

## Research Article

# Multiobject Reliability Analysis of Turbine Blisk with Multidiscipline under Multiphysical Field Interaction

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To study accurately the influence of the deformation, stress, and strain of turbine blisk on the performance of aeroengine, the comprehensive reliability analysis of turbine blisk with multiple disciplines and multiple objects was performed based on multiple response surface method (MRS) and fluid-thermal-solid coupling technique. Firstly, the basic thought of MRS was introduced. And then the mathematical model of MRS was established with quadratic polynomial. Finally, the multiple reliability analyses of deformation, stress, and strain of turbine blisk were completed under multiphysical field coupling by the MRS, and the comprehensive performance of turbine blisk was evaluated. From the reliability analysis, it is demonstrated that the reliability degrees of the deformation, stress, and strain for turbine blisk are 0.9942, 0.9935, 0.9954, and 0.9919, respectively, when the allowable deformation, stress, and strain are  $3.7 \times 10^{-3}$  m,  $1.07 \times 10^9$  Pa, and  $1.12 \times 10^{-2}$  m/m, respectively; besides, the comprehensive reliability degree of turbine blisk is 0.9919, which basically satisfies the engineering requirement of aeroengine. The efforts of this paper provide a promising approach method for multidiscipline multiobject reliability analysis.

## 1. Introduction

An aeroengine as the power system of aircraft seriously influences the performance and reliability of air vehicle [1]. Bladed disk as one pivotal part of aeroengine is the important fault source of aeroengine for suffering from high temperature, high pressure, and high rotation speed during operation [2]. Of the faults of aeroengine, the rate of blisk fault is 25%. The performances of aeroengine safety, reliability, and robustness are to decline sharply once blisk fault occurs [3]. Therefore, it is of great significance for improving the whole performance and reliability of aeroengine to investigate the reliability of blisk.

Recently, some efforts spring up on the improvement of aeroengine. Qi et al. studied the time history variation of the blade-tip clearance of aeroengine high turbine by finite element method under considering the effects of temperature, pressure, and rotation speed [4]. Pillidis and

Maccallum, focused on the change rule of aeroengine high-pressure blade-tip radial running clearance through calculating the radial deformations of turbine disk, blade, and casing by adopting thermal-solid coupling method under the influences of heat load and centrifugal force load [5]. Wang et al. analyzed the stress of contact region on the blade and disk of aeroengine based on finite element method [6]. Meguid et al. discussed the effect of impact force by simulating the impact of bird against the blade of aeroengine using finite element method [7]. The above investigations only focus on the deterministic analysis without considering the randomness of influencing parameter on aeroengine blisk, so that it is very difficult to gain reasonable results for blisk design and analysis.

To address this issue, one viable alternative to deterministic analysis is probabilistic analysis, which does consider the randomness of factors to describe the blisk deformation of aeroengine with acceptable accuracy. The probabilistic

analysis method has been widely applied in many fields. For instance, Lü and Low conducted the probabilistic analysis of underground rock excavations [8]; Kartal et al. implemented the probabilistic nonlinear analysis of CFR dams [9]; Fitzpatrick et al. applied probabilistic analysis method to multivariate sensitivity evaluation patellofemoral mechanics [10]; Zona et al. studied design assessment of continuous steel concrete composite girders with probabilistic analysis [11]. Meanwhile, some works were also done in the probabilistic analysis of typical aeroengine components. Hu et al. researched the probabilistic design for turbine disk at high temperature [12]; Nakamura and Fujii analyzed the transient heat of an atmospheric reentry vehicle structure using probabilistic method [13]; Fei et al. finished the probabilistic analyses of turbine disk [14] and casing [15, 16]. Additionally, some approaches of probabilistic analysis have been developed such as Monte Carlo method (MCM) [13], response surface method (RSM) [17, 18], extremum response surface method [14, 15], and support vector machine [16, 19], for the probabilistic analyses and reliability analyses of typical aeroengine components and the blade-tip radial running clearance of aeroengine high-pressure turbine. The efforts only keep a watchful eye on the reliability analysis of single object which needs to build one model and do not consider the influences of all factors. In fact, although the computational precision and efficiency were greatly improved by the above method, blisk reliability is determined by many failure models and multiple disciplines. Although multiple response surface model (MRSRM) was developed for the reliability analysis of aeroengine blade-tip clearance by establishing many response surface models for different disciplines [18], two deficiencies yet exist: (1) only consider the influence of centrifugal load and heat load without the effect due to fluid; (2) only finish the reliability analysis of single object by single response surface model without considering multiple output response (multiobject) by multiple response surface models.

To solve the above issues, accompanied with the heuristic idea of MRSRM [18], the comprehensive reliability analysis of aeroengine turbine blisk with multifailure models (multiobject) was completed by considering multidiscipline of heat, fluid, and structure.

In what follows, Section 2 introduces the basic thought of MRSRM and establishes its mathematical model based on quadratic polynomial. In Section 3, the fluid-thermal-structural analysis of turbine blisk is completed by considering various parameters from different disciplines. Section 4 focuses on the comprehensive reliability evaluation of turbine blisk from the reliability analyses of deformation, stress, and strain of blisk under the effect of fluid-thermal-solid interaction. Section 5 summarizes the conclusions of this work.

## 2. Multiple Response Surface Method (MRSRM)

*2.1. Basic Principle.* For structural reliability analysis with multiple disciplines and multiple objects, MRSRM is

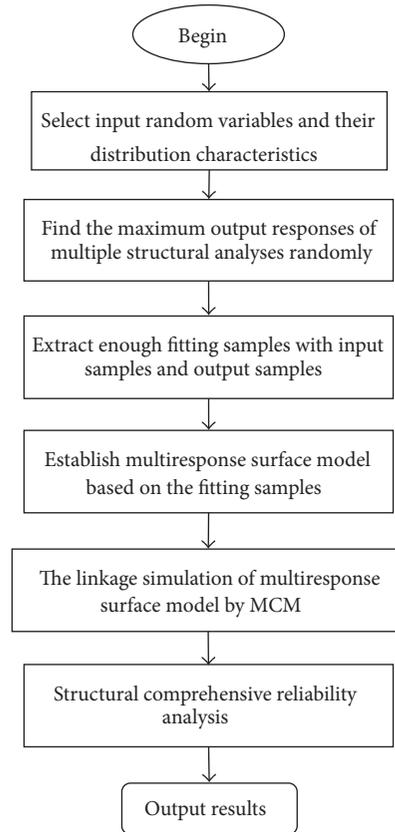


FIGURE 1: Flow chart of structural reliability analysis based on MRSRM.

structured and applied based on response surface method. The basic thought of MRSRM is summarized as follows:

- (1) Select input random variables reasonably to complete the deterministic analyses of multiple objects for complex structure.
- (2) Find the maximum values of multiobject analytical results as output responses to complete multiobject reliability analysis.
- (3) Structure the multiple response surface models by extracting the samples of input variables and calculating the output response of each object based on simulation methods like MCM [13].
- (4) The reliability analysis of complex structure with multidiscipline and multiobject is completed by simulating the multiple response surface models by using MCM.

The flow chart of structural reliability analysis based on MRSRM is shown in Figure 1.

*2.2. Mathematical Model of MRSRM.* Response surface method (RSM) is used to fit a simple response surface by a series of deterministic analyses replacing the real limit-state function [15]. When  $y$  and  $\mathbf{X}$  express the output response and the vector of input random variables, respectively,

the quadratic polynomial response surface function is structured as follows:

$$y(\mathbf{X}) = A + \mathbf{B}\mathbf{X} + \mathbf{X}^T\mathbf{C}\mathbf{X} \quad (1)$$

in which  $A$ ,  $\mathbf{B}$ , and  $\mathbf{C}$  are the coefficient of constant, the vector of linear term coefficients, and the matrix of quadratic term coefficients, respectively.  $\mathbf{B}$ ,  $\mathbf{C}$ , and  $\mathbf{X}$  are denoted by

$$\mathbf{B} = [b_1 \ b_2 \ \cdots \ b_k],$$

$$\mathbf{C} = \begin{bmatrix} c_{11} & & & & \\ & c_{22} & & & \\ & & c_{33} & & \\ & & & \ddots & \\ & & & & c_{kk} \end{bmatrix}, \quad (2)$$

$$\mathbf{X} = [x_1 \ x_2 \ \cdots \ x_k]^T,$$

where  $k$  is the number of input random variables.

In this paper, the mathematical model of MRSM was established on the foundation of quadratic polynomial response surface function. Assuming that the reliability analysis of a complex structure involves  $m$  ( $m \in \mathbb{Z}$ ) output objects, the input random variable vector of the  $i$ th output object is  $\mathbf{X}^{(i)}$ , and the corresponding output variable is denoted by  $y^{(i)}$ , the relationship of  $\mathbf{X}^{(i)}$  and  $y^{(i)}$  is

$$y^{(i)} = f(\mathbf{X}^{(i)}) \quad (i = 1, 2, \dots, m) \quad (3)$$

in which  $f(\cdot)$  is the function of input random variables.

In the light of quadratic polynomial response surface function, (3) is rewritten as

$$y^{(i)}(\mathbf{X}^{(i)}) = A^{(i)} + \mathbf{B}^{(i)}\mathbf{X}^{(i)} + (\mathbf{X}^{(i)})^T \mathbf{C}^{(i)}\mathbf{X}^{(i)}, \quad (4)$$

where  $A^{(i)}$  is the constant coefficient of the  $i$ th output object,  $\mathbf{B}^{(i)}$  the coefficient vector of linear term of the  $i$ th output object, and  $\mathbf{C}^{(i)}$  the coefficient matrix of quadratic term.

Equation (4) is also reshaped as

$$y^{(i)} = a^{(i)} + \sum_{j=1}^k b_j^{(i)} x_j^{(i)} + \sum_{j=1}^k c_j^{(i)} (x_j^{(i)})^2 \quad (5)$$

$$(p = 1, 2, \dots, k)$$

in which  $x_j^{(i)}$  denotes the  $j$ th component of the input variable  $x$  in the  $i$ th output response (object) and  $a^{(i)}$ ,  $b_j^{(i)}$ , and  $c_j^{(i)}$  denote the undetermined coefficients of constant term, linear term, and quadratic term, respectively. The number of undetermined coefficients is  $m(2k + 1)$ . The undetermined coefficients are gained based on least square method when the number of samples is enough, because the vector  $\mathbf{D}^{(i)}$  is formed by

$$\mathbf{D}^{(i)} = [A^{(i)} \ b_1^{(i)} \ b_2^{(i)} \ \cdots \ b_k^{(i)} \ c_{11}^{(i)} \ c_{22}^{(i)} \ \cdots \ c_{kk}^{(i)}]. \quad (6)$$

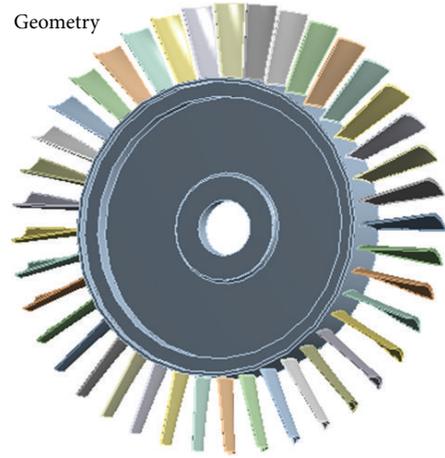


FIGURE 2: Structure model of blisk.

From (4),  $\mathbf{D}^{(i)}$  may be deduced as

$$\mathbf{D}^{(i)} = [(\mathbf{X}^{(i)})^T \mathbf{X}^{(i)}]^{-1} (\mathbf{X}^{(i)})^T y^{(i)}. \quad (7)$$

From (6), we can gain the undetermined coefficients of (5) and further the mathematical model of MRSM is

$$y^{(1)} = a^{(1)} + \sum_{j=1}^k b_j^{(1)} x_j^{(1)} + \sum_{j=1}^k C_j^{(1)} (x_j^{(1)})^2$$

$$y^{(2)} = a^{(2)} + \sum_{j=1}^k b_j^{(2)} x_j^{(2)} + \sum_{p=1}^k C_j^{(2)} (x_j^{(2)})^2$$

$$\vdots$$

$$y^{(m)} = a^{(m)} + \sum_{j=1}^k B_j^{(m)} x_j^{(m)} + \sum_{j=1}^k C_j^{(m)} (x_j^{(m)})^2. \quad (8)$$

### 3. Fluid-Thermal-Solid Coupling Analysis of Turbine Blisk

The working condition of aeroengine is so harsh that the blisk of turbine suffers from the high-temperature gas and large centrifugal force. To simulate the real work condition of turbine blisk, the fluid-thermal-solid coupling analysis was executed based on the discrete coupling analysis method [20, 21]. Therein, the structure of turbine blisk is shown in Figure 2 and TC4 alloy was selected as the material of turbine blisk. In this deterministic analysis, the inlet speed is 160 m/s, the inlet pressure is 600 000 Pa, gas temperature is 1150 K, and the rotation speed of blisk is 1168 rad/s [17–19]. The inlet flow velocity  $v$  of air, inlet pressure  $p$ , material density  $\rho$ , temperature  $t$ , and rotation speed  $w$  were selected as random variables obeying normal distributions with mutual independence.



FIGURE 3: Flow field grid of blisk.

3.1. *Fluid Analysis of Turbine Blisk.* In fluid analysis, the standard  $k$ - $\varepsilon$  turbulence model [22, 23] without gravity effect was selected as follows:

$$\begin{aligned}
 & \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) \\
 &= \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M \\
 & \quad + S_k, \\
 & \frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) \\
 &= \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) \\
 & \quad - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon, \\
 & \mu_t = \rho C_\mu \frac{k^2}{\varepsilon},
 \end{aligned} \tag{9}$$

where  $k$  is the turbulence energy;  $\varepsilon$  the specific dissipation rate;  $\mu_t$  the eddy viscosity;  $G_k$  the turbulence energy generated from the mean velocity gradient;  $G_b$  the turbulence energy generated from flottage; and  $Y_M$  the effect of the fluctuating expansion of compressible speed turbulence on the total dissipation rate. The coefficients  $C_\mu$ ,  $\sigma_k$ ,  $\sigma_\varepsilon$ ,  $C_{1\varepsilon}$ ,  $C_{2\varepsilon}$ , and  $C_{3\varepsilon}$  were the constants of 0.09, 1,  $\sigma_\varepsilon = 1.3$ ,  $C_{1\varepsilon} = 1.44$ , and  $C_{2\varepsilon} = 1.92$ , respectively, and the  $G_b$  and  $Y_M$  were not considered in fluid analysis. The flow field model of turbine blisk is built with the diameter 1.2 m and the length 2 m. The finite element model of flow field was established as shown in Figure 3 with the number of elements being 589 428 and the number of nodes being 842 703. In line with the boundary condition of blisk flow field, the numerical simulation analysis of flow field was completed based on the finite element volume method and  $k$ - $\varepsilon$  standard turbulence model. From the analysis, the static pressure distribution of turbine blisk is revealed in Figure 4.

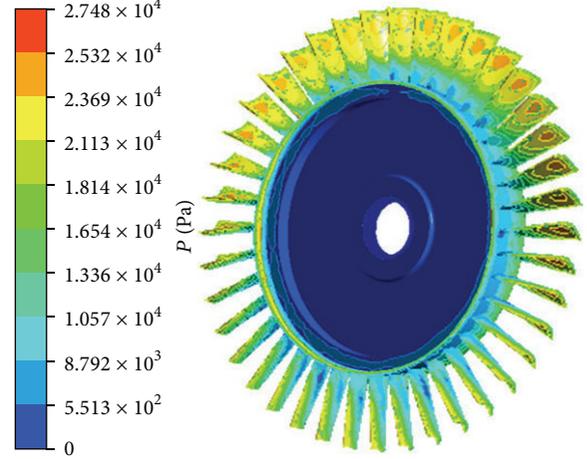


FIGURE 4: Static pressure distribution of blisk surface.

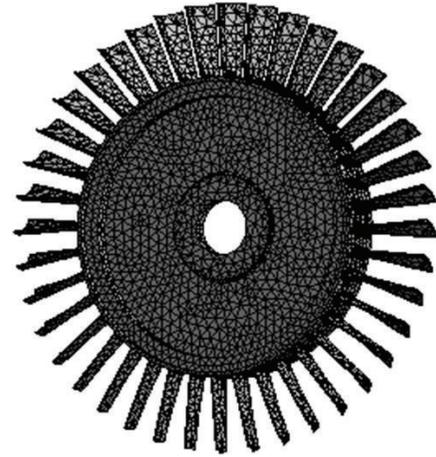


FIGURE 5: Grid of blisk.

3.2. *Thermal Analysis of Turbine Blisk.* The thermal analysis of turbine blisk was finished based on the following energy conservation equation [23]:

$$\begin{aligned}
 & \frac{\partial}{\partial t} (\rho C_p T_0) + \frac{\partial}{\partial x} (\rho v_x C_p T_0) + \frac{\partial}{\partial y} (\rho v_y C_p T_0) \\
 & \quad + \frac{\partial}{\partial z} (\rho v_z C_p T_0) \\
 &= \frac{\partial}{\partial x} \left( K \frac{\partial T_0}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial T_0}{\partial y} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial T_0}{\partial z} \right) \\
 & \quad + W_v + E_k + Q_v + \Phi + \frac{\partial P}{\partial t}
 \end{aligned} \tag{10}$$

in which  $C_p$  is the specific heat,  $T_0$  the total temperature,  $K$  the heat conductivity coefficient,  $W_v$  the viscous dissipation,  $E_k$  the kinetic energy,  $Q_v$  the volume heat source, and  $\Phi$  the item of viscous heat.

The finite element model of turbine blisk was built as shown in Figure 5, which includes the number of elements, 34 875, and the number of nodes, 68 678. The heat loads

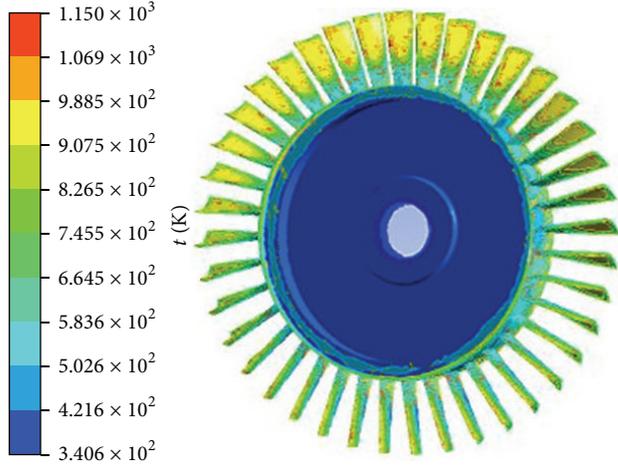


FIGURE 6: Temperature distribution of blisk surface.

from high-temperature gas were exerted on the blisk of turbine, where the temperature distribution of turbine blisk is demonstrated in Figure 6.

**3.3. Structural Analysis of Turbine Blisk.** Tetrahedron was selected as the element of blisk's finite element model. The structural analysis of turbine blisk was performed by transforming the analytical results of fluid analysis and thermal analysis into the surface of turbine blisk based on finite element method. In order to more accurately express the results of structure analysis, the shape function of tetrahedron elements (in (11)) and the displacement equations (in (12)) [24] are applied to solve the node deformation of turbine blisk. The concentrated force and moment of joints are equivalent to the distribution force based on the results of nodes deformation and the relationship between displacement and stress (in (13)). Besides, the strain results of turbine blisk are gained by using (14).

The shape function of tetrahedron elements is

$$N_i = \frac{1}{6V} (a_i + b_i x + c_i y + d_i z) \quad (i = 1, 2, 3, 4); \quad (11)$$

here  $V$  is the volume of tetrahedron and  $a_i$ ,  $b_i$ ,  $c_i$ , and  $d_i$  are the related coefficients of node geometry.

The displacement equations of element node on three directions are

$$\begin{aligned} u(x, y, z) &= a_0 + a_1 x + a_2 y + a_3 z, \\ v(x, y, z) &= b_0 + b_1 x + b_2 y + b_3 z, \\ w(x, y, z) &= c_0 + c_1 x + c_2 y + c_3 z. \end{aligned} \quad (12)$$

The relationship between displacement and stress on the element of turbine blisk is denoted by

$$\begin{aligned} \sigma_x &= \frac{\partial u}{\partial x}; \\ \sigma_y &= \frac{\partial v}{\partial y}; \end{aligned}$$

TABLE 1: Input random variables of MRSM reliability analysis.

Input random variables	Distribution	Mean	Standard deviation
Inlet speed, $v$ /(m/s)	Normal	160	3.2
Inlet pressure, $p$ /Pa	Normal	600 000	18 000
Temperature, $t$ /K	Normal	1 150	15.56
Material density, $\rho$ /(kg/m <sup>3</sup> )	Normal	4 620	92.4
Rotation speed, $w$ /(rad/s)	Normal	1 168	23.36

$$\begin{aligned} \sigma_z &= \frac{\partial w}{\partial z}, \\ \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}; \\ \gamma_{yz} &= \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}; \\ \gamma_{zx} &= \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}. \end{aligned} \quad (13)$$

The relationship between stress and strain on the element of turbine blisk is expressed by

$$\{\boldsymbol{\sigma}\} = [\mathbf{D}] \{\boldsymbol{\varepsilon}^{el}\}, \quad (14)$$

where  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_z$  and  $\gamma_{xy}$ ,  $\gamma_{yz}$ , and  $\gamma_{zx}$  are the normal stresses and shear stresses on  $x$ ,  $y$ , and  $z$  directions, respectively;  $\{\boldsymbol{\sigma}\} = [\sigma_x, \sigma_y, \sigma_z, \gamma_{xy}, \gamma_{yz}, \gamma_{zx}]^T$  are the components of stress;  $[\mathbf{D}]$  is the elastic matrix (or elastic stiffness matrix or the stress and strain matrix);  $\{\boldsymbol{\varepsilon}^{el}\}$  is the vector of elastic strain.

Under the effect of fluid pressure, heat stress, and centrifugal force, the deformation, stress, and strain of turbine blisk were analyzed. From this analysis, the nephograms of deformation, stress, and strain are listed in Figure 7. In Figure 7,  $u$ ,  $\sigma$ , and  $\varepsilon$  indicate the deformation, stress, and strain of turbine blisk (similarly hereinafter). The changing curves of deformation, stress, and strain are shown in Figure 8. Figures 7 and 8 reveal that the maximum deformation locates on the blade-tip of turbine blisk, while the maximum stress and strain locate on root of turbine blisk.

As shown in Figures 7 and 8, the highest temperature locates on the top of blisk; meanwhile, the temperature gradually reduces from the top of blisk to the root of blisk. However, the maximum stress and strain are on the root of blisk, and the stress and strain decrease from the root of blisk to the top of blisk in which the variations of the stress and strain of turbine blisk hold close relationship with the geometrical shape of turbine blisk. The above conclusions are consistent with practical engineering.

#### 4. Reliability Analysis of Turbine Blisk

In the light of the results of fluid-thermal-solid coupling analysis, the points corresponding to the maximum values of blisk's deformation, stress, and strain are regarded as the computational point of reliability analysis of turbine blisk. In accordance with the input random variables in Table 1

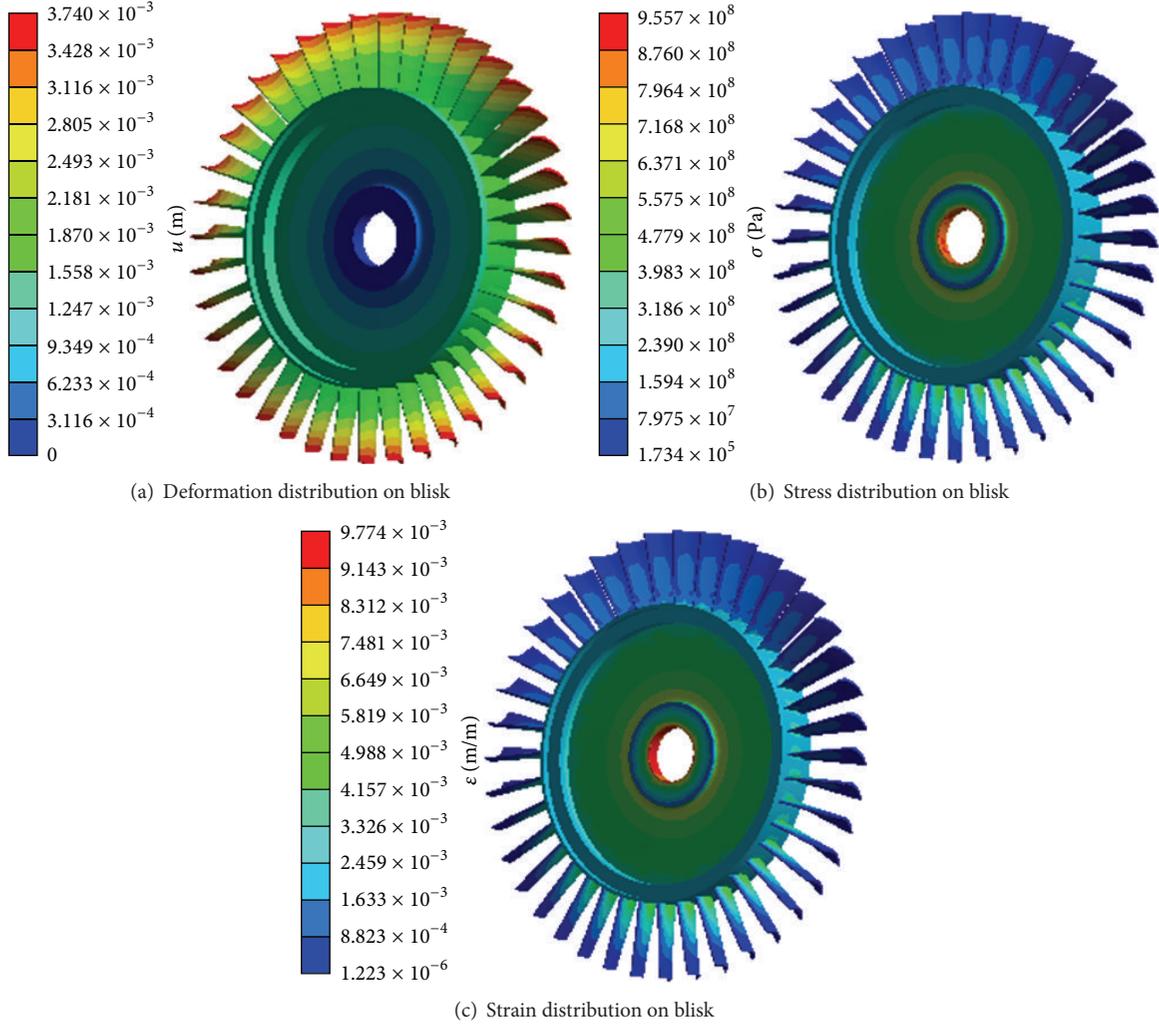


FIGURE 7: Deformation, stress, and strain distribution on blisk.

and the thought of MRSM, the multiresponse surface model turbine blisk was established as follows:

$$\begin{aligned}
 y_1 = & -1.43 \times 10^{-2} + 9.8308 \times 10^{-5}v + 2.0023 \\
 & \times 10^{-9}p + 6.1827 \times 10^{-6}t + 1.1185 \times 10^{-6}\rho \\
 & + 1.6421 \times 10^{-6}w - 3.1758 \times 10^{-7}v^2 \\
 & - 1.6927 \times 10^{-15}p^2 - 2.6173 \times 10^{-9}t^2 \\
 & - 8.1784 \times 10^{-11}\rho^2 + 7.0349 \times 10^{-10}w^2, \\
 y_2 = & 3.5147 \times 10^8 - 8.179 \times 10^6v + 1.6905 \times 10^3p \\
 & + 1.7985 \times 10^6t + 9.3053 \times 10^3\rho - 1.3004 \\
 & \times 10^6w + 2.5955 \times 10^4v^2 - 1.386 \times 10^{-3}p^2 \\
 & - 19.2157t^2 - 0.6358\rho^2 + 6.1378 \times 10^2w^2,
 \end{aligned}$$

TABLE 2: Single-object sampling statistics of blisk.

Object variables	Maximum allowable values	Sampling number
$y_1/\text{m}$	$\leq 3.7 \times 10^{-3}$	9942
$y_2/\text{Pa}$	$\leq 1.07 \times 10^9$	9935
$y_3/\text{m/m}$	$\leq 1.12 \times 10^{-2}$	9954

$$\begin{aligned}
 y_3 = & 0.0045 - 8.7321 \times 10^{-5}v + 1.822 \times 10^{-8}p \\
 & + 1.6927 \times 10^{-5}t + 1.0621 \times 10^{-7}\rho + 1.3835 \\
 & \times 10^{-5}w + 2.7717 \times 10^{-7}v^2 - 1.494 \\
 & \times 10^{-14}p^2 + 9.7086 \times 10^{-10}t^2 - 7.515 \\
 & \times 10^{-12}\rho^2 + 6.5152 \times 10^{-9}w^2.
 \end{aligned}$$

(15)

When the maximum allowable deformation, stress, and strain of turbine blisk are  $u_a = 3.7 \times 10^{-3}$  m,  $\sigma_a = 1.07 \times 10^9$  Pa, and  $\epsilon_a = 1.12 \times 10^{-2}$  m/m, the built multiresponse surface model was simulated by 10 000 times using MCM. The analytical results are listed in Table 2. The histograms and

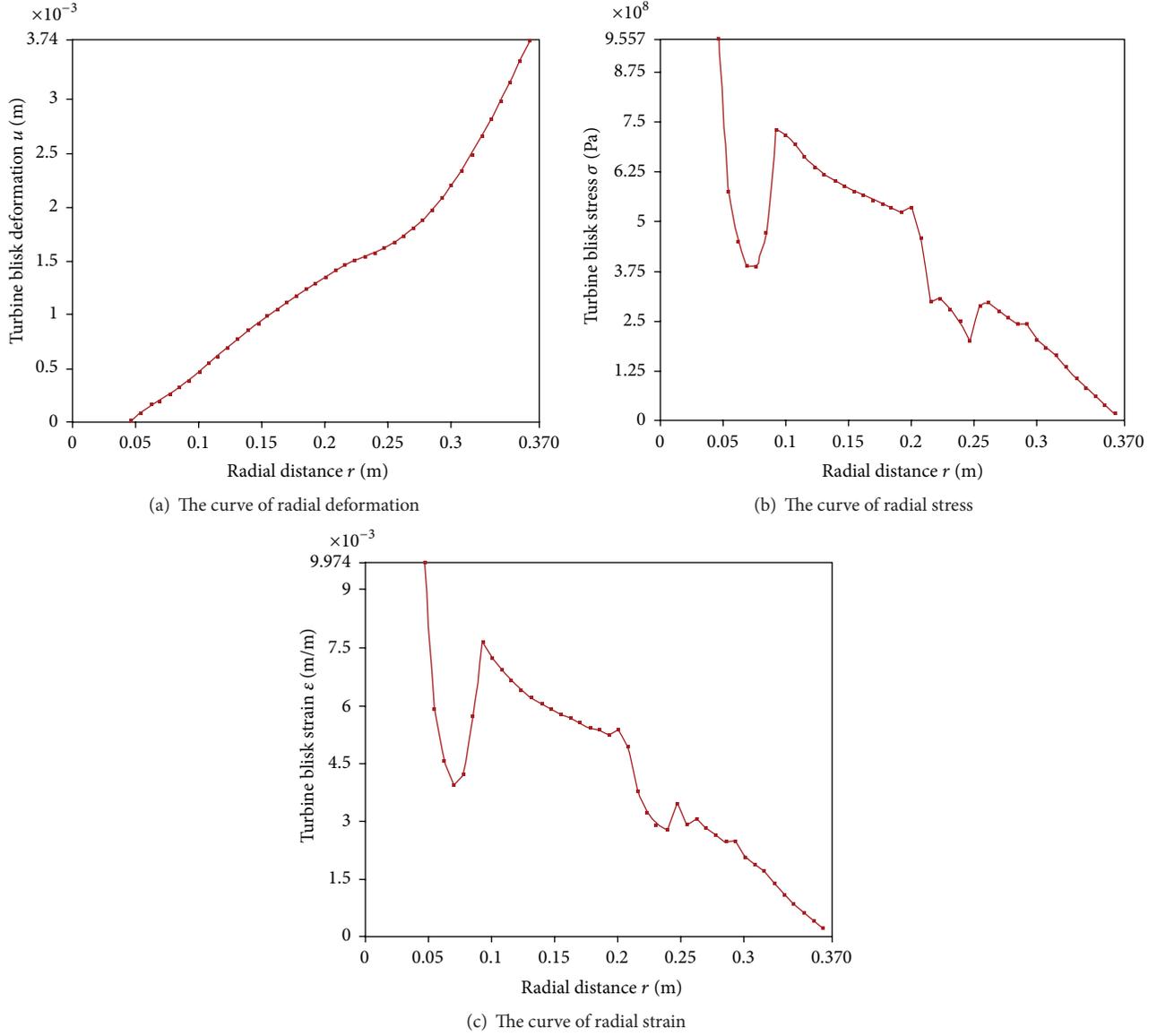


FIGURE 8: The curves of turbine blisk deformation, stress, and strain along radial direction.

TABLE 3: Multiobject sampling statistics of blisk.

$y_1/m, y_2/Pa, y_3/m/m$	Number of samples
$y_1 \leq 3.7 \times 10^{-3} \cap y_2 \leq 1.07 \times 10^9 \cap y_3 \leq 1.12 \times 10^{-2}$	9919
$y_1 > 3.7 \times 10^{-3} \mid y_2 > 1.07 \times 10^9 \mid y_3 > 1.12 \times 10^{-2}$	81

simulation history curves of maximum deformation  $u_{max}$ , maximum stress  $\sigma_{max}$ , and maximum strain  $\epsilon_{max}$  are shown in Figures 9 and 10, respectively. Through the comprehensive performance evaluation, the results were summarized in Table 3.

As shown in Figure 10, the output responses (deformation  $y_1$ , stress  $y_2$ , and strain  $y_3$ ) for turbine blisk obey normal distributions with the corresponding mean values of

$3.452 \times 10^{-3}$  m,  $9.974 \times 10^8$  Pa, and  $1.040 \times 10^{-2}$  m/m and the corresponding standard deviation of  $8.476 \times 10^{-9}$  m,  $7.672 \times 10^2$  Pa, and  $8.385 \times 10^{-8}$  m/m, respectively. From Table 2, it is illustrated that the reliability degrees for the deformation, stress, and strain of turbine blisk are 0.9942, 0.9935, and 0.9954, respectively. The above conclusions pledge the reliability and security of turbine blisk design.

As revealed in Table 3, the comprehensive reliability degree of turbine blisk is obtained as 0.9919 through joint reliability analysis, which basically meets the design requirement of aeroengine turbine blisk.

## 5. Conclusions

The goal of this effort is to apply the high accuracy and high efficiency MRSM to the comprehensive reliability evaluation

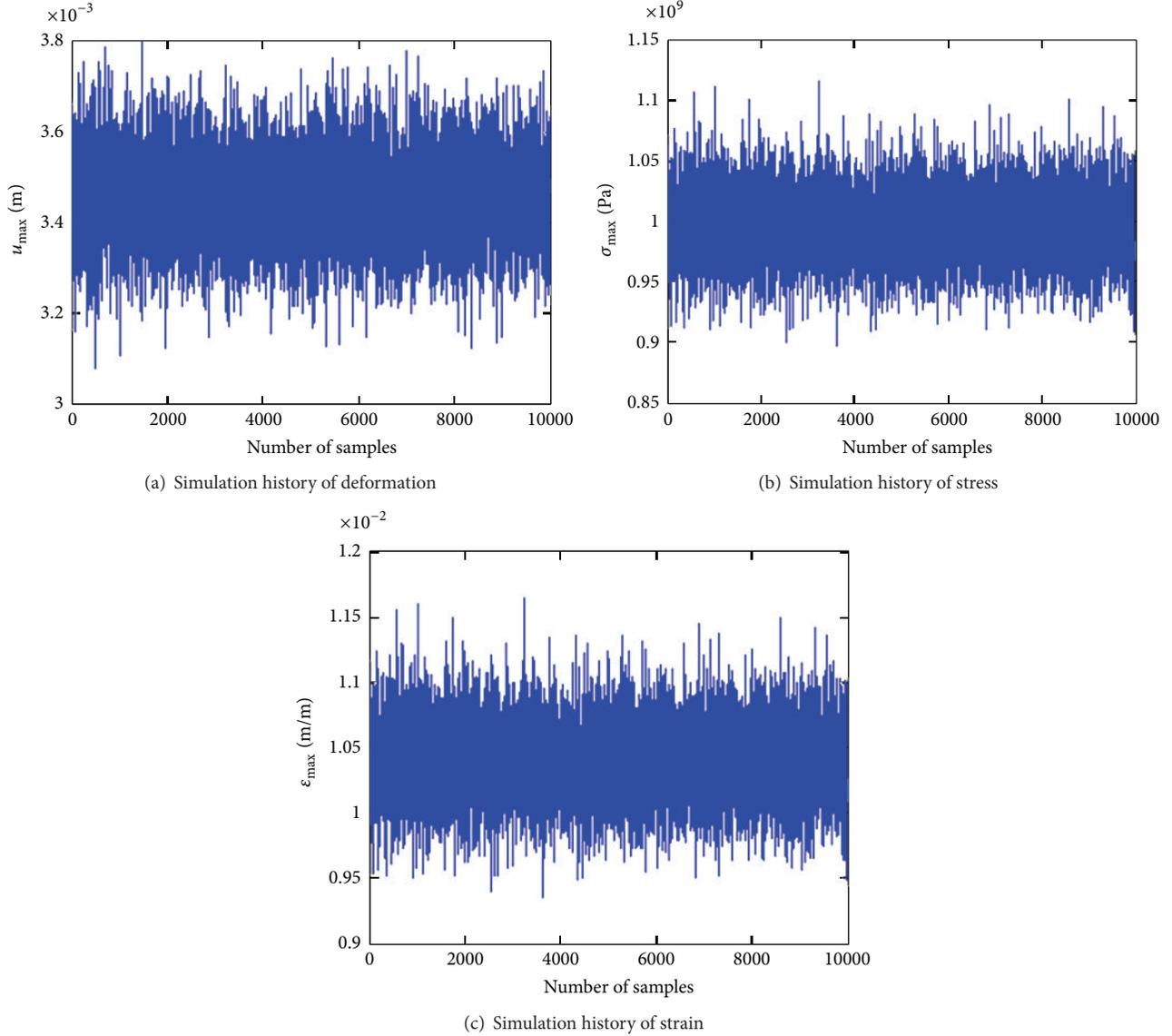


FIGURE 9: Simulation samples of turbine blisk.

of aeroengine turbine blisk through the multiobject reliability analyses of the deformation, stress, and stress of turbine blisk based on fluid-thermal-structural coupling analysis. The present study establishes the mathematical model of MRSM with the quadratic response surface function. Some conclusions are drawn as follows:

- (1) The maximum deformation, maximum stress, and maximum strain of blisk are  $3.74 \times 10^{-3}$  m,  $9.557 \times 10^8$  Pa, and  $9.974 \times 10^{-3}$  m/m, respectively. Besides, the distributions of blisk's deformation, stress, and strain are gained.
- (2) The reliability degrees of blisk's deformation, stress, and strain are 0.9942, 0.9935, and 0.9954, respectively, when the allowable deformation, stress, and strain

are  $u_a = 3.7 \times 10^{-3}$  m,  $\sigma_a = 1.07 \times 10^9$  Pa, and  $\epsilon_a = 1.12 \times 10^{-2}$  m/m, respectively. Based on the conclusions, the comprehensive reliability degree of blisk is 0.9919.

- (3) The fluid-thermal-structural coupling analysis method is adopted for the reliability analysis of aeroengine turbine blisk, which is promising to improve computational accuracy.
- (4) The efforts of this paper demonstrate that MRSM can be adopted to solve the comprehensive reliability analysis with multiple disciplines and multiple objects besides single-object reliability analysis, which provide a promising approach for complex structural reliability analysis.

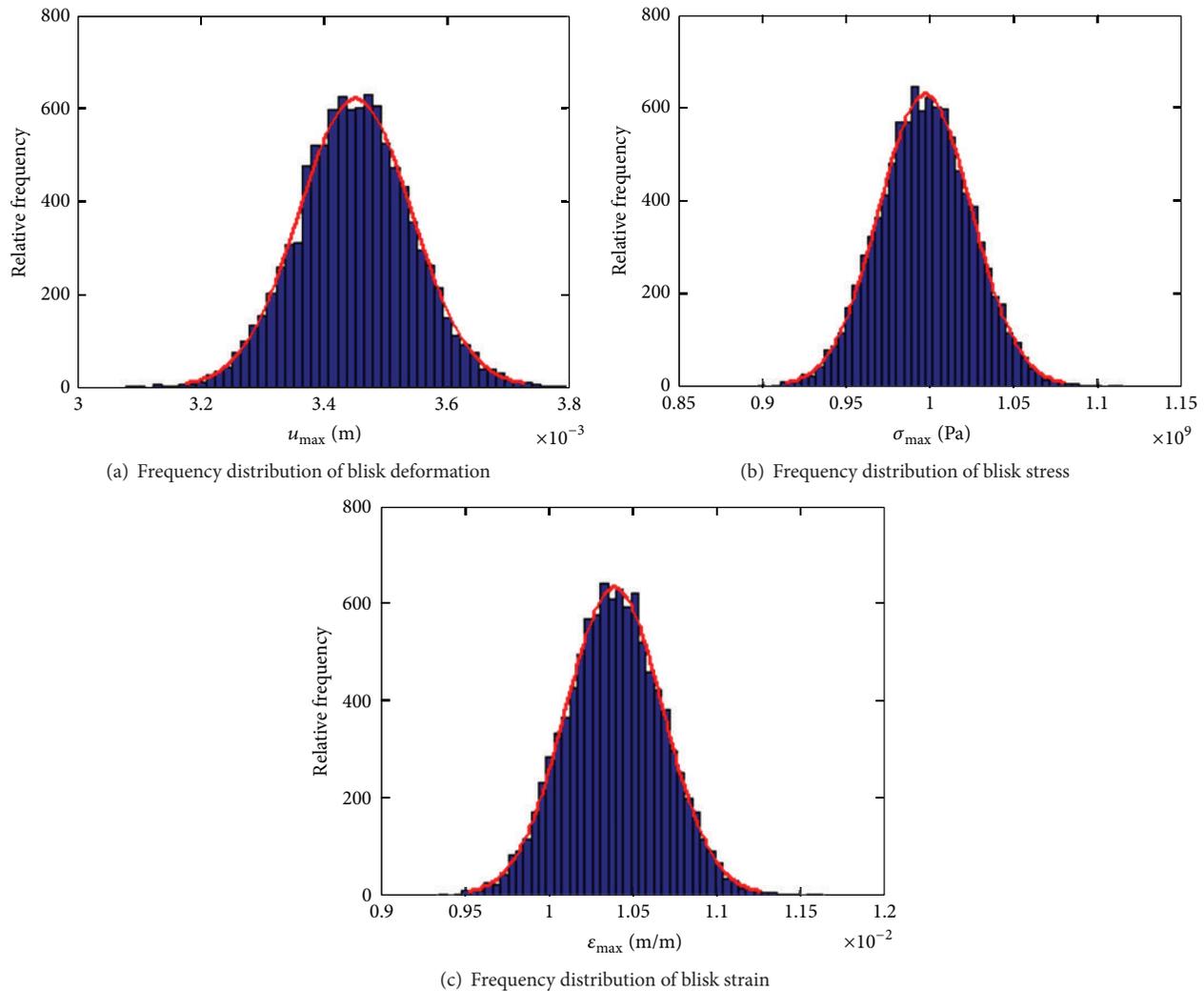


FIGURE 10: Frequency distribution of turbine blisk.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

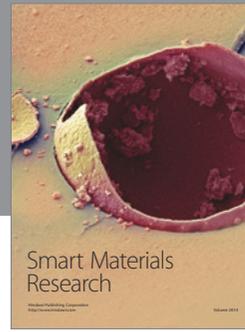
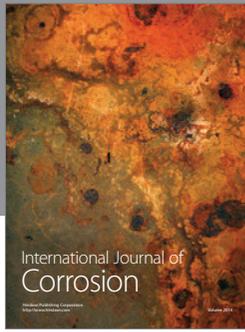
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