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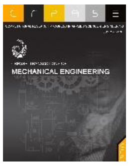

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Research Article

Fatigue Life Prediction Based On Nonlinear Fatigue Accumulation Damage Model Under Combined Cycle Loadings

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Keywords

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Turbine blades,
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Life prediction.

Abstract

Combined high and low cycle fatigue (CCF) of aircraft turbine blades was studied in this paper. With the aim to accurately estimate the CCF damage of turbine blade alloys, a new life prediction model was presented on the basis of nonlinear damage rule to address the loading history and interaction of high cycle fatigue and low cycle fatigue. To conduct the model validation, four experimental data sets of turbine blade alloy materials and turbine blades were utilized. The statistical analysis of model validation and model errors suggested that the presented model provides the highest accurate predictions by comparing with those of three typical common models.

1. Introduction

Failure modes of aircraft turbine blades are a complicated interaction of small frequency, large amplitude forces superimposed with low level, high frequency vibrations simultaneity causing a combined fatigue failure during operation [1, 2]. In other words, both of high cycle fatigue (HCF) resulted from the high cycle vibration force and low cycle fatigue (LCF) caused by the low cycle centrifugal stress induce failure of aircraft turbine blades, known by the name of combined high and low cycle fatigue (CCF) [3, 4]. As a matter of fact, uncertain information resulted from material properties, service environment and loads exists during flight, which leading to an enormous challenge when carrying out the reliability analysis and fatigue life prediction of turbine blades [5-8].

For most previous fatigue failure studies of engine components, the effects of load interactions on CCF damage and combined life are rarely considered. Moreover, pure HCF and pure LCF, compared with CCF damage, do not adequately reflect actual operational process and accurately establish the damage accumulation models based on its damage mechanism for fatigue strength design of aeroengine [9]. To date, the investigations about CCF life prediction of turbine components have been performed under its operation loadings. Similar to the damage cumulative methods under multilevel stress loadings, Miner's rule has been one of the commonly applied models due to the simple structure and fewer data demanded [10]. As discussed previously, Miner's rule provided a non-conservative predicted result because it ignored the coupled damage generated by HCF-LCF interaction and loading history [3]. Specially, the damage curve approach developed by Manson et. al [11] to estimate the fatigue life under variable amplitude loading following a specific damage cumulative curve. Based on this, Yue et. al [12] proposed a nonlinear damage accumulation model for life prediction taking HCF-LCF interaction into account under combined loadings, which presented a high accuracy compared with the original formulation. The three–point secant method was used to predict the CCF life of GH2036 specimen [13]. Han et. al [14] put farward a life prediction model of turbine blade on the basis of damage mechanics under CCF loadings, which was capable of estimating the blade life with a acceptable accuracy. However, the interaction of HCF-LCF and loading history shown significant effects on fatigue damage accumulation and life prediction. In view of this, a new life prediction method based on damage curve approach

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considering loading interaction and loading history under CCF loadings.

The rest of this work is organized as follows. Section 2 reviews the common damage accumulation methods for life prediction under CCF loadings, and the proposed model based on damage curve approach was presented in the following section. In section 4, model validation and corresponding comparison were preformed by employing three experimental datasets of turbine blade materials and one dataset of full-scale turbine blades. In last section, the conclusion was made to this study.

2. Existing Life Prediction Models Under CCF Loadings

Actually, Fuchs et al. [15] were the first to notice the structure fatigue under CCF loadings. Until now, CCF analysis has been one of the hot topics for blade strength design and fatigue life prediction. To study the CCF behavior, a CCF test loading spectrum was designed in laboratory conditions [16-21], as shown in Figure 1. In general, this CCF load waveform mainly consists of four load parameters, including the high cycle loading magnitude σ_H and its frequency f_H, the low cycle loading magnitude σ_L and its frequency f_L.

