IDENTIFICATION OF FATIGUE DAMAGING EVENTS USING A WAVELET-BASED FATIGUE DATA EDITING ALGORITHM

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Abstract

This paper describes a technique to identify the important features in fatigue road load data that cause the majority of the total damage. Fatigue damaging events, called bumps, are extracted from the original road load time history using a wavelet-based algorithm, called Wavelet Bump Extraction (WBE). WBE can be used to produce a mission signal that retains most of the fatigue damage whilst preserving the cycle sequences. Bumps are identified from characteristics frequency bands by means of the orthogonal wavelet transform based on 12th order of Daubechies wavelet functions. The bump identification process has been evaluated by analysing two variable amplitude fatigue loadings with WBE in which both data sets were measured on a road vehicle suspension arm. In this study the total damage caused by the combination of all bump events was close to the original data sets. The findings suggest that WBE is a suitable approach for mission synthesis applications by producing a shortened mission signal for accelerated fatigue test.

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. Automobile manufacturers go to great lengths to instrument vehicles and subject them to a variety of driving conditions. Vehicle development requires accelerated fatigue testing and this is often accomplished by correlating test tracks with public roads. Both roads and test tracks generate variable amplitude (VA) load time histories [1]. Since it is generally the large amplitude cycles that cause the majority of damage, they should be retained for durability testing [2]. It is suggested that improvements in correlating the damage generated during accelerated testing and real service life may be obtained by preserving the local load-time sequence of cycles associated with particular events such as curb strikes or driving through pot-holes.

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 [3]. In the time domain, the local strain [4], damage window joining function [5] and Smith-Watson-Topper (SWT) parameter range [6] approaches have been defined to identify and retain high amplitude cycles that produce great fatigue damage. In frequency domain methods, the VA loadings are low pass filtered based on the fact that high frequency cycles have small amplitudes which produce little damage [7]. This

filtering method does not shorten the time series as the number of points is the same [5]. The time-frequency approach has been applied to the problem of fatigue data editing through its use in spike removal and denoising [8]. However, none of these methods considers the importance of selecting the individual fatigue damaging events from the original VA fatigue loadings.

Increasing demands to reduce development time while simultaneously improving confidence in the durability of a product means that there is interest in investigating issues of mission synthesis. A method for summarising the road load fatigue data by identifying fatigue damaging events and extracting them from the history whilst preserving the load cycles sequence is important. This has led to the development of a new fatigue data editing algorithm [9] which is designed specifically to identify and extract the fatigue damaging events using a wavelet-based approach. This algorithm is called Wavelet Bump Extraction (WBE) and its objective is to maintain the fatigue damage of the mission signal (the shortened output signal) as close as possible to that of the original signal. An important characteristics of the WBE output is that the mission signal retains most of the fatigue damage while maintaining the correct original sequence of high and low amplitude cycles.

A Wavelet-Based Fatigue Data Editing Algorithm

Wavelet Bump Extraction (WBE) is a wavelet-based fatigue data editing technique which is used to identify and extract fatigue damaging events, and to produce a shortened mission signal of similar behaviour. A flowchart describing the WBE processing is presented in Fig. 1. There are two main stages of the algorithm that can be observed in the flowchart: the application of the wavelet decomposition process and the identification of fatigue damaging events.

In the first stage of WBE, the power spectral density (PSD) of the input signal is calculated in order to determine its vibrational energy distribution in the frequency domain. This PSD approach is applied in the wavelet decomposition process of the input signal. 12th order of Daubechies' wavelets were chosen as the basis functions to form an orthogonal set due to the efficiency in providing a large number of vanishing statistical moments. The 12th order representation was adopted due to its successful use in previous studies for comfort [10] and fatigue mission synthesis [11] applications involving automotive road data. The wavelet levels produced in the wavelet decomposition consist of the reconstructed signals for a given value of scale a_0^{-m} and each level describes the time behaviour of the signal within a specific frequency band.

