Application of a Computational Data Editing Algorithm to Summarise Fatigue Road Loadings

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Abstract: - One of the input variables in the durability analysis in automotive research is the load history. Since the nature of fatigue road loadings contain a mixture of high and low amplitude cycles, high amplitude cycles play a part in determining the degree of damage occurring. Therefore, it seems appropriate to see a method to summarise road load data. The process can be performed using a computational algorithm of fatigue data editing, known as Wavelet Bump Extraction (WBE) algorithm. This algorithm was developed for extracting fatigue damaging events, or bumps, from a fatigue road loading in order to produce a shortened signal. Finally, it is important to maintain the fatigue damage of the shortened signal as close to the original signal, with the retention of the original load sequences.

Key-Words: - Automotive, Computational, Fatigue, Fatigue road loadings, Simulation, Variable amplitude, Wavelet, WBE

1 Introduction

Fatigue damage analysis is one of the key stages in the design of vehicle structural components. One of the vital input variables in the fatigue assessment of consumer products is the load history. For ground vehicles, which have an extremely wide range of uses, a representative road load time history can be hard to quantify. Since it is generally the large amplitude cycles presence in the load histories that cause the majority of damage, they should be retained for durability testing [1].

Several approaches for retaining high amplitudes cycles have been introduced in various domains: time, peak and valley, frequency, cycles, damage and histogram. The most commonly applied procedures in the research literature have been based in the time and the frequency domains [2]. The latest approach applied for the fatigue data editing is using the wavelet transform [3] using the railway data set.

A new wavelet-based fatigue data editing method introduced by the author for summarising the road load fatigue data [4,5] by identifying fatigue features (or also known as fatigue damaging events or bumps) and extracting them from the history whilst preserving the load cycles sequence is important. This method was specifically designed to identify and extract the fatigue features using the orthogonal wavelet transform by means of the 12th order of the Daubechies wavelet family [6]. This algorithm is called Wavelet Bump Extraction (WBE)

Thus, the objective of this paper is to present the computational application of WBE in summarizing fatigue road loadings which have a variable amplitude pattern. In this analysis, the mission signal fatigue damage (the shortened output signal) is equivalent to that of the original signal.

2 Literature Background

2.1 Wavelet Bump Extraction Algorithm

The WBE algorithm has been previously developed by the main author [4,5] which contains three main stages (Fig. 1): the wavelet decomposition process, the identification and extraction of the fatigue damaging events, and the production of a mission signal.

In WBE, the 12th order of the Daubechies wavelet transform [6] was chosen as a function for the signal decomposition into the wavelet levels. Each level describes the time behaviour of the signal within a specific frequency band. Using the WBE algorithm, fatigue damaging events are identified in wavelet groups. A wavelet grouping stage is used to cluster wavelet levels into a single region of significant vibrational energy or based on the Power Spectral Density (PSD) plot, which is plotted in the frequency domain. This subdividing of the original signal permits analysis to be performed for each frequency region independently, avoiding situations where small bumps in one region are concealed by the greater energy of other regions of the frequency spectrum. Detail of the WBE operation can be found in the related literature [4].

In this algorithm, a bump (Fig. 2) or also known as fatigue damaging event is defined as an oscillatory transient which has a monotonic decay envelope either side of a peak value. Bump was identified in wavelet groups based on a search which identifies the points at which the signal envelope inverts from decay behaviour. The identified bumps are then extracted by removing from the original time history the complete section between the start and the end of the bump. All the bump segments are then combined in order to produce the WBE mission signal. Ideally, the WBE mission signal has shorter time length but equivalent in the global signal statistics and the fatigue damage values.

