Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
©2023 ESREL2023 Organizers. *Published by* Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P167-cd

Life prediction of an aero-engine turbine shaft considering the fracture of sealing labyrinth

Song Bai

School of Mechanical and Electrical Engineering,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
Center for System Reliability and Safety,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
baisong@std.uestc.edu.cn

Tudi Huang

School of Mechanical and Electrical Engineering,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
Center for System Reliability and Safety,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
huangtudi@std.uestc.edu.cn

Yan-Feng Li

School of Mechanical and Electrical Engineering,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
Center for System Reliability and Safety,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
yanfengli@uestc.edu.cn

Ning Lu

School of Mechanical and Electrical Engineering,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
Center for System Reliability and Safety,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
ninglu@std.uestc.edu.cn

Hong-Zhong Huang

School of Mechanical and Electrical Engineering,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
Center for System Reliability and Safety,
University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
hzhuang@uestc.edu.cn

Combined high and low cycle fatigue (CCF) loading has a significant impact on the fatigue strength of aero-engine hot section components. Aiming at the fracture of a turbine shaft under CCF loading in the actual fatigue test, this study proposes a CCF life prediction method considering interaction damage to more accurately assess the fatigue life of the shaft. Under the procedure of the proposed method, the turbine shaft is firstly analyzed through finite element analysis (FEA), then the pure low cycle fatigue (LCF) life and high cycle fatigue (HCF) life are predicted by traditional life prediction models based on simulation data, respectively. Finally, using a damage accumulation model considering interaction damage, the CCF life of the turbine shaft is predicted, which is quite approximate to the actual test data. What's more, the proposed method is verified to have higher accuracy compared with traditional life prediction models due to its full consideration of CCF loading characteristics and interaction damage. The proposed method is quite suitable for the turbine shaft, and provides a new idea for aero-engine components' CCF life prediction.

Keywords: CCF loading, damage accumulation, fatigue life prediction, turbine shaft.

1. Introduction

Aero-engine components serve under complex load condition for a long term, and the fatigue failure, which is the most common failure mode of these components, has always been a concern for decades [1, 2, 3]. Many scholars have proposed many methods for the fatigue problem of the components, such as Bayesian-based method [4, 5], the information fusion method [6, 7] in the case of small samples, and so on. Once fatigue failure occurs, it will cause huge economic losses and even threaten the lives of crew members and passengers, so it is necessary to accurately predict the fatigue life of aero-engine components in order to take preventive measures before larger disaster occurs. In general, the components with the problem of fatigue damage include turbine blades, turbine discs, and turbine shaft and so on. Many researches on fatigue of turbine blades or turbine discs have been conducted in recent years [8-10], but the fatigue of turbine shafts, which is also existent and with threat, has not been studied systematically. In the fatigue experiment of a turbine shaft, the sealing labyrinth of the shaft fatigue fractured under combined loading of axial force, torque and bending moment, which caused the attention of researchers. The axial force and torque are with high stress amplitude and low loading frequency, which are called low cycle loads. The bending moment is with low stress amplitude and high loading frequency, which is called high cycle load. The combined loading of all the loads is a CCF loading condition for the turbine shaft. Therefore, the goal of this study is to investigate the CCF damage and life of the turbine shaft's critical region.

CCF loading is a common loading condition for aero-engine components. When the turbine blades and turbine discs serve at high speed, CCF damage accumulates due to the combined loading of centrifugal force and vibration [11]. It is especially true for turbine shafts, which serve under a long-term combined loads with different stress amplitude and loading frequency such as axial force, torque and bending moment. Trufyakov et al. [12] studied on the CCF life of different metal materials, and pointed the stress ratio and loading frequency ratio have a significant influence on metal materials' CCF life. Wang and Hu et al. [13, 14, 15] built the CCF test platform for turbine components, and carried out a large number of experimental studies. On the basic of existing experimental data, many researchers propose damage accumulation models [8, 11, 16] for CCF life prediction, most of which are based on the linear damage accumulation theory, non-linear damage accumulation theory and damage mechanics theory. Studying on turbine shafts, Jin et al. [17] loaded both LCF loads and HCF loads on turbine blades in the fatigue test. Yu [18] et al. modified the Manson-Coffin model for the fatigue life prediction of a low pressure turbine shaft with high-low cycle loading. Considering the effect of multiple symmetric critical region on the spline of a turbine shaft, Liu et al. [19] proposed an empirical coefficient to modify the fatigue life. All the researches show CCF damage is doubtlessly the main concern for the study on fatigue of the turbine shafts.

