Study on Correlation between Strain and Vibration Signal Using Hybrid I-Kaz Method

S. ABDULLAH, N. ISMAIL, M. Z. NUAWI, M. Z. NOPIAH & A. ARIFFIN
Department of Mechanical and Materials Engineering,
National University of Malaysia,
43600 UKM Bangi, Selangor,
Malaysia.
shahrum1@gmail.com

Abstract: - This study was specifically focuses on the coil spring, one of the suspension system parts. Under its service life, this component will be driven over different surfaces profile that will give the different displacement and vibration response. This paper explores the correlation between the strain signal resulted from displacement and vibration response when subjected to the variable amplitude loading. This comparative study was implemented using fatigue damage assessment, \((\varepsilon-N)\) and Hybrid Integrated Kurtosis-based Algorithm for Z-notch filter Technique (Hybrid I-kaz). Hybrid I-kaz method provides a two dimensional graphical representation of the measured strain and vibration signal and Hybrid I-kaz coefficient, \(Z_{\infty}^h\) to measure the degree of data scattering. An experiment has been performed on an automotive suspension system machine. This study considered the test signal which is excited based on ten different frequencies that are 1 Hz to 10 Hz. The strain gauge of 5 mm size and accelerometer was mounted on the inner surfaces of the coil spring to measure the fatigue signals and vibration responses, respectively due to the loading. The time domain fatigue signal and vibration signal was then analysed based on Coffin-Manson model for fatigue damage assessment and Hybrid I-kaz method. The total fatigue damage and Hybrid I-kaz coefficients, \(Z_{\infty}^h\) for each signal of the different frequency were compared in order to correlate the relationship. From the analysis, it was found that the strain signal was linear proportionally related to the vibration responses.

Key-Words: - Fatigue, Vibration response, Random loading, I-kaz Hybrid, Coefficient, Correlation

1 Introduction

In service life, automotive suspension system experiencing the significant load that cause the vibration and displacement that contributing to mechanical failure due to fatigue [1]. Vehicle vibration may actually be due to an improperly functions of automotive suspension system. These two parameters were important as to achieve the higher quality levels of vehicles in term of riding comfort and be resistant to high load [2]. This study was focuses on the coil spring, one part of the suspension system as this system was directly experiencing the load when the vehicle was driven over the road.

Vehicle was influenced by the excitations due to the road unevenness. Vehicle responses were different at the different velocities although at the same road condition. This factor was taking into consideration to induce different displacement and vibration of the coil spring under it service conditions.

Analysis to be performed for the purpose of this paper is the fatigue damage assessment. The strain-life \((\varepsilon-N)\) is used for the analysis as the case study was related to the low cycle fatigue, which is a suitable approach to analyse random data collected from automotive components [3]. Another analysis to be performed for the purpose of this paper is the statistical analysis, which is using the newly developed statistical-based method, called Hybrid Integrated Kurtosis-based Algorithm for Z-notch filter Technique (Hybrid I-kaz). Hybrid I-kaz method calculates the related coefficient for the measured signal that is the Hybrid I-kaz coefficient, \(Z_{\infty}^h\) and three dimensional graphic displays of the magnitude distribution. The input signal of the fatigue damage assessment and I-kaz Hybrid method was strain and vibration signal that was collected from the automotive suspension system machine.

This work was assessing the total fatigue damage \((D)\) and \(Z_{\infty}^h\) of strain and vibration signals for different frequencies. The goal is to determine the correlation between the strain and vibration signal of the coil spring in term of \(D\) and \(Z_{\infty}^h\).

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2 Literature Review

2.1 Total fatigue damage

Three major approaches have widely been used to analyse fatigue damage or fatigue life, namely the stress-life approach (S-N), the strain-life approach (ε-N) and the linear elastic fracture mechanics (LEFM) [4]. However, the strain-life (ε-N) is used for the analysis as the case study was related to the low cycle fatigue, which is a suitable approach to analyse random data collected from automotive components. The foundation of the strain-life approach is the Coffin-Manson relationship [5, 6] and it is defined as the following equation

$$\varepsilon = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon' (2N_f)^c$$

(1)

In the real data application of the fatigue service loading, mean stress can have a substantial effect on the metallic fatigue behaviour. In this strain-life approach, two mean-stress effect models are commonly being used, i.e. the Morrow and the Smith-Watson-Topper (SWT) strain-life models. The Morrow’s strain-life model [7] is mathematically defined by

$$\varepsilon = \frac{(\sigma_f)}{E} \left(1 - \frac{\sigma_f}{\sigma_i}\right) (2N_f)^b + \varepsilon' (2N_f)^c$$

(2)

The SWT strain-life model [8] is mathematically expressed by

$$\varepsilon_{\text{max}} = \frac{(\sigma_f)}{E} (2N_f)^b + \sigma_f' (2N_f)^c$$

(3)

For all those three strain-life expressions, E is the material modulus of elasticity, ε is a true strain amplitude, 2N is the number of reversals to failure, σ is a fatigue strength coefficient, b is a fatigue strength exponent, σmax is a maximum fatigue stress, ε is a fatigue ductility coefficient and c is a fatigue ductility exponent.

The fatigue damage caused by each cycle is calculated by reference to material life curves, i.e. stress life (S-N) or strain life (ε-N) curves. The Ni value for each cycle can be obtained from Eq. (1) to (3), and the fatigue damage value, D, for one cycle is calculated as

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

(4)

The total damage caused by N cycles is referred to the Palmgren-Miner rule, for which the accumulated damage, ΣD, is expressed as

$$\Sigma D = \sum \frac{N_i}{N_j}$$

(5)

Where Ni is the number of cycles within a particular stress range and mean, and Nj is the number of cycles to failure for a particular stress range and mean.

2.2 I-kaz Hybrid method

The global signal statistics are frequently used to classify random signals and the most commonly used statistical parameters are the mean value, the standard deviation value, the root-mean-square (r.m.s.) value, the skewness and the kurtosis [9]. In actual applications, mechanical signals can be classified to have a stationary or non-stationary behaviour. Stationary signal behaviour showed that the statistical property values remained unchanged with the changes in time. For non-stationary, however, the statistical parameter values of a signal are dependent to the time of measurement. For both stationary and non-stationary signal, the engineering-based signal analysis is important to explore the characteristics and behaviour of the signal, and the outcomes of these can also related to the fault detection and analysis.

In this work, statistic analysis had been performed in order to achieve the objective of this paper. Both signals were analysed using the I-kaz method, a new statistical-based method. I-kaz method was developed based on the concept of frequency distribution about its centroid. This method provides a two dimensional graphical representation of the frequency distribution and the I-kaz Hybrid coefficient, Z, as shown in the Eq. (6) which calculates the distance of each data point from signal centroid.

$$Z^2 = \frac{1}{N} \left( \frac{K{\varepsilon}^4 + K{S}_V^4}{S\varepsilon S_V} \right)$$

(6)

Where N is the number of data, Kε and KV are the kurtosis of strain and vibration signal, respectively and Sε and SV are the standard deviation of strain and vibration respectively. The standard deviation (S) for n data point is mathematically defined as
Kurtosis value was mathematically defined as Eq. (8). Kurtosis, which is the signal 4th statistical moment, is a global signal statistic which is highly sensitive to the spikiness of the data. Higher kurtosis values indicate the presence of more extreme values than should be found in a Gaussian distribution. Kurtosis is used in engineering for detection of fault symptoms because of its sensitivity to high amplitude events [10].

3 Methodology

Before measuring the strain and vibration signal, the Finite element analysis (FEA) approach has been performed in order to determine higher static stress location. This analysis implemented using MSC. Patran and MSC. Nastran. The aim of the FEA stress analysis was to identify higher stress location and this information will be used to place the strain gauges and accelerometer on the coil spring during the automobile road driving test for the strain and the vibration signals measurement. Hence, the study focuses on the critical zone as these zones contribute to the significant fatigue failure of this component. Fig. 1 illustrates the critical stress zones experiencing by the spring under the static loading. The different colour contours in this figure indicates different stress values observed on the coil spring at specific location. The red colour contour illustrates the maximum stress at 2.24 kPa and the green colour contour indicates that outer surfaces that experiencing the critical stress. From this FEA observation, it was found that the inner coil surface is the most damaging zone compared to other surfaces.

In order to have a more accurate FEA analysis, an actual road-load testing needs to be carried out. The purpose of this test is to capture the strain data from the coil spring under several driving condition. These strains loading can then be used as the input information for the cyclic- based FEA calculation. Therefore the life of this coil spring under an actual load can be estimated.

The cyclic analysis was then performed in order to have a further validation for the static analysis result. Experimentally it has been difficult to stick a strain gauge on an inner surface of a coil spring. In order to overcome the circumstances therefore the outer surfaces that experiencing the maximum stress in static based FEA calculation, was used for the gauge placement, as shown in Fig. 2. Finally, the car was driven over the road for collecting the strain signal that will be used as the input for the cyclic analysis. During the test, the car was constantly driven at 40 km/h on the damage-surface road surface.

Fig. 3 shows the measured strain signal which was later used for the FEA-based fatigue life prediction. On the other hand, Fig. 4 shows the obtained results for the FEA-based cyclic simulation, indicating the maximum critical stress for the inner and outer surfaces was in concordance to the result in Fig. 1. Therefore, it is true that the outer surface of the coil spring has been chosen for further analysis in this subject since it was agreed with the static and cyclic simulation, for which it is clearly contributed to the failure of an automobile component.
The laboratory experiment was then carried out on the durability test rig, which the rig was designed in a full scale of the automotive suspension system (see Fig. 5). The 5 mm strain gauge and the Endevco® model 751 accelerometer were mounted on the outer surfaces of the coil spring for capturing the strain and vibration signals respectively. SoMat eDAQ Data Acquisition was used for the strain signal measurement and PXI System was used for the vibration response measurement. The main reason for capturing the strain and vibration signals was to determine the correlation between these two parameters.

During the laboratory test, different frequencies were used as excitations to the coil spring, as the selected frequency values were 1 Hz to 10 Hz. Different frequencies are important for this study since the recorded strain and vibration data are needed for their correlation purposes. In the signal analysis, the fatigue damage assessment and the I-kaz Hybrid method were applied for each collected signal. Finally, the correlation analysis was then performed using the total fatigue damage and I-kaz Hybrid coefficient and also the observation of the two dimensional graphical representation. All the previously discussed methodology can be referred in Fig. 6.
4 Results and Discussion

4.1 Time domain signal

The captured strain and vibration signals varying from 1 Hz to 10 Hz was then analysed in the time domain signal plots. The original time domain signal for strain and vibration were obtained, and their time histories are presented in Fig. 7 and Fig. 8, respectively. Both signals were sampled at 500 Hz for 60 seconds record length. Thus, the time series of 30,000 data points was then produced.

From Fig. 7 it shows clearly the highest frequency, 10 Hz, contributes more displacement to the coil spring and then followed by 9 Hz and 8 Hz. The lowest frequency that is 1 Hz gives the lowest displacement. The amplitude of the strain signal was increased as the frequency increases. Increment of the frequencies illustrates the increment of the displacement. This situation was similar when the vehicles was driven with the different velocity on the same road surface, the coil spring will experience the higher shock at high velocity compared to the low velocity because of the higher amount of load was transmitted to the coil spring. Then, the significant amount of this load will give the significant displacement to the coil spring.

The same case goes to the vibration signal. Increment of the frequency illustrates the increment of the vibration responses. As can be seen in Fig. 8, 10 Hz frequency gives the highest vibration responses. Then it was followed by 9 Hz, 8 Hz and 7 Hz. The lowest frequency that is 1 Hz was found to contribute the lowest amplitude to the coil spring.
Fig. 7 The time series plots of the measured strain signal at different frequencies (a) 1 Hz, (b) 2 Hz, (c) 3 Hz, (d) 4 Hz, (e) 5 Hz, (f) 6 Hz, (g) 7 Hz, (h) 8 Hz, (i) 9 Hz and (j) 10 Hz

Fig. 8 The time series plots of the measured vibration signal at different frequencies (a) 1 Hz, (b) 2 Hz, (c) 3 Hz, (d) 4 Hz, (e) 5 Hz, (f) 6 Hz, (g) 7 Hz, (h) 8 Hz, (i) 9 Hz and (j) 10 Hz

4.2 Total Fatigue Damage Assessment, D
Table 1 shows the results for the D after analysing using GlyphWorks® and strain signal as the input. This analysis was based on Coffin-Manson approaches. Referring to Table 1, strain signal at 10 Hz produced the highest D which was found at 4.6x10^-1. It was followed by 9 Hz, 8 Hz and 7 Hz that is at 5.5x10^-2, 3x10^-2 and 2.8x10^-2, respectively. According to the D value as tabulated in Table 1, the lower frequency illustrates the lower D value. It can be seen clearly at the lowest frequency, 1 Hz, that is does not contributes any damages to the coil spring.
This value was agreed with the time domain signals in Fig. 7. Displacement of 1 Hz was too low compared to the other frequency. This is because low amplitude did not physically affect to the coil spring. The $D$ values for the rest of the frequency can be seen in Table 1.

Table 1: Total Fatigue Damage of Each Frequency

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Total Fatigue Damage, $D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>$9 \times 10^{-9}$</td>
</tr>
<tr>
<td>3</td>
<td>$1.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>4</td>
<td>$4.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>5</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>6</td>
<td>$5.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>7</td>
<td>$6.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>8</td>
<td>$7.8 \times 10^{-2}$</td>
</tr>
<tr>
<td>9</td>
<td>$1.2 \times 10^{-1}$</td>
</tr>
<tr>
<td>10</td>
<td>$6.0 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

4.3 I-kaz Hybrid Coefficient, $Z_{hk}^{\infty}$

In order to correlate the relationship between the strain and the vibration signal, statistical analysis was performed using the I-kaz Hybrid method as mentioned previously. I-kaz Hybrid method was used the strain and vibration signals as the input signal. The results obtained from I-kaz Hybrid analysis for all signals were presented in Fig. 9 which is illustrating the I-kaz Hybrid coefficient and two dimensional graphical representations of the amplitude distribution for the strain and vibration response signal, respectively.

From Fig. 9, I-kaz Hybrid coefficient, $Z_{hk}^{\infty}$ for 10 Hz was produced the highest $Z_{hk}^{\infty}$ which was found at 0.072. It was followed by 9 Hz, 8 Hz and 7 Hz at 0.0400, 0.0367 and 0.0277, respectively. The lowest frequency that is 1 Hz gave the lowest $Z_{hk}^{\infty}$ that was at 0.00002. These values exhibit higher $Z_{hk}^{\infty}$ illustrates the higher frequency that was applied to the tyre. The obtained results were agreed with the amplitude of the strain and vibration signals that had been shown in Fig. 7 and Fig. 8, which was show the higher frequency, illustrates the higher amplitude of the displacement and vibration responses. In addition, this value was strongly supported by the observation on the space of scattering of I-kaz hybrid display. This graphical representation shows the bigger space of scattering illustrates the amplitude of the fatigue signal was comparatively going higher. The rest value of $Z_{hk}^{\infty}$ each of the frequency was tabulated in Table 2.

From Table 2, it obviously showed the $Z_{hk}^{\infty}$ increment was due to the increment of the frequency. This relationship was supported by the statistical values as Tabulated in Table 3. As mentioned before, I-kaz Hybrid was developed based on Kurtosis and Standard Deviation that was mathematically defined as Eq. (6) and Eq. (7). As the frequency increased, the strain and vibration signal tends to have more spikiness rather than lower frequency. Higher kurtosis value indicates the presence of more extreme value.
Kurtosis of strain versus Kurtosis of vibration was plotted in order to explain the reason of the increment of $Z_{h\infty}$ as the frequency increases. Based on the Fig. 10, it was clearly shows that kurtosis of the strain signal also linear related to the standard deviation of the vibration signal. It absolutely proved why the $Z_{h\infty}$ increased as the frequency increased.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>I-kaz Hybrid Coefficient ($Z_{h\infty}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00002</td>
</tr>
<tr>
<td>2</td>
<td>0.0006</td>
</tr>
<tr>
<td>3</td>
<td>0.0029</td>
</tr>
<tr>
<td>4</td>
<td>0.0061</td>
</tr>
<tr>
<td>5</td>
<td>0.0108</td>
</tr>
<tr>
<td>6</td>
<td>0.0174</td>
</tr>
<tr>
<td>7</td>
<td>0.0277</td>
</tr>
<tr>
<td>8</td>
<td>0.0367</td>
</tr>
<tr>
<td>9</td>
<td>0.0400</td>
</tr>
<tr>
<td>10</td>
<td>0.0720</td>
</tr>
</tbody>
</table>