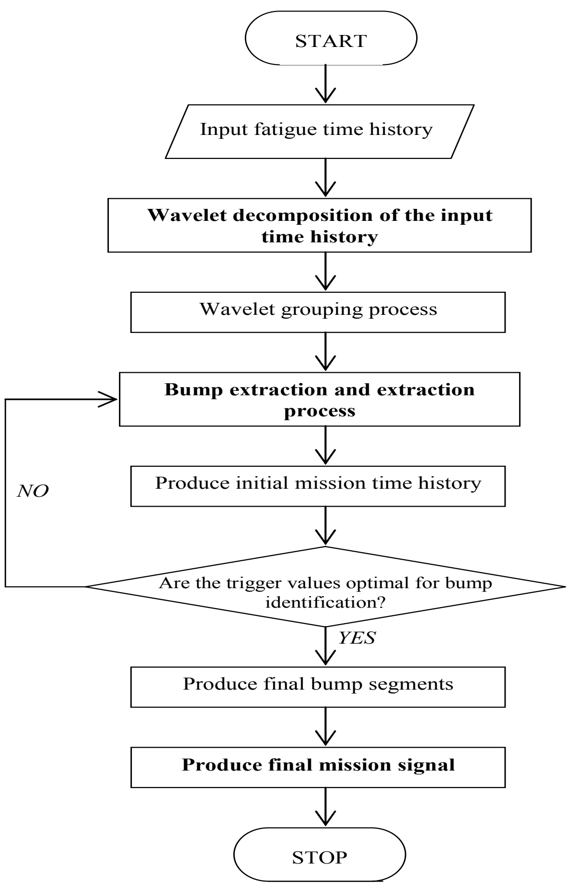


Fig. 1. Flowchart of the WBE algorithm

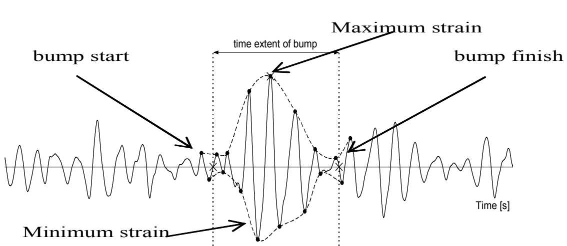


Fig. 2. A decay enveloping of a bump

2.2 Mathematical Model for Fatigue Damage

It is common that the service loads acquired on components of machines, vehicles, and structures are analysed for fatigue life using crack growth approaches. For these components, it is important to predict crack initiation in order to avoid fatigue failure by replacing the part from service at the appropriate time [7]. Hence, a fatigue life estimation based on the related strain-based approach is usually used in these cases.

In practice, fatigue loadings measured on the automotive components exhibit random and VA loading behaviour. Currently, the majority of fatigue life predictions are based on the Palmgren-Miner linear cumulative damage rule. This approach (associated with the established strain-life model, i.e. the Coffin-Manson relationship, the Morrow and Smith-Watson-Topper (SWT) mean stress correction effects) assumes no load-interaction accountability that occurs in variable amplitude fatigue loadings. Hence, an improved method of fatigue life prediction have been developed by DuQuesnay *et al.* [8], called the Effective Strain Damage (ESD) strain-life model. This model has been developed to solve the load sequence effects problem exposed in the cases using variable amplitude loadings on the basis of the material crack growth. This mathematical model is defined as

$$E\Delta\varepsilon^* = A(N_f)^B \tag{1}$$

where E is the material modulus of elasticity, $\Delta\varepsilon^*$ is a net effective strain range for a closed hysteresis loop, A and b are the material constants, and N_f is the number of cycles to failure.

The magnitude of $E\Delta\varepsilon^*$ for a given cycle is a function of the material crack-opening stress and it is dependant on the prior stress and strain magnitudes in the loading history. For considering the cycle sequence effect, the model was optimised based on the crack opening changes for each cycle [9]. For the fatigue life calculation using this model, a variable amplitude loading must be rainflow counted in order to extract fatigue cycles. Finally, the fatigue life, N_f, for each cycle can then be calculated using Eq. (1).

In the post-processing analysis to determine the fatigue damage potential, a round bar specimen was assumed to have a smooth surface with unity fatigue notch factor and made from BS 080A42 steel. In Eq. (1), the parameters A and B were found to be at 119,000 MPa and -0.5, respectively [4]. The monotonic mechanical properties of BS 080A42 steel are listed in Table 1.

Table 1. Monotonic properties of BS 080A42 steel

Ultimate tensile strength, S_u [MPa]	624
Modulus of elasticity, E [GPa]	210
Static yield stress 0.2%, S_y [MPa]	342
Area reduction, (%)	51.9
Elongation (%)	28.4

3 Computational Data Simulation: Results and Discussions

In order to verify the ability of WBE to compress VA fatigue signals, three fatigue road loadings containing a range of possible behaviours were created. These signals (T1 – T3) are shown in Fig. 3.

3.1 Signals Selection for the WBE Application

The T1 signal (Fig. 3a), is a road loading amplitude (VA) loading sampled at 200 Hz for 45,000 data points. The 225-second signal was measured on the front left lower suspension arm of an automobile which was travelling on public road surface (mixture of smooth and irregular asphalt). T3 was used to validate the ability of the WBE algorithm in selecting an appropriate number of bumps when attempting to summarise a long time history.

Signal T2 (Fig. 3b) is a strain signal which was measured on a lower suspension arm of a van travelling at 34 km/h over a pavé test track. This signal was sampled at 500 Hz for a total of 23,000 data points, producing a record length of 46 seconds.

The final signal for the WBE validation, T3, is illustrated in Fig. 3d. T3 contains 12,500 discrete points and was sampled at 204.8 Hz, producing a total record length of 61 seconds. It was measured on an automobile (not the same as T1) front suspension component while travelling over a proving ground manoeuvres, containing rough road surface. T3 exhibits a low frequency background that contains occasional shocks.

3.2 Results Obtained from the WBE Application

The first menu of WBE is shown in Fig. 4, which requests four user inputs about the data that is to be analysed. The first and second inputs are the fatigue history filename and number of data points. For these, the fatigue loading data file must be a time series in ASCII format (.txt, .asc, .dat). The data file must have a single column for the specified number of discrete data points. The third input is the sampling frequency, which is used to generate the PSD used in the frequency analysis and wavelet decomposition process. Finally, the frequency upper limit value is the maximum frequency of the PSD. The maximum value of the frequency upper limit allowed is at the Nyquist frequency, which is half of the sampling frequency.

In the WBE computational application, T1 was decomposed into 16 wavelet levels and three peaks were found in the PSD plot (Fig. 3a). Resonance peaks were found at three frequencies, i.e. 0.1 Hz, 1.8 Hz and 98.8 Hz, suggesting there were three wavelet groups. T2 was decomposed into 15 wavelet levels and referring to the PSD plot in Fig. 3b, resonance peaks were found at four frequencies, i.e. 1.4 Hz, 2.7 Hz, 11.7 Hz and 35.9 Hz. This signal was divided into four wavelet groups. Finally, T3 was decomposed into 14 wavelet levels. Referring to the PSD plot in Fig. 3d, resonance peaks were found at two frequencies, i.e. 0.1 Hz and 1.4 Hz, forming two wavelet groups.

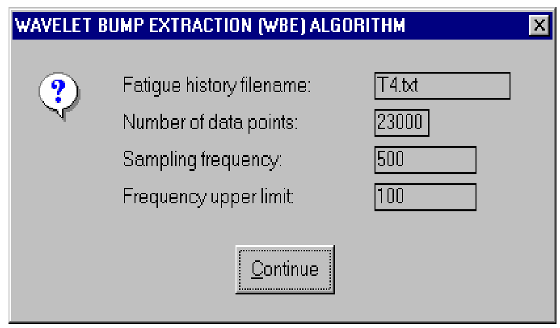


Fig. 4. Front menu of the WBE algorithm

In order to identify the fatigue damaging events, trigger level values were set based on the global signal statistics difference between the original and mission signals. For this case, the use of ±10% difference in signal statistical values between the mission and the original signal was used in order to retain the signal energy and amplitude ranges [10].

Using T1, the ±10% difference in global signal statistical values was applied for the bump identification process. At this value, the mission signal time length (Fig. 4a) was 181.9 seconds or 83.4% of the original signal. For T2, the length of the mission signal (Fig. 4b) was 18.8 seconds or 40.9% of the original signal. At this time length, 9,129 data points were extracted to produce the mission signal. The data compression properties showed that higher signal compression could be obtained from the signal measured on the pavé test track surface.

Finally, the time length of the T3 mission signals were 46.4 seconds or 76.1% of the original signal, as illustrated in Fig. 4c. Referring to the T3 mission signal pattern, it is shown that the low frequency content signal gave a significant contribution to the determination of the length of bump segments and mission signals. This signal type demonstrated difficulty in producing a substantially shortened mission signal.

Fig. 5 shows the PSD of the test signals and their WBE mission signals, showing the preservation of the original frequency content and signal energy in the mission signal. The overlapping pattern of PSD between the mission and the original signals can be observed. It is due to the technique of bump identification in the individual frequency band or wavelet group. Therefore, the frequency information was accounted for in the bump segments extraction and the mission signals construction.

3.3 Computational Fatigue Damage Analysis

Using Eq. (1), the fatigue damage of the original and the mission signals for all loadings (T1 – T3) were computational calculated and the results are tabulated in Table 2. In this table, the T1 and T2 mission signals preserved all (100%) the original fatigue damage potential. On the other hand, 93% fatigue damage of the T3 original signal was retained in its mission signal. With respect to the WBE algorithm as a fatigue data editing technique, the majority of fatigue damage can be preserved when the analysed fatigue road loadings were substantially shortened.

With these results, it indicates that the WBE algorithm associates with the ESD model is suitable for a fatigue data editing technique whilst retaining the cycle sequence within the history. In the practical automotive application, it is important to accelerate the fatigue tests in order to reduce the testing time, hence to reduce the operational costs. Based on the results in Table 2, the WBE algorithm provides an alternative method of producing a shortened signal for this kind of test. Since the original cycle sequence effects were accounted for in the WBE and ESD analysis (this is the first fatigue data editing algorithm considers the cycle sequence effects factor in its analysis) the use of this approach can lead to an accurate fatigue life prediction in the automotive accelerated fatigue test. In addition, the WBE algorithm would be expected to prove useful in numerous automotive testing applications.

4 Conclusion

The Wavelet Bump Extraction (WBE) algorithm was developed to produce the shortened signal for automotive accelerated fatigue test, whilst retaining the original cycle sequence. In this study, the use of both WBE and the ESD model produced a good relationship between the fatigue damage caused by the original fatigue road loadings and their mission signals. The ability of the WBE algorithm to shorten these signals, while simultaneously retaining at least 93% of the original fatigue damage in the respective mission signal would be expected to prove useful for accelerated fatigue tests, especially in the automotive research and applications.

References:

[1] A. Conle, TH. Topper, Overstrain effects during variable amplitude service history testing, *International Journal of Fatigue*, Vol. 2, No. 5, 1980, pp. 130-136.

[2] W. El-Ratal, M. Bennebach, X. Lin, R. Plaskitt, Fatigue life modelling and accelerated test for components under variable amplitude loads, *Symposium on Fatigue Testing and Analysis Under Variable Amplitude Loading Conditions,* France, 29-31st May 2002.

[3] C-S. Oh, Application of wavelet transform in fatigue history editing, *International Journal of Fatigue*, Vol. 23, 2001, pp. 241-250.

[4] S. Abdullah, JR. Yates, JA. Giacomin, Wavelet Bump Extraction (WBE) algorithm for the analysis of fatigue damage, *Proc of the 5th Int Conf on Low Cycle Fatigue (LCF5)*, Berlin, Germany, 9-11th September 2003, pp. 445-450.

[5] S. Abdullah, A. Zaharim, Using the orthogonal wavelet transform to identify fatigue features in variable amplitude fatigue loadings, *WSEAS Transactions on Signal Processing*, Vol. 2, Issue 10 (October 2006), 2006, pp. 1416 – 1420.

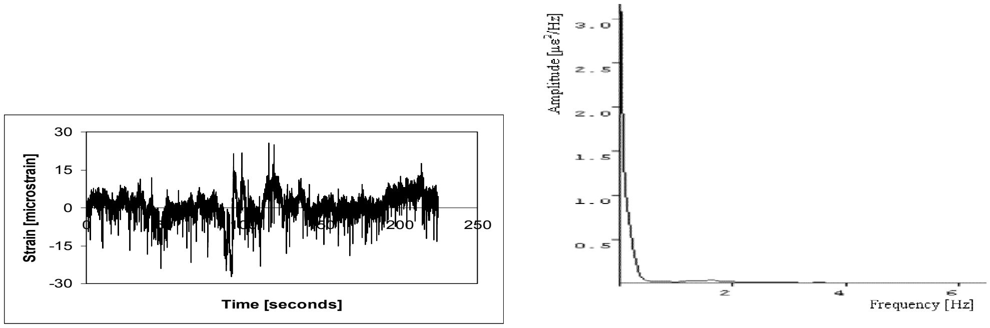
[6] I. Daubechies, *Ten Lectures on Wavelets*, SIAM, 1992.

[7] NE. Dowling, *Mechanical Behaviour of Materials: Engineering Methods for Deformation, Fracture and Fatigue*, Prentice Hall, New Jersey, 1999.

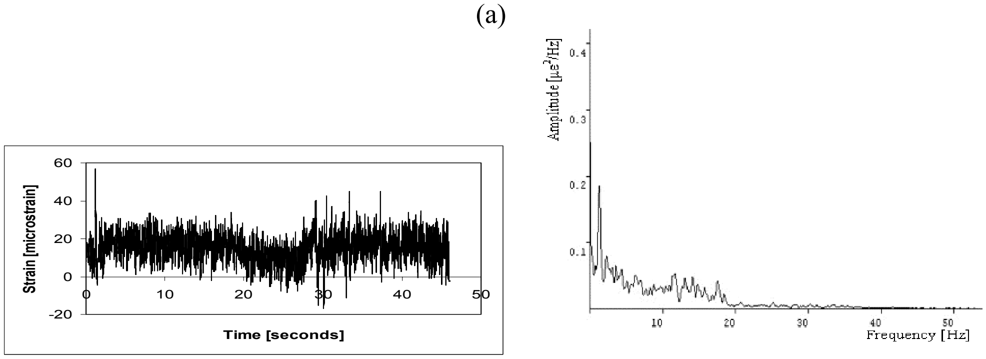
[8] DL. DuQuesnay, MA. Pompetzki, TH. Topper, Fatigue life prediction for variable amplitude strain histories, *SAE Transactions (SAE930400)*, Vol. 102, 1993, pp. 455-465.

[9] M. Khalil, TH. Topper, Prediction of crack-opening stress levels for 1045 as-received steel under service loading spectra, *International Journal of Fatigue*, Vol. 25, 2003, pp. 149-157.

[10] S. Abdullah, JA. Giacomin, JR. Yates, A mission synthesis algorithm for fatigue damage analysis, *Proc of the Instn of Mech Engrs, Part D, Journal of Automobile Engineering*, Vol. 218, No. D3, 2004, pp. 243-258.



(a)



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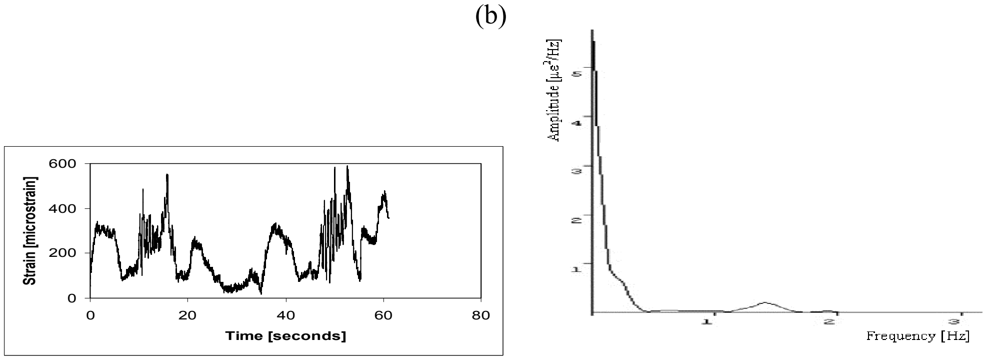
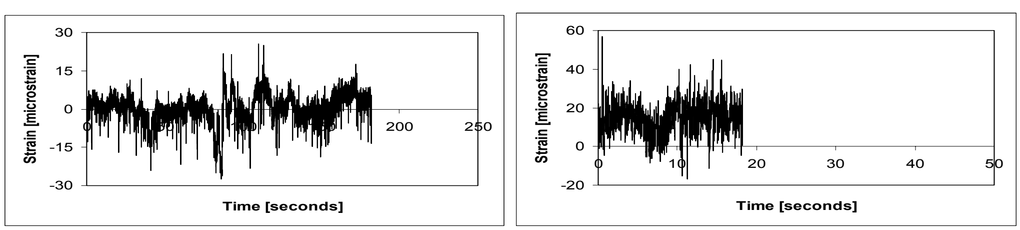
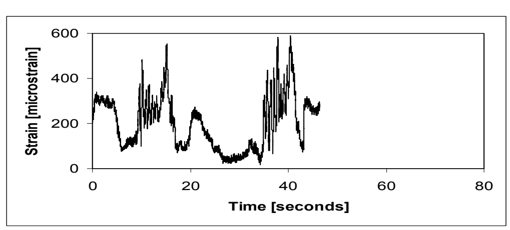


(d)

Fig. 3. Time histories and power spectral densities of the original fatigue road loadings: (a) T1, (b) T2, (c) T3.

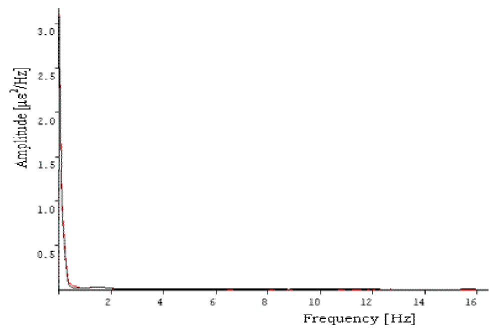


(a) (b)

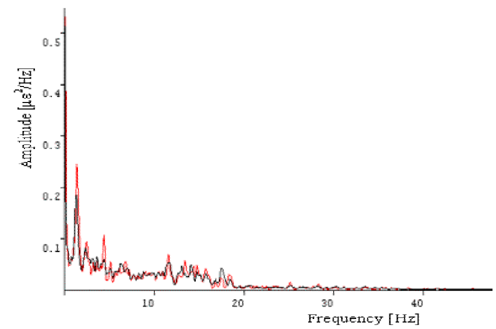


(c)

Fig. 4. The mission signals produced from the computational WBE processing: (a) T1, (b) T2, (c) T3



(a)



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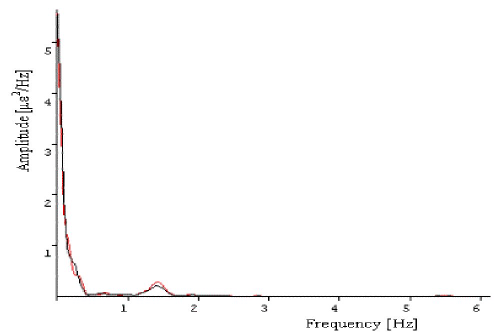

(c)

Fig. 5. PSD comparison (an overlapping pattern) between the original signal and its equivalent WBE mission signal: (a) T1, (b) T2, (c) T3

Table 2. The compression characteristics of signal length and fatigue damage values between the original and mission signals.

Signal Name		Signal length [Seconds]	Time ratio [%]	Fatigue Life [Numbers of blocks to failure]	Fatigue damage ratio (mission/original), [%]
T1	Original	225.0	83.4	1.04×10^{-5}	100
	Mission	181.9		1.04×10^{-5}	
T2	Original	46.0	40.9	9.66×10^{-7}	100
	Mission	18.8		9.66×10^{-7}	
T3	Original	61.0	76.1	1.26×10^{-3}	93
	Mission	46.4		1.17×10^{-3}	

[Time ratio (%) = ($t_{mission}$ / $t_{original}$) x 100%; Fatigue Damage (D) ratio (%) = ($D_{mission}$ / $D_{original}$) x 100%]