The number of discrete sampling points in the time history determines how many wavelet levels can be decomposed. When the number of sampling points N is equal to 2^n ($N = 2^n$), the number of levels obtainable from the wavelet decomposition is $n + 1$. A wavelet grouping stage in WBE permits the user to group wavelet levels into single regions of significant energy. Each wavelet group is defined by the user to cover frequency regions of specific interest, such as high energy peaks caused by a subsystem resonances. 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 [9-11].
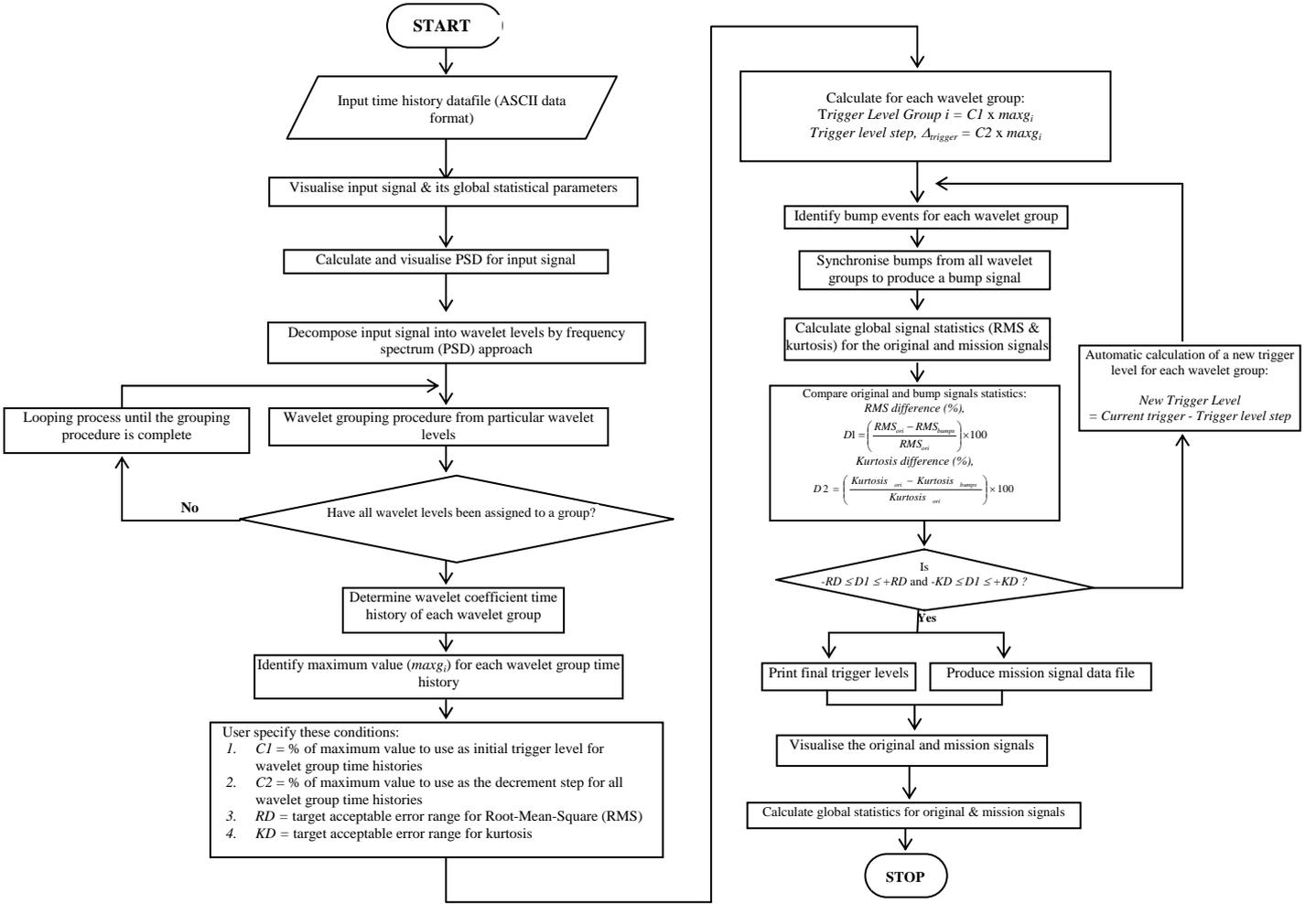
FIGURE 1. A flowchart of the WBE algorithm

