Aerospace Science and Technology 79 (2018) 636–646

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Substructure-based distributed collaborative probabilistic analysis method for low-cycle fatigue damage assessment of turbine blade–disk

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ARTICLE INFO

Article history:
Received 5 July 2017
Received in revised form 16 May 2018
Accepted 18 June 2018
Available online 28 June 2018

Keywords:
Reliability analysis
Fatigue damage
Turbine blade–disk system
Random variable
Substructure method
SDCPAM

ABSTRACT

A numerical simulation-based probabilistic analysis methodology, substructure-based distributed collaborative probabilistic analysis method (SDCPAM), is proposed for accurate and efficient fatigue prognosis based on distributed collaborative response surface method (DCRSM) and substructure analysis method. This paper focuses on the low-cycle fatigue (LCF) damage assessment for turbine blade–disk system. Based on the established probabilistic strain–life models and fatigue reliability model for tandem system, the LCF damage principle of turbine blade–disk system is proposed and integrated with SDCPAM. Following that, the LCF life prediction of the turbine blade–disk is completed, and probabilistic sensitivity analyses of blade and disk to the LCF life of the turbine blade–disk system are achieved. According to the above efforts, the feasibility and effectiveness of SDCPAM is verified. Finally, the LCF damage assessment for the blade–disk system is accomplished, and the influences of applied cycle and reliability level on the LCF damage are investigated. Through the comparisons of the proposed with traditional fatigue reliability model, it is illustrated that the proposed fatigue reliability model is reasonable. The results show that blade and disk almost have the same great influence on the blade–disk LCF life. In addition, applied cycles under normal and lognormal distributions produce the same LCF damage reliability that decreases with increasing applied cycle and reliability level. The efforts of this study indicate the reasonability of the proposed method and models in describing the LCF damage reliability of the blade–disk system, and enrich the reliability theory and method for the complex structure with multi-component and multi-failure mode.

1. Introduction

As the main component of gas turbine engine, turbine blade–disk system greatly influences the reliability of the whole aero-engine and even flight safety. Low-cycle fatigue (LCF) exerts an important impact on the fatigue performance of the turbine system [1–4]. The LCF failure may be caused from fatigue crack of any one of both blade and disk for the turbine blade–disk assembled through firtree-tenon. Therefore, the LCF damage analysis and evaluation are critical to the initial design and maintenance planning during service [5]. Generally, LCF life prediction is conducted applying deterministic analysis methods. However, practical fatigue crack propagation is a random process in nature due to the involved various uncertain variables [6]. Along with the development of reliability analysis theory and numerical method, the probabilistic concept is introduced into the design and analysis of turbine components. Numerous efforts on LCF life prediction and damage reliability evaluation have been made considering the influence of the uncertain variables for the past several decades.

Various simulation-based probabilistic methods and models focusing on the uncertainty have been proposed to carry out the LCF life prediction of turbine components. Chen et al. [7] developed the power-exponent function model based on power transformation for LCF life prediction. Sun and Hu [8] proposed a nonlinear accumulation model to assess the LCF life of a steam turbine rotor. Chen et al. [9] introduced a reliability assessment model of LCF and high energy impact based on the local stress–strain approach. Holycross et al. [10] developed an energy-based fatigue life prediction method to accurately predict lifetimes of coupon specimens. Lv et al. [11] proposed a modified Walker strain life prediction model without the mean stress correction for the fatigue life prediction of turbine disk. Zhu et al. [12–14] proposed

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https://doi.org/10.1016/j.ast.2018.06.023
1270-9638/

and developed several probabilistic analysis models and methods for the LCF life prediction of turbine discs, including viscosity-based life prediction model based on ductility exhaustion theory and generalized energy-based damage parameter, Bayesian framework by quantifying the uncertainty, and probabilistic physics of failure-based framework by incorporating the overall uncertainties in structural integrity assessment. Gao et al. [15,16] developed distributed collaborative response surface method to the LCF life and damage prediction for gas turbine blades by applying the probabilistic Morrow mean stress correction.

However, the investigations on the life prediction of turbine structure mainly focused on component level. In fact, the LCF life prediction of turbine blade–disk system with firtree-tenon involves two component, blade and disk. Along with the rapid development of computer technology and test equipment, the accuracy and efficiency of the LCF life prediction for complex structure system get an effective improvement. Chen et al. [17] presented a two-dimensional thermal off-design model to predict the fracture critical location and crack initiation life of an integrally cast blisk with a semi-empirical projecting approach. Kharyton and Bladh [18] proposed an assessment of the fatigue damage incurred to transonic compressor blisk subjected to stall-induced dynamic loading through tip timing technology. Naboulsi [19] implemented a finite strain computational crystal plasticity constitutive approach to investigate time-dependent fretting fatigue life of turbine blade to disk attachment.

From the previous efforts, the relationship between components is very important to the accurate LCF life prediction for the turbine blade–disk system. On the basis of the evaluation of the present numerical simulation methods, a more efficient probability design method is the main purpose of this study. Substructure simulation method [20] can acquire the interaction between components through node coupling rather than contact boundary constraint, and generate each complex finite element model (FEM) into super-element to reduce computational efforts, which can greatly enhance the computational accuracy and efficiency for high nonlinear problems with hyper-parameters. In addition to these advantages, the distribution and collaboration concepts are integrated to propose substructure-based distributed collaborative probability analysis method (SDCPAM) in order to further improve the evaluation accuracy and efficiency.