The structure of this paper is as follow. In Section 2, CCF damage accumulation of the turbine shaft is analyzed, and the procedure of the CCF life prediction in this study is presented. In Section 3, the turbine shaft is analyzed through FEA, and the stress or strain responses of the sealing labyrinth are presented. In Section 4, the CCF life of the turbine shaft is predicted through different methods, and the predicted results are compared with the actual test data. In Section 5, some conclusions are obtained.

2. CCF DAMAGE ACCUMULATION OF THE SHAFT

For aero-engine components, low cycle loads include centrifugal force, axial force, torque and so on, which are with low frequency and high amplitude, and high cycle loads include vibration, bending moment and so on, which are with high frequency and low amplitude. When the engine operates at high speed, the components endure CCF loading, where the interaction influence of LCF loading and HCF loading on fatigue damage accumulation and life of the components can't be ignore.

According to the actual service situation of the turbine shaft, the CCF loading is the combined loading of axial force, torque and bending moment. The loading spectrum of the turbine shaft is shown in Fig. 1. From the results of fatigue test, the turbine shaft under this CCF loading spectrum fractured before meeting the requirement of infinite life design (>10^7).

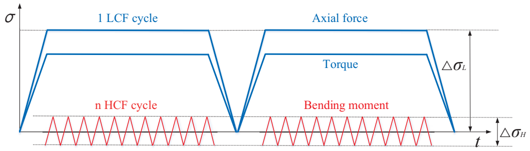

Fig. 1. Loading spectrum of the turbine shaft

CCF life of the turbine shaft is not only affected by its LCF or HCF loading amplitude and frequency, but greatly related to the stress amplitude and frequency ratio of HCF loading to LCF loading. The stress ratio and frequency ratio is shown in equation (1) and equation (2), respectively.

$$\alpha=\frac{\Delta\sigma_H}{\Delta\sigma_L} \tag{1}$$

$$n=\frac{f_H}{f_L} \tag{2}$$

where α is the stress ratio of HCF loading to LCF loading, $\Delta\sigma_H$ is the stress amplitude of HCF loading, $\Delta\sigma_L$ is the stress amplitude of LCF loading, n is the frequency ratio of HCF loading to LCF loading, f_H is the frequency of HCF loading and f_L is the frequency of LCF loading.

In general, Miner's rule shown in equation (3) is a common theory to be introduced in the description of aero-engine components' damage accumulation. However, due to the neglect of enormous influence of interaction between LCF loading and HCF loading, Miner's rule is not well applicable for describing the damage accumulation under CCF loading.

$$D=\sum\frac{n_i}{N_i} \tag{3}$$

where D is the total damage, n_i is the number of loading cycle under the i-level loading and N_i is the fatigue life under the i-level loading. The Miner's rule is quite widely used in practical engineering, however, this theory can't well describe CCF damage evolution because it doesn't consider the characteristics of CCF loading. Miner's rule just consider the LCF loading and HCF loading in each loading block as two-stage loading, which are independent of each other, and the CCF damage accumulation based on Miner's rule is shown in equation (4).

$$D=N_c\left(\frac{n}{N_H}+\frac{1}{N_L}\right) \tag{4}$$

Based on Miner's rule, and considering the characteristics of CCF loading, Zhu [11] developed a non-linear damage accumulation model, which contains the stress ratio and frequency ratio, and can better describe the damage accumulation under CCF loading, as shown in equation (5).

$$D=\frac{N_c}{n}\left(\frac{n}{N_H}+\frac{1}{N_L}+\frac{1}{(n+1)\lg(N_H)^{\alpha}}\right) \tag{5}$$

where N_{HCF} is the fatigue life under pure HCF loading, N_{LCF} is the fatigue life under pure LCF loading and N_c is the fatigue life under CCF loading.