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 (RMS) and kurtosis of the original signal and the mission signal. The RMS 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. Mathematically, RMS and kurtosis are define by following equations

$$RMS = \left\{ \frac{1}{N} \sum_{j=1}^{N} x_j^{\,2} \right\}^{1/2} \tag{1}$$

$$K = \frac{1}{N(RMS)^4} \sum_{j=1}^{N} \left(x_j - \bar{x} \right)^4 \tag{2}$$

where where x_j is the instantaneous value, N is the number of points and $\bar{x}$ is the mean of the time history.

The trigger level is then automatically determined to achieve the requested statistics for each wavelet group. The RMS and kurtosis values of this mission signal are compared to those of the original signal. If the statistics exceed the required difference, the trigger levels are reduced incrementally by a step size that is specified by the user until both statistical values of the mission signal achieve the user-specified tolerance. Fig. 2a presents a set of possible trigger levels for an individual wavelet group to determine a bump. Bumps identification is performed by means of a search which identifies the points at which the signal envelope inverts from a decay behaviour. The two inversion points, one on either side of the peak value, define the temporal extent of the bump event as shown in Fig. 2b.
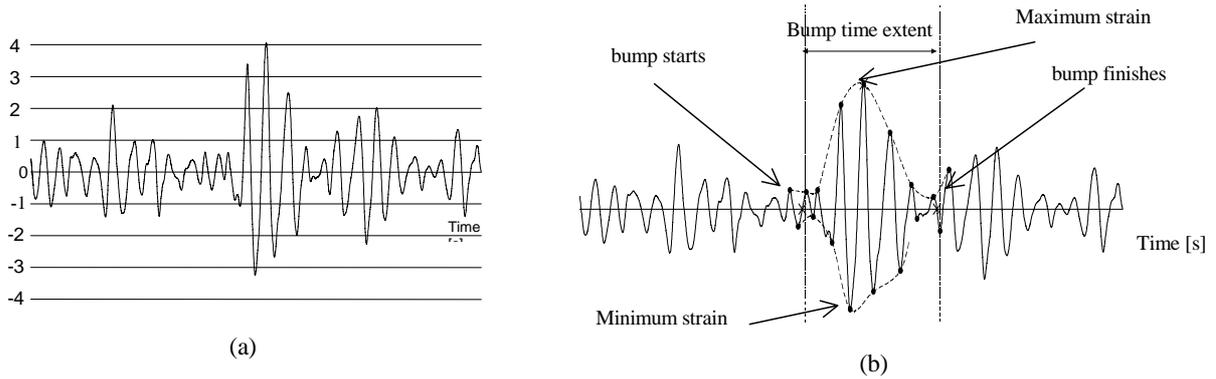

FIGURE 2. Schematic diagrams for the identification of a fatigue damaging event in VA loadings: (a) Possible trigger level values across the data set, (b) Decay enveloping of a fatigue damaging event that satisfied the trigger level requirements
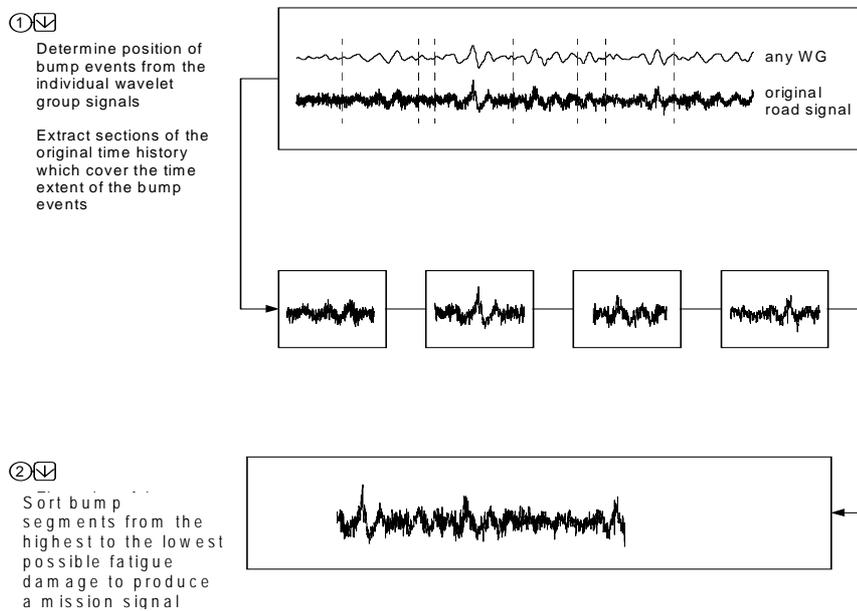

