Relationship between time domain and frequency domain strain signal – Application to real data

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ABSTRACT

This paper presents the behaviour of time domain and frequency domain signal for fatigue signal based on the parameters used in each domain. Frequency domain analysis were used in noise signal applications. For structures that are subjected to irregular and random loading, the general problem faced are the complicated in statistical in term of characteristic. Especially, in amplitudes and total damage distribution obtained from number of cycles count. The traditional method of rainflow cycle counting were compared with PSD-based analysis. It is shown that the component of system can be computed by using transfer function of component and PSD of excitation strain. The statistical analysis are used to see the behaviour of the signal in time domain. It can be seen that bracket component is more critical compared to suspension component. The analysis continued with verifying the developed fatigue data editing in order to have the good relation with frequency domain analysis as the area under the PSD graph shows the energy contained in the particular signals independently. The linear relationship between the two parameters with R-square value measured are high, up to 0.8 for suspension component and 0.97 for bracket component. Thus, it has been suggested that frequency domain analysis can then be used in the time domain fatigue testing as the strong relationship obtained for both parameter used.

Keywords: *Fatigue, frequency domain, power spectral density, time domain*.

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Introduction

Fatigue is a regular cause of failure in mechanical structures which subjected to time variable loadings. Fatigue failure can occur for any structure even the structure is subjected to low amplitude cyclic loads [1]. The cycle obtained is the main element to represent a certain amount of fatigue damage. If the fatigue damage reaches a certain value, the fatigue failure occurs. There has a lot of factors that can lead to fatigue failure such as materials, loading types, surrounding conditions and many more [2]. The usual approach is time domain based analysis that evaluate the time histories such as level crossing, range and rainflow. This approach allow the identification of cycles with different amplitude and mean values. Next, the Palmgren-Miner rule were introduced to evaluate the total damage as a sum of single cycle damage contribution [3]. In many cases, the fatigue data history were edited by removing the small amplitude contained in the signal to produce useful and economic testing [4].

In the automotive applications, especially for cars on the rough road condition are exposed to random loads due to inconsistent road surface. The random loads obtained can be viewed as a random Gaussian process that suit to be describe in the frequency domain by power spectral density (PSD) [5][6]. The signal representation in PSD gives the picture of the power distribution over frequencies [3]. Normally, frequency domain analysis were used in noise signal applications. Noise PSD are used in speech improvement system due to its significant effect on the quality of the noise reduced speech [7]. PSD estimation for wide-sense stationary signals from sub-Nyquest has been done in developing a compressed sensing based approach. This approach employs multi set sampling and produced multi resolution PSD estimates at low sampling rates [8]. The resultant PSD of stress also been implemented in rainflow cycle counting. The traditional method of rainflow cycle counting were compared with PSD-based analysis of an exhaust muffler for a bus application. The result shows that PSD approach can be obtained from a very short time signal compared to the rainflow cycle counting in statistic representative [9].

For structures that subjected to irregular and random loading, the main problem that have to face are the complicated statistic characteristic. In term of amplitudes and total damage distribution obtained from number of cycles counted. In this study, the behaviour of time domain and frequency domain signal for fatigue signal has been compared statistically. Therefore, the objective for this paper is to prove the PSD result obtained to see the behaviour of signals from different component of suspension and bracket parts. The necessity of a fatigue analysis using frequency domain was reviewed. Thus, the behaviour of fatigue analysis of time domain and frequency domain is the main idea to drive the analysis in frequency domain for fatigue analysis in more wide.

Theory

Fatigue life estimation

Structures when subjected to repeated cyclic load experience damage by fatigue. In time domain, the expression of the response of the structure are as stress or strain time history. The magnitude of each cycle is not the main causes to cause failure, but the large number of cycles are therefore needed for failure to occur. A part from that, other factors such as mean and range amplitude also contributed to fatigue failure. Need to be highlighted here that the behaviour of metal structure under cyclic loading load differs from that under monotonic load.

Other than the damage-until-failure behaviours, the damage intensity also have been introduced by Benasciutti and Tovo [1]. The following equation shows the damage intensity parameter to value the damage per unit of time:

$$\overline{D} = v_p C^{-1} \int_0^{\infty} s^k p_a(s) ds \tag{1}$$

where v_p is the expected peak occurrence frequency, C and k are the material properties and $p_a(s)$ is the cycle amplitude probability density function in order to consider the frequency domain methods for fatigue analyses.

The assessment of frequency domain methods can be done by comparing the fatigue life estimate T in seconds. The expression is obtained from the damage intensity, $\overline{D}$ as followed:

$$T = \frac{1}{\overline{D}} \tag{2}$$

The summation of damages caused by the time history can therefore be obtained to form the cycles as known as stress range histogram, which also known as the Palmgren-Miner accumulated damage rule.

Power spectral density

The response of irregular stress or strain in structural component are as a stationary Gaussian stochastic process, $\{G(x)\}$. The process is characterized alternatively in frequency domain of a power spectral density (PSD). Usually, method for calculating fatigue analysis from a PSD is to regenerate a characteristic of time history. This is a normalised density plot describing the mean square amplitude of each wave with respect to its frequency. The amplitude can then be estimated using following equation:

$$A = \sqrt{2.MeanSquare} \tag{3}$$

Lastly, the PSD for sequence $[x_1, x_2, \dots, x_n]$ is given by the following formula:

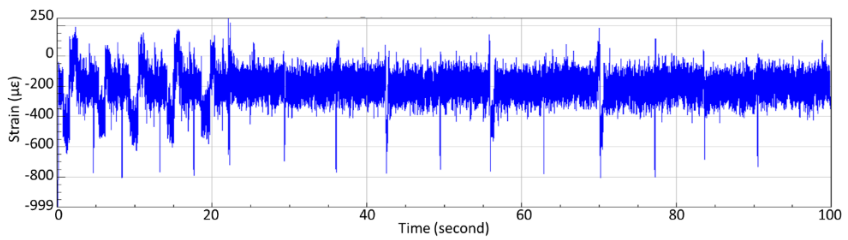
$$S\left(e^{j\omega}\right)=\frac{1}{N}\left|\sum_{i=1}^{n}x_i e^{-j\omega i}\right|^2 \tag{4}$$

where ω is frequency. This expression defined the power distribution of the signal in the frequency domain.

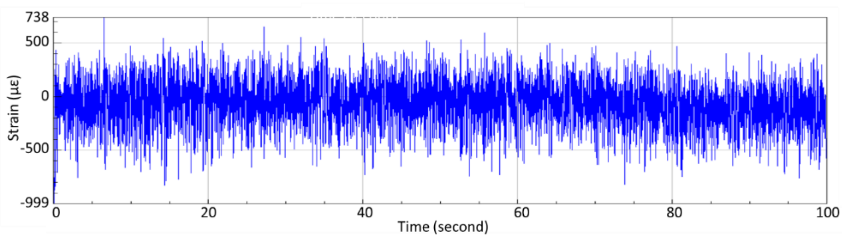
Methodology

Time domain and frequency domain analysis

In this study, the behaviour of strain signal were observed for time domain and frequency domain. For time domain, fatigue analysis were run by using commercial software to obtain the fatigue life of the components. On the other hand, the use of PSD was utilised to observe the frequency responds and spectrum distribution of the fatigue signal in frequency domain. Both domain were compared with the different components used in this study which are bracket and suspension components in automotive industries.



(a)



(b)

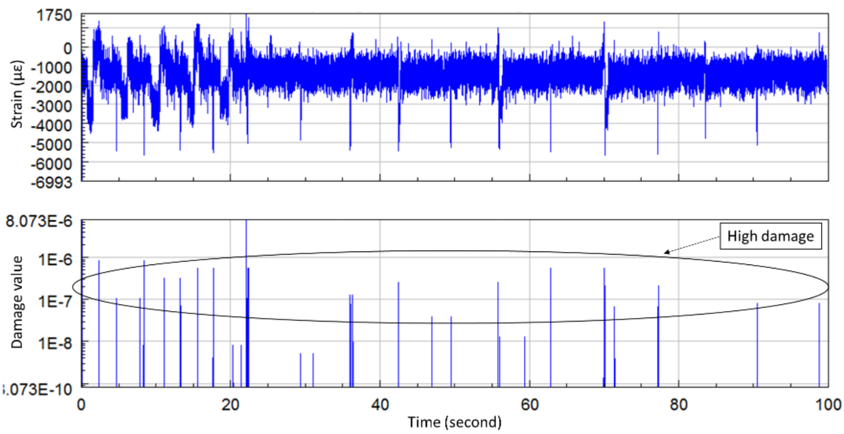
Figure 1 Time domain signal for (a) Suspension, and (b) Bracket

The data was measured from experiment using strain gauge and the data logger instrument that connected to the car's bracket and suspension components developed by the Society of Automotive Engineer (SAE). The material used is SAE5160 carbon steel. Figure 1 shows the signal used in this study in order to achieve the main target of this paper. All data recorded at 200 Hz sampling rate after considering the main components of the signal are not lost during measurement [10]. The strain signal obtained were used to execute fatigue analysis using commercial software in order to see the fatigue life of the particular components. In order to obtain the frequency domain analysis, the PSD graph were used by using same commercial software. The statistical analysis were run to identify the characteristic for each signal obtained and been compared.

Results and Discussion

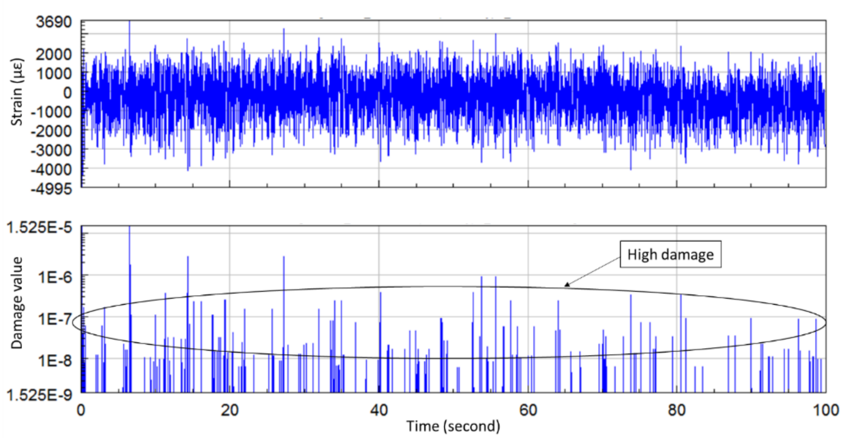
The fatigue life analysis was carried out using rainflow cycle counting method. Based on the signals obtained, car bracket and suspension was considered to experience the random compression loading. The mean value from statistical analysis shown the negative values. The Morrow approach has been considered for this types of signal. Figure 2 and Figure 3 shows the result for fatigue analysis for both components. The running damage obtained from the signal contributed higher damage the most for suspension components are at the beginning of the data collection and some at the mid of data collection. This is different compared to the bracket where damage value distributed high throughout the data collection process. This can be conclude that the bracket component experienced higher damage compared to suspension component. Damage value for suspension component is 2.58×10^{-10} with total number of cycles to failure are 3.87×10^{9} cycles and damage value for bracket component is 4.73×10^{-8} with total number of cycles to failure are 2.12×10^{7} cycles. Higher life recorded for suspension component compared to bracket component.

The calculation of statistical analysis has been performed in time domain signal for both components. For this case of time domain, the statistical analysis is shown in Table 1. The parameter considered in statistical analysis were the values of mean, root mean square (RMS), kurtosis and skewness for time domain signal. Based on the mean value obtained, both components experienced compression loading along services as the negative value indicate the compression and positive value indicate the tension loading. While the zero value shows the component having zero mean loading. The standard deviation value indicate the distribution of the data due to the high strain amplitude signals inherent in the resulting distribution of data scattered far from the mean and standard deviation provides a great value. Therefore, bracket component shows the higher standard deviation value compared to suspension component. The RMS value depend on the amplitude of the observed strain signal by strain gauges. It was observed that the higher the average value of the strain obtained, the higher the resulting value RMS. Both component shows the higher RMS value that indicate the high amplitude activities experienced by the components. The kurtosis value for suspension component is more than three which is 4.165 compared to bracket is less than three which is 2.718. High kurtosis value (kurtosis > 3) indicates the observed data has a lot of transient signals which contribute to material damage [11].



(a)

Figure 2 Running damage for suspension



(a)

Figure 3 Running damage for bracket

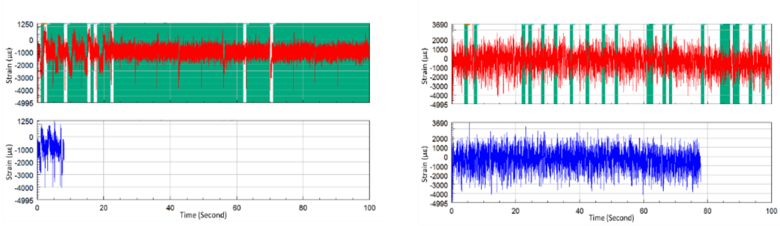
Signal editing showed the various signal condition based on the specification needed in research work. This method offers the ability to analysed, create and modify the large data set. Either the signal is long period of recorded data or needing to create complex scenario testing. In this study, the damage value is the indicator for the signal editing processed. Damage retain is the main parameter need to be followed in order to fulfil the requirement of signal editing [12]. There are various order of percentage damage retained was set up from 100%, 95%, 90%, 85% and 80% damage retain. The consideration for the retained damage is to determine only the high amplitude is the most contributed in fatigue failure. Besides, the effect of original signal must be considered due to the original signal are the actual responses from the engineering structure. Figure 4 shows the process of signal editing obtained by considering only the high amplitude and damage retain as the bench mark from the original signal. As shown, the suspension signal contained low amplitude signal compared to bracket component. The damage retain are the elimination of low amplitudes, which is why the edited signal for suspension is shorter compared to bracket signal.

Table 1 Statistical result for suspension and bracket

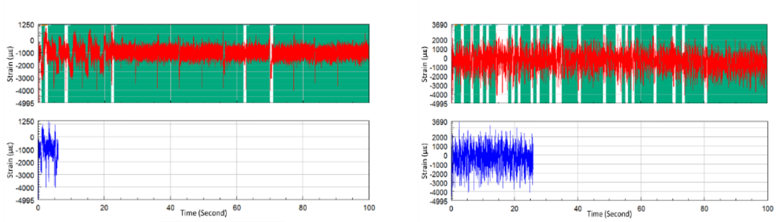
Statistic parameter	**Suspension**	**Bracket**
Mean, (με)	-1034.31	-345.55
Standard deviation, (με)	627.71	1103.18
RMS, (με)	1209.87	1156.00
Kurtosis	4.165	2.718

Figures 5 and 6 show the distribution of total damage and total number of cycles for each damage retained, respectively. The results show that the less the damage retained, the more the damage value. This is due to the low amplitudes were eliminated as damage was retained. This low amplitude does not contribute to the component failure. Since the total number of cycles, N is the inversely proportional to total damage, D and the expression is $N = 1/D$. Therefore, lower number of cycles were recorded as the damage retained increasing.

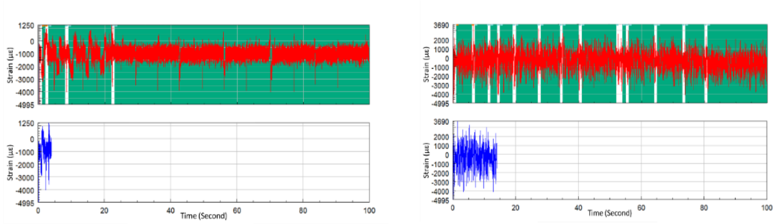
The transformation of Fast Fourier Transform (FFT) was carried out to obtain the frequency domain signal. The sampling frequency used are 200 Hz for both signals. This sampling frequency was determined based on number of data in one second from time domain signal. The frequency domain has been used to determine the PSD of the signal obtained as shown in Figure 7. The PSD result shows the harmonic frequency occurred on the component that happened because of the higher amplitude contained in the signal. From the result obtained, both components contain the fatigue damage features in the low frequency distribution. This is prove that low amplitude events of the fatigue cycles can be found in the higher frequency distribution of a frequency spectrum.



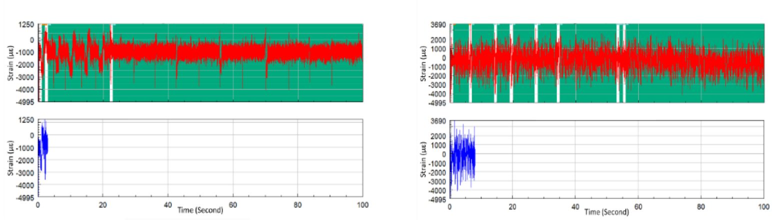
(a) 100% damage retained for suspension and bracket components



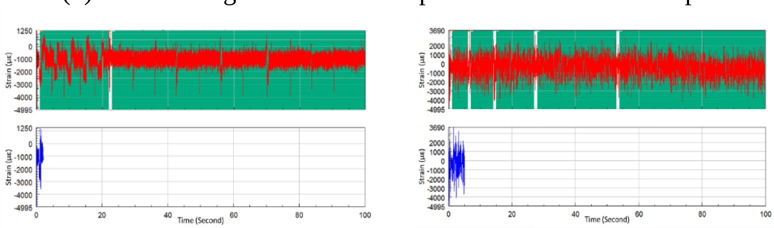
(b) 95% damage retained for suspension and bracket components



(c) 90% damage retained for suspension and bracket components



(d) 85% damage retained for suspension and bracket components



(e) 80% damage retained for suspension and bracket components

Figure 4 The signal editing using damage retained for (a) 100%, (b) 95%, (c) 90%, (d) 85% and (e) 80%