It is obvious that pure HCF life and pure LCF life are necessary inputs for the developed model, so in this research, simulation analysis of the turbine shaft is divided into pure HCF simulation and pure LCF simulation. The whole simulation process in this study can be divided into 3 steps. Firstly, the FEA is conducted for obtaining the responses under LCF loading and HCF loading, respectively. Then, pure LCF life and pure HCF life of the turbine shaft is predicted, respectively, which are both the inputs of the CCF life prediction model. The last step, calculating the CCF life of the turbine shaft based on the damage accumulation model considering interaction damage. The procedure of CCF life prediction of the turbine shaft is shown in Fig. 2.

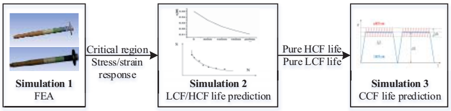

Fig. 2. Procedure of the turbine shaft's CCF life prediction

3. III. FEA OF THE TURBINE SHAFT

In general, the FEA of a turbine component includes establishment of 3D model, meshing, application of constraints and boundary conditions, and solution. The 3D model is established according to the geometric parameters of the shaft, as shown in Fig. 3, and the meshing is shown in Fig. 4.

Fig. 3. Establishment of 3D model of the turbine shaft

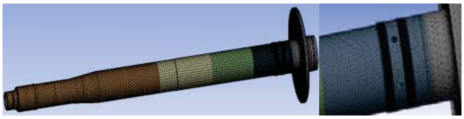

Fig. 4. Meshing

The material of the turbine shaft is GH4169, whose performance parameters include elastic modulus E, shear modulus G, poisson's ratio μ, coefficient of linear expansion α', ultimate tensile strength σ_b and so on. The shaft endures the combined loading of axial force F, torque T and bending moment M during service. The material parameters [20] and load parameters related to simulation analysis are presented in TABLE I.

TABLE I. MATERIAL AND LOAD PARAMETERS OF THE TURBINE SHAFT

Material parameters	E (MPa)	G (MPa)	μ	α' (×10^{-6}/°C)	σ_b (MPa)
	181000	71000	0.3	13.5	1270
Load parameters	F (N)	T (N·m)	M (N·m)		
	234573	44388	20253		

The application of constraints and boundary conditions is shown in Fig. 5.

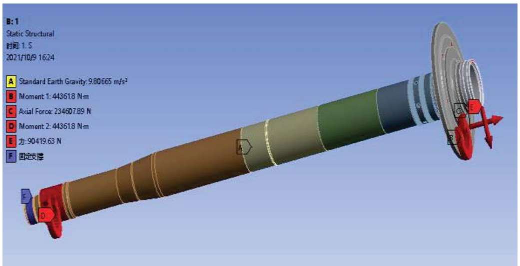

Fig. 5. Application of constraints and boundary conditions

According to the actual experimental results, the sealing labyrinth of the shaft fractured under CCF loading. So the critical region of the turbine shaft is determined to be the sealing labyrinth, which will be emphatically analyzed in FEA. The simulation result of the critical region is shown in Fig. 6 and Fig. 7.

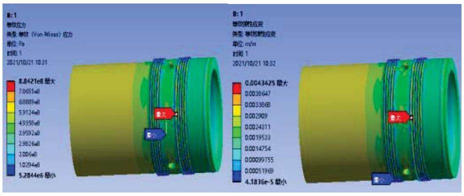

Fig. 6. Response of the turbine shaft's sealing labyrinth under pure LCF loading

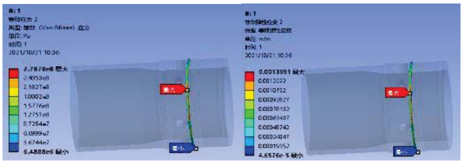

Fig. 7. Response of the turbine shaft's sealing labyrinth under pure HCF loading

The value of the critical region's stress and strain response is shown in TABLE II. $\Delta\sigma_L$ is the stress range under LCF loading, $\Delta\varepsilon_L$ is the strain range under LCF loading, $\Delta\varepsilon_H$ is the strain range under HCF loading, σ_{Hmax} is the maximum stress under HCF loading, and cause the stress ratio of HCF loading is -1, the stress range $\Delta\sigma_H$ under HCF loading can be determined to be twice the maximum stress. Through the simulation data, the stress ratio of HCF to LCF can be further determined to be 0.6306.

TABLE II. VALUE OF STRESS AND STRAIN RESPONSES

$\Delta\sigma_L$ (MPa)	$\Delta\varepsilon_L$	σ_{Hmax} (MPa)	$\Delta\sigma_H$ (MPa)	$\Delta\varepsilon_H$
884.21	0.0043425	278.78	557.56	0.0013691

4. CCF LIFE PREDICTION OF THE TURBINE SHAFT

A. Pure LCF and Pure HCF life prediction of the turbine shaft

The Manson-Coffin model shown in equation (6) is used for the pure LCF life prediction of the turbine shaft.

$$\frac{\Delta\varepsilon_L}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}=\frac{\sigma_f{}'}{E}(2N_L)^b+\varepsilon_f{}'(2N_L)^c \quad (6)$$

where $\Delta\varepsilon_e$ is the elastic strain, $\Delta\varepsilon_p$ is the plastic strain, $\sigma_f{}'$ is the fatigue strength coefficient, b is the fatigue strength exponent, $\varepsilon_f{}'$ is the fatigue ductility coefficient and c is the fatigue ductility exponent. The value of each model parameters can refer to [20], and the Manson-Coffin model can be further represented as equation (7).

$$\frac{\varepsilon_L}{2}=\frac{1224}{181000}(2N_L)^{-0.07}+0.1298(2N_L)^{-0.63} \quad (7)$$

The *S-N* curve is used for the HCF life prediction of the turbine shaft. And according to the material manual [20], the parameters of the *S-N* curve in this research can be determined, as shown in equation (8).

$$\lg N = 25.5716 - 7.5626\lg(\sigma_{Hmax}-114.6) \quad (8)$$

Based on the simulation data through FEA, and using the Manson-Coffin model and *S-N* curve, the pure LCF life and pure HCF life of the turbine shaft can be calculated, as shown in TABLE III.

TABLE III. PURE LCF LIFE AND PURE HCF LIFE OF THE SHAFT

N_L (cycles)	N_H (cycles)
5763008	6.6072×10^8

B. CCF life prediction of the turbine shaft considering interaction damage

In general, the frequency ratio of HCF loading to LCF loading can be represented empirically as the ratio of materials' limit cycle life to the components' field service life. In this research, the value of loading frequency ratio is 1000. The inputs of the damage accumulation model considering interaction damage have been fully obtained, as shown in TABLE IV.

TABLE IV. INPUTS OF THE DAMAGE ACCUMULATION MODEL

N_L (cycles)	N_H (cycles)	n	α
5763008	6.6072×10^8	1000	0.6306

In this research, the turbine shaft is regarded as failure when the damage reaches 1. Through equation (5), CCF life of the turbine shaft can be calculated as 5.51×10^6. In the actual fatigue experiment, the CCF life of the turbine shaft between 10^6~10^7, which does not meet the requirement of infinite-life design (10^7). The predicted result based on damage accumulation theory is quite close to the experimental value.

C. Results and discussion

If using Miner's rule for the CCF life prediction of the turbine shaft, the predicted result is 5.9276×10^5 cycles, and the deviation is large. The main reason for the large deviation is the interaction damage is not fully considered based on this theory.

If ignoring the frequency ratio of HCF loading to LCF loading, and loading both HCF load and HCF loads in FEA, the stress and strain responses are shown in Fig. 8.

