Fatigue Life Assessment Using Signal Processing Techniques

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Abstract: - This paper presents the fatigue life assessment using signal processing approaches which study on the characteristics of the fatigue signal in frequency and time-frequency domain. The signals used in this research were variable amplitude fatigue signal which consisted of a synthetic data and experimentally measured data. As frequency domain method is one of the techniques to analyse random signal, it can be applied to observe strain characteristic of the signal in frequency domain. Thus, Power Spectral Density (PSD) algorithm was used to gain the power distribution of the input signals. The short-time Fourier transform (STFT) method was then used to transform the input signal into the time-frequency domain. The transformation of time domain signal into time-frequency domain provides the power distribution display with respect to the particular time and frequency information. From the power distribution gained, the fatigue damage features can be identified. Finally, the life estimation of the components was calculated in order to study its durability.

Key-Words: - Automotive, Fatigue, Fatigue road loadings, Signal processing, Simulation, Variable amplitude.

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 especially for components like automobile engine, steering and suspension parts [1]. For these cases, the strain-based approach is commonly used to predict fatigue life [2]. 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.

In signal processing approach, the fatigue signal can be analysed in frequency domain and time frequency domain. Frequency analysis data is typically presented in graphical form as Power Spectral Density (PSD). Essentially a PSD display the amplitude of each sinusoidal wave of a particular frequency. Frequency is given on the x-axis. The mean squared amplitude of a sinusoidal wave at any frequency can be determined by finding the area under the PSD over that frequency range [3]. The short-time Fourier transforms (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 [4]. Finally, the STFT provides information on when and at what frequencies a signal occurs.

In this paper, two fatigue signals were analysed using signal processing approach in order to observe the signal characteristics in frequency and time-frequency domain. The fatigue life for each signal was then predicted using strain life based to study the durability of the structures under variable amplitude loading.

2 Methodology
The methodology of this activity involves the fatigue data measurement and also fatigue data analysis. The purpose of this type of analysis is to verify the durability of a component after being affected by a spectrum fatigue loading, which lead to the improvement of the structural integrity of any related system. Two data sets have been used for this study, named as T1 (a synthetic data) and T2 (experimentally measured data).

The logic of creating T1, as shown in Fig. 1a, was to observe the data processing ability to deal with any signal containing large transients in a small amplitude background, so that the high amplitude events which lead to the fatigue damage can be properly identified [5,6]. This data was defined with 16,000 data points and sampled at 400 Hz. It consists of a combination of sinusoidal and random signals of...
various amplitudes and frequencies, and it was intentionally defined to be a mixture of both high amplitude events and low amplitude harmonic background.

The second, named as T2 (see Fig. 1b), is a fatigue strain signal that was measured on a component of a specific structural system. It was sampled at 200 Hz for a total of 30,000 data points that produced a total record length of 150 seconds. This signal exhibits a slight change in mean of the whole signal with a little low frequency content. This data set was chosen because it contained many transient events in the signal background. The data was measured using fatigue data acquisition system, called SOMAT eDAQ®, and further analysis for both T1 and T2 was performed using the software developed by nCode International, i.e. GlyphWorks®. Fig. 2 shows the schematic arrangement for data collection and analysis.

3 Results and Discussions: Signal Analysis
The analysis of the collected data for both T1 and T2 was statistically carried out in order to determine the meaningful statistical properties for the fatigue damage analysis. This global signal statistical analysis is also being performed for determining determination of the signal behaviour. The signal root-mean-square (r.m.s.) value, which is the 2nd statistical moment, is used to quantify the overall energy content of the oscillatory signal. The kurtosis, which is the signal 4th statistical moment value, is also being used to quantify the nongaussianity of the data since it is highly sensitive to outlying data among the instantaneous values. For both data sets, these statistical parameters are tabulated in Table 1.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>T1</td>
<td>80</td>
<td>-0.0192</td>
<td>1.4835</td>
</tr>
<tr>
<td>T2</td>
<td>150</td>
<td>2.6044</td>
<td>11.4873</td>
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</table>

The power spectral density (PSD) analysis is later being performed for observing the distribution of vibrational signal energy across the frequency domain. A PSD is used to convert a signal from the time domain to the frequency domain using the fast Fourier transform (FFT) method. In the relation of the PSD with the FFT, the PSD is a normalised density plot describing the mean square amplitude of each sinusoidal wave with respect to its frequency. The plot of PSD for both T1 and T2 can be seen in Fig. 3, showing that both signals contain the fatigue damage features in the low frequency distribution. It shows the same argument with the theoretical findings, i.e. the low amplitude events of the fatigue cycles can be found in the higher frequency distribution of a frequency spectrum. With the application of low pass filter, these high frequency cycles with low strain amplitude can be removed.