FIGURE 3. A schematic diagram of the bumps extraction process from the VA fatigue loadings (Stage 1) and of the mission signal definition (Stage 2)

After all the bumps are identified in the wavelet groups, a method of searching the bump start and finish points from the original time history has been introduced. If a bump event is

found in any of the wavelet groups, a block of data covering the time frame of the bump feature is extracted from the original data set. This data selection strategy, which is shown in Fig. 3, retains the amplitude and phase relationships of the original signal. The final process in the WBE processing is to produce a shortened mission signal, in which the bump segments extracted from the original time history are joined together in the order of high to low possible fatigue damage.

Fatigue Damaging Events Identification of the Road Load Data

The accuracy of the fatigue damaging event identification process was evaluated by the application to two VA strain histories that were measured on vehicle suspension arms. The first signal, named T1, was measured on a van while driving over a pavé test track [12]. T1 was sampled at 500 Hz with a record length 46 seconds. The second signal, named T2, was measured on a suspension arm of an automobile driven through proving ground maneuvers [13]. This signal contains low frequency background with the sampling frequency at 204.8 Hz, and its time length is 61 seconds. Fig. 4 presents both time histories in the units of microstrain.

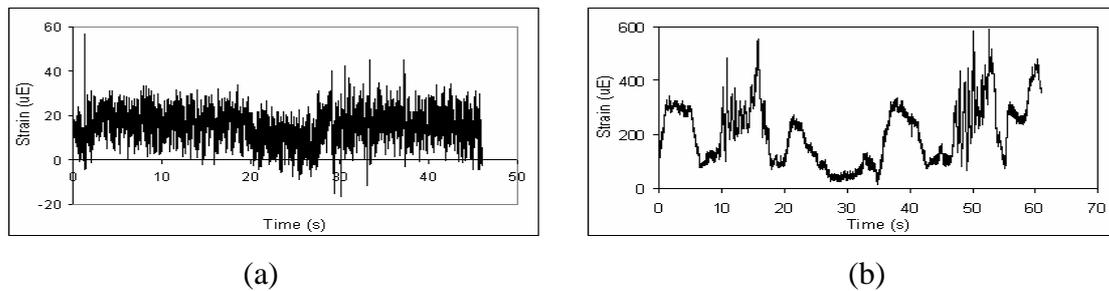| (a) | (b) |

FIGURE 4. Time histories of the signals analysed: (a) T1, (b) T2

Using the WBE algorithm T1 was decomposed into 12 wavelet levels and the levels were later assembled into four wavelet groups [9]. The wavelet coefficients from the wavelet levels contained in each wavelet group were used to construct its time history as in Fig. 5a. In addition, the location of fatigue damaging events or bumps present in each wavelet group is shown in Fig. 5c. The individual bumps in each wavelet group are identified within ±10% RMS and kurtosis difference between the original and mission signals. For T2, the original data set was decomposed into 12 wavelet levels and the levels were clustered into two wavelet groups for which their time histories are shown in Fig. 6a. The bumps of T2 that were identified in each wavelet group at the same value of the global statistical difference is shown in Fig. 6b. The difference of ±10% in RMS and kurtosis was used with a consideration of at least 10% of the original road data contained low amplitudes which gave minimal fatigue damage.

For both data sets, the extracted bumps from all wavelet groups were used for identifying the start and finish points of the respective bump segments. Fig. 5c for T1 and Fig. 6c for T2 show all bump segments at their original time position with respect to the original signals. Nine segments of fatigue damaging events were extracted from T1 and two segments from T2. The mission signals produced by adding the bump segments are shown in Fig. 5d and Fig. 6d. These mission signals retain almost all the original fatigue damage of their respective original signals. By comparing the bump segments for the two data sets, it can be seen that

the low frequency content of the road load data has an important role in determining the overall length of the bump segments. With reference to Fig. 5 and Fig. 6 the bump segments of T2 had longer time extent compared to the bump segments of T1. It is not easy to heavily compress VA fatigue loadings with a substantial low frequency content (such as signal T2) because most of the mission time length was caused by a single bump from the low frequency wavelet group. Since T1 was measured on a pavé test track surface, a higher compression factor (more than 50% of the time length) is obtainable to produce the mission signal.

(a)   (b)

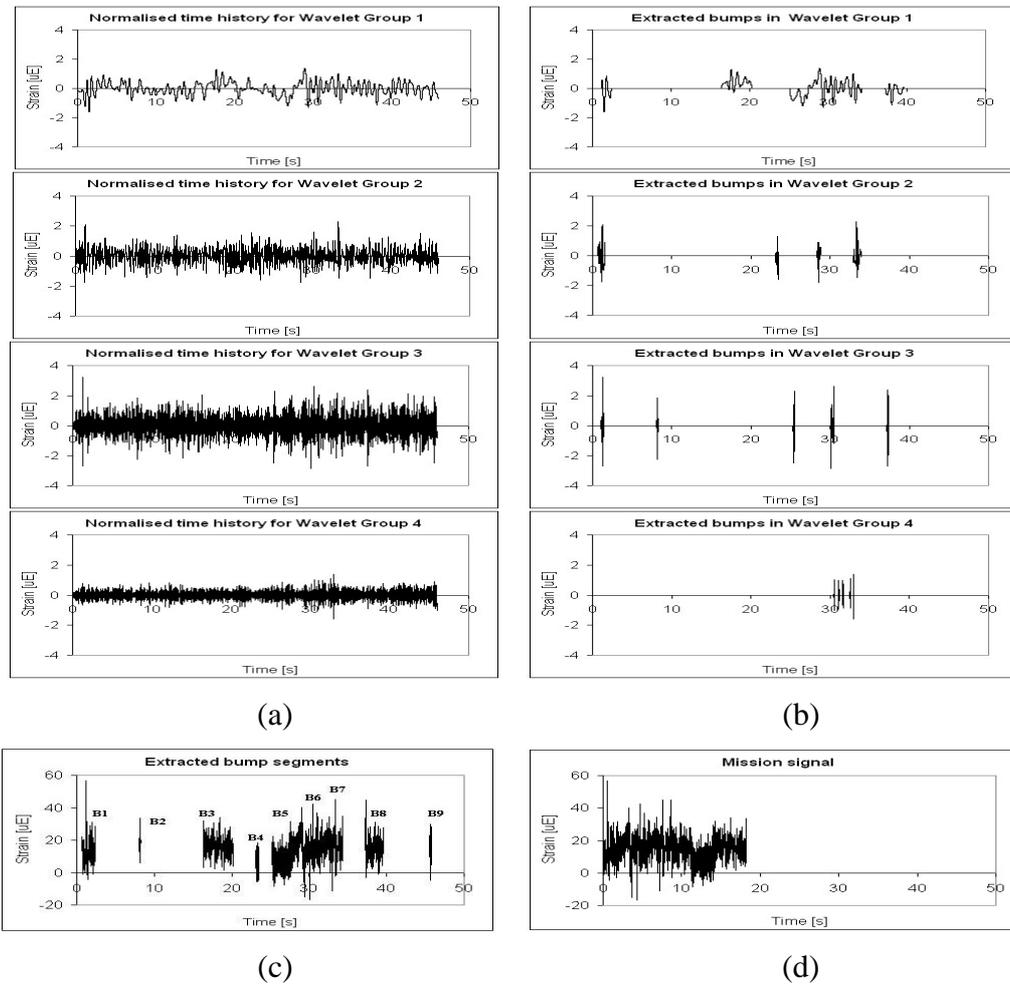(c)   (d)