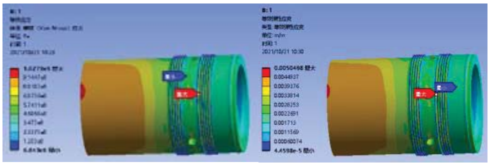

Fig. 8. Simulation result with both LCF loading and HCF loading

Using the simulation result, CCF life can be predicted just by Manson-Coffin model shown in equation (7), and the calculated result is 7.1396×10^5, and the deviation is also large. The main reason for the large deviation is the loading characteristics of CCF has not been focused on during the process of simulation analysis.

The predicted results by different method are listed in TABLE Ⅴ. It is obvious that the proposed method has high accuracy when predicting CCF life of the turbine shaft due to its full consideration of CCF loading characteristics and interaction damage.

TABLE V. PREDICTED RESULTS BY DIFFERENT METHOD

Proposed method	Miner's rule	Manson-Coffin model	Experimental result
5.51×10^6	5.9276×10^5	7.1396×10^5	10^6~10^7

The predicted error by different model can be further presented clearly, through equation (9), where *Error* is the predicted error, N_p is the predicted CCF life by a model, N_t is the test data. The histogram describing the error is shown in Fig. 9.

$$Error = \left|\lg(N_p) - \lg(N_t)\right| \tag{9}$$

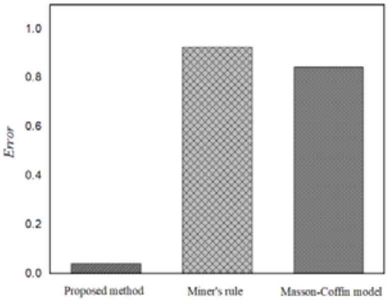

Fig. 9. Predicted error by different method

5. CONCLUSIONS

This paper uses a CCF damage accumulation model considering interaction damage for the CCF life prediction of an aero-engine turbine shaft, and proposes a damage accumulation theory-based CCF life prediction procedure, which includes FEA, pure LCF and pure HCF life prediction, and CCF life prediction considering interaction damage. The predicted results by CCF damage accumulation model, Miner's rule and Manson-Coffin model are compared with the actual test result, and the predicted result following the procedure proposed in this paper is obviously more reasonable and approximate. The main conclusions are shown as follow.

1 The predicted result based on CCF damage accumulation model is 5.51×10^6, which is quite close to actual experimental result.

2 Though comparison, the proposed analysis procedure considering interaction damage can better predict the CCF life of turbine shaft.
Footnote.[a] Endnotes will be permitted for legal affairs type of papers only.

Acknowledgement
This research is financially supported by the National Science and Technology Major Project under contract number 2017-IV-0009-0046.

References

N.S. Xi, P.D. Zhong, H.Q. Huang, H. Yan, C.H. Tao, "Failure investigation of blade and disk in stage compressor," Engineering Failure Analysis, vol. 7(6), pp. 385-392, 2000.
S.P. Zhu, H.Z. Huang, W.W. Peng, H.K. Wang, S. Mahadevan, "Probabilistic physics of failure-based framework for fatigue life prediction of aircraft gas turbine discs under uncertainty," Reliability Engineering & System Safety, vol. 146, pp. 1-12, 2016.
D.Y. Hu, R.Q. Wang, J. Fan, X.L. Shen, "Probabilistic damage tolerance analysis on turbine disk through experimental data," Engineering Fracture Mechanics, vol. 87, pp. 73-82, 2012.
J. Guo, H. Zheng, B. Li, G.Z. Fu, "A Bayesian approach for degradation analysis with individual differences," IEEE Access, vol. 7: 175033-175040, 2019.
H. Li, C.G. Soares, H.Z. Huang, "Reliability analysis of a floating offshore wind turbine using Bayesian networks," Ocean Engineering, vol. 217:107827, 2020.

---

[a] This is a sample footnote. Aim to keep all footnotes with in two to three lines. Footnotes take up space, so use them sparingly.

J. Guo, H. Zheng, B. Li, G.Z. Fu, "Bayesian hierarchical model-based information fusion for degradation analysis considering non-competing relationship," IEEE Access, vol. 7: 175222-175227, 2019.

H. Li, H.Z. Huang, Y.F. Li, J. Zhou, J.H. Mi, "Physics of failure-based reliability prediction of turbine blades using multi-source information fusion," Applied Soft Computing, vol. 72, pp. 624-635, 2018.

L. Han, D.W. Huang, X.J. Yan, C. Chen, X.Y. Zhang, M.J. Qi, "Combined high and low cycle fatigue life prediction model based on damage mechanics and its application in determining the aluminized location of turbine blade," International Journal of Fatigue, vol. 127, pp. 120-130, 2019.

X.J. Yan, R.J. Sun, Y. Deng, Z.N. Liu, J.X. Nie, "Experimental study on fatigue curve law of turbine blade under combined high and low cycle loading," Journal of Aerospace Power, vol. 26(8), pp. 1824-1829, 2011.

Y.K. Zhang, S.X. Guo, "Research on the fatigue performance of TC6 compressor blade under the CCF effect," International Journal of Aerospace Engineering, vol. 2018:7154784, 2018.

S.P. Zhu, P. Yue, Z.Y. Yu, Q.Y. Wang, "A combined high and low cycle fatigue model for life prediction of turbine blades," Materials, vol. 10(7):698, 2017.

V.I. Trufyakov, V.S. Kovalchuk, "Determination of life under two frequency loading. Report no. 2. Proposed method," Strength of Materials, vol. 14(10), pp. 1303-1308, 1982.

D.Y. Hu, R.Q. Wang, "Combined fatigue experiments on full scale turbine components," Aircraft Engineering and Aerospace Technology, vol. 85(1), pp. 4-9, 2013.

D.Y. Hu, F.C. Meng, H.W. Liu, J. Song, R.Q. Wang, "Experimental investigation of fatigue crack growth behavior of GH2036 under combined high and low cycle fatigue,". International Journal of Fatigue, vol. 85, pp. 1-10, 2016.

D.Y. Hu, Q. Yang, H.W. Liu, J.X. Mao, F.C. Meng, Y.F. Wang, M.X. Ren, R.Q. Wang, "Crack closure effect and crack growth behavior in GH2036 superalloy plates under combined high and low cycle fatigue," International Journal of Fatigue, vol. 95, pp. 90-103, 2017.

P. Yue, J. Ma, C.H. Zhou, H. Jiang, P. Wriggers, "A fatigue damage accumulation model for reliability analysis of engine components under combined cycle loadings," Fatigue & Fracture of Engineering Materials & Structures, vol. 43(8), pp. 1880-1892, 2020.

H.Z. Jin, J. Liu, H.Z. Gou, "A study on turbine shaft technical life of an aero engine series," Gas Turbine Experiment and Research, vol. 15(4), pp. 21-24, 2002.

L. Yu, H. Chen, J. Zhou, H.S. Yin, H.Z. Huang, "Fatigue life prediction of low pressure turbine shaft of turbojet engine," Int J Turbo Jet Eng, vol. 34(2), pp.149-154, 2017.

D.W. Liu, "Research on modeling and method of aero-engine turbine shaft fatigue reliability," University of Electronic Science and Technology of China, 2019.

Editorial Board of China Aeronautical Materials Manual, "China Aeronautical Materials Handbook," Beijing: Standards Press of China, 2001.

Author, N. (2021, Month).Title. Working paper, School.

Author, N. and N. Author (1986).Article title. *Journal title Volume number*, Page start–page end.

Author, N., N. Author, and N. Author (1990).*Book Title* (Edition ed.). Publisher Name. Note.

Author, N., N. Author, N. Author, and N. Author (1987).Article title. *Journal title Volume number*, Page start–page end.

Author, N., N. Author, N. Author, and N. Author (1994). Title. Working Paper, University of Name.