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Distributed collaborative probabilistic design of multi-failure structure with fluid-structure interaction using fuzzy neural network of regression

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ABSTRACT

To improve the computing efficiency and precision of probabilistic design for multi-failure structure, a distributed collaborative probabilistic design method-based fuzzy neural network of regression (FR) (called as DCFRM) is proposed with the integration of distributed collaborative response surface method and fuzzy neural network regression model. The mathematical model of DCFRM is established and the probabilistic design idea with DCFRM is introduced. The probabilistic analysis of turbine blisk involving multi-failure modes (deformation failure, stress failure and strain failure) was investigated by considering fluid–structure interaction with the proposed method. The distribution characteristics, reliability degree, and sensitivity degree of each failure mode and overall failure mode on turbine blisk are obtained, which provides a useful reference for improving the performance and reliability of aeroengine. Through the comparison of methods shows that the DCFRM reshapes the probability of probabilistic analysis for multi-failure structure and improves the computing efficiency while keeping acceptable computational precision. Moreover, the proposed method offers a useful insight for reliability-based design optimization of multi-failure structure and thereby also enriches the theory and method of mechanical reliability design.

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1. Introduction

For multi-failure structure like the turbine blisk of an aeroengine, the reliability, security and performance of mechanical system are seriously influenced by a variety of failure modes on structure responses such as deformation failure, stress failure, strain failure and so forth [1–3]. It is important to accurately estimate the multi-failure traits of the complex structure. However, the coupling effect among multi-physics loads (such as fluid load, heat load and centrifugal load) and multiple structural responses (such as deformation, stress and strain) cause the high nonlinearity and complexity of structure limit state function, which leads to the difficulty of design analysis of multi-failure structure [4,5]. Therefore, efficient analysis methods are expected to reasonably design multi-failure structure. Although much progress of experimental and numerical investigations has been implemented for multi-failure structure via deterministic analysis methods [6–8]. These works are not always concerned the uncertainty of various factors impacting the performance of multi-failure structure. Probabilistic

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analysis is one viable alternative, which concerns stochastic factors just like physical field loads and material parameters, and describes the responses of multi-failure structure with acceptable precision as well [9–11]. The probabilistic analysis as one key technique has been widely applied in many fields [12–14]. Nevertheless, less work applies the probabilistic analysis into multi-failure structure design.

Classic probabilistic analysis methods are Monte Carlo method (MCM) [15–17] and response surface method (RSM, also called surrogate model) [18–20] and distributed collaborative RSM (DCRSM) [21–24]. MCM is applied in many fields due to its high computing precision in the reliability evaluation and design. However, it is difficult for MCM to cater for the requirements of solving limit state functions with high nonlinearity and strong coupling. As one focus of structural probabilistic analysis, RSM can improve computing efficiency and precision. Nevertheless, RSM is only suitable to approximate limit state function of single failure mode rather than the probabilistic analysis with multiple failure responses of multi-failure structure [20]. To process the nonlinearity and multi-failure problem in the probabilistic analysis of multi-failure structure, DCRSM was developed to process many single-failure modes and coordinate many single-output responses of multi-failure structure [22,23]. However, it is not perfect to describe the strong nonlinearity characters and huge computational task in probabilistic analysis of multi-failure structure due to its distributed collaborative response surface function (DCRSF) developed from quadratic polynomial (QP) with insufficient accuracy and efficiency [24]. Therefore, an efficient approach is anticipant to further improve the probabilistic design of multi-failure structure.

Fuzzy logic system, an uncertain system, can express fuzzy or qualitative knowledge reasonably by defining input variables, output responses and state variables on the fuzzy rule sets. As the fuzzy system holds many advantages of strong regularization ability and human-like inference ability, it has been used in control strategy and optimization problems [25–27]. Artificial neural network (ANN) algorithm is regarded as an intelligent learning method with the advantages of strong nonlinear mapping ability and good robustness ability. In view of to the superiority of requiring few training samples and holding high computational efficiency and precision, the ANN has been widely applied to adaptive critic design and pattern recognition [28–30].

In light of the above merits of fuzzy logic system and ANN algorithm, the fuzzy neural network (FNN) was developed, by fusing the fuzzy logic system and artificial neural network algorithm, and employed in reliability analysis [31–33] and probabilistic analysis [34–36]. The FNN is a kind of intelligent statistical learning algorithm with high efficiency and acceptable precision and transforms the complexity and nonlinearity problems of output responses between uncertainty variable into the regression computation problems of the FNN model. Moreover, the human-like inference ability from fuzzy logic system and self-learning ability from ANN algorithm are the advantages of FNN in probabilistic analysis. Thus, FNN is potential to improve computing efficiency and computing accuracy of probabilistic design.

The purpose of this study is to develop a DCRSM based on FNN of regression (FR) (called as DCFRM) for distributed collaborative probabilistic design of multi-failure structure. And then by considering fluid-structure interaction, the probabilistic design of turbine blisk with multi-failure modes (deformation failure, stress failure and strain failure) is accomplished based on DCFRM. The efforts offer an effective way for the reliability design of multi-failure structure and enrich mechanical reliability theory and method. Moreover, the present research provides a useful insight for optimization design of multi-failure structure for future research.

In what follows, Section 2 discusses the basic theory of DCFRM based on DERSM and FR for distributed collaborative probabilistic design. Section 3 investigates the thought of the probabilistic analysis of multi-failure structure with DCFRM. The proposed method is validated by turbine blisk distributed collaborative probabilistic design in Section 4. Section 5 summaries some conclusions and outlooks on this study.

2. Basic theory

2.1. Fuzzy neural network of regression

Fuzzy neural network (FNN) as one surrogate model comprises Takagi-Sugeno (T-S) fuzzy logic system with human-like thinking inference ability and artificial neural network learning algorithm of self-adaptive adjusting fuzzy parameters ability. FNN holds many advantages of strong self-adaptive ability, nonlinear mapping and good regularization. In view of these virtues, the FNN is taken as a response surface function (RSF) to present DCFRM. The FNN model is shown in Fig. 1.

From a certain kind of random variables $\boldsymbol{x}$ ($\boldsymbol{x} \in \mathbf{R}^n$), a set of output response $\boldsymbol{y}(\boldsymbol{x})$ ($\boldsymbol{y} \in \mathbf{R}$) is fitted by the FNN regression function $f(\boldsymbol{x})$, which maps a point in n-dimensional space $\mathbf{R}^n$ onto one-dimensional $\mathbf{R}$. The FNN function is denoted by

$$f(\boldsymbol{x}) = \{\boldsymbol{y}(\boldsymbol{x}) = f(\boldsymbol{x}, \boldsymbol{w}), \boldsymbol{w} \in \Lambda | f : \mathbf{R}^n \to \mathbf{R}\} \tag{1}$$

where Λ is a set of parameters, $\boldsymbol{w}$ an undetermined network parameter vector of FNN.

In accordance with the FNN topology model, the mathematical model of FNN is established by integrating antecedent network with matching fuzzy rules ability and consequent network with generating fuzzy rules ability. After the collaborative analysis of antecedent network and consequent network, the mathematical model of FNN is constructed as follows:

2.1.1. Antecedent network

To make input variables have fuzziness, the variables are blurred into fuzzy variables in the blurring layer by using membership function, which is defined by

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