FIGURE 5. Results for T1: (a) Normalised time history for all wavelet groups (b) Location of bumps in all wavelet groups, (c) The extracted bump segments (in original scale) at their original location of the input fatigue signal, (d) The mission signal

For the fatigue damage analysis, the damage values were calculated by applying the Palmgren-Miner's cumulative linear damage rule by means of the nSoft® software package [14]. Two strain-life models with mean stress correction terms were considered for comparison purposes, i.e. SWT and Morrow. Fig. 7 shows the level of fatigue damage for the bump segments, the original signal and the mission signal. For the comparison of fatigue damage between the original signal and its mission signal, at least 94% of fatigue damage for T1 was retained when its original history was compressed to approximately 60% of the original time. However for T2, about 85% fatigue damage was retained when the original T2 was compressed to 34% of the original time. Therefore, most of the original damage was

retained in the mission signals, and this indicates the suitability of WBE to be used in fatigue data editing applications.
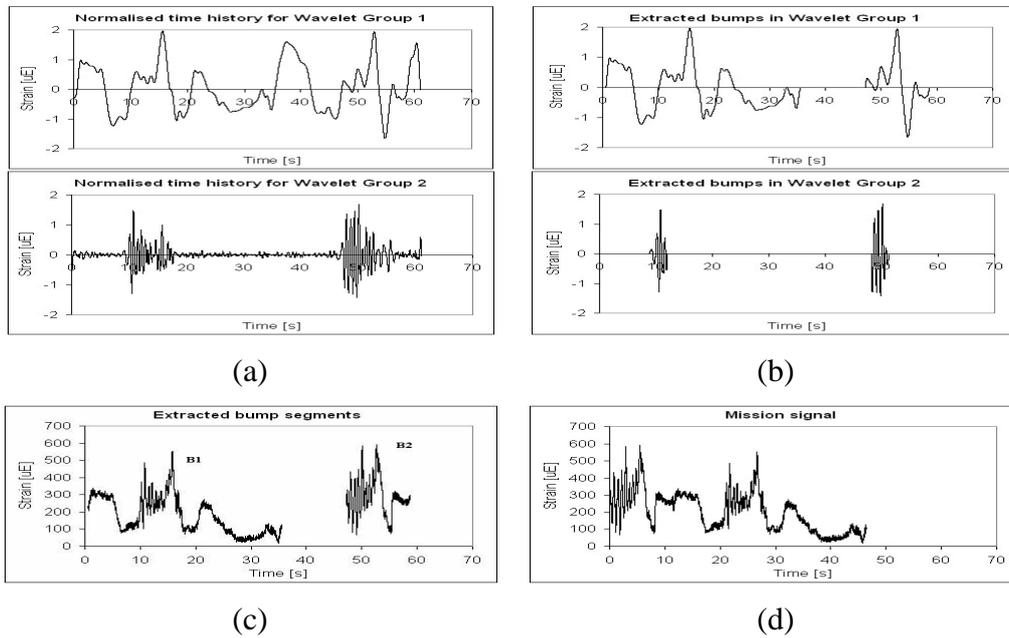

(a)

(b)

(c)

(d)

