The applicability of the short-time Fourier transform (STFT) for fatigue data editing

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Abstract: - This paper presents the fatigue data editing technique for accelerating the simulation of fatigue durability testing. This technique was performed by removing low amplitude cycles contained in the original signal in order to produce a shortened signal using the short-time Fourier transform (STFT) method. The transformation of time domain signal into time-frequency domain provides the energy distribution display with respect to the particular time and frequency information. In this study, low amplitude cycles were eliminated according to the cut-off level of the signal energy distribution in the time representation. The simulation results showed that, the edited signal contained at least 94% of the original fatigue damage in the 124-seconds edited signal, i.e. 78% of the original signal time length. Thus, it has been suggested that this shortened signal can then be used in the laboratory fatigue testing for the purpose of accelerated fatigue testing. Finally, this STFT-based fatigue data editing approach is also suggested to be an alternative technique in fatigue durability study.

Key-Words: - Fatigue data editing, Random loading, Signal processing, STFT, Time-frequency analysis.

1 Introduction

For many automotive components, the primary mode of failure can be attributed to fatigue damage resulting from the application of variable amplitude loading. Predicting the life of part stressed above the endurance limit is at best a rough procedure [1] especially for components like automobile engine, steering and suspension parts [2]. For these cases, the strain-based approach is commonly used to predict fatigue life [3]. The strain-life fatigue model relates the plastic deformation that occurs at a localized region where fatigue cracks begin to the durability of the structure. This model is often used for ductile materials at relatively short fatigue lives. This approach can also be used where there is little plasticity at long fatigue lives. Therefore, this is a comprehensive approach that can be used in place of the stress-based approach.

For fatigue life assessment study, fatigue data editing is described as a method of summarising the fatigue data with removing small amplitude cycles for reducing the test time and cost. Several fatigue data editing techniques have been developed for used in the time domain analysis [4]. Some of the previous algorithms were developed for eliminating low amplitude cycles, hence to retain high amplitude cycles [5]. In the frequency domain, a time history is low pass filtered on the basis that high frequency cycles have small amplitudes which are not damaging [6]. The filtering method does not shorten the signal because it does not provide the time base information.

The time-frequency approach had been applied to the problem of fatigue data editing through the compromise between the time- and frequency-based views of a signal. The short-time Fourier transform (STFT) or windowed Fourier transform is one of the methods for transforming the time domain signal into the time-frequency domain. In addition, the STFT adapted the Fourier transform to analyse only a small section of the signal at one specific time [7]. Finally, STFT provides information on when and at what frequencies a signal occurs.

In this paper, the STFT method was used to transform the time domain signal into time-frequency domain in order to trace the low energy cycle contained in the original signal. Those cycles was then removed from the original signal in order to gain a new edited signal which having segments of high amplitude cycles. For this reason, low amplitude cycles which have been removed have minimal or no fatigue damage potential. Therefore, the original fatigue damage can be retained in the edited signal produced at the end of the process.

For this study, finally, the effectiveness of this technique was validated based on the fatigue damage retention in the shortened signal, and it was then compared to the original signal.

2 Literature Background

2.1 Fatigue Damage

Current industrial practice for fatigue life prediction is to use the Palmgren–Miner (PM) linear damage rule [8]. For strain-based fatigue life prediction, this rule is normally applied with strain-life fatigue damage models, such as the Coffin–Manson relationship [9,10], i.e.

$$\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (1)$$

where E is the material modulus of elasticity, ε_a is a true strain amplitude, $2N_f$ is the number of reversals to failure, σ'_f is a fatigue strength coefficient, b is a fatigue strength exponent, ε'_f is a fatigue ductility coefficient and c is a fatigue ductility exponent.

2.2 Short-time Fourier Transform (STFT)

Many time-frequency analyses are based on windowed or short-time Fourier transforms [11]. Sliding data windows were used to obtain time-localised spectra which together put up the time-frequency representation of the data. In principle, any window function can be used, but window size and shape determine the time-frequency resolution and the spectral leakage [12].

