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Multi-objective reliability-based design optimization approach of complex structure with multi-failure modes

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A B S T R A C T

To make multi-objective reliability-based design optimization (MORBDO) more effective for complex structure with multi-failure modes and multi-physics coupling, multiple response surface method (MRSM)-based artificial neural network (ANN) (ANN-MRSM) and dynamic multi-objective particle swarm optimization (DMOPSO) algorithm are proposed based on MRSM and MOPSO algorithm. The mathematical model of ANN-MRSM is established by using artificial neural network to fit the multiple response surface function. The DMOPSO algorithm is proposed by designing dynamic inertia weight and dynamic learning factors. The proposed approach is verified by the MORBDO of turbine blisk deformation and stress with respect to fluid–thermal-structure interaction from probabilistic analysis. The optimization design results show that the proposed approach has the promising potentials to improve computational efficiency with acceptable computational precision for the MORBDO of turbine blisk deformation and stress. Moreover, Pareto front curve and a set of viable design values of turbine blisk are obtained for the high-reliability high-performance design of turbine blisk. The presented efforts provide an effective approach for MORBDO of complex structures, and enrich mechanical reliability design theory as well.

1. Introduction

For complex structure like the turbine blisk of an aeroengine, the reliability, performance and security of mechanical system is seriously influenced by a variety of failure modes on structure responses such as deformation failure, stress failure, fatigue failure, and so on [1–3]. Especially, the design and control of one failure mode leads to the change of another due to the mutual influence among many failure modes. Therefore, it is vital to conduct the reliability-based design optimization (RBDO) of complex structure with multi-failure modes from a multiple objectives perspective to improve the reliability and performance of mechanical system [4,5]. This is called as multi-objective RBDO (MORBDO) of complex structure. Along with the enhancement of computing capacity of current computer, finite element (FE) method has become an important technique in product development process, which has been applied to fluid analysis, thermal analysis, stress analysis and fatigue life estimates and design of turbine typical components [6–9]. However, for the MORBDO of complex structure, thousands of running times are required to calculate the reliability as one reliability analysis that needs a large number of FE calculations. Moreover, complex loads like high gas temperature and high speed in fluid–thermal-structure coupling field, result in enormous computational tasks in each FE calculation. Therefore, it is infeasible to deal with the exceedingly huge amount of computation by FE method. To improve the computational speed, stochastic FE method, high order moment method and other numerical methods are developed and widely used [10–12]. In fact, the fitting precision of these methods to the limit state surface of complex structure is unacceptable though these numerical methods can greatly improve computational speed, which leads to the application difficulty in MORBDO of complex structure. To improve computational accuracy and efficiency and complete MORBDO of complex structure, this study adopts two key techniques: 1) establishment of a numerical surrogate model to calculate comprehensive reliability under multi-failure modes; 2) development of a dynamic algorithm to resolve the MORBDO model.

The first technique is to establish a numerical surrogate model to approximate the limit state function of complex structure. The surrogate model only needs a small amount of FE analysis, which greatly reduces the computing time. This method is also called as response surface method (RSM), which has been widely used

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Acronym list

RBDO	reliability-based design optimization
MORBDO	multi-objective reliability-based design optimization
MOPSO	multi-objective particle swarm optimization
DMOPSO	dynamic multi-objective particle swarm optimization
ANN	artificial neural network
BP-ANN	back propagation-artificial neural network
MRSM	multiple response surface method
MRSF	multiple response surface function
QP	quadratic polynomial
RSM	response surface method
QP-MRSM	multiple response surface method-based quadratic polynomial
QP-MRSF	quadratic polynomial-multiple response surface function
ANN-MRSM	multiple response surface method-based artificial neural network
RSF	response surface function
ANN-MRSF	artificial neural network-multiple response surface function
FE	finite element
BR	Bayesian regularization
MCM	Monte Carlo method