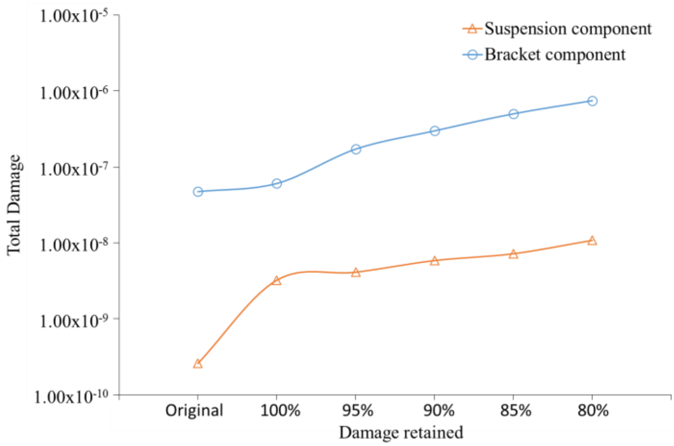


Figure 5 Damage value for each edited signal based on damage retained percentage

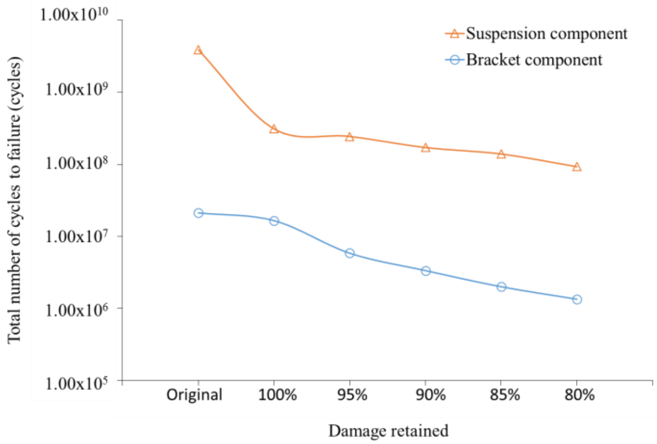
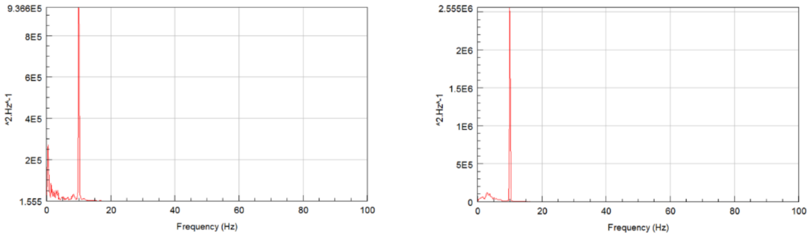
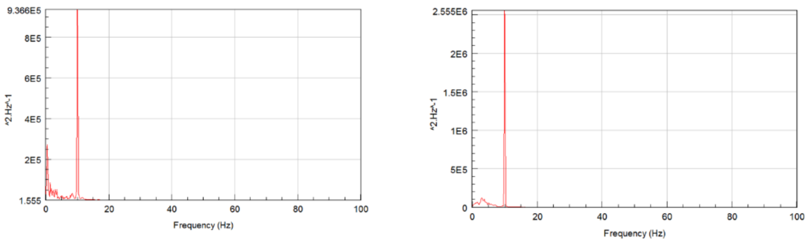


Figure 6 Fatigue life for each edited signal based on damage retained percentage

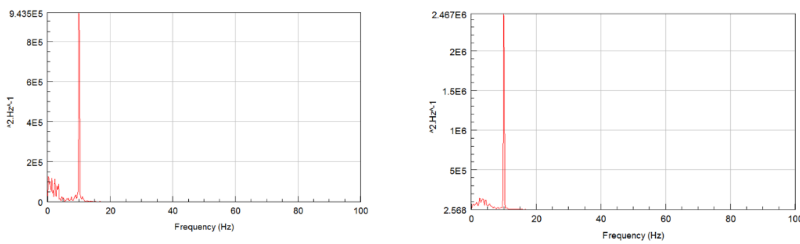
The area under the graph for PSD have been compared for both components and is illustrated in Figure 8 to represent the energy contained for the given signal. From the result obtained, the energy contained has been increasing significantly from the PSD for the original signal to PSD for the 80% damage retained signal. This is shows that the increasing of fatigue damage value gave the significant changes of energy contained in the signal. Therefore, the relationship between fatigue analysis using time domain give a significant information in frequency domain. The PSD result plays a vital role in changes in the time domain signal and provide the meaningful information to fatigue analysis.



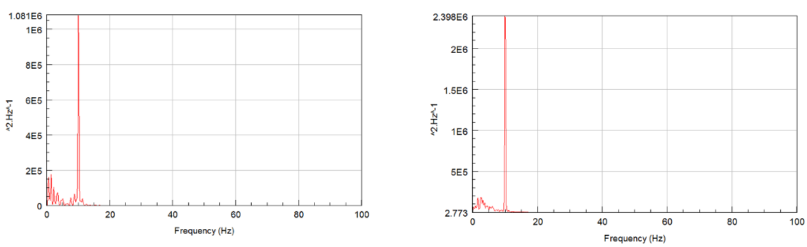
(a) Original for suspension and bracket



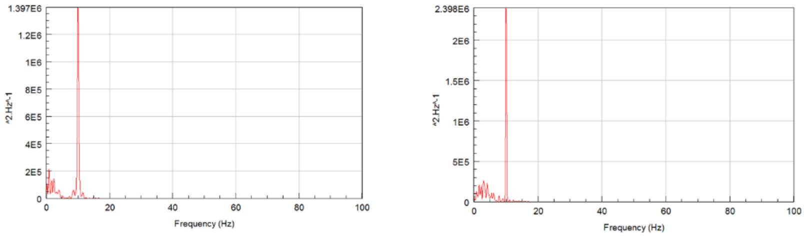
(b) 100% damage retained for suspension and bracket



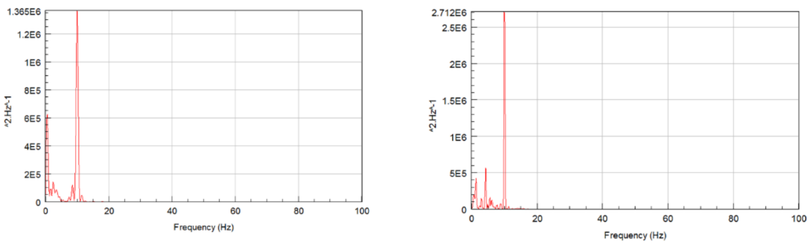
(c) 95% damage retained for suspension and bracket



(d) 90% damage retained for suspension and bracket



(e) 85% damage retained for suspension and bracket



(f) 80% damage retained for suspension and bracket

Figure 7 Power spectral density for each damage retained (a) 100%, (b) 95%, (c) 90%, (d) 85% and (e) 80%

Mathematical relation between the total number of cycles and area under the PSD graph have been performed. The consideration of the first order linear equation to fit the data. The relationship between both coefficients is shown in Figure 9. It can be observed that, there is a linear relationship between the two parameters with the R-square value measured are higher up to 0.80 for suspension component and 0.97 for bracket component. As the R-square value close to 1, the parameters satisfy the conditions for a better fit [13]. The R-squared value for suspension is quite low compared to bracket component which is 0.8027, so 80.27% of the variability in total number of cycles is explained by energy contained in PSD. Even though the result is a little inferior, but it is still good [14]. Larger values of the coefficient of determination indicate a better fitting model. In additions, the low R-squared value obtained for suspension component are due to the original signal that contained noise signal. The noise signal obviously disturbed the energy contained for the PSD graph compared to the others edited signal, which were low amplitude been filtered.

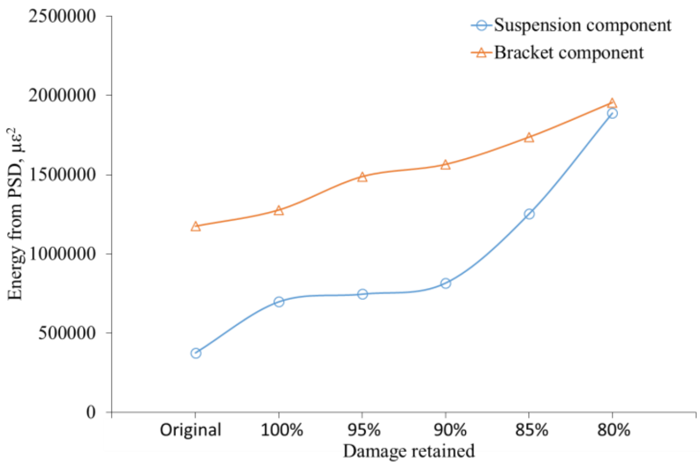


Figure 8 Energy from PSD for each damage retained

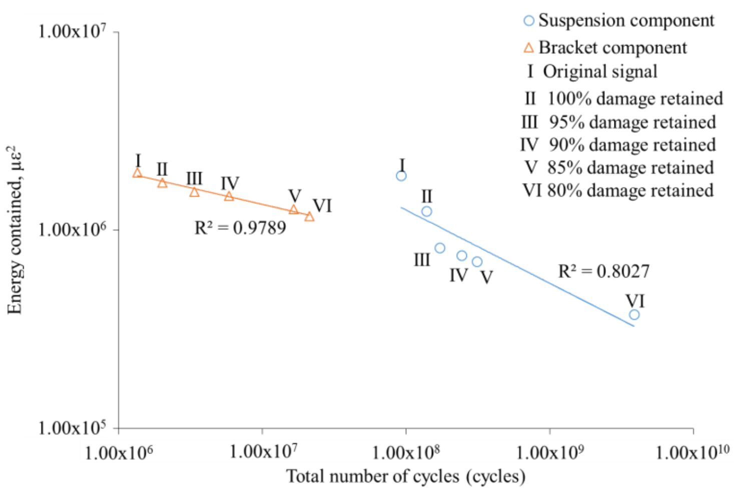


Figure 9 Relation of total number of cycles and area under the graph

Conclusion

This paper study on the characteristic of a fatigue data editing technique in time domain and frequency domain by using FFT. The characteristic was compared between the time domain fatigue analysis and frequency domain analysis. It is prove that the component of system can be computed by using transfer function of component and PSD of excitation strain. In this study, two types of automotive components were used i.e. suspension and bracket. The fatigue analysis is done by comparing the damage values and number of cycles to failure for both component. Next, the statistical analysis are used to see the behaviour of the signal in time domain. It can be seen that bracket component is more critical compared to suspension component.

The signal were edited by adjusting the retained damage for each components (100%, 95%, 90%, 85% and 80% retained damage). The FFT is done for each signal composed and the area under the graph were obtained. The total number of cycles and area under the graph were compared in order to see the correlation between these two parameter. From the result obtained, the edited fatigue data signal was able to have the good relation with frequency domain analysis as the area under the PSD graph shows the energy contained in the particular signals independently.

References

[1] M. Cesnik and J. Slavic, "Vibrational Fatigue and Structural Dynamics for Harmonic and Random Loads," *J. Mechanical Engineering* 60 (5), 339-348 (2014).

[2] J.T. Burns, Sangshik Kim and R.P. Gangloff, "Effect of Corrosion Severity on Fatigue Evolution in Al–Zn–Mg–Cu," *Corrosion Science* 52, 498–508 (2010).

[3] D. Benasciutti and R. Tovo, "Spectral Methods for Lifetime Prediction under Wide-Band Stationary Random Processes," *Int. J.Fatigue* 27, 867–877 (2005).

[4] R.I. Stephens, P.M. Dindinger and J.E. Gunger, "Fatigue Damage Editing for Accelerated Durability Testing Using Strain Range and SWT Parameter Criteria," *Int. J. Fatigue* 19, 599−606 (1997).

[5] M. Mrsnik, J. Slavic and M. Boltezar, "Frequency-Domain Methods for A Vibration-Fatigue-Life Estimation - Application to Real Data," *Int. J. Fatigue* 47, 8-17 (2013).

[6] Seong-In Moon, Il-Je Cho1 And David Yoon, "Fatigue Life Evaluation of Mechanical Components Using Vibration Fatigue Analysis Technique," *J. Mechanical Science And Technology* 25 (3), 631-637 (2011).

[7] Xin Dang, Takayoshi Nakai and M.I.A. Khan, "Noise Power Spectral Density Estimation Based on Maximum A Posteriori and Generalized Gamma Distribution," *Int. J. Advanced Science and Technology* 54, 77-88 (2013).

[8] D. Donoho and J. Tanner, "Counting The Faces of Randomly-Projected Hypercubec And Orthants, With Applications," *Discrete And*

Computational Geometry 43 (3), 522–541 (2010).

[9] A. Halfpenny and F, Kihm, "Rainflow Cycle Counting and Acoustic Fatigue Analysis Techniques for Random Loading," *10th International Conference On Recent Advances In Structural Dynamics*, Southampton (2010).

[10] Y. Prawotoa, M. Ikedaa, S.K. Manvillea and A. Nishikawa, "Design and Failure Modes of Automotive Suspension Springs," *Engineering Failure Analysis* 15 (8), 1155–1174 (2008).

[11] F.J. Gravetter and L.B. Forzano, R*esearch Methods for the Behavioral Sciences,* 4th ed. (Cengage Learning, 2011), pp. 416 – 486.

[12] W. El-Ratal, M. Bennebach, X. Lin and R. Plaskitt, "Fatigue Life Modelling And Accelerated Test for Components under Variable Amplitude Loads," *Symp. Fatigue Testing and Analysis under Variable Amplitude Loading Conditions*, Tours, France (2002).

[13] S. Priya, M.R. Ramesh1 and V.P.S. Naidu, "Bearing Health Condition Monitoring: Frequency Domain Analysis," *Int. J. Advanced Research In Electrical, Electronics And Instrumentation Engineering* 3 (5), 260-268 (2014).

[14] P. Sivaka and E. Ostertagovab, "Evaluation of Fatigue Tests by Means of Mathematical Statistics," *Procedia Engineering* 48, 636 – 642 (2012).