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Novel method and model for dynamic reliability optimal design of turbine blade deformation

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ABSTRACT

Turbine blade radial deformation seriously influences the Blade-Tip Radial Running Clearance (BTRRC) of the high pressure turbine and the performance and reliability of gas turbine engine. For blade radial deformation design under gas turbine operating conditions, Extremum Response Surface Method (ERSM)-based Support vector machine of Regression (SR) (SR-ERSM) and Importance Degree Model (IDM) were proposed for structural dynamic reliability optimal design. The mathematical model of SR-ERSM was established by taking SR model as an extremum response surface function. The IDM was developed by considering important random parameters obtained by probabilistic analysis. The proposed SR-ERSM and IDM were applied to the reliability optimal design of turbine blade radial deformation based on nonlinear material properties and time-varying loads. The optimization results show that SR-ERSM and IDM are promising to reduce additional design samples and calculated load as well as improve computational efficiency with acceptable precision for nonlinear dynamic structural optimized design. Moreover, a viable design value of blade radial deformation is gained for BTRRC control and high-performance high-reliability gas turbine design. The presented efforts provide a high-efficiency and high-accuracy method and a rapid model for dynamic optimization design of structures for further research as well as enriching mechanical reliability design theory.

1. Introduction

The transient nature of turbine blade radial deformation seriously influences the variation of High Pressure Turbine (HPT) Blade-Tip Radial Running Clearance (BTRRC) and the performance and reliability of gas turbine engines [6,24,32]. Large radial deformation directly reduces BTRRC, resulting in the friction fault between blade tip and casing and even catastrophic failure under operation. In contrast, small radial deformation increases BTRRC and decreases gas turbine performance [2]. To control BTRRC efficiently, the optimal design of blade radial deformation should be executed subject to constraints on reliability and some practical conditions. With the growth in computing power and the advances in computational techniques, Finite Element (FE) method has become a common and important technique in product development processes such as stress analysis, thermal analysis, vibration analysis and fatigue life estimates on designing aeroengine components [15,18,21,25]. The reliability optimization of blade radial deformation involves a large number of variables and large-scale FE analyses with dynamic mechanical and thermal loads. If FE method is used, an unacceptable runtime may occur. To improve computational speed and efficiency, two techniques are applied: 1) construction of a simple surrogate model; 2) decreasing the number of design variables.

The first technique is to construct a simple surrogate model to approximate the response of a costly FE model [16]. The surrogate model often requires only a small number of FE analyses, which is promising to reduce computational time. This method is also called Response Surface Method (RSM), which has been widely applied to engineering optimization problems [3,7,8,12,14,19,20,22,23,26,27,29] by typical surrogate models such as polynomial response surface model [19,22,27,29], Support Vector Machine (SVM) [3,7,8,14,20,26], etc. A polynomial response surface model is a widely used surrogate model due to its simplicity and effectiveness. This model uses least-squares regression analysis to fit low-order polynomials to a set of experimental data [27,29]. An SVM is a kind of intelligent statistical learning method and an implicit performance function, which currently has been employed to reliability analysis and optimal design [3,8,14,20,26] with small training samples, high computational accuracy and efficiency. However, the

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aforementioned two RSMs are unfit for the nonlinear dynamic optimization analysis of complex structures because each one only approximates the performance function around one design point and belongs to the local RSM [4,8,13]. Under the circumstances, Extremum RSM (ERSM), a global response surface approach, was proposed based on Quadratic Polynomial (QP) to overcome the localizations of the aforementioned RSMs. The ERSM presently has been successfully applied to the globe reliability analysis of flexible robot manipulator [30], the nonlinear dynamic probabilistic design of aeroengine typical components [5,10,11,28] and mechanical dynamic assembly reliability analysis of the HPT [9]. Despite the particular merits demonstrated by these works, the ERSM is not always able to sometimes ensure the computational efficiency and precision owing to low fitting precision and low simulating speed for QP. To address these issues, the ERSM-based SVM Regression (SR-ERSM) has been presented and verified to yield be high efficiency and high precision in the nonlinear dynamic probabilistic analysis of turbine casing radial deformation [8]. Up to now, the SR-ERSM has not been found in the application of applied to complex structure optimization yet.

The second technique is to develop a rapid model for nonlinear dynamic structural reliability optimal design through reasonably decreasing the number of random design variables. Because of nonlinear dynamic system analysis referring to too many impact factors, an excess of random design variables invariably results in unacceptable optimization speed and efficiency based on General Mean Model (GMM) [31]. In fact, a portion of random design variables have little impact on the results of reliability optimization, so that these random variables may be ignored in nonlinear dynamic structural optimization. If only the important variables are only selected as random design variables from probabilistic analysis rather than all variables, the computational task of dynamic reliability optimization is greatly reduced, so that the corresponding optimization efficiency and speed can be improved.

The objective of the present study is to develop a high efficiency and high precision optimization method (SR-ERSM) and a rapid optimization model (Importance Degree Model, IDM) for dynamic structural reliability optimization. The proposed method and model is applied in the multi-disciplinary reliability optimization of blade radial deformation considering nonlinear material properties, transient thermal load and centrifugal force.

2. Basic theory

2.1. Extremum Response Surface Method (ERSM)

In dynamic reliability analysis, ERSM merely calculates a single extreme value (global value) of dynamic (transient) output responses rather than all values under different input vectors within a time domain $[0, T]$, which is equivalent to transforming a stochastic process into a random variable for output response [10,30]. Based on ERSM the dynamic reliability analysis procedure follows:

(1) Establish FE model or kinetic equation and configure reasonable parameters (dynamic load, constraint condition, time domain, etc.) and their distribution features;
(2) Extract a handful of samples for input/output variables and gain extremum output responses for each sample within time domain $[0, T]$;
(3) Fit an extremum response surface function (ERSF) to these sample vectors comprising input samples and output samples;
(4) Accomplish structural/system dynamic reliability analysis and optimal design based on ERSF.

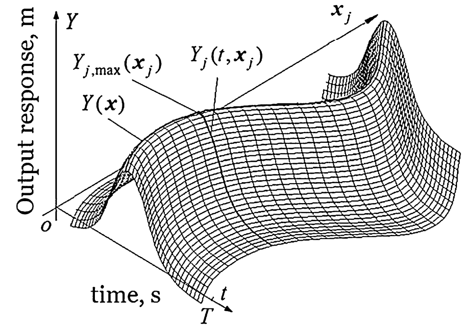

Fig. 1. Basic principle of ERSM.

Obviously, ERSM is able to address dynamic (transient) system/structural nonlinear multidisciplinary reliability design, and is promising to reduce computing cost and enhance calculation efficiency [5,10,11,28].

The basic principle of ERSM is structured as shown in Fig. 1. With the jth input samples $\boldsymbol{x}_j$, the extremum of output response $Y_j(t, \boldsymbol{x}_j)$ is $Y_{j,\max}(\boldsymbol{x}_j)$ within the time domain $[0, T]$. The data set $\{Y_{j,\max}(\boldsymbol{x}_j): j = 1, 2, \ldots, l\}$ consisting of the maximum output responses is used to fit the extremum response curve $Y(\boldsymbol{x})$

$$Y(\boldsymbol{x}) = f(\boldsymbol{x}) = \{Y_{j,\max}(\boldsymbol{x}_j): j = 1, 2, \ldots, l\}, \tag{1}$$

here $f(\boldsymbol{x})$ is an ERSF; l denotes the number of sample vector. If the ERSF is applied to the dynamic reliability design of complex mechanical structure/system replacing the corresponding FE model, this method is called ERSM, which belongs to global response surface method.

2.2. ERSM-based Quadratic Polynomial (QP-ERSM)

The ERSF is a key factor in dynamic reliability design because a valid ERSF directly enhances computational efficiency and precision [10]. When the QP is taken as an ERSF (denoted by QP-ERSF), Eq. (1) can be rewritten as

$$Y(\boldsymbol{x}) = f(\boldsymbol{x}) = a_0 + \boldsymbol{B}\boldsymbol{x} + \boldsymbol{x}^{\mathrm{T}}\boldsymbol{C}\boldsymbol{x}, \tag{2}$$

where $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{x}$ are determined by

$$\boldsymbol{B} = [b_1, b_2, \cdots, b_r],$$
$$\boldsymbol{C} = \begin{pmatrix} c_{11} & & \\ & \ddots & \\ 0 & & c_{rr} \end{pmatrix},$$
$$\boldsymbol{x} = [\boldsymbol{x}_1, \boldsymbol{x}_2, \cdots, \boldsymbol{x}_r]^{\mathrm{T}},$$

in which r is the number of random variables.

If the QP-ERSF is applied to structural dynamic optimal design replacing an FE model, this method is called as QP-ERSM, which is also a whole response surface method. Despite Although QP-ERSM demonstrates reveals much strength capability in the nonlinear dynamic multi-disciplinary reliability analysis of complex structures [5,10,11,28], the method still exhibits confronts with two issues: (1) Needs too many FE analyses to fit QP-ERSF; (2) The QP deficiently reflects the real FE model for nonlinear, dynamic and multi-disciplinary analysis. Thus a novel ERSM is expectant to be developed based on a more effective ERSF is required to resolve the two issues.

2.3. Extremum Response Surface Method-based Support vector machine Regression (SR-ERSM)

SVM is an important surrogate model based on intelligent statistical learning theory [14] and holds high computational