in structure reliability analysis and optimization design [13–16]. Currently, RSM generally uses quadratic polynomial (QP) function or artificial neural network to construct response surface model. Wherein, QP response surface model fits the limit state surface by the least square regression, by gaining the explicit response surface function (RSF) and a series of response values [17–21]. Artificial neural network response surface model is an implicit RSF fitted by network training to complete the reliability calculation by replacing the state function. Artificial neural network response surface model has been widely applied to engineering optimization problems because of the superiority of requiring few training samples and holding high computational efficiency and precision [22–24]. The aforementioned two RSMs are unfit to calculate directly the comprehensive reliability under multi-failure modes because RSM only calculate one single response and the reliability under one failure mode. To address this issue, multiple RSM (MRSM) is proposed based on QP, called as QP-MRSM. QP-MRSM has been widely used in the fatigue damage analysis of the turbine disk [25,26], and the RBDO of turbine blade-tip clearance from probabilistic perspective [27,28]. Despite of the particular merits of QP-MRSM, the QP-MRSM is not always able to ensure acceptable computational precision and efficiency owing to low fitting accuracy and low simulating speed [29,30]. To resolve these issues, ANN-MRSM is proposed by integrating MRSM and ANN to complete the comprehensive reliability calculation under multi-failure modes, and improve the computational efficiency and precision effectively.

The second technique is to develop a dynamic algorithm to resolve the MORBDO model, the various optimization objectives have interaction effect in MORBDO model, and are almost impossible to achieve at the same time. Therefore, a global algorithm, which can coordinate the multiple objectives simultaneously, is required to solve the MORBDO problem [31–33]. Because of the characteristics of the parallel search and independent to the forms of objective functions, the multi-objective particle swarm optimization (MOPSO) algorithm has been widely used in MORBDO in engineering [34–37]. When the MOPSO algorithm is used to MORBDO model, the distance between the particles and the feasible solutions is far away at the early period, which requires a larger speed. Moreover, the particles are gradually close to the feasible solutions at the later search period, and the smaller particle velocity is more conducive to push it to the feasible solutions. Nevertheless, the search speed of algorithm MOPSO is generally fixed, so that it cannot effectively control the whole particle swarm by adjusting the parameters of the particles. Aiming at solving the above problems, the dynamic MOPSO (DMOPSO) algorithm is proposed by improving the MOPSO that inertia weight and learning factors are changed with the number of iterations. With the increase of the iteration numbers, the algorithm dynamically adjusts the search speed and position, so that the Pareto optimal solutions with high search speed and accuracy is promising to be acquired.

The objective of this study is to develop a reliability analysis method (ANN-MRSM) to improve computational efficiency and precision and a dynamic algorithm (DMOPSO) to resolve the MORBDO model of complex structure with multi-failure modes. Then the proposed approach is applied in the MORBDO of the turbine blisk with the emphasis on deformation and stress failures and fluid–thermal-structure interaction.

In what follows, Section 2 studies on ANN-MRSM for comprehensive reliability analysis under multi-failure modes including the basic thought and mathematical model of ANN-MRSM, and the basic principle of probabilistic analysis as well. In Section 3 DMOPSO algorithm is investigated to resolve the MORBDO model, and the basic thought of dynamic search is discussed by designing the dynamic inertia weight and dynamic learning factors. Section 4 validates the proposed approach (ANN-MRSM and DMOPSO) by the MORBDO of turbine blisk. Some conclusions and outlook are summarized in Section 5.

2. Basic theory

2.1. Multiple response surface method (MRSM)

Reliability calculation is to adopt the random dispersion of random variables to analyze the probability that the structure meet the specified function in the practical engineering. To calculate the comprehensive reliability under multi-failure mode, the MRSM is proposed [27]. The basic thought is summarized as follows:

(1) Establish FE model, set operating condition parameters such as fluid velocity, gas temperature, rotor speed, distribution characteristics, and so forth.
(2) Calculate output responses of structure by using FE model, and extract a small amount of samples for input random variables and output responses.
(3) Aiming at different failure modes, establish response surface models between input variable $\boldsymbol{x}$ and output response $Y(\boldsymbol{x})$, respectively.
(4) Fit the multiple RSF (MRSF) by the response surface models and specified structure failure criterion.
(5) Carry out the linkage sampling to MRSF to gain the comprehensive reliability under multi-failure modes.

Obviously, MRSF deals with the correlation among multi-failure modes and converts the stochastic process of output responses and reliabilities for complex structure into the random variables in a probabilistic analysis. The MRSM is a heuristic way to reduce the computing time and improve the computing efficiency in reliability calculation of complex structure.