Short-time Fourier transform (STFT) is a method of time-frequency analysis which aims to produce frequency information which has a localisation in time [7]. It provides information about when and at what frequencies a signal event occurs. The STFT approach assumes that if a time-varying signal is divided into several segments, each can be assumed stationary for analysis purposes. The Fourier transform is applied to each of the segments using a window function and the most important parameter in the analysis is the window length, which is chosen so as to isolate the signal in time without any distortions.
components, it is also feasible to predict crack initiation so as to avoid fatigue failure by monitoring and preventing the part from failure at the appropriate time. A fatigue life estimate is usually made in such cases by means of a strain-based approach [2,8,9].

The strain-life fatigue models relate the plastic deformation that occurs at a localised region where fatigue cracks begin to the durability of the structure. This model is often used for ductile region where fatigue lives of relatively short fatigue lives. This approach is also used where a little plasticity is acceptable at long fatigue lives. Therefore, strain-based approaches are comprehensive and can be used in place of stress-based approaches. Current industrial practice for fatigue life prediction is to use the Palmgren-Miner (PM) linear damage rule. For strain-based fatigue life prediction, this rule is normally applied with strain-life fatigue damage models, such as the Coffin-Manson relationship, i.e.

\[ \varepsilon_a = \frac{\sigma_0 f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c \] (1)

where \(E\) is the material modulus of elasticity, \(\varepsilon_a\) is a true strain amplitude, \(2N_f\) is the number of reversals to failure, \(\sigma_0\) is a fatigue strength coefficient, and \(b\) is a
fatigue strength exponent, $\varepsilon'_f$ is a fatigue ductility coefficient and $c$ is a fatigue ductility exponent.

According to the analysis presented in this paper using both signals, the fatigue life assessment was performed using the GlyphWorks® software package. The basic procedure of performing this kind of durability analysis is the application of service load (fatigue data) onto a component which was fabricated from the designated material. Therefore, the SAE1018 carbon steel was selected for the purpose of simulation, and also this kind of material are also being used in the piping industry. The strain-life curve that indicates the fatigue life at specific strain amplitudes was presented in Fig. 5.

Fig. 6 shows the histogram plots of the fatigue damage potential, showing highest point of fatigue damage in the red colour. This damage value was calculated using the Coffin-Manson relationship, based on the $N_f$ value when referring to Equation (1). Thus, the fatigue damage $(D)$ can then be calculated as in Equation (2):

$$D = \frac{1}{N_f}$$

(2)

Using both Equation (1) and (2), the fatigue lives for both signals were calculated and are presented in Table 2.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Signal length [seconds]</th>
<th>Fatigue life Blocks to failure</th>
<th>Total time to failure [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>80</td>
<td>$1.491 \times 10^9$</td>
<td>$3.31 \times 10^3$</td>
</tr>
<tr>
<td>T2</td>
<td>150</td>
<td>$1.760 \times 10^3$</td>
<td>73.3</td>
</tr>
</tbody>
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Fig. 5: The strain-life curve for SAE1018 carbon steel

Table 2: The fatigue life values for T1 and T2

5 Conclusions

This works has been presented in order to expose a better overview of structural integrity assessment of structural or system components using the combination approach of signal analysis and fatigue life assessment. It can be said as a new approach introduced to the structural integrity research since the last decade. In this paper, two fatigue strain loadings, or later called signals, which exhibiting the variable amplitude pattern has been analysed using the MatLab (for signal analysis) and the GlyphWorks® (for fatigue life assessment)
software packages. With the application of the short-time Fourier transform (STFT), the fatigue damage features can be identified. Later part of this paper, the fatigue lives for both signals were calculated, indicating how long a component can be lasted without failure under the given strain loading. Finally, it is suggested that the approach presented in this paper can be then be applied for determining the life span of any metallic structures.

References: