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Design and Optimization Method of a Two-Disk Rotor System

Abstract: An integrated analytical method based on multidisciplinary optimization software Isight and general finite element software ANSYS was proposed in this paper. Firstly, a two-disk rotor system was established and the mode, humorous response and transient response at acceleration condition were analyzed with ANSYS. The dynamic characteristics of the two-disk rotor system were achieved. On this basis, the two-disk rotor model was integrated to the multidisciplinary design optimization software Isight. According to the design of experiment (DOE) and the dynamic characteristics, the optimization variables, optimization objectives and constraints were confirmed. After that, the multi-objective design optimization of the transient process was carried out with three different global optimization algorithms including Evolutionary Optimization Algorithm, Multi-Island Genetic Algorithm and Pointer Automatic Optimizer. The optimum position of the two-disk rotor system was obtained at the specified constraints. Meanwhile, the accuracy and calculation numbers of different optimization algorithms were compared. The optimization results indicated that the rotor vibration reached the minimum value and the design efficiency and quality were improved by the multidisciplinary design optimization in the case of meeting the design requirements, which provided the reference to improve the design efficiency and reliability of the aero-engine rotor.

Keywords: two-disk rotor system, ANSYS, Isight, optimization and design

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Introduction

With the continuous improvement of the aero-engine performance and the increasingly demanding of operation stability, rotor with more flexibility is expected to design. However, the vibration controlling difficulty of rotor system increases at the increased flexibility and unsuitable controlling will induce serious accidents [1]. There is an urgent need for an optimal design method to optimize the dynamics characteristics of aero-engine at the design process. For this reason, a lot of researches in this area were carried out by many researchers [2–14]. Choi B G and Yang B S utilized the genetic algorithm to optimize the dynamics design of rotor [3]. Huang Jin and Lu Yongzhong optimized the design of a rotor with squeeze film dampers with the gradient shadow method [5]. Cole M O et al. optimized vibration and stability in rotor system based on LMI (linear matrix inequalities) [9]. Wang Donghua et al. optimized the design of the critical speed of the rotor system with hybrid genetic algorithm [12]. Yu Jin et al. optimized the design of rotor system with conjugate gradient method by ANSYS [14].

These above-mentioned scholars seldom considered the transient process in the design optimization of the rotor system. However, short start, little vibration and light weight were required in the modern aero-engines. Meanwhile, rotor system was required to work and cross the critical speed because of the application of the flexible rotor, and approaches were taken to accelerate to cross the critical speed in order to avoid rub phenomenon caused by excessive vibration of rotor. Hence, it is necessary to analyze and optimize the dynamic characteristics of the transient process [15]. Additionally, the optimization parameters (optimization variables, optimization objectives and constraints) in the above literatures were mostly given in advance and the analysis of the relationship between the optimization variables and objectives was lacked, while the choice of optimal design parameters was a difficulty.

This paper addressed the two-disk rotor system under the aero-engine support structure of typical 1-0-1. The mechanics model of the two-disk rotor system was established and the mode, humorous response and transient response at acceleration condition were analyzed with

ANSYS. The two-disk rotor model was then integrated to the multidisciplinary design optimization software Isight. According to the design of experiment (DOE) and the dynamical characteristics, the relationship between the positions of the two disks and the maximum amplitudes crossing first-order critical speed was analyzed, and the optimization variables and objectives were confirmed. Finally, the multi-objective design optimization of the transient process was carried out with three different global optimization algorithms. The optimum position of the two-disk rotor system was obtained at the specified constraints and the accuracy and calculation numbers of different optimization algorithms were compared. The optimization method could provide the reference and guide to the design of real aero-engine rotor.

Modeling and simulation

Dynamic model need to be established firstly to analyze the dynamics when solving an optimal design problem. The schematic of a two-disk rotor system with simply supported structure is shown in Figure 1. This two-disk rotor system was composed of one shaft, two disks and two bearings. In this paper, shaft was simulated with Beam188 element, rigid disk was simulated with Mass21 element and bearings were simulated with Combin14. Detail parameters of the rotor system are shown in Table 1. m_1 and m_2 represented the mass of disk 1 and disk 2, respectively, L_1 represented the distance between bearing 1 and left end, L_2 represented the distance between bearing 1 and disk 1, L_3 represented the distance between disk 1 and disk 2, L_4 represented the distance between disk 2 and bearing 2 and L_5 represented the distance between bearing 2 and right end. R_z represented the axis radius and E represented the elasticity modulus.

When the transient response of the rotor system was simulated, the calculation time of each load step was relatively long and it would take very long time to obtain the load response of multi-cycles. In this case, it had its unique advantages to use Beam118 and Mass21 to model rotor system, which could shorten the time of transient analysis in the case of ensuring the correct calculation and accelerate the optimization process. The dynamic model of the two-disk rotor system based on Beam 118 and Mass21 is shown in Figure 2.

Table 1: Detailed parameters of the two-disk rotor system.

m_1 (kg)	m_2 (kg)	L_1 (mm)	L_2 (mm)	L_3 (mm)	L_4 (mm)	L_5 (mm)	R_z (mm)	E (GPa)
0.796	0.601	50	75.5	325.5	53	31	5	207

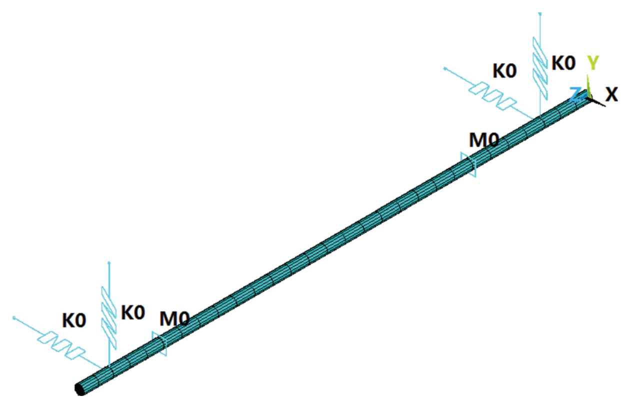

Figure 2: Dynamic model of the two-disk rotor system.

Because the vibration characteristics of the structure determined the response characteristics of the structure to the loads with various power, mode characteristics were analyzed firstly before other dynamic analysis. Figure 3 illustrates the Campbell diagram of the two-disk rotor system. Campbell diagram shows the relationship between the natural frequency of rotor with the rotation frequency. Natural frequency of the rotor is the main factor that influences the rotor dynamics. When the excitation frequency of the rotor is equal to the natural

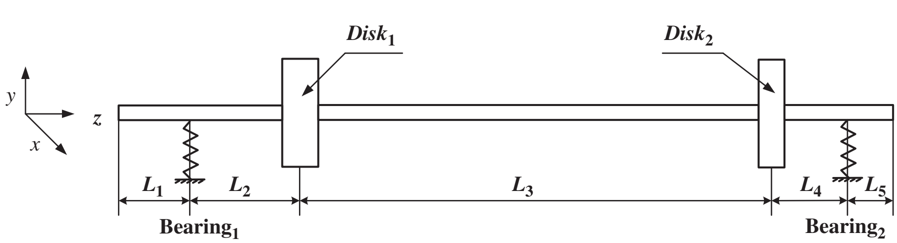

Figure 1: Schematic of the two-disk rotor system.

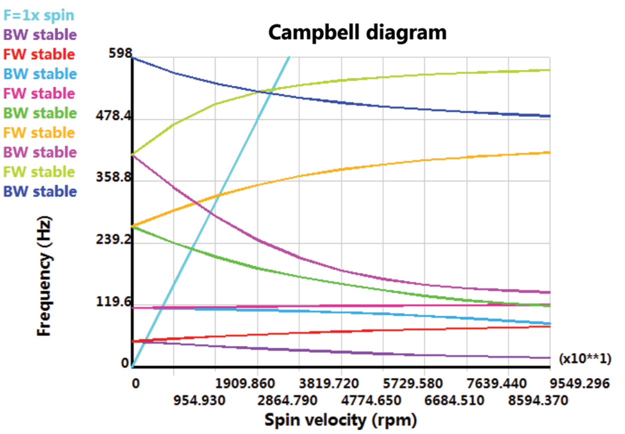

Figure 3: Campbell diagram of the two-disk rotor system.