Fig. 9 I-kaz Hybrid coefficient, $Z_{h\infty}$ at the frequencies of (a) 1 Hz, (b) 2 Hz, (c) 3 Hz, (d) 4 Hz, (e) 5 Hz, (f) 6 Hz, (g) 7 Hz, (h) 8 Hz, (i) 9 Hz and (j) 10 Hz

Kurtosis of strain versus Kurtosis of vibration signal was plotted versus the standard deviation of the vibration signal as shown in Fig. 11. It shows the standard deviation of the strain signal also linear related to the standard deviation of the vibration signal. It absolutely proved why the $Z_{h\infty}$ increased as the frequency increased.

Fig. 10 Graph of Kurtosis of Strain Signal versus Kurtosis of Vibration Signal.

Fig. 10 I-kaz Hybrid coefficient, $Z_{h\infty}$ at the frequencies of (a) 1 Hz, (b) 2 Hz, (c) 3 Hz, (d) 4 Hz, (e) 5 Hz, (f) 6 Hz, (g) 7 Hz, (h) 8 Hz, (i) 9 Hz and (j) 10 Hz

Kurtosis of strain versus Kurtosis of vibration signal was plotted in order to explain the reason of the increment of $Z_{h\infty}$ as the frequency increases. Based on the Fig. 10, it was clearly shows that kurtosis of the strain and vibration signal was linear related to each other. In addition, similar result was obtained as the standard deviation of the strain signal was plotted versus the standard deviation of the vibration signal as shown in Fig. 11. It shows the standard deviation of the strain signal also linear related to the standard deviation of the vibration signal. It absolutely proved why the $Z_{h\infty}$ increased as the frequency increased.

Table 2: I-kaz Hybrid coefficient, $Z_{h\infty}$

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>I-kaz Hybrid Coefficient ($Z_{h\infty}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00002</td>
</tr>
<tr>
<td>2</td>
<td>0.0006</td>
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<tr>
<td>3</td>
<td>0.0029</td>
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<td>0.0061</td>
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<td>5</td>
<td>0.0108</td>
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<td>6</td>
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<td>0.0367</td>
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<tr>
<td>9</td>
<td>0.0400</td>
</tr>
<tr>
<td>10</td>
<td>0.0720</td>
</tr>
</tbody>
</table>

$R^2 = 0.9906$
In order to achieve the objective of this paper, the total fatigue damage for each frequency was plotted versus the I-kaz Hybrid coefficient in logarithmic scale as shown in Fig. 12. Each data point represents the \( D \) and \( Z_h^\infty \) value in Table 1 and Table 2 for each frequency. The result shows \( D \) was linear proportionally related to the \( Z_h^\infty \) and mathematically defined as Eq. (9) and generally defined as Eq. (10). Constant \( \alpha \) and \( \beta \) were varied based on the material and type of component used, respectively. Different material and type of component give the different value of constant \( \alpha \) and \( \beta \).

\[
\begin{align*}
\log D &= 1.6 \log Z_h^\infty + 1.2 \\
D &= 15.8 (Z_h^\infty)^{1.6} \\
D &= \alpha Z_h^\infty + \beta
\end{align*}
\]

(8)  
(9)  
(10)

### 5 Conclusion

This paper was discussed on the relationship between the strain signal and the vibration signal of the automotive suspension system. Both strain and vibration signals were measured on the coil spring which was excited by 10 different frequencies and were then used as the subject of this study. This comparative analysis was performed by means of the I-kaz Hybrid method which was produced the respectively I-kaz coefficient and also 2D graphical presentation for each velocities value.

From the obtained results of the I-kaz Hybrid method analysis, the I-kaz Hybrid coefficient value was increased when the velocity was increased. This statement was true for strain and vibration signals. In addition, these results were also supported by the observation on the scattering of the I-kaz Hybrid display, that is illustrating larger space of scattering indicated that the I-kaz Hybrid coefficient is comparatively increased. Thus, it can be concluded that strain signal was proportionally related to the vibration signal with the coefficient of correlation was found to be at 98%.

### References:


