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RELIABILITY ASSESSMENT FOR AN AUTOMOBILE CRANKSHAFT UNDER RANDOM LOADING

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Abstract

This paper presents the stochastic process for reliability assessment based on the fatigue life data under random loading for structural health monitoring of an automobile crankshaft due tofatigue failure. This is based on reported failure of the component due to the effect of the random loads that acts on the component during its operating condition over a given period of time. Since there are significant limitations of the experimental analysis in terms of actual loading history, therefore, the reliability assessment is considered to be less accurate. Hence, the reliability assessment based on fatigue life data using the Markov process by incorporating loading data to synthetically generate loading history has been proposed in this study. The Markov process has the capability of continuously updating the loading history data to reduce the intervals between each data point for reliability assessment based on the fatigue life data. The accuracy of the proposed monitoring system for reliability assessment was validated through its statistical method. The reliability assessment from the Markov process corresponded well by providing an accuracy of more than 95% when compared towards the actual sampling data. The reliability of the crankshaft based on the fatigue life assessment provides a highly accurate for the improvement and control of risk factors in terms of structural health monitoring by overcoming the extensive time and cost required for fatigue testing.

Keywords: Automobile; durability; fatigue; random loading; reliability

Abstrak

Tujuan kajian ini dijalankan adalah untuk menilai keboleharapan hayat lesu aci engkol dengan menggunakan kaedah stokastik berasaskan kepada beban rawak yang bertindak pada komponen terutamanya dalam aspek integriti struktur. Adalah diketahui dari kajian lepas bahawa pelbagai pendekatan berketentuan telah digunakan untuk menilai kerosakan lesu dan keboleharapan struktur dan disebabkan oleh kekurangan data pembebanan, maka penilaian keboleharapan menjadi kurang tepat. Oleh itu, proses stokastik melalui pendekatan kaedah Markov telah digunakan dalam penilaian keboleharapan kitaran hayat lesu penggabungan data persampelan dalam penilaian kebolehtahanan. Melalui kaedah ini, lebih banyak data dijana dan dicerap, set data dikemaskinikan bertujuan untuk mengurangkan julat antara setiap selang data untuk meningkatkan ketepatan. Nilai ketepatan proses Markov ini ditentusahkan secara statistik melalui perbandingan nilai purata ralata dengan data persampelan dan didapati hasil perbandingan proses Markov ini mempunyai ketepatan yang melebihi 95%. Justeru, penilaian keboleharapan kitaran hayat berasaskan kepada proses stokastik dapat digunakan dalam penilaian integriti struktur aci engkol bagi memastikan ia selamat dan mampu berfungsi dengan efektif.

Kata kunci: Automobil; kebolehtahanan; leu, beban rawak, keboleharapan

1.0 INTRODUCTION

Reliability assessment based on fatigue life is becoming an important aspect in the design of mechanical structures and components, especially in the automobile industry whereby it branches out from the conventional technique fatigue failure in terms of forensic engineering. Moreover, fatigue tests require a lot of time and effort, much research has been focused on estimating the fatigue life of a structure or component in terms of the strain-life curve. Over the recent decade, various fatigue monitoring systems such as the structural neural system has been proposed to monitor and detect the occurrence of cumulative damage in real time under random loading during the operation of a given structure [1]. Given the limitations of the strain gauge in terms of its sensitivity in capturing and handling real time data, various expert systems [2-3] have been developed using artificial intelligence for the fatigue life assessment of metallic materials using their actual loading history data. It is becoming increasingly important to develop systems that are capable of monitoring the durability mechanisms of components and structures under random loading by incorporating the probabilistic method of the stochastic process for appropriate data processing.

However, the reliability assessment is still incomplete, even with the assessment of fatigue life. This is due to the stochastic process for fatigue life assessments proposed from previous studies [4-5] was modelled using the computational or experimental techniques to capture scatters in loads data. The captured scatters in loads data that will be used to model the operational behaviour of the component though the monotonic failure rate from the strain life curve. Therefore, the reliability assessment based on the fatigue life is essential for the reliability function, hazard rate function and the mean time to failure in terms of number of cycles [6] using the Weibull distribution. The reliability assessment has the capabilities of providing safety limits for the benefit of designers when designing a component [7-8].