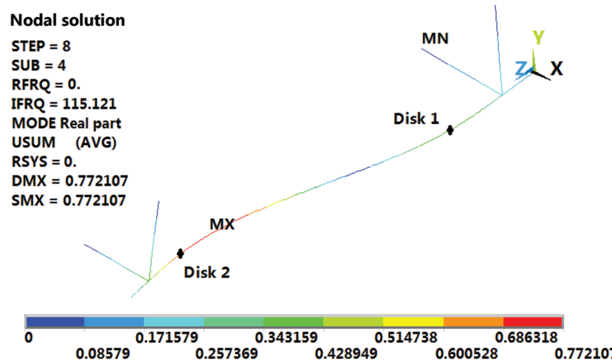

Figure 5: The second-order mode shape diagram.

frequency of the rotor, the rotor resonance occurs, resulting in very large amplitude. Hence, the natural frequency of the rotor determines the critical speed distribution of each order. According to Figure 3, the first and second critical speeds were $n_1 = 3{,}092.63231$ r/min and $n_2 = 6{,}906.33599$ r/min.

Figures 4 and 5 show the first- and second-order mode shape diagrams of the two-disk rotor system, respectively. According to Figure 4, when the rotation speed reached the first-order critical speed (self-resonant frequency of 51.5 Hz), the rotor was elastically deformed similar to a bow, which meant that the maximum deformation occurred at the middle part of the shaft and deformation at disk 1 was larger than that at disk 2. When the rotation speed reached the second-order critical speed (self-resonant frequency of 115.1 Hz), the rotor was elastically deformed similar to “S” and the maximum deformation occurred near disk 2. Obviously, the deformations of rotor at different critical speeds were different. Compared to other rotation speeds, the deformations at critical speeds were severe, resulting in the largest hazard. Hence, it was very necessary to control the maximum amplitude of rotor system crossing the critical condition when optimizing the rotor system.

Harmonic analysis is to analyze the dynamic response of structure under harmonic load of different frequencies, which is associated with the load that the structure suffered [16]. The unbalance added to disk 1 was 3.5 g · mm and the angle was 94° when calculating the harmonic response, while the unbalance added to disk 2 was 5.25 g · mm and the angle was 0°. Figure 6 shows the harmonic response diagram of the two-disk rotor system. The resonance frequency of the first order of the crossing second-order two-disk rotor system was 51.5 Hz (or 51.5 r/s) and the corresponding rotation speed of the first-order was 51.5×60 r/min $= 3{,}090$ r/min. The resonance frequency of the second order of the crossing second-order two-disk rotor system was 115.1 Hz and the corresponding rotation speed of the second-order was 115.1×60 r/min $= 6{,}906$ r/min. According to the above analysis, the resonance frequencies of harmonic response

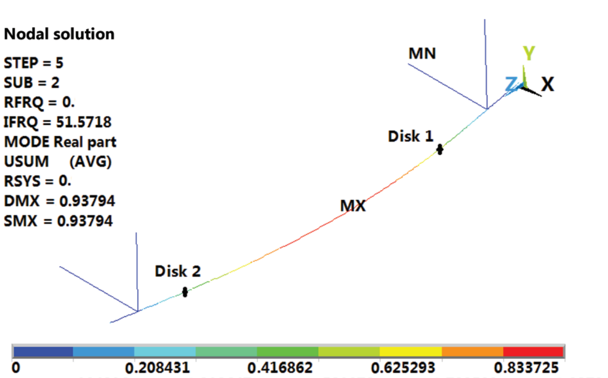

Figure 4: The first-order mode shape diagram.

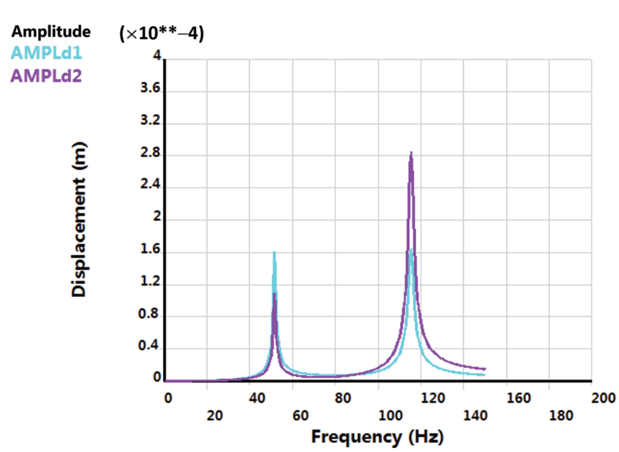

Figure 6: Harmonic response diagram of the two disks.

analysis were consistent with the natural frequencies of the modal analysis, which were also close to the first and second critical speeds. The differences between the resonance frequencies and the critical speeds were caused by the simplification of the two disks when establishing dynamic model, which was different to the real structure. The maximum deviation was less than 0.4%, which was within the error range.

Transient dynamic analysis (also known as the time-history analysis) is used to determine the dynamic response of the structure withstanded any load changing with time, which can truly reflect the scanning process along a path of the Campbell diagram. The characteristics of some special points on the Campbell diagram could be observed in the time-history curves. Transient response can also reflect the nonlinear characteristics of the bearings, the stability of the rotor movement and other issues [17]. The transient response was analyzed at the accelerated speed of 1,000 r/(min · s), whose results were shown in Figures 7–9.

According to Figures 7–9, deflections of the two disks achieved the peak values at the time of 3.3 and 7.0 s (the corresponding rotation speed was 3,300 and 7,000 r/min), which indicated that the rotor system reached the first and second critical speeds. Similar to mode shape diagrams, the deviations of mode shape of disk 1 at the first- and second-order modes were both low. Meanwhile, the deviation of mode shape of disk 2 at the first-order mode was lower and much higher at the second-order mode. The two calculation results agreed with each other, which verified the accuracy of the finite element model calculation results.

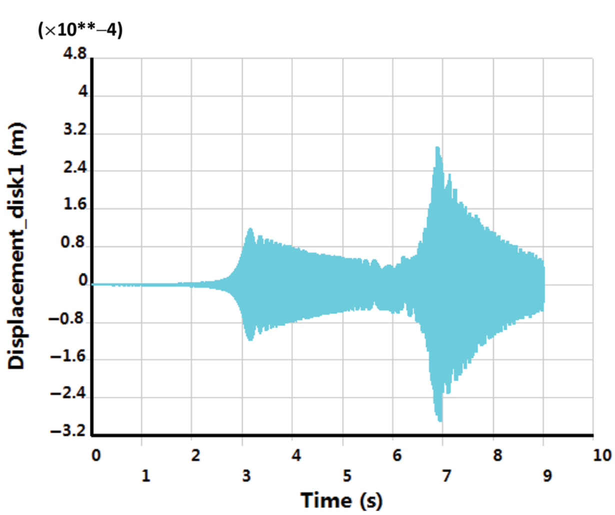

Figure 7: Amplitude of disk 1 at direction of y vs speed.

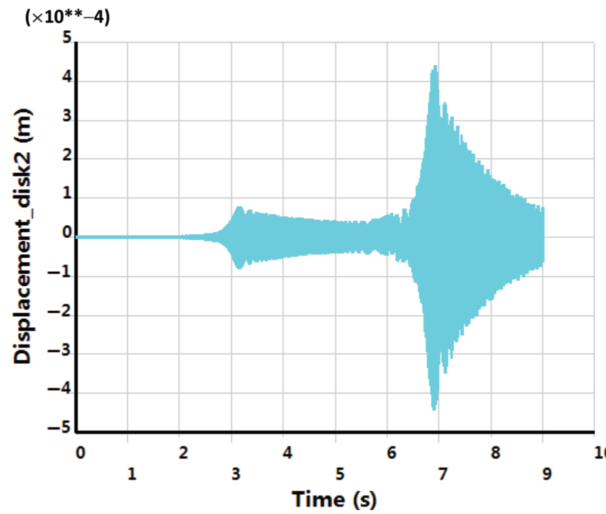

Figure 8: Amplitude of disk 2 at direction of y vs speed.