The STFT is performed by dividing the signal into small sequential or overlapping data frames. Then, fast Fourier transform (FFT) has been applied to each data frame [13]. The output of successive STFT can provide a time–frequency representation of the signal. In order to accomplish this, the signal is truncated into short data frames by multiplying it by a window so that the modified signal is zero outside the data frame. In order to analyse the whole signal, the window is then translated into a time and reapplied to the signal.

The STFT is composed by the local spectra of segments of the primary function, as viewed through a translating window of fixed shape. The local spectra at all points on the primary time axis constitute the STFT [14]. The general expression is

$$STFT(t,f) = \int_{-\infty}^{\infty} h(t)w(t-\tau)\exp(-2\pi i f\tau)d\tau \qquad (2)$$

where h is the primary function, τ is the time and f is the frequency. The position of the translating window w is determined by t, which has the same units as τ. If w is replaced with the value of 1 in Equation (2), the STFT reduces to H, i.e. the Fourier transform of h. The modulus of the STFT is also known as the spectrogram.

3 Methodologies

In this study, the input signal was a variable amplitude (VA) loading sampled at 200 Hz for 32,000 data points. It gave the total record length of the signal of 160 seconds. The signal was measured on the front left lower suspension arm of a car which was travelling on a public road surface. This data contained many small amplitude and high frequency in the signal background, as illustrated in Fig. 1.

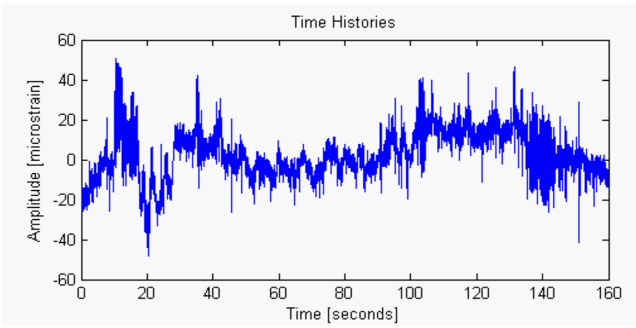


Fig. 1. The original test signal

For the fatigue damage calculation, the selected material for the simulation testing purpose was the SAE1045 steel. This material was chosen because it was commonly used to fabricate a vehicle lower arm suspension structure. The material properties and their definitions are given in Table 1, and Fig. 2 shows the strain life of the SAE 1045 steel.

In this study, the fatigue data editing using STFT method was based on the following main stages: the time-frequency analysis, the generation of a new edited signal and fatigue damage analysis.

Table 1. Mechanical properties of the SAE1045 steel

Properties	SAE1045 steel
Ultimate tensile strength, S_u (MPa)	621
Modulus of elasticity, E (GPa)	204
Fatigue strength coefficient, σ'_f (MPa)	948
Fatigue strength exponent, b	-0.092
Fatigue ductility exponent, c	-0.445
Fatigue ductility coefficient, ε'_f	0.26

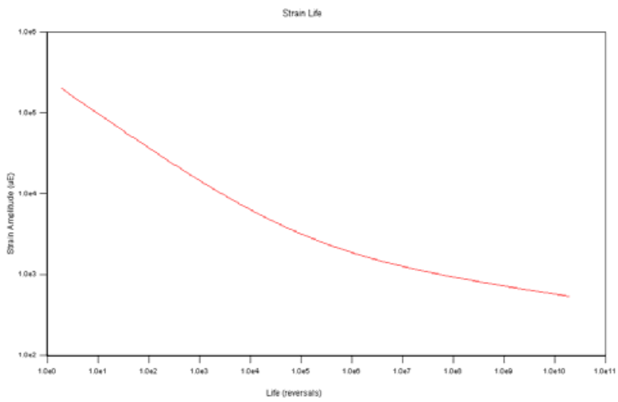


Fig. 2. The strain-life curve for the SAE 1045 steel

4 Results and Discussions

4.1 Time-frequency Analysis

In the analysis, the signal in time domain was converted into time-frequency domain using the STFT method. The time history signal was separated into a number of windows using the Gaussian window with 128 of window size. The 120 number of overlaps were used in order to provide the high resolution in the time representation. For each window, the Fourier transform was applied for the calculation of the signal energy contained in each window. The energy calculation was gained from the power spectral density (PSD) that produced the *spectrogram* of the STFT. For this case, the PSD is defined as the distribution of the signal energy.