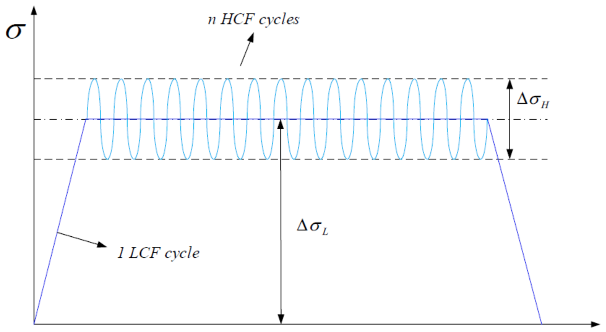


Figure 1. Load spectrum of CCF analysis

For the load spectrum of CCF loadings, CCF damage accumulation based on the linear damage accumulation method can be derived as follows [3, 16-18]:

$$D_i = \frac{n_{HCF,i}}{N_{HCF,i}} + \frac{1}{N_{lCF,i}} \tag{1}$$

where $n_{HCF,i}$ is the number of loading cycles of HCF at the ith combined cycle block, $N_{HCF,i}$ is the number of cycles to failure of HCF at the given combined cycle block for the ith level, $N_{LCF,i}$ is the number of cycles to failure of LCF at the given combined cycle block for the ith level .

Then the total CCF fatigue damage with N combined cycle blocks is written by

$$D = N\left(\frac{n_{HCF,i}}{N_{HCF,i}} + \frac{1}{N_{lCF,i}}\right) \tag{2}$$

The damage critical value is reached for $D = 1$, then CCF life can be derived once loading range of HCF and LCF of the load spectrum for CCF are invariable:

$$N = \frac{n+1}{\frac{n}{N_{HCF}} + \frac{1}{N_{lCF}}} \tag{3}$$

where N_{HCF} and N_{LCF} are high cycle fatigue life, the number of cycles to failure of LCF, respectively. n is the ratio of high and low cyclic loading frequency.

However, the above method predicts CCF life by the superposition of the damage of HCF and LCF damage individually ignoring the influence of the HCF-LCF interaction on CCF damage under CCF conditions. Similarly, a nonlinear fatigue damage model according to damage curve approach was presented by Manson et al. [11].

$$\begin{cases} D_i = \left(\dfrac{n_i}{N_i}\right)^{q_i} \\ q_i = BN_i{}^{\beta} \end{cases} \tag{4}$$

where N_i is the number of cycles to failure, q_i is the damage exponent, B and β are material constants.

According to the analysis of fatigue tests, Trufyakov et al. [22] developed a model for CCF life prediction by introducing a material constant γ as:

$$N = (1+n)N_{lCF}\left(\frac{1}{n}\right)^{\gamma^{\sigma_{a,HCF}/\sigma_{a,LCF}}} \tag{5}$$

where $\sigma_{a,HCF}$ and $\sigma_{a,LCF}$ are the stress amplitude of LCF and the stress amplitude of HCF, respectively.

Generally, interaction damage resulted from the mutual effect of the CCF loadings exists and produces larger influence on CCF life rather than the sum of pure HCF damage and LCF damage [23-25]. Then above-mentioned methods do not give enough thought to the HCF-LCF interaction and load history under combined loading conditions. According to this, a new CCF life prediction approach is proposed for accurate life predictions.

3. Page Limitation

Seen from the CCF load spectrum in Figure 1, there are $(1+n)$ cycles consisting of n HCF cycles and a LCF cycle in one combined cycle block, then the damage of a combined cycle block D_B on the basis of the Miner linear damage rule under CCF loading can be expressed

$$D_B = \frac{1}{N_{lCF}} + \frac{n}{N_{HCF}} \tag{7}$$

In order to account for the load history under multi-level stress loadings [26-28], damage curve approach was developed to follow a particular damage accumulation rate, as shown in Figure 2.

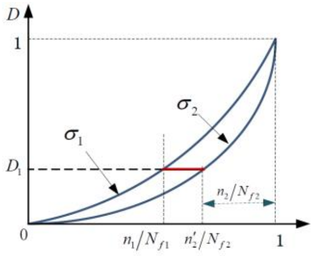


Figure 2. Damage accumulation process under two level loading

Similarly, the damage of one combined cycle block under CCF loadings can be obtained as [29]:

$$D_B = \left(\frac{1}{N_{lCF}}\right)^{\left(\frac{N_{LCF}}{N_{HCF}}\right)^{0.4}} + \frac{n}{N_{HCF}} \tag{7}$$

Noting from that the following relationship with respect to LCF life and high and low cycle stress range α is equal to 1

$$D_B = log(N_{HCF})^{-\alpha} \cdot log(N_{HCF})^{\alpha} \tag{8}$$

where α is the ratio of high and low cycle stress range, and $\alpha = \frac{\Delta\sigma_H}{\Delta\sigma_L}$.

According to Figure 1, σ_L depended on rotational speed and working temperature of the engine can be considered as a constant for given condition, while σ_H shows great uncertainties associated with aerodynamically in-flight vibrations. Moreover, the HCF-LCF interaction with uncertainty should be addressed during the process of predicting fatigue life. Accordingly, combining with Eq. (8), Eq. (7) can be rewritten by modifying the HCF damage as follows

$$D_B = \left(\frac{1}{N_{lCF}}\right)^{\left(\frac{N_{LCF}}{N_{HCF}}\right)^{0.4}} + \frac{n}{N_{HCF} log(N_{HCF})^{-\alpha} \cdot log(N_{HCF})^{\alpha}} \tag{9}$$

As investigated in the previous studies, Manson-Halford model shown a conservative predicted results under CCF loadings [29]. Furthermore, the value of $log(N_{HCF})^{-\alpha}$ that is less than 1 can be omitted from the HCF damage in Eq. (9), and the rest part is just capable of reflecting the coupled damage caused by HCF-LCF interaction under CCF loading conditions [3]. Thus, the HCF damage can be expressed by the following relationship

$$D_H = \frac{n}{N_{HCF} log(N_{HCF})^{\alpha}} \tag{10}$$

Specially, the total fatigue damage of N combined cycle blocks required to a transformation so that the damage curve approach can be applied under CCF loading conditions. Therefore, according to Eqs. (7), (9) and (10), the total fatigue damage under CCF loadings is calculated as follows:

$$D = \left(\frac{N}{N_{lCF}}\right)^{\left(\frac{N_{LCF}}{N_{HCF}}\right)^{0.4}} + \frac{Nn}{N_{HCF} log(N_{HCF})^{\alpha}} \tag{11}$$

When critical value of cumulative damage reaches one, the combined fatigue life is derived by using the number of N combined cycle blocks calculated in Eq. (11)

$$N_f = (1+n)N \tag{12}$$

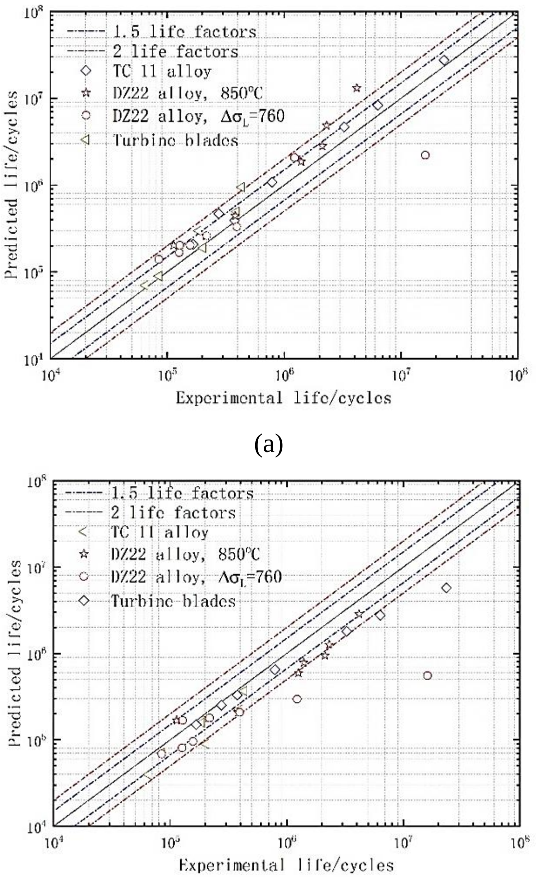
4. Experimental Validation and Model Comparison

In this section, several experimental data sets of alloy materials, including TC11 [17], DZ22 [30], and full-scale turbine blades [20], are applied to evaluating the precision of prediction under CCF loadings. Moreover, predictions by Miner's linear damage rule, Manson-Halford's method and Trufyakov-Kovalchuk's method are applied to make a comparison with the proposed one under CCF conditions, as shown in Figure 3.

These CCF test data were obtained under different low cycle stress range condition of TC11 alloy at 800MPa and 750MPa, DZ22 alloy with given temperature 850 °C, and DZ22 alloy with low cycle stress range 736MPa as well as full-scale turbine blades for different vibration loads with mean LCF life of 40530 cycles.

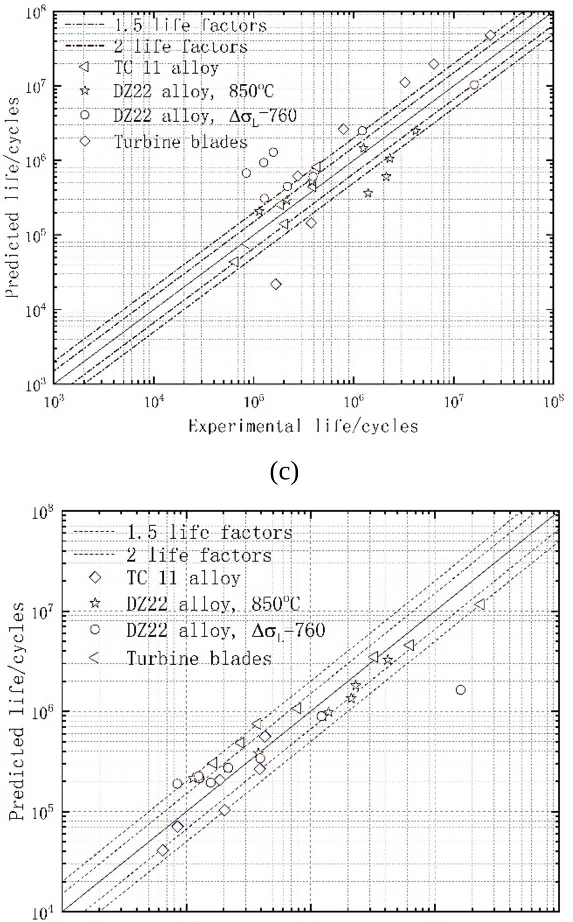
Combined with other fatigue tests, like low cycle fatigue and creep fatigue, the combined high and low cycle fatigue shown more complex failure modes and more loadings parameters, whose fatigue tests needed to carry out including low cycle fatigue, high cycle fatigue and combined high and low cycle fatigue tests. According to Fig. 1, the trapezoidal wave was used to denote the LCF loads of large amplitude with low frequency, while the sinusoidal wave was represented the HCF loads with high frequency and small amplitude. In detail, the CCF tests can be found in the existing literatures [17, 20, 30].

In order to calculate the number of combined cycle blocks, the damage of one combined cycle block required to be computed based on damage curve approach, and the high cycle fatigue damage was modified using Eq. (10). Then the total cumulative damage can be obtained according to Eq. (11) combined with the nature of CCF loadings that is different from the expression of multi-level stress loadings. Finally, the combined fatigue life can be presented by using Eq. (12) on the basis of the number of combined cycle blocks solved previously.



(a)

(b)



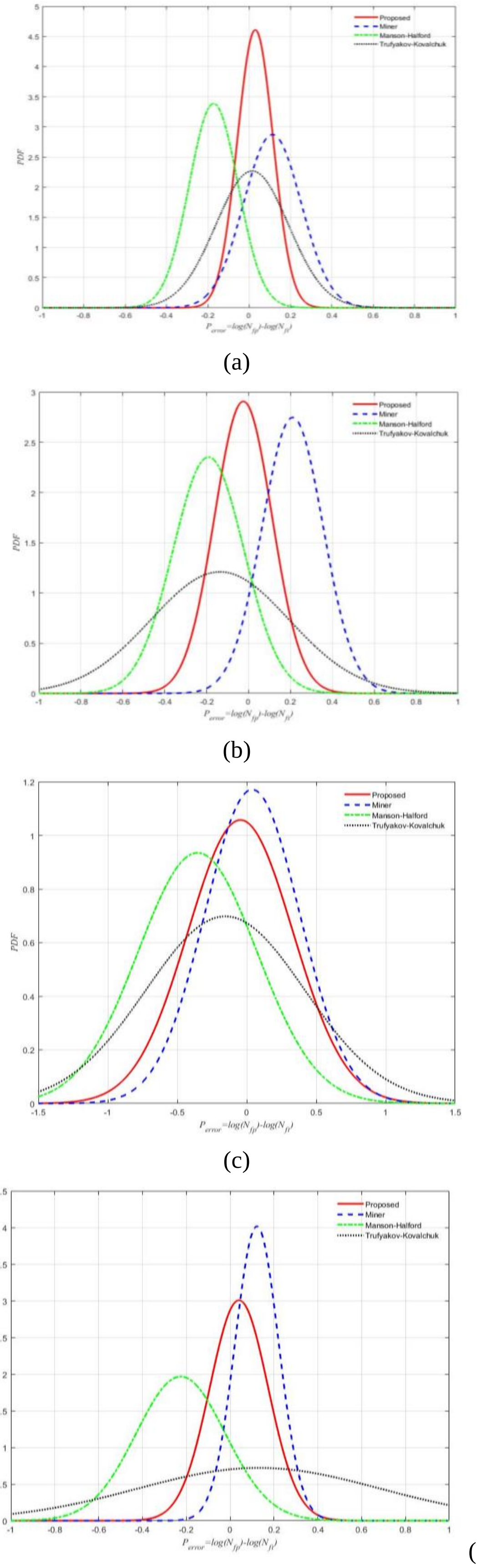
(c)

(d)

Figure 3. Comparison between experimental lives and model predictions by (a) Miner's rule, (b) Manson-Halford model, (c) Trufyakov-Kovalchuk model and (d) the proposed model

Seen from the in Figure 3, for the developed model, aside from 3 data points, nearly all predictions for these four turbine blade alloys lie in the range of ±2 life factors. From the viewpoint of the overall performance, this model provides the more accurate predictions than others with a tighter dispersion. The linear damage method overestimates the CCF lives, while the Manson-Halford model shows a conservative prediction. In addition, the predictions by Trufykov-Kovalchuk model provide the results with a larger scatter.

In order to perform the comparison of these models, a statistical analysis was applied based on the logarithm of predicted lives and experimental results, and the individual model prediction errors can be calculated by their deference [31-33]. Figure 4 presents the model prediction error by the proposed model as well as the other three models. In general, lower mean and standard deviation of prediction errors represent higher accuracy.



(a)

(b)

(c)

(d)

Figure 4. model prediction errors for (a) TC11 alloy, (b) Turbine blades (c) DZ22 alloy with given temperature of 850 °C and (d) DZ22 alloy with given low cycle stress range of 736MPa

As can be seen from Fig. 4, the proposed model shows the most reasonable prediction error results with lower mean and standard deviation values. Under CCF loadings, the predicted results of linear rule are non-conservative and the conservative predictions with negative mean errors for Manson-Halford model. Moreover, the Trufykov-Kovalchuk model shows a larger scatter prediction due to fitted material constant.

5. Conclusions

In this paper, a novel CCF life prediction model was presented accounting for HCF-LCF interaction and loading history based on the damage curve approach . More specially, the HCF damage was modified to reflect the load interaction between HCF and LCF by introducing the load parameters of combined high and low cycle fatigue and the fatigue life of HCF. To verify the prediction accuracy of proposed model, four datasets of alloys were used for model comparison together with the Miner's rule, Manson-Halford model and Trufyakov-Kovalchuk model. Moreover, the statistical analysis indicated that the proposed model offered the better prediction accuracy under CCF loading conditions in contrast to the others.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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