In this study, the fatigue reliability evaluation system is developed using the Markov process for reliability assessment in terms of structural health monitoring for an automobile crankshaft. This is due to fact that fatigue failure for this component has been viewed as a deterministic issue in the past, without consideration for the loading history in fatigue reliability. Therefore, this study proposes the use of a stochastic process for generating the loading history data by incorporating the actual sampling data to assess the durability in terms of fatigue life assessment for the structural health monitoring of a component. As more data is generated within the given boundary condition with minimal intervals, the credible error in terms if accuracy would be reduced. More importantly, this monitoring system not only deals with fatigue life assessment but also evaluates the reliability of the fatigue life data through a statistical analysis. Therefore, the purpose of having this stochastic monitoring system is to provide an accurate, efficient and fast reliability assessment in terms of monitoring in order to improve the design life of the component by controlling the risk factors based on the loads.

2.0 METHODOLOGY

The reliability assessment based on the fatigue life under random loading is still considered to be limited due to the loading history based on the random geometric parameters and material properties of the component, which tends to be lengthy and costly. Therefore, this study proposed the development of a monitoring system using the stochastic process in combination with the Markov technique, as show in Figure 1, to assess the reliability of its fatigue life. The probabilistic technique is capable of generating synthetic loading history data by incorporating the sampling maximum and minimum loading data. As more data is generated with intervals, the reliability assessment in fatigue life by considering the local strain method would be more accurate.

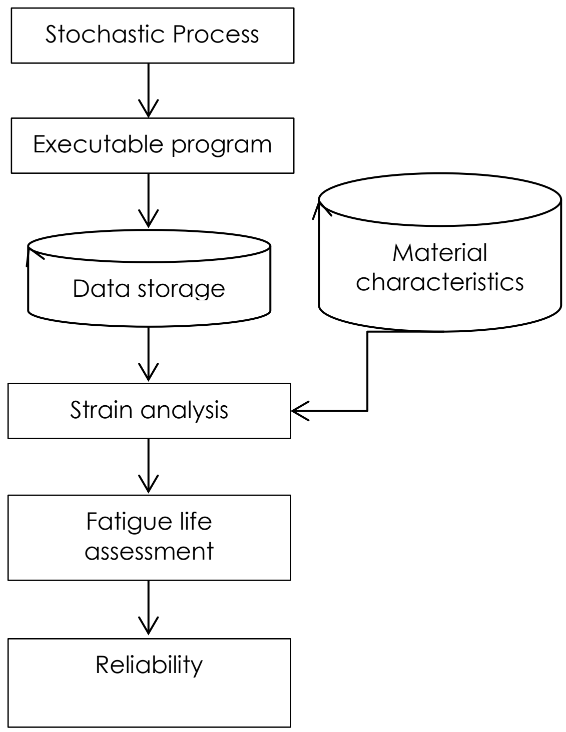

Figure 1 Methodology process of the reliability assessment model

The methodological flow shown in Figure1 is used to predict the reliability of the fatigue life for based on the probabilistic state condition of stresses during the operating condition of the crankshaft. The Markov probabilistic state condition is used to generate the loading history for the component by incorporating sampling data obtained from the automobile industry based on the transition probability function.

$$P_r\{X_{t+1} = T|X_0 = B, X_1, \ldots, X_n = i_n\} = P_r\{X_{t+1} = T|X_t = B\} \quad (1)$$

where *X* is the state condition for the given phases of bending, *B* and torsion, *T* over a given period of time, *t*.

Hence, the reliability in the life cycle was accounted for through the reliability function, hazard rate function and mean time to failure of the component through the data characterization properties denoted as {β, θ, γ and Γ}. The Weibull distribution function model of the life cycle distribution for the reliability of the crankshaft was expressed as,

$$f(t:\beta,\theta,\gamma) = \frac{\beta}{\theta}\left(\frac{t-\gamma}{\theta}\right)^{\beta-1} \times \exp\left[-\left(\frac{t-\gamma}{\theta}\right)^{\beta}\right] \quad (2)$$

where β, θ, γ and t are the shape, scale and location parameters for the given random loading data, respectively.

The estimated shape parameter is used to evaluate the reliability and hazard rate based on the monotonic failure properties from the random loading. The γ parameter had been neglected due to no accelerated or decelerated in reliability assessments were performed in this study. Therefore, the reliability and hazard rate functions were rewritten in the following forms,

$$R(t:\beta,\theta,\gamma) = \exp\left[-\left(\frac{t-\gamma}{\theta}\right)^{\beta}\right] \quad (3)$$

$$\lambda(t:\beta,\theta,\gamma) = \frac{\beta}{\theta}\left(\frac{t-\gamma}{\theta}\right)^{\beta-1} \quad (4)$$

where *R* and *λ* are the reliability and hazard rate functions, respectively for the random loading of each of the given rotations per minute for predicting the failure of the component through the mean cycle to failure. The final process of reliability assessment based on fatigue life is the mean cycle to failure. The purpose for this is for the preventive maintenance of the component and to ensure that the component possessed the durability to undergo the given loads. The mean cycle to failure was expressed as follows,

$$MTTF = \theta\Gamma\left(1 - \frac{1}{\beta}\right) \quad (5)$$

where Γ is the gamma function.

The verification of the stochastic process was tested using the statistical technique of mean square error (MSE). This will provide a predictive verification of the stochastic model used in predicting the reliability of the crankshaft against sampling data.

$$MSE = \sum_{i=1}^{n}\left(\frac{Y - Y_i}{n}\right)^2 \quad (6)$$

3.0 RESULTS AND DISCUSSION

3.1 Reliability Rate

From the fatigue life data, the reliability for fatigue life of each rotation per minute was derived from Equation 3 based on the synthetic data generation obtained from Equation 1 which is statistically distributed using the Weibull distribution from Equation 2. The reliability rate of the fatigue life plays an important role in improving and controlling the risk factors in terms of uncertainties due to the random loading of the crankshaft. The reliability from the simulated predicted fatigue life using the embedded Markov process of each rotation per minute of 1000,

R_{2000}, R_{3000}, ..., R_{6000} was compared against the reliability from the actual predicted fatigue life of $\bar{R}_{1000}$, $\bar{R}_{2000}$, $\bar{R}_{3000}$, ..., $\bar{R}_{6000}$.

The accuracy of the predicted reliability function is statistically correlated using the 90% boundary condition to determine the accuracy of the data obtained from the Markov process towards the actual sampling data, as shown in Figure 2. The 90% boundary condition is actually used to model the accuracy of a given set of simulated data towards the actual sampling data, whereby any data out of the boundary level is considered to be inaccurate in terms of fatigue life assessment as mentioned by Zhao & Liu [9]. It was observed that the assessment reliability agrees well with the sampling data with an accuracy of 98.97% as shown in Figure 3. Besides that, all the points were within the boundary condition of 90% for reliability of the fatigue life assessment.

The statistical confidence level is constructed to verify the simulation model towards the reliability assessment of the crankshaft in order to observe the presence of outliers. It was observed that the assessment results agreed very well with the experimental results for the simulated loading history, where the simulated results from the Markov process were close to the diagonal line. Hence, it was noted that the statistical fatigue life assessment provided a smaller variance in the assessment since most of the assessment results were within the boundary condition.

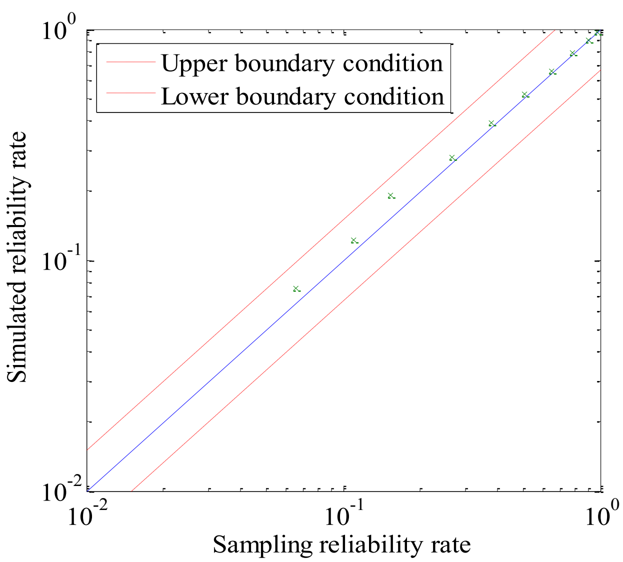

Figure 2 Statistical boundary condition of the Markov data for reliability

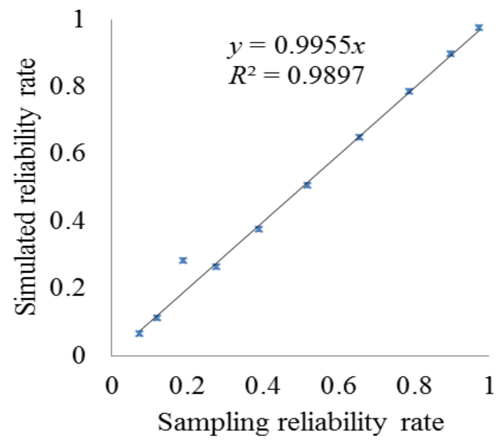

Figure 3 Accuracy of the Markov data compared against the sampling data for reliability assessment

3.2 Hazard Rate

The hazard rate was predicted using the embedded Markov process of each rotation per minute λ_{1000}, λ_{2000}, λ_{3000}, ..., λ_{6000}, and then comparing it against the sampling hazard $\bar{\lambda}_{1000}$, $\bar{\lambda}_{2000}$, $\bar{\lambda}_{3000}$, ..., $\bar{\lambda}_{6000}$. The hazard rate from Equation 4 is used to evaluate the fatigue failure of the component prior to the occurrence of any catastrophic failure. From Figure 4 and 5, it is observed that the hazard rate had an incremental failure with an accuracy of 98.46% for both sets of fatigue life data. The statistical confidence level of 90% was constructed to verify the simulation model with regard to the reliability and hazard rate of the crankshaft as shown in Figure 4. This explains that the simulated data is significantly related towards the sampling data with minimal variance of error [10].

It was observed that the assessment of the hazard rate agreed very well with the experimental results for the simulated loading history, where the simulated results from the Markov process as it is located very close to the diagonal line. Hence, the statistical fatigue life assessment provided a smaller variance in the assessment since most of the assessment results were within the boundary condition. Therefore, there is a covariance between both the sampling and the probabilistic fatigue life assessment curve under random loading and this must be taken into consideration in the analysis and design of the crankshaft. It was observed that the assessment reliability agrees well with the sampling data with an accuracy of 93.8% as shown in Figure 5. Hence the Markov process was not only able to synthetically generate the loading history for fatigue life assessment, but also had the capability to assess the reliability of the fatigue life data with high accuracy in the for structural health monitoring.

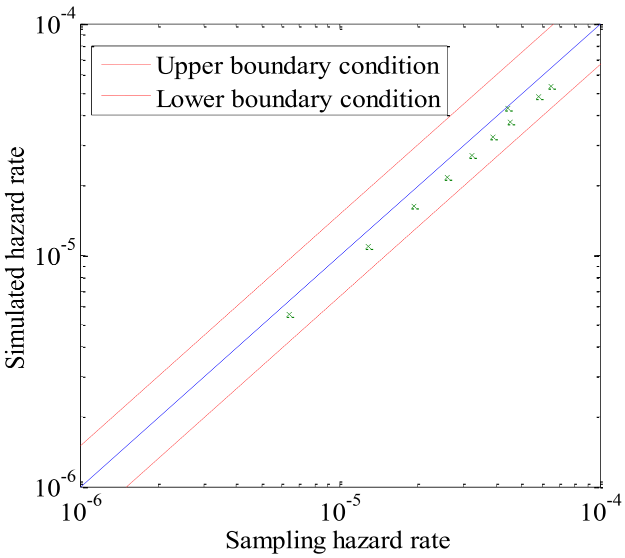

Figure 4 Statistical boundary condition of the Markov data for hazard rate

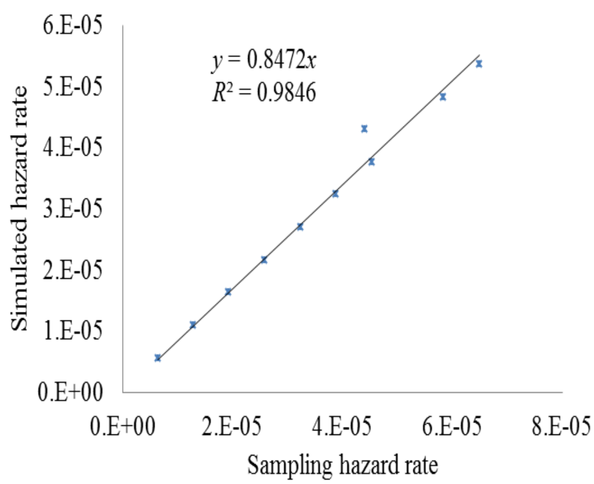

Figure 5 Accuracy of the Markov data compared against the sampling data

3.3 Mean Time to Failure

In this final part for reliability assessment, the mean time to failure in terms of the number of cycles to failure for each rotation per minute of the crankshaft was derived using Equation 5 using the estimated Weibull shape parameter. It is observed that all the data points are within the 90% range for survival rate for the component as shown in Figure 6. This indicates that the data has a high accuracy in predicting the mean time to failure for the crankshaft. This indicates that the Markov process agrees well with the actual sampling data in terms of reliability assessment and analysis. Hence, the approach provides important information for reliability assessment in terms of improving the design life of the component by controlling the risk factors in terms of preventive maintenance, operational maintenance and safety limits.

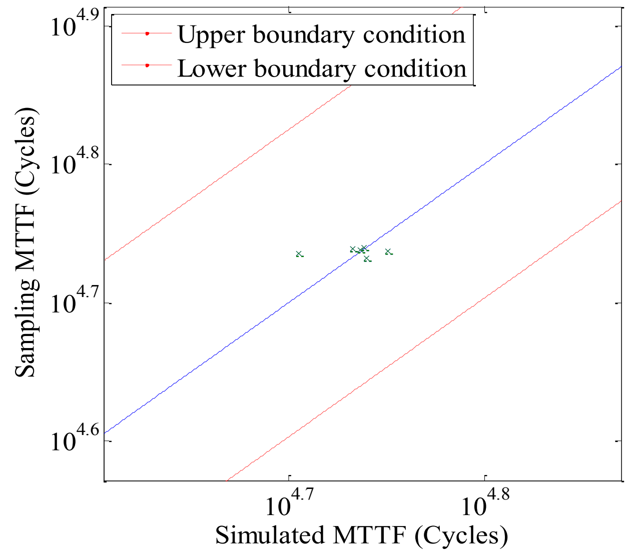

Figure 6 Statistical boundary condition for mean time to failure

4.0 CONCLUSION

This paper presented the reliability assessment using the probabilistic methodology in generating the synthetic loading history data by incorporating the actual sampling data for structural health monitoring of the automobile crankshaft. The reliability of the fatigue life were predicted by considering the geometric structure, material properties and random loading on the component using the Markov process. Hence, this integrated system reduces the intervals between the loading data points, making the fatigue life assessment more accurate and reliable within a scatter of 90%, with a mean squared error of less than 10%, as shown, using the statistical correlation properties. It was observed that the predicted reliability based on fatigue life actually lay close to the diagonal line and is statistically correlated with a 90% boundary condition towards the actual reliability. Hence, the Markov process agrees well with the actual sampling data. Therefore, through the predicted reliability for fatigue life fatigue life data can be used to improve and control the risk factors by overcoming the extensive time and cost that are required for fatigue testing, resulting in greater accuracy in the of durability.

Acknowledgement

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