Using the MATLAB software, the STFT plot of the original fatigue signal showed a two dimensional view of the energy distribution, as observed in the time-frequency plane. This result was plotted in Fig. 3. The level was presented by a colour contour, for which the red colour showed the highest energy content and followed by yellow, green and blue.

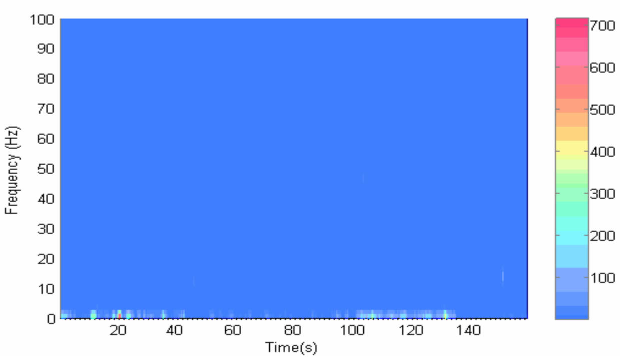


Fig. 3. The STFT localisation of the test signal

Based on the energy parameter obtained in the STFT processing, the spectrogram value was decomposed into a time domain display in order to represent the energy distribution in time history. The energy display in the time domain provided the time location containing the low energy cycle. The STFT energy distribution is illustrated in Fig. 4. Accordingly, the low energy cycles will be eliminated for summarising the signal length without compromised the original fatigue damage potential. For a specific fatigue data, the low energy cycles mean these cycles had a low amplitude strain which is not damaging.

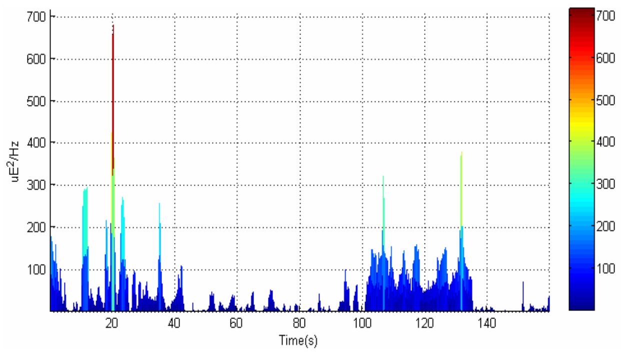


Fig. 4. The STFT energy distribution for the analysed signal

For solving the subject matters of this paper, a STFT-based computational algorithm was developed in order to analyse the signal according to the fatigue damage calculation and also to remove cycles with low energy content. Thus, the cycles with higher energy content has been retained for further analysis. These cycles (combination of a group of cycle sequences to form of a segment) was then joined for producing the new edited signal, which has shorter time length. In addition, this edited signal should also have equivalent fatigue damage to the original signal.

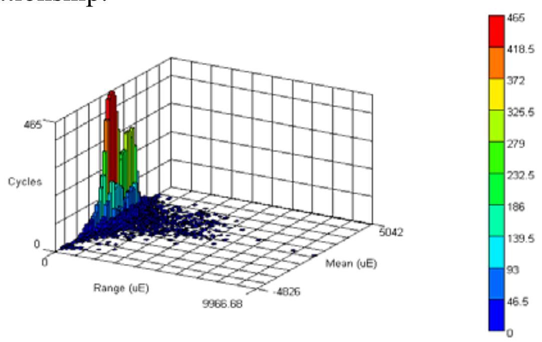
Referring to Fig. 4, the low energy cycles were removed from the time domain signal based on the location of low energy cycle in time history energy distribution. A new parameter has been set called cut-off energy (COE), which represents the minimum energy value to be retained from the original signal. It means that, the cycles with energy bellow than COE value will be eliminated. Various COE values were used in order to exhibit the effectiveness of the edited signal with respect to the fatigue damage retention.

4.2 Fatigue Damage Analysis

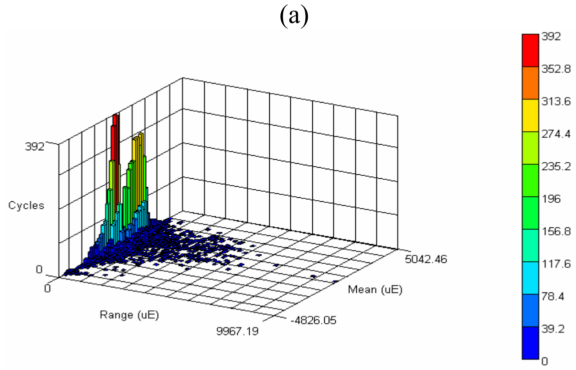
In order to achieve the objective of this paper, the fatigue damage retention was the most important parameter for the application of fatigue data editing technique. In an automotive application, the edited fatigue data required to retain the fatigue damage with below than 10% deviation compared to the original signal.

In order to verify the effectiveness of the edited signal, the fatigue damage for the original signal and the edited signals will be determine. The edited signals considered the signal were produced from the difference COE value. The fatigue was estimated by utilizing the strain-life module contained in the GlyphWorks® ver. 4.0 software. The fatigue damage calculation was based on the Coffin-Manson strain-life relationship.

By using Equation (1), the number of reversals, N_f, were determined in order to find cumulative fatigue damage. The values of σ'_f, E, ε'_f, b and c were given in Table 1, while the values of ε'_a were obtained from rainflow cycle counting method. The example histogram of cycle counting for the original signal and edited signal were illustrated in Fig. 5. The cumulative fatigue damage was then determined using the Palmgren–Miner (PM) linear damage rule. The damage histogram of the signal was then plotted as in Fig. 5, showing the damage potential for each cycle calculated using the Coffin-Manson relationship.



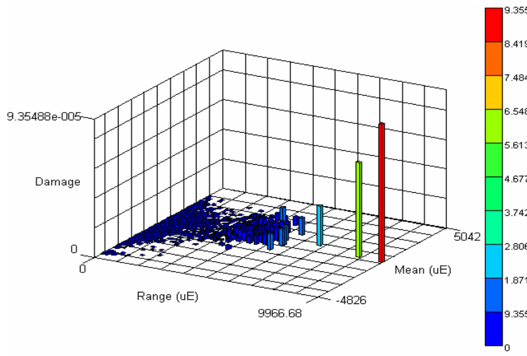
(a)



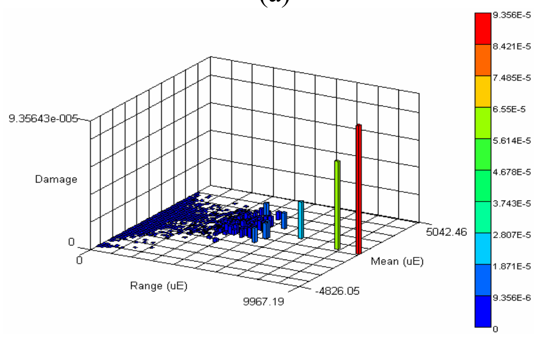
(b)

Fig. 5: The cycle counting histogram for the COE value of 5 $\mu\varepsilon^2Hz^{-1}$: (a) The original signal, (b) The edited signal

In this study, nine signals (8 edited signals and the original signal) were simulated for the purpose of the verification the efficiency of fatigue data editing using STFT method. The edited signals were produced at eight COE values, i.e. 5, 10, 15, 20, 25, 30, 35 and 40$\mu\varepsilon^2Hz^{-1}$. The edited signals produced from these eight COE values were shown in Fig. 7. From the fatigue damage analysis of each edited signal, the optimum value of COE was then determined based on the capability of each COE (reflect to each edited signal) to produce the equivalent fatigue damage potential as compared to the original signal.



(a)



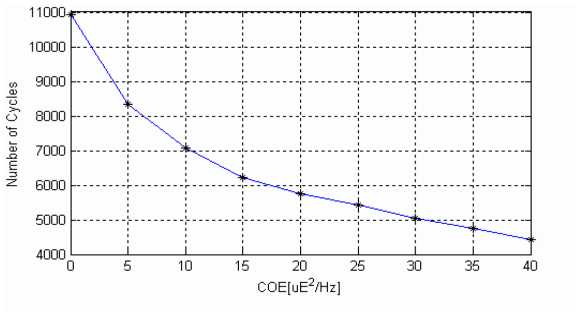
(b)

Fig. 6. The fatigue damage histogram for the COE value of 5 $\mu\varepsilon^2Hz^{-1}$: (a) The original signal, (b) The edited signal

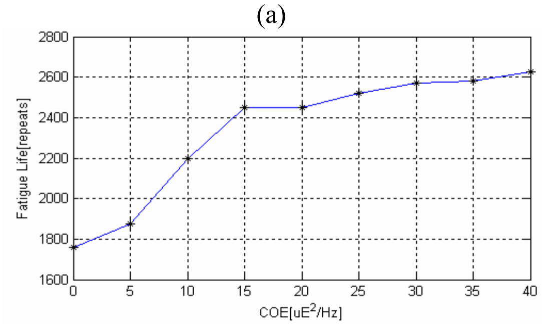
The trends of using different COE were illustrated in Fig. 8, where the fatigue life, fatigue damage and number of cycle counting were considered. The 0 $\mu\varepsilon^2Hz^{-1}$ value in the graph was representing the original signal. From the fatigue damage calculation results, it was found that the value of 5 $\mu\varepsilon^2Hz^{-1}$ to be an optimum COE value. It is because of the fatigue damage value that was produced from this edited signal have only 6% deviation when compared to the original signal.

For the other edited signals, however, they were unable to retain the fatigue damage difference within the 10% deviation of the original signal. At the 5 $\mu\varepsilon^2Hz^{-1}$ of the COE value, it has been showed that the cycles that have been removed can be neglected for the reason of these cycles gave minimal or no contribution to the fatigue failure.

Finally, the applicability of fatigue data editing with the adaptation of the STFT method was proven for the situation to shorten the signal length with the retention of the majority of the original fatigue damage. At this fatigue damage ratio (i.e. at the 6% difference), the new edited signal was produced at the 124 seconds, which is 36 seconds shorter than the original signal length. These values gave 22% of the original time length reduction.



(a)



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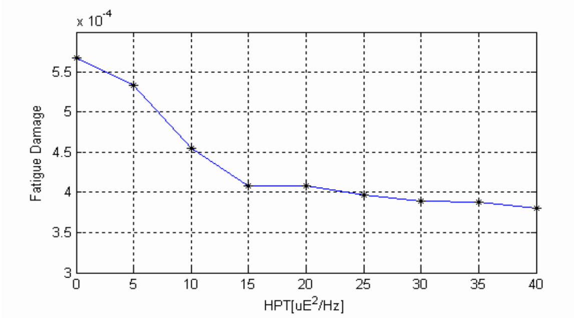

(c)

Fig. 8. Graph of parameter changes over COE: (a) Number of cycle counting, (b) Fatigue life, (c) Fatigue damage

4 Conclusion

This paper discussed on the study of a fatigue data editing technique in time-frequency domain by using STFT method. The STFT-based computational algorithm was developed to remove the low amplitude cycles that contained in the original signal. From the simulation results, the edited signal at the COE value of 5 $\mu\varepsilon^2 Hz^{-1}$ was found to be an optimum value in retaining at least 94% of the original fatigue damage in the 124-seconds edited signal. With respect to the time retention, 78% of the original signal time length was retained using this method.

In terms of the applicability of the shortened signal, this kind of signal is normally used in the laboratory fatigue testing for the purpose of accelerated fatigue testing. Finally, this method is suggested as an alternative technique in fatigue durability study, especially for the automotive engineering field.

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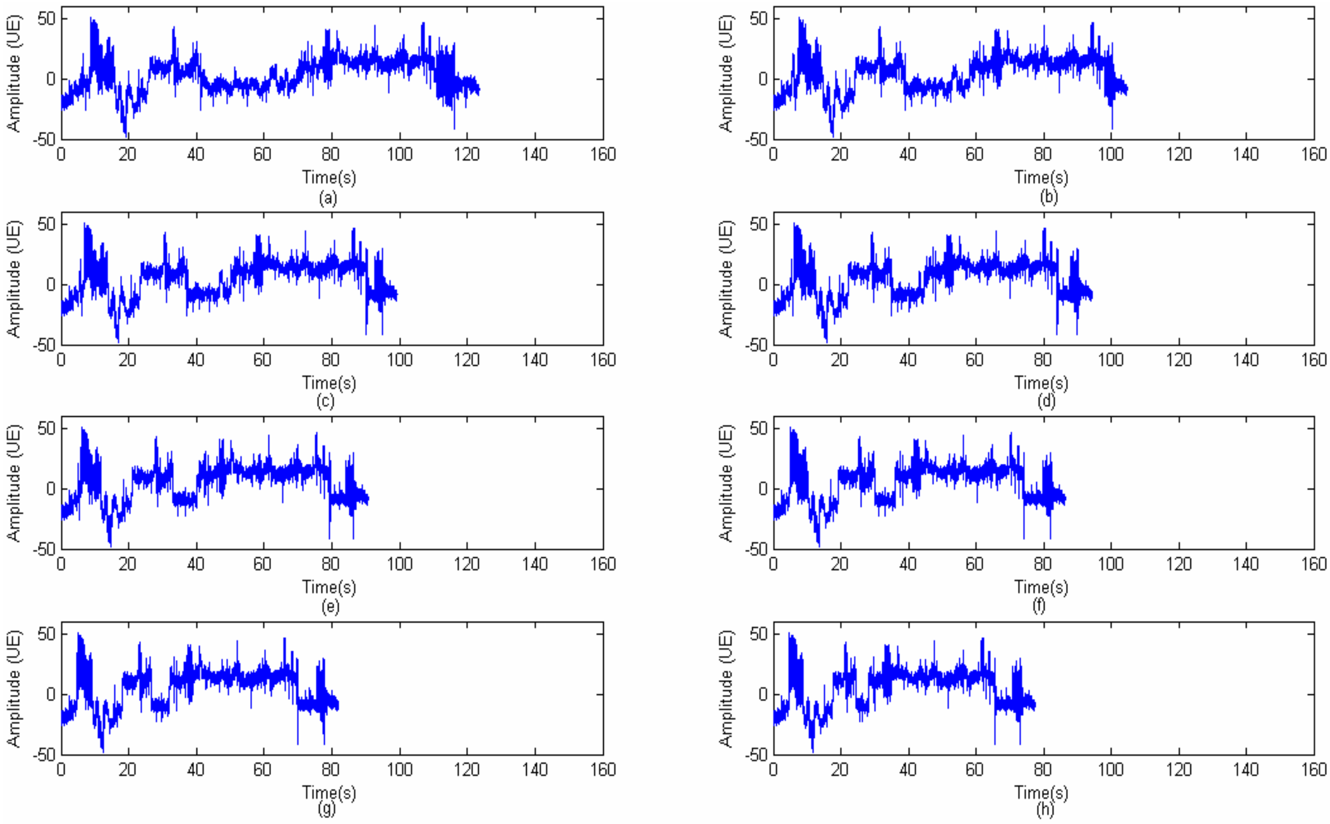

Fig. 8. The edited signals at the different COE values: (a) 5 $\mu\varepsilon^2Hz^{-1}$, (b) 10 $\mu\varepsilon^2Hz^{-1}$, (c) 15 $\mu\varepsilon^2Hz^{-1}$, (d) 20 $\mu\varepsilon^2Hz^{-1}$, (e) 25 $\mu\varepsilon^2Hz^{-1}$, (f) 30 $\mu\varepsilon^2Hz^{-1}$, (g) 35 $\mu\varepsilon^2Hz^{-1}$, (h) 40 $\mu\varepsilon^2Hz^{-1}$