In this paper, a general methodology for probabilistic fatigue life prediction is proposed based on distributed collaborative response surface method (DCRSM) and substructure simulation method. Against the conclusion [15] the LCF damage of turbine blade takes lower reliability at the confidence level of 0.95 than 0.9 and 0.5, the probabilistic strain–life relationships at the reliability levels of 0.5, 0.9 and 0.95 under the confidence level of 0.95 are proposed applying linear heteroscedasticity regression analysis method. The LCF damage prediction principle for the turbine blade–disk system is proposed. And then, the LCF life prediction of the turbine blade–disk system at the reliability levels of 0.5, 0.9 and 0.95 are completed, and the sensitivities and normalized significances of blade and disk to LCF life are acquired. Considering the influence of applied cycle with different distributions, the LCF damage prognosis of the turbine blade–disk system is conduced. Finally, the proposed method and model are verified by comparing with the traditional fatigue reliability methods and model.

2. Substructure-based distributed collaborative probabilistic analysis method

Distributed collaborative response surface method (DCRSM) has been validated to be accurate and efficient [15]. In the current study, SDCPAM is proposed based on the integration of substructure analysis method [20] with the DCRSM to further improve analytical efficiency for structural fatigue reliability analysis.

2.1. Substructure simulation method

For the complex mechanical structure system with multi-object and multi-failure mode, multi-parameter and limited computer memory severely restrict simulation efficiency and computation scale. In addition to increasing computer capacity, efficient simulation method should be taken into account to overcome these problems. In this paper, substructure simulation method is introduced to further enhance the computational accuracy and efficiency.

Substructure simulation method decompose a large simultaneous equation into several small set of equations to reduce computational efforts and achieve the purpose of using microcomputer to tackle large issue. The basic thought is as follows: (1) Generation pass: To acquire the stiffness matrix of each super-element; (2) Use pass: To complete the superposition of all stiffness matrixes based on the principle the external nodal degrees of freedom (DOFs) and the corresponding DOFs of the global stiffness matrix show an overlap, and analyze the combination system to acquire all nodal displacements; (3) Expansion pass: To resolve detailed solutions (e.g., displacements and stresses) within the substructure.

Substructure simulation method can reduce complex system matrix into a small set of DOFs to derive the detailed solutions within the substructure. Before the reduction, substructure is essentially a super-element with a considerable amount of DOFs. In order to decrease computational efforts, the DOFs within the super-element are condensed prior to the linkage of substructures. Through appropriate node number, the static equilibrium equation $\boldsymbol{K}\boldsymbol{a}=\boldsymbol{P}$ may be partitioned into two groups, the master (retained) DOFs denoted by the subscript 'm' and the slave (removed) DOFs denoted by the subscript 's':

$$\begin{pmatrix} \boldsymbol{K}_{mm} & \boldsymbol{K}_{ms} \\ \boldsymbol{K}_{sm} & \boldsymbol{K}_{ss} \end{pmatrix} \begin{pmatrix} \boldsymbol{a}_m \\ \boldsymbol{a}_s \end{pmatrix} = \begin{pmatrix} \boldsymbol{P}_m \\ \boldsymbol{P}_s \end{pmatrix}, \tag{1}$$

where $\boldsymbol{K}$ is the stiffness matrix. $\boldsymbol{a}$ is the corresponding nodal displacement vector, and $\boldsymbol{P}$ is load vector.

Solving Eq. (1) for the internal node displacement vector $\boldsymbol{a}_s$,

$$\boldsymbol{a}_s = \boldsymbol{K}_{ss}^{-1}\boldsymbol{P}_s - \boldsymbol{K}_{ss}^{-1}\boldsymbol{K}_{sm}\boldsymbol{a}_m, \tag{2}$$

According to the Gauss–Jordan elimination method, substituting Eq. (2) into Eq. (1) to solve the external node displacement vector $\boldsymbol{a}_m$, as shown in Eq. (3).

$$\left(\boldsymbol{K}_{mm} - \boldsymbol{K}_{ms}\boldsymbol{K}_{ss}^{-1}\boldsymbol{K}_{sm}\right)\boldsymbol{a}_m = \boldsymbol{P}_m - \boldsymbol{K}_{ms}\boldsymbol{K}_{ss}^{-1}\boldsymbol{P}_s, \tag{3}$$

where $\boldsymbol{K}_{mm}^{*} = \boldsymbol{K}_{mm} - \boldsymbol{K}_{ms}\boldsymbol{K}_{ss}^{-1}\boldsymbol{K}_{sm}$ and $\boldsymbol{P}_m^{*} = \boldsymbol{P}_m - \boldsymbol{K}_{ms}\boldsymbol{K}_{ss}^{-1}\boldsymbol{P}_s$ are the coefficient (e.g., stiffness) matrix and the load vector of the considered super-element, respectively.

Based on the interrelation between super-element DOFs and coefficient matrix, super-elements are analyzed by establishing the coupling of the linked nodes to acquire the node responses, which is super-element use pass.

In the preceding development, the super-element load vector $\boldsymbol{P}^{*}$ has been treated as total load vector. The same derivation may be applied to any number of independent load vectors, which in turn may be individually scaled in the super-element use pass. For example, the analyst may wish to apply thermal, pressure, gravity, and other loading conditions in varying proportions. The load vectors $\boldsymbol{P}_m$ and $\boldsymbol{P}_s$ should be expanded as

$$\boldsymbol{P}_m = \sum_{i=1}^{N} b_i \boldsymbol{P}_{mi}, \qquad \boldsymbol{P}_s = \sum_{i=1}^{N} b_i \boldsymbol{P}_{si}, \tag{4}$$