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AN EXPERIMENTAL VALIDATION OF THE FATIGUE DAMAGING EVENTS EXTRACTED USING THE WAVELET BUMP EXTRACTION (WBE) ALGORITHM

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ABSTRACT

This paper describes an experimental validation of the fatigue damaging events that were identified and extracted using a wavelet-based fatigue data editing technique. This technique, known as the Wavelet Bump Extraction (WBE) algorithm, is specifically designed to summarise a long record of fatigue variable amplitude (VA) loading whilst preserving the original load cycle sequence. Using WBE the fatigue damaging events were identified and extracted in order to produce a mission signal. In order to validate the effectiveness of WBE in practical applications a VA road load time history that was measured on a road vehicle suspension arm was taken as a case study. Uniaxial fatigue tests were performed using the original signal, the WBE mission signal and the individual WBE extracted segments. A mirror polished specimen of SAE 1042 steel was tested using a servo-hydraulic machine. The fatigue lives measured for these VA loadings were then compared to the fatigue lives calculated from a VA strain loading fatigue damage model. The results show a good fatigue life correlation at the coefficient of 0.98 between the prediction and experiment. For the road load time history considered, the WBE mission signal was found to be only 40% the time duration of the original time history while maintaining 60% of the fatigue damage according to analytical calculation and 87% according to experimental testing.

1. INTRODUCTION

Fatigue life prediction is important towards the design of vehicle structural components, and the essential input variable for this prediction is the load history. For road vehicles, there can be an extremely wide range of uses and hence a representative variable amplitude (VA) road load time history is hard to quantify. Automobile manufacturers go to great lengths to instrument vehicles and subject them to a variety of driving conditions. By necessity, vehicle development requires accelerated fatigue testing and this is often accomplished by correlating test tracks with data from public roads. Loads that are predicted to do little or no damage can be eliminated, and the large amplitude cycles that cause the majority of damage should be retained when producing the shortened road load [1].

In the durability area, the retaining of the large amplitude cycles to produce shorter load histories is known as fatigue data editing. Time domain editing is the most popular method, and can be based on several approaches: the use of local strain parameter in removing small cycles [2], the use of a damage window joining function to produce an edited signal [3], the application of Smith-Watson-Topper (SWT) parameter to determine the range of low cycles that should be eliminated [4], and the choosing of overloads and underloads to retain only high amplitudes [5,6]. In the frequency domain, VA loadings are normally edited using a low

pass filter due to the fact that high frequency cycles have small amplitudes which produce little damage. The time-frequency approach has been applied to the problem of fatigue data editing, but only for the purpose of spike removal and de-noising [7]. In all these works, the fatigue life of the summary signals was predicted and was compared to the experimental test results in order to check the degree of correlation.
No previously developed fatigue data editing method makes use of the wavelet transform as the basis of the editing of the VA loading time histories. The use, by the authors, of the wavelet transform has led to the development of a method to summarise the data whilst preserving the load cycles sequence [8]. The method has been named the Wavelet Bump Extraction (WBE) algorithm, and is designed to identify fatigue damaging events and to produce short mission signals. To date, WBE has been used in analytical studies of road load data sets [8,9]. This paper, however, presents an experimental validation of the algorithm using both the complete mission signal and the individual fatigue damaging events extracted by WBE. The strain history that was used was measured on the lower suspension arm of a road vehicle while driving over a pavé (cobblestone) road surface.

2. WAVELET BUMP EXTRACTION (WBE) ALGORITHM

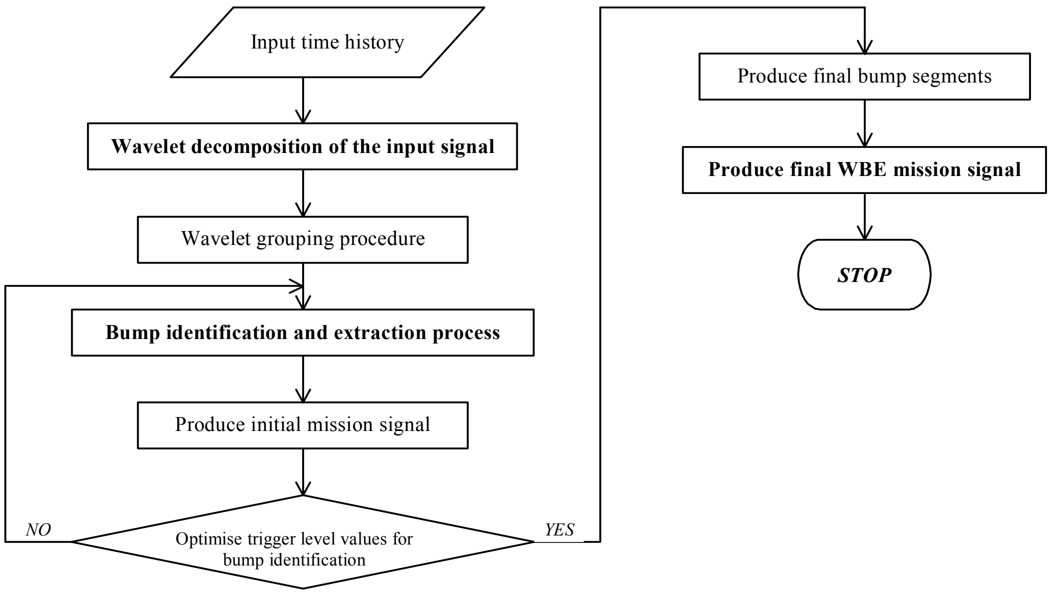


Fig. 1. Simplified flowchart of the WBE algorithm

The WBE algorithm has three main stages (see Fig. 1) which are: the wavelet decomposition process, the identification and extraction of the fatigue damaging events, and the production of a mission signal. WBE uses 12th order Daubechies' wavelets which were chosen as the basis functions based on the results in previous studies involving automotive data [8-11]. Each wavelet 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 [9]. A wavelet grouping stage permits the user to cluster wavelet levels into a single region of significant vibrational energy. In this way it is possible to avoid situations where small peaks in one region are concealed by the greater energy of other regions of the frequency spectrum.
In WBE, a bump is defined as an oscillatory transient which has a monotonic decay envelope either side of a peak value. Bump identification is achieved in each wavelet group time history by means of an automatic trigger level that is specific to the wavelet group as shown in Fig. 2a.

Bump identification is performed by means of a search which identifies the points at which the signal envelope inverts from decay behaviour. Fig. 2b shows the two inversion points, one on either side of the peak value, which define the temporal extent of the bump event. After all the bumps are identified in all the wavelet groups, bump segments are extracted (see Fig. 2c) by removing from the original time history the complete section between the start and the end of the bump. The extracted bump segments are then combined together to produce a mission time history that replicates the statistical and fatigue damage characteristics of the original time history.

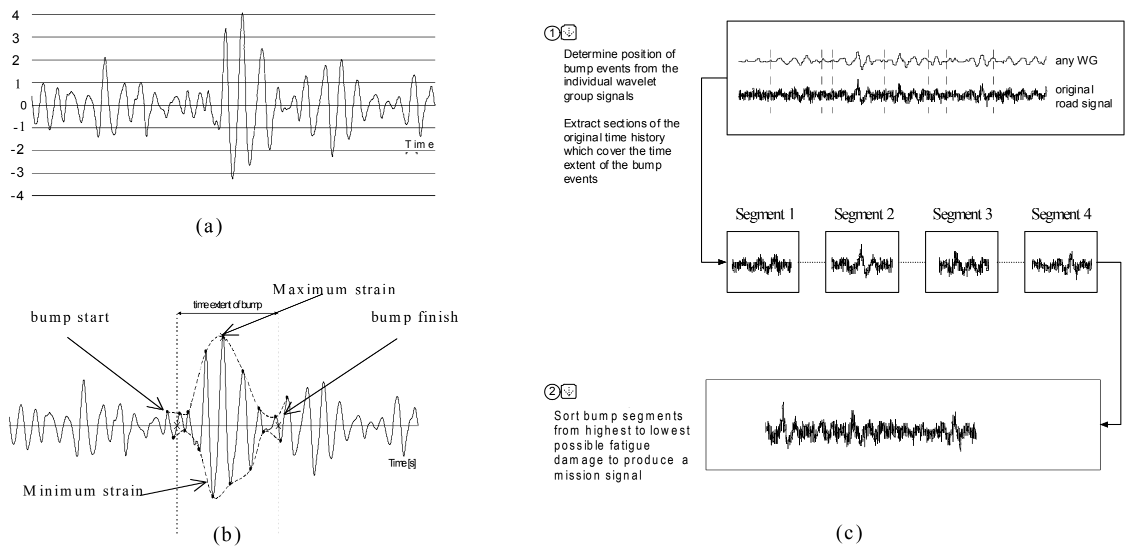


Fig. 2. Bump identification and extraction: (a) possible trigger level values, (b) decay enveloping of a bump, (c) production of a mission signal from the individual bump segments

3. FATIGUE LIFE PREDICTION

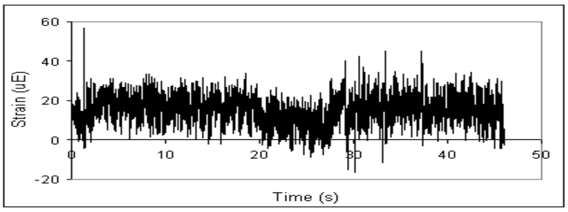
Most fatigue life predictions are based on the Palmgren-Miner's linear cumulative damage rule. Such analysis assumes no load sequence effect and does not consider the load-interaction accountability that occurs in fatigue service loadings. Improved methods of fatigue life prediction have been developed for components subjected to variable amplitude loading which consider the influence of load sequence [5]. To solve the problem of load interaction effects, a fatigue damage model for VA strain loadings associated with the crack growth of the material was developed [5,6], and its analytical expression is

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

where E is the elastic modulus of the material, $\Delta\varepsilon^{*}$ is a net effective strain range for a closed hysteresis loop, A and b are 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 crack-opening stress (S_{op}) and it is dependant on the prior stress and strain magnitudes in the loading history. Considering the cycle sequence effect, the model was redeveloped to consider the crack opening changes for each cycle [12,13]. Detailed descriptions of this fatigue damage model can be found in several studies [5,6,12,13]. For the application of this model, the loading spectrum must be rainflow counted [14] in order to find the fatigue life associated with each cycle. Based on Equation (1), the fatigue life for each cycle can be calculated using the expression

$$N_f = \left(\frac{E \Delta \varepsilon^*}{A} \right)^{1/b} \tag{2}$$

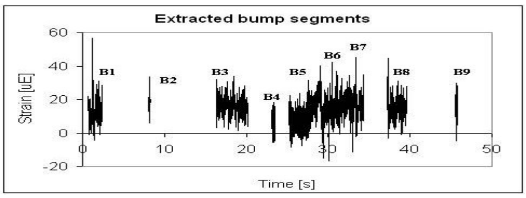
4. APPLICATION OF THE WBE ALGORITHM

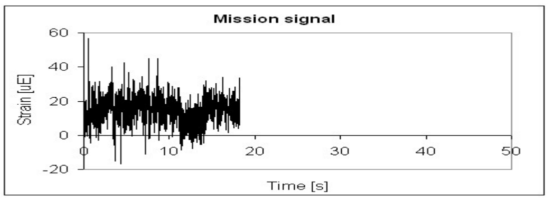


(a) (b)

Fig. 3. (a) Pavé test track used for measuring fatigue road load, (b) time history of the experimetally measured signal [15]

The effectiveness of the WBE algorithm was evaluated using a VA strain loading time history that was measured on a van suspension arm while driving over a pavé test track [15]. The signal (in units of microstrain) was sampled for 23,000 discrete points at a sampling rate of 500 Hz. Fig. 3 presents a photograph of the pavé surface used and a plot of the acquired 46-second time history. Using the WBE algorithm the bump segments that produced the majority of fatigue damage were identified and extracted, as shown in Fig. 4a. These segments were combined in order to produce the mission signal as shown in Fig. 4b. For this application, the bump segments were identified using a trigger level which was automatically set by WBE so as to achieve a final mission signal which matched the original data within ±10% in terms of the global signal statistics of root-mean-square (r.m.s.) and kurtosis value. The suspension arm pavé test data set was chosen as the signal for the experimental validation of WBE because this signal contained many small amplitude, high frequency, bumps in the signal background.



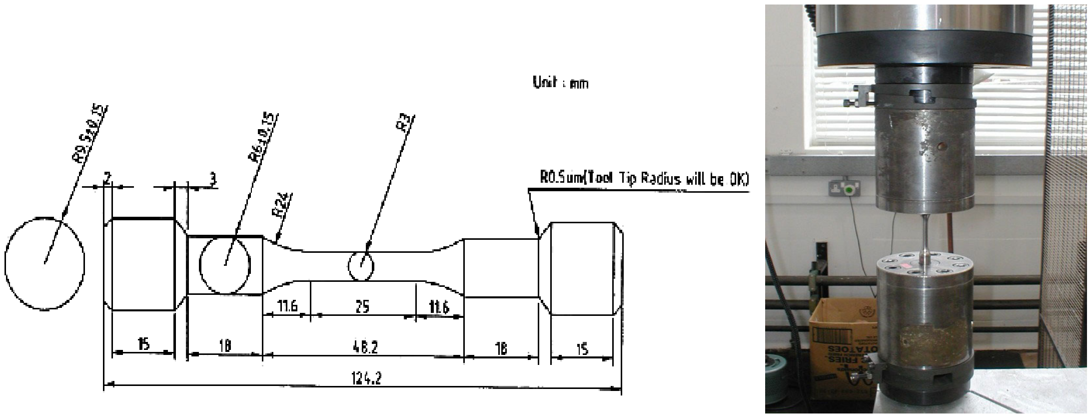


(a) (b)

Fig. 4. WBE results: (a) Extracted bump segments with the bump label numbers, (b) The final 18.8-second mission signal

5. EXPERIMENTAL FATIGUE TEST

In order to verify the effectiveness of WBE, uniaxial fatigue tests were performed using the suspension arm pavé test time histories. The original signal, the WBE mission signal and the individual WBE bump segments were all used to perform fatigue tests. The material chosen for the test sample was SAE 1042 steel (0.4% carbon steel), which is often used in the suspension components of passenger cars. The specimen was manufactured as a cylindrical bar which complied with ASTM E606-92 [16]. In order to produce a mirror surface finish, it was polished using several grades of sand paper and by 6-µm diamond compound. An Instron 8501 servo-hydraulic test machine was used in displacement control mode for all tests. Fig. 5 shows the geometry of the specimen, and the specimen position at the machine during a fatigue test. From the data obtained from the constant amplitude (CA) fatigue tests, a strain-life curve was defined as shown in Fig. 6a. Monotonic and cyclic mechanical properties of this material were also determined from the test data, and are presented in Tab. 1.



(a) (b)

Fig. 5. (a) Geometry of the fatigue test specimen based on ASTM E606-92, (b) The position of specimen at the servo-hydraulic machine

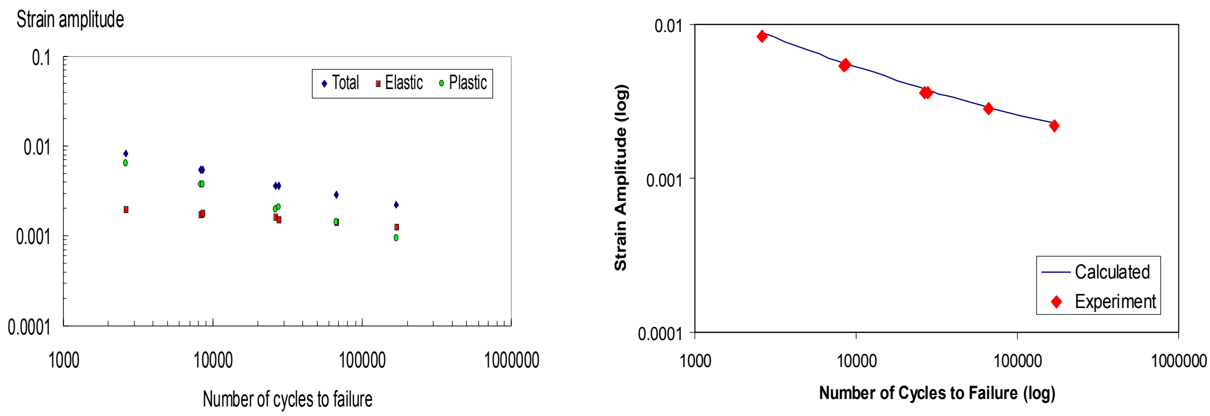
Tab. 1 Mechanical properties of SAE 1042 steel determined from fatigue test data

Monotonic mechanical properties		Cyclic mechanical properties	
Ultimate tensile strength, (MPa)	624	Fatigue strength coefficient, σ'_f (MPa)	971
Young Modulus, *E* (MPa)	2.10×10^5	Fatigue strength exponent, *b'*	-0.11
Static yield stress 0.2%, (MPa)	342	Fatigue ductility coefficient, ε'_f	0.23
Area reduction, (%)	51.9	Fatigue ductility exponent, *c*	-0.46
Elongation (%)	28.4	Strain hardening exponent, *n'*	0.29
Strain hardening exponent	0.32	Material constant for Equation 1, *A* (MPa)	119,000
		Material constant for Equation 1, *b*	-0.5

For Equation (1), the parameter values of the material constants *A* and *b* were determined from the fatigue data test and were found to be 119,000 MPa and –0.5, respectively. Given the values of *A* and *b*, Equation (1) can be expressed as

$$210000\ \Delta\varepsilon^{*} = 119000\ (N_f)^{-0.5} \tag{3}$$

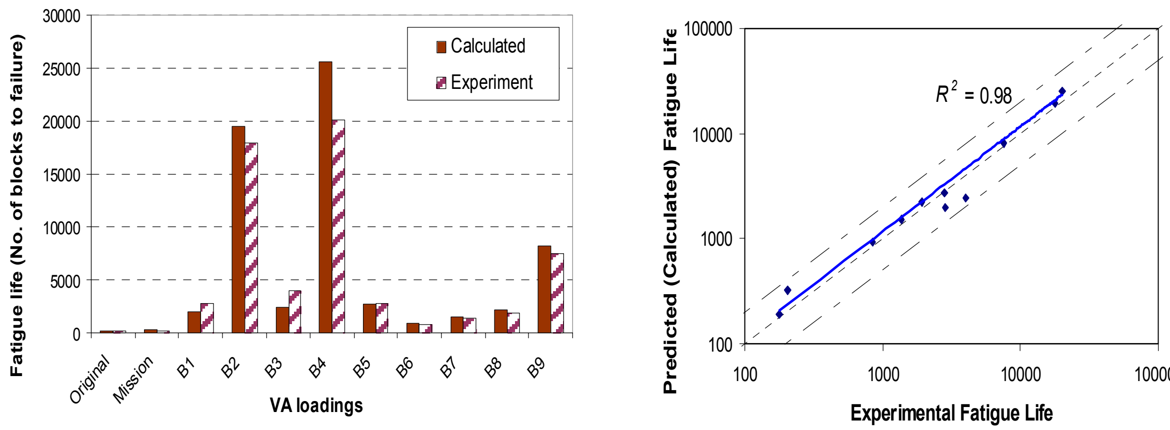
Fig. 6b presents the comparison of the strain-life curve produced from the experimental procedure and the curve produced using Equation (3). The two are similar, suggesting the suitability of this VA fatigue damage model for use in conjunction with the WBE algorithm.



(a) (b)

Fig. 6. (a) Experimented strain-life curve for SAE 1042, (b) Comparison of the strain-life curve between calculated and experimental results

For the experimental validation of WBE, the uniaxial fatigue tests were performed using eleven samples of VA loadings. The loading used were the original signal (see Fig. 3b), the WBE mission signal (see Fig. 4b) and the nine WBE extracted segments (see Fig. 4a). Fig. 7a presents the fatigue life distributions calculated using Equation (3) and those obtained from the experimental tests.



(a) (b)

Fig. 7. (a) Fatigue life distributions for the 11 loading time histories (b) Fatigue life correlation between calculation and experiment for the 11 loading time histories

Fig. 7b presents the correlation of the analytical and experimental fatigue life estimates obtained for 11 all data sets. In the figure each data point represents a loading condition from Fig. 7a. The fatigue lives can be seen to be distributed around the 1:1 line, suggesting the closeness of the calculated fatigue life to the experimental fatigue life. In the field of fatigue life prediction, estimates which are within a factor of 2 with respect to the true fatigue life are commonly encountered and often considered acceptable. For this data set, the coefficient of variation (R^2) between the predicted and the experimental values was found to be 0.98 (see Fig. 7b), suggesting the close correspondence of the analytical and the experimental results. WBE produced a mission signal which was 40% of the time length of the original signal. At this compression value, 60% and 87% of the original fatigue damage was retained in the WBE mission signal according to the results obtained from calculation and from experiment, respectively.

6. CONCLUSIONS

Wavelet Bump Extraction (WBE) is the algorithm used to extract the important fatigue damaging events or bumps from the original time history so as to produce a shortened mission signal. In this study, a VA time history measured on a lower arm suspension of a van driven on a pavé test track was used as a case study, leading to the extraction of nine bump segments. The fatigue life of the original road load time history, the WBE produced mission signal, and each of the nine individual bump segments was determined both analytically, using a VA fatigue damage model, and experimentally. A coefficient of variation (R^2) of 0.98 was found between the analytical and the experimental fatigue life estimates of all data sets. For the data editing application using WBE, the WBE mission signal was found to have a total time duration that was only 40% of the original road load signal while retaining 60% and 87% of the fatigue damage in the prediction and experiment, respectively. The ability to shorten fatigue loading time histories by more than half their original length, while simultaneously retaining as much as 87% of the fatigue damage would be expected to prove useful in numerous automotive testing applications.

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