

**A MISSION SYNTHESIS ALGORITHM FOR EDITING VARIABLE
AMPLITUDE FATIGUE SIGNALS**

S. Abdullah*, J.R. Yates* and J.A. Giacomin*

This paper presents a wavelet-based fatigue data editing algorithm, known as Wavelet Bump Extraction (WBE), to summarise long record of fatigue loadings. The key point of this algorithm is to produce a shorter time history (mission signal) that retains the majority of the original fatigue damage whilst preserving cycle sequence information. In WBE, features or bumps are identified in characteristic frequency bands using the Daubechies' wavelet transform. Comparison of the fatigue life between the original and mission signals was performed to validate the algorithm. The fatigue life was predicted using a variable amplitude fatigue damage model and the results showed a good correlation between the damage caused by the original and mission signals. Finally, the findings suggest that WBE is a suitable approach for producing a shortened mission signal for accelerated fatigue testing.

INTRODUCTION

Fatigue life prediction is important in the design process of vehicle structural components, and the essential input variable in the fatigue is the load history. Practically, 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 public road data. Both roads and test tracks generate variable amplitude (VA) load time histories. 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. In the durability area, a method to retain the large amplitude cycle to produce a shortened history is known as fatigue data editing, and several have been they were developed in various domains. However, time domain and peak-valley editing is the most popular used [1]; examples include the application of local strain parameter [2], the damage window joining function [3], the range of Smith-Watson-Topper (SWT) parameter [4] and the effect of overload and underload associated with crack opening stress [5,6]. In the frequency domain, VA loadings are edited using a low pass filter based on the fact that

*Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, United Kingdom (Email: shahrum@vlsi.eng.ukm.my, j.yates@sheffield.ac.uk, j.a.giacomin@sheffield.ac.uk)

high frequency cycles have small amplitudes which produce little damage. The time-frequency approach has been applied to the problem of fatigue data editing through its use in spike removal and denoising [7].

However, none of these methods considers the application of the wavelet transform in editing VA fatigue loadings with a consideration of retaining the cycle sequences. Therefore, a method to summarise the road data which has led to the development of the Wavelet Bump Extraction (WBE) algorithm that is designed to identify the fatigue damaging events and to produce the mission signal (the shortened output signal) that replicates similar statistical and fatigue behaviour of the input signal. This algorithm is able to extract large amplitude segments that retain the cycle sequence of the original time history. Finally, this algorithm is available to maintain the fatigue damage of the mission signal close to that of the original signal.

Development of Wavelet Bump Extraction (WBE) Algorithm

A flowchart describing WBE is presented in Figure 1 and it shows the three stages of the algorithm. In the first stage, the power spectral density (PSD) of the input signal is calculated in order to determine its vibrational energy distribution in the frequency domain. 12th order of Daubechies' wavelets were chosen as the basic functions to form an orthogonal set due to the efficiency in providing a large number of vanishing statistical moments. Having applied this wavelet transform, the output will be a series of wavelet level time histories each characterised by a subband in the frequency domain. A wavelet grouping stage in WBE permits the user to group wavelet levels into single regions of vibrational energy. This subdividing permits an 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 [8].

Figure 1 A flowchart of the Wavelet Bump Extraction (WBE) algorithm

In the second stage of the WBE algorithm fatigue damaging events or bumps are identified in each wavelet group. A bump is defined as an oscillatory transient which has a monotonic decay envelope either side of the 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. At program launch the user specifies the maximum acceptable percentage difference between the root-mean-square (r.m.s.) and kurtosis of the original signal and the mission signal. The r.m.s. is used to quantify the overall energy content of the oscillatory signal, and the kurtosis is used as a measure of non-gaussianity since it is highly sensitive to outlying data among the instantaneous values. The trigger level is then automatically determined to achieve the requested statistics for each wavelet group. Both statistical parameters are identified as the main control parameters in

the determination of trigger levels. Figure 2a presents a set of possible trigger levels for an individual wavelet group to determine a bump. The two inversion points of a peak, one on either side of the peak value, define the temporal extent of the bump event (Figure 2b). At a later stage of WBE, the r.m.s. and kurtosis of the mission signal are compared to those of the original signal. If the statistics exceed the required difference, the trigger levels are reduced by a user specified step until the statistical values achieve the user-specified tolerance.

In the final WBE stage, a method of searching the bump start and finish points from the original time history has been introduced, as shown in the schematic diagram of in Figure 2c. If a bump event is found in any of the wavelet groups a block of data covering the time frame of the bump is taken from the original data set. Using this strategy, it retains the amplitude and phase relationships of the original signal. Once all bump segments have been identified, they are assembled to produce a mission signal that has shorter in time length.

Figure 2 (a) Possible trigger level values across the data set, (b) Decay enveloping of a fatigue damaging event, (c) Process to seek the start and finish points of a bump segment to produce a mission signal

Applications of the WBE Algorithm with the VA Signals

The accuracy of the fatigue damaging event identification process was evaluated by the application to two VA histories. An artificial signal, named T1 (Figure 3a), was defined with 16000 data points and sampled at 400 Hz. The logic of creating T1 was to test the ability to select large transient events in a small cycle background. The other signal, named T2 (Figure 3e), was measured on a van while driving over a pavé test track. T2 was sampled at 500 Hz with a record length of 46 seconds. Using the WBE algorithm, T1 was decomposed into 11 wavelet levels and these levels were grouped into four wavelet groups. T2 was decomposed into 12 wavelet levels that gave four wavelet groups. Figure 3b shows the location of bumps in the wavelet groups for T1. This figure shows the bumps were identified at $\pm 75\%$ r.m.s. and kurtosis difference between the original and the mission signals. For this, a large difference in statistical values occurred because approximately 70% of the original signal contained low amplitude cycles.

Figure 3 Plots of the analysed VA loadings: (a) T1 - original time history, (b) T1 - bump locations in each wavelet group, (c) T1 - extracted bump segments, (d) T1 - mission time history, (e) T2 - original time history, (f) T2 - bump locations in each wavelet group, (g) T2 - extracted bump segments, (h) T2 - mission time history

For T2, the transient events were identified in four wavelet groups and their respective positions are shown in Figure 3f. The individual bumps in each wavelet group were identified within $\pm 10\%$ r.m.s. and kurtosis difference between the original and mission signals. The difference value of r.m.s. and kurtosis was

implied with a consideration of an approximate 10% of the original road data contained low amplitudes. With referring to the bumps identified in the wavelet groups, it can be seen that a low frequency bump provides important information to determine the length of the extracted segments from the original signal.

Figure 3c (T1) and Figure 3g (T2) show the position of the WBE bump segments extracted from the original time history. With referring to Figure 3c, all the high amplitude sections were selected during the bump identification and extraction process. For the mission signal production, the bump segments were assembled which gave a 12.5-second mission signal for T1 (Figure 3a) and a 18.8-second mission signal for T2 (Figure 3h).

Fatigue Life Prediction: Results and Discussions

Most fatigue life predictions are based on the linear cumulative damage concept known as Palmgren-Miner's rule which assume no load sequence effects. To overcome this difficulty, a fatigue damage model for VA strain loading was developed by DuQuesnay et al. [5,6]. It is a general model that associated with crack growth of the material and its mathematical function is expressed as

$$E\Delta\mathbf{e}^* = A(N_f)^b \quad (1)$$

where E is the elastic modulus of the material, \mathbf{De}^* 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 $E\mathbf{De}^*$ for a given cycle is a function of crack-opening stress (S_{op}) level and it is dependant on the prior stress and strain magnitudes in the loading history. To consider the cycle sequence effect the model was redeveloped to account for crack opening changes for each cycle [9,10]. For the application, the loading spectrum needs to be rainflow counted to calculate the fatigue life (N_f) for each cycle. Using the damage summation technique the total fatigue life for a block loading can be found. Details of the development of this fatigue damage model can be found in references [5,6,9,10]. In this study, the material used in the fatigue damage prediction is SAE 1045 steel ($E = 206$ GPa), which it is typical material for automotive component [5]. Based on the references [5,9], parameters A and b were established at 112,000 MPa and -0.5 , respectively. Given the values of A and b , Eq. (1) can be expressed as

$$206000 \Delta\mathbf{e}^* = 112000 (N_f)^{-0.5} \quad (2)$$

Figure 4 shows the sequence-based arrangement of the time history (T2) data points. This is the reconstructed history for the cycle reversals in order to determine the fatigue life for each cycle. This history was formed based on the comparison between the rainflow cycles to the peak-valley reversals. Using Eq.(2), the fatigue life of the original and mission signals were predicted and the damage

distribution was shown in Figure 5a and Figure 5b shows the correlation of fatigue life prediction between the mission and original signals. In this figure the fatigue lives are scattered at the 1:1 line, suggesting the closeness of the mission fatigue life to the original fatigue life.

Figure 4 Reconstructed history of T2, with respect to the original cycle sequence

Figure 5 (a) Fatigue life levels between the original and mission signals, (b) Fatigue life correlation between the mission and original signals.

With respect to the WBE algorithm as a fatigue data editing technique, the mission signal of T1 was 31% (12.5 seconds) of its original signal. At this record length, the mission signal retained all (100%) the original fatigue damage. For T2, the mission signal length was 41% (19 seconds) of the original signal. At this record length, approximately 92% of the original fatigue damage was retained in the mission signal. With these results, it indicates that the WBE algorithm associates with VA fatigue damage model are suitable for a fatigue data editing technique whilst retaining the cycle sequence within the history.

Conclusions

The Wavelet Bump Extraction (WBE) algorithm was developed in order to identify the fatigue features that give the majority of fatigue damage whilst retaining the original cycle sequence. In this study, the use of both WBE and VA fatigue damage model produced a good correlation between the damage caused by the original and mission signals. Finally, the ability of WBE to shorten VA signals by more than half their original length, while simultaneously retaining at least 92% of the fatigue damage would be expected to prove useful in numerous accelerated fatigue testing in automotive applications.

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FIGURES

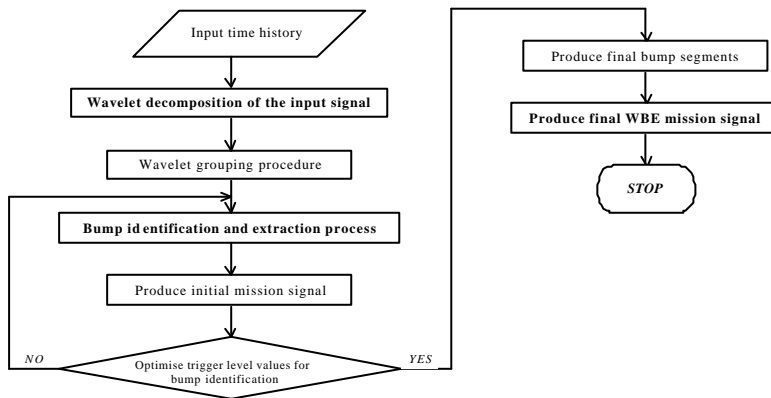


Figure 1 A flowchart of the Wavelet Bump Extraction (WBE) algorithm

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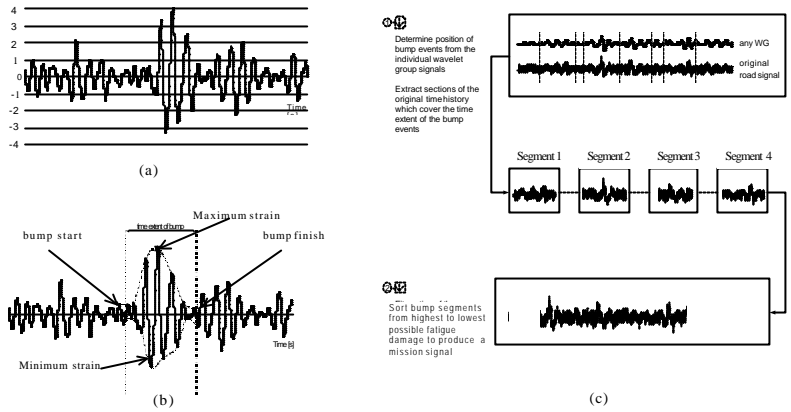


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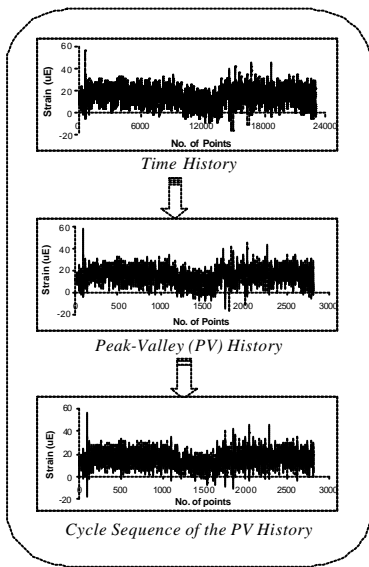


Figure 4 Reconstructed history of T2, with respect to the original cycle sequence

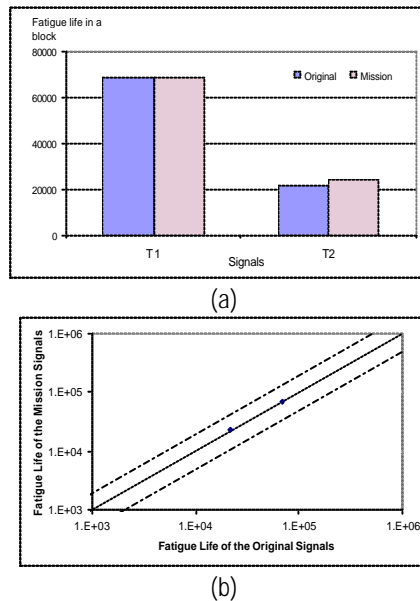


Figure 5 (a) Fatigue life levels of the original and mission signals, (b) Fatigue life correlation between the mission and original signals.

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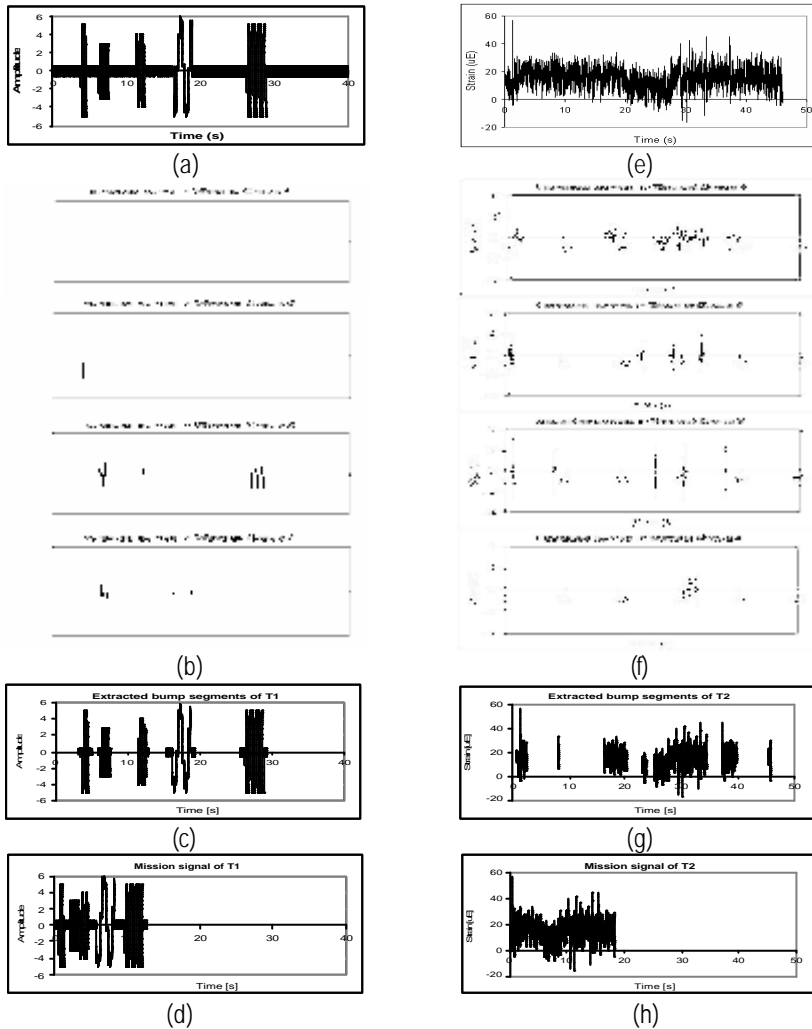


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