FIGURE 6. Results for T2: (a) Normalised time history for all wavelet groups (b) Location of bumps in all wavelet groups, (c) The extracted bump segments (in original scale) at their original location of the input fatigue signal, (d) The mission signal
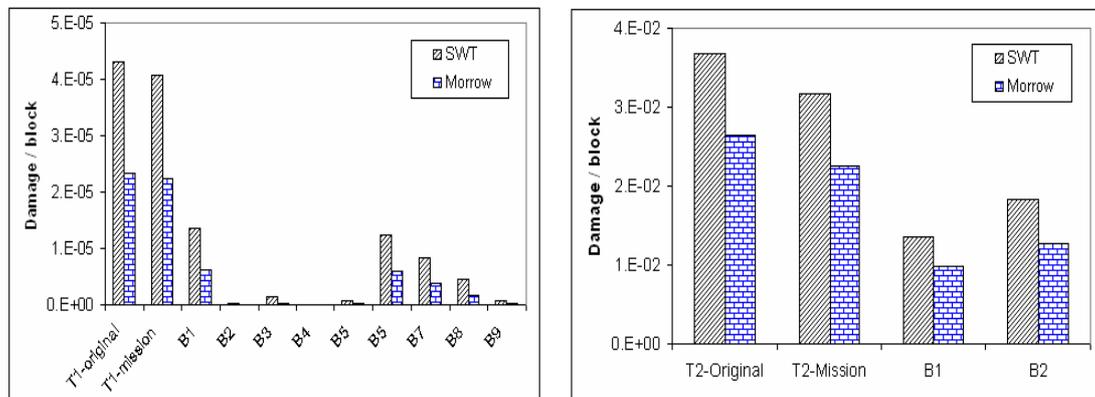

FIGURE 7. Damage distribution for the original signal, the mission signal and bump segments for both T1 and T2. B1-B9 is the bump numbers with respect to Fig. 5c and Fig. 6c.

Conclusions

Wavelet Bump Extraction (WBE) is an algorithm which is able to identify the important fatigue damaging events or bumps, and to extract them from the original time history, whilst preserving their sequences of load cycles. Using the WBE procedure the total damage produced by the combination of the extracted fatigue damaging events was close to that of the original data set. In the mission signals, the original VA fatigue loadings were compressed by up to 40% of the signal length with at least 85% of the total fatigue damage retained. Based on these results, WBE appears to be a suitable wavelet-based approach for

identifying fatigue damaging events and to produce mission signals. Since the original fatigue damage is retained in the mission signal, therefore it is suitable for accelerated fatigue testing.

Acknowledgements

References

1. Yan, J.H., Zheng, X.L. and Zhao, K., *Int. J. Fatigue*, vol. **23**, 403-415, 2001.

2. Canfield, R.E. and Villaire, M.A., *SAE Technical Paper Series*, SAE920660, 1-11, 1992.

3. El-Ratal, W., Bennebach, M., Lin, X. and Plaskitt, R., Paper presented in *Symposium on Fatigue Testing and Analysis Under Variable Amplitude Loading Conditions, Tenth International Spring Meeting of SF2M*, Tours, France, 29-31st May, 2002.

4. Conle, A. and Topper, T.H., *Int. J. Fatigue*, vol. **1**, 23-28, 1979.

5. Austen, I. and Gregory, R., *VTT Symposium*, vol. **3** (Part 157), 169-187, 1995.

6. Stephens, R.I., Dindinger, P.M. and Gunger, J.E., *Int. J. Fatigue*, vol. **19**, 599-606, 1995.

7. Morrow, D. and Vold, H., SAE paper (SAE930403) in *Recent Developments in Fatigue Technology,* edited by R.A. Chernenkoff and J.J. Bonnen, Society of Automotive Engineers (SAE), USA, 1997.

8. Oh, C-S., *Int. J. of Fatigue*, vol **23**, 241-250, 2001.

9. Abdullah, S., Yates, J.R. and Giacomin, J.A., In *Proceedings of in Fifth International Conference on Low Cycle Fatigue (LCF5)*, 9-11th September, Berlin, Germany, 2003.

10. Giacomin, J., Steinwolf, A. and Staszewski, W.J., *Engineering Integrity*, vol. **7** (January), 44-56, 2000.

11. Abdullah, S., Giacomin, J.A. and Yates, J.R., *Proc. of the Instn. of Mech. Engrs, Part D, Journal of Automobile Engineering,* vol. **218**, 243-258, 2004.

12. Leyland Technical Centre (LTC), Aston Way, Leyland, Preston, PR5 3TZ, England.

13. Leser, C., Juneja, L., Thangjitham, S. and Dowling, N.E., SAE paper (SAE 980696) presented at *SAE World Congress*, 23rd – 26th February, Detroit, USA, 1998.

14. nSoft V5.3, nCode International Ltd., Sheffield UK, 2001.