at 500Hz. With 12 levels of signals generated, the corresponding frequencies were determined as listed in Table 2. From the decomposed signals, the general separation of the data is clearly divided into locally non-overlapping time scale components [8]. For example, early levels for all signals are almost similar to the original signals and lie in the region of 2:1 and 1:2 as can be observed in Figure 4, which shows a comparison of the predicted fatigue life by the present strain-life model for all types of road conditions. It is seen that the early levels of decomposition fatigue life signals are in agreement with the original signal. This is due to the aim for decomposition is to remove noise in the original signal based on its own frequency band [11]. As the level increased, the fatigue life has been increased due to the high amplitude events that contribute to failure is eliminated. This is shown the higher level of decomposition is useful to form the signal without the effect of high amplitude. Based on Figure 4, level 1 and level 2 for highway road and residential road are located in the acceptable region for fatigue life durability. Meanwhile, levels 1 up to 3 for rural roads lie in the acceptable region. The fatigue life values from level 10 until level 12 for rural and residential road type are very small. Therefore, the value is not given due to being below the endurance limit. This result can be used as an indicator that the proposed early level of decomposition signal is related to the fatigue life of the component and that the other levels can be considered as a lesser effect or noise from the road surface. From the results obtained, this method is capable of correlating the fatigue life of the component. DWT can filter the noise from the signal and, from the authentic signals, construct a new signal able to give the characteristic for each signals constructed [10].



(a)

(b)



(c)

Fig. 3 The 12 levels of decomposition signals for:
(a) Highway road, (b) Rural road and (c) Residential road

Table 2 Fatigue life of 12 levels of decomposed signals at different frequency.

Signal	Frequency (Hz)	Highway road	Rural road	Residential road
Level 1	0-500	3.39×10^5	1.01×10^5	5.97×10^5
Level 2	0-250	3.26×10^5	1.24×10^5	7.81×10^5
Level 3	0-125	1.38×10^5	1.86×10^5	1.56×10^6
Level 4	0-62.5	9.06×10^4	9.05×10^5	3.31×10^6
Level 5	0-31.25	6.77×10^4	5.60×10^5	2.14×10^6
Level 6	0-15.625	6.49×10^4	4.10×10^5	2.16×10^6
Level 7	0-7.813	1.10×10^5	7.88×10^5	1.19×10^7
Level 8	0-3.906	2.16×10^6	5.55×10^6	1.78×10^8
Level 9	0-1.953	2.70×10^6	9.17×10^7	6.02×10^8
Level 10	0-0.9766	9.65×10^6	-	-
Level 11	0-0.4883	2.23×10^7	-	-
Level 12	0-0.1221	1.51×10^8	-	-

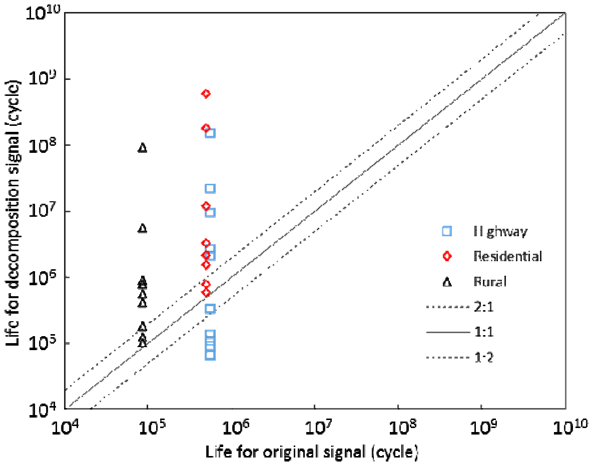


Fig. 4 Correlation analysis to determine the suitability of fatigue life.

5. Summary

The road surface effect was studied by using three road types, which were highway, rural, and residential roads. The time domain signal for a highway road showed fewer peaks compared to the other type of roads with values of fatigue life at 5.51×10^5 cycles, 8.61×10^4 cycles and 4.99×10^5 cycles for highway road, rural road and residential road, respectively. The different fatigue life values usually occur because smooth road surfaces have a higher fatigue life compared to other road surfaces, which may be bumpy with potholes and uneven road surfaces contributing to a shorter fatigue life. Therefore, the Daubechies Wavelet Transform method is used to decompose the signals into each levels in order to characterise the signal behaviour.

A performance of Daubechies Wavelet Transform revealed that this approach can be used to separate different frequency components of the signal efficiently. A close similarity was observed between the original signal and early level decomposition signals. Based on a comparison of predicted fatigue life by the presented strain-life model for all types of road conditions, the early levels of decomposition fatigue life signals are in agreement with the original signals. Level 1 and level 2 for highway roads and residential roads are within the acceptable region for fatigue life durability, while level 1 up to level 3 lies in the acceptable region for rural roads.

In conclusion, this result can be used as an indicator that the proposed early level of a decomposition signal is related to the fatigue life of the component, and that the other levels can be regarded as a lesser effect or noise from the road surface. From the results obtained, this method is capable of correlating the fatigue life of the component which contributes to failure of the suspension system.

References

[1] Cesnik, M., and Slavic. J. Vibrational fatigue and structural dynamics for harmonic and random loads. *Journal of Mechanical Engineering*, Volume 60, (2014), pp. 339-348.

[2] Burns, J.T., Kim, S., and Gangloff. R.P. Effect of corrosion severity on fatigue evolution in Al–Zn–Mg–Cu. *Corrosion Science*, Volume 52, (2010), pp. 498–508.

[3] Braccesi, C., Cianetti, F., Lori, G., and Pioli, D. Random multiaxial fatigue: A comparative analysis among selected frequency and time domain fatigue evaluation methods. *International Journal of Fatigue*, Volume 74, (2015), pp. 107–118.

[4] Putra, T. E., Abdullah, S., Schramm, D., Nuawi, M. Z., and Bruckmann, T. Reducing cyclic testing time for components of automotive suspension system utilising the wavelet transform and the fuzzy c - means. *Mechanical Systems and Signal Processing*, Volume 90, (2017), pp. 1–14.

[5] Belsak, A., and Flasker, J. Wavelet analysis for gear crack identification. *Engineering Failure Analysis*, Volume 16, (2009), pp. 1983–1990.

[6] Apetre, N., Arcari, A., Dowling, N., Iyyer, N. and Phan, N. Probabilistic model of mean stress effects in strain-life fatigue. *Procedia Engineering*, Volume 114, (2015), pp. 538–545.

[7] Azmi, A., Khaman, K.K., Ibrahim, S., Khairi, M.T.M., Faramarzi, M., Rahim, R.A., Yunus, M.A.M. Artificial Neural Network and wavelet features extraction applications in nitrate and sulphate water contamination estimation. *International Journal of Integrated Engineering*, Volume 9, (2017), pp. 64-75.

[8] Medina-Daza, R.J., Vera-Parra, N.E., Upegui, E. Wavelet daubechies (db4) transform assessment for worldview-2 images fusion. *Journal of Computers*, Volume 12, (2017), pp. 301-308.

[9] Ustundag, M., Sengur, A., Gokbulut, M., and Ata, F. Performance comparison of wavelet thresholding techniques on weak ECG signal denoising. *Przeglad Elektrotechniczny*, Volume 89, (2013), pp. 63-66.

[10] Sifuzzaman, M., Islam, M.R., and Ali., M.Z. Application of wavelet transform and its advantages compared to Fourier transform. *Journal of Physical Sciences*, Volume 13, (2009), pp. 121-134.

[11] Jamaluddin, F.N, Bakti, Z.A.K., Harun, M.K., Aminnudin, A., Wavelet analysis on FECG detection using two electrodes system device. *International Journal of Integrated Engineering*, Volume 5, (2013), pp. 20-25.