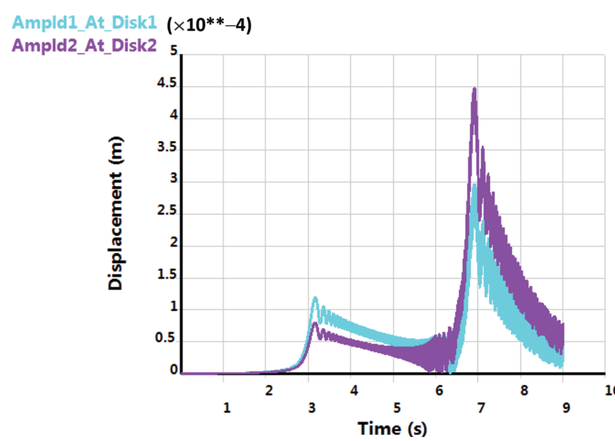

Figure 9: Transient response curves at the two disks.

Design optimization of transient dynamics

Determination of optimization objectives, variables and constraints

Based on the model establishment and analysis of dynamics characteristics of a rotor, the three elements of design optimization were discussed: optimization variables, optimization objectives and constraints.

Optimization variables were the adjustable parameters of rotor, such as the support stiffness and damping, support position, shaft geometry, disk position and geometry and so on. The positions of the two disks were determined as the optimization variables in this paper. That was Var: P_{1_weizhi} and P_{2_weizhi}.

For real two-disk rotor, the overall optimization objective is to reduce the overall vibration of the system, unbalance response and support forces in order to avoid the hazard resulted from the big vibration. Hence, the maximum amplitudes (a_1 and a_2) of the two disks crossing the first-order critical speed were the optimization objectives, which should be the smallest. That was Min: a_1 and a_2.

The rotor becomes flexible facing high thrust to weight ratio requirements of current aero-engine, and the aero-engine is often operated over the critical speed. Hence, the critical speed could be used as the constraint and there was a certain margin between the operating speed and the critical speed. Based on this idea, the variation of the first-order critical speed was controlled at the range of 10% in the optimization of this rotor system. That was 2,780 r/min $\leq n_1 \leq$ 3,400 r/min.

DOE is a branch of mathematical statistics, which is one of the most important statistical methods in current product development, process optimization and so on. Usage of the DOE method can identify the key factors of experiment. The two-disk rotor system was optimized with the optimal Latin hypercube design (Opt LHD) algorithm of DOE. This could make all of the test points distribute in the design space as uniformly as possible with very good space filling and balance. Sampling points were 100 points and the main effect plots of the two disks are shown in Figure 10.

The average difference between the levels of a factor is called the main effect of this factor. The main effect plots show the effect of individual factor on the result, from which the value can be seen when the factor realizes the greatest effect on the result [18]. According to Figure 10, the positions of the two disks (p_{1_weizhi}, p_{2_weizhi}) showed the great effect on the maximum amplitudes of the two disks (a_1, a_2) and there were nonlinear relationships between the positions and the maximum amplitudes. Therefore, it was suitable to select the positions of the two disks (p_{1_weizhi}, p_{2_weizhi}) as the optimization variables.

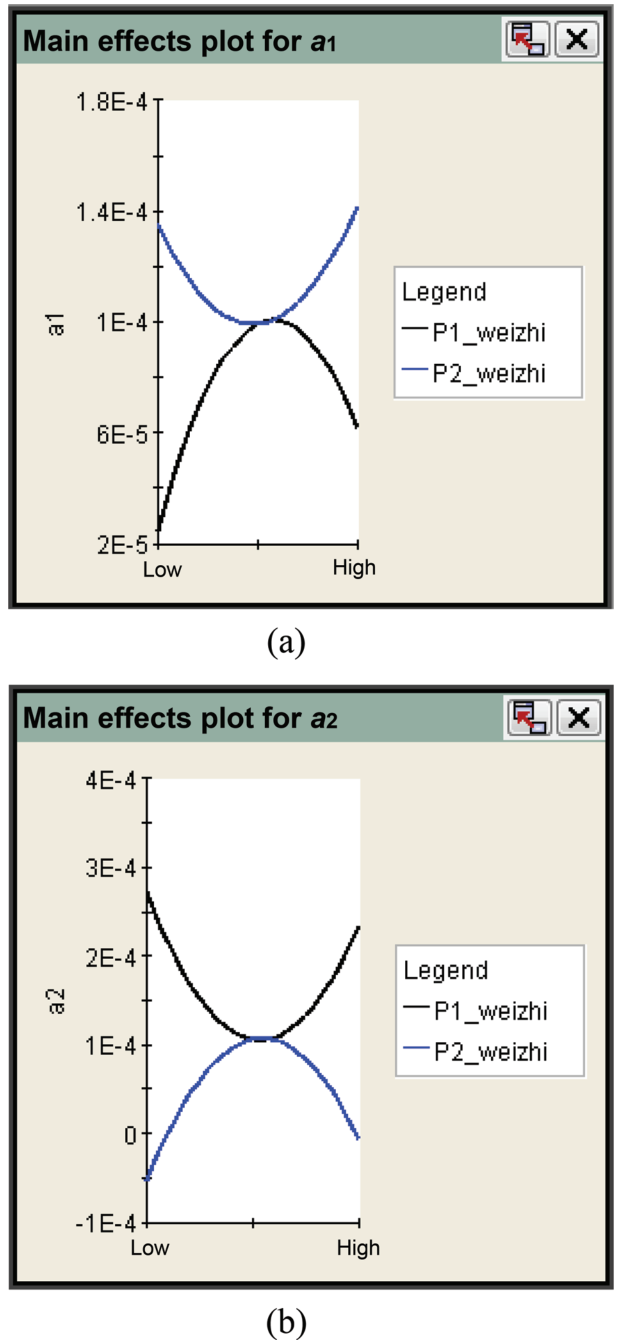

Figure 10: Main effect plots: (a) Main effect plot of a_1 and (b) main effect plot of a_2.

Optimization method

The user interface that ANSYS was integrated into Isight through Simcode components with command stream is shown in Figure 11. Script commands were used in batch mode to drive ANSYS software to calculate and obtain the values of optimization objectives. Variables were modified according to the selected optimization algorithm. The modified variables were then returned to the input file and delivered to ANSYS to calculate new optimization objectives. Thus, optimization objectives tended to be optimal value in the process of iterations.

Optimization algorithms can be divided into two categories: the first category is based on the method of gradient, the other is non-gradient-based method. Optimization algorithms based on the method of gradient

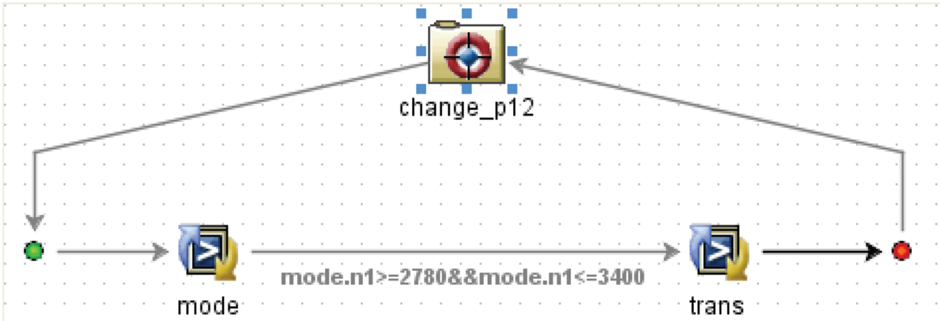

Figure 11: Picture of integrated interface.

were widely used in the design optimization of rotor dynamics at the early stage due to the fast calculating speed and small memory. However, gradient-based algorithms need to solve the derivative of dynamic response to the design parameters, and not all of the derivative of dynamic response to the design parameters can be easily calculated. Moreover, this method is not good for multi-objective optimization. All of the above shortcomings limit the use of the gradient-based optimization algorithms. Non-gradient-based optimization algorithms can be divided into local search algorithms and global search algorithms. Engineering optimization problems are often complex without derivative and gradient information. With the improvement of computer performance, global optimization methods have gradually become the main tools for the design optimization of rotor dynamics, which provide new way of thinking and means to solve such complex problems. Genetic algorithms are the most frequently used algorithms among the global optimization algorithms [18]. The design optimization was carried out with Evolutionary Optimization Algorithm, Multi-Island Genetic Algorithm (MIGA) and Pointer Automatic Optimizer in this paper. Figure 12 shows the flowchart of the design optimization.

Evolutionary Algorithm is a kind of randomness global search method based on biological evolutionary mechanisms and becomes a popular optimizing method due to the advantages in synchronization and global search capability among the existing optimization algorithms.

MIGA is a modified algorithm of parallel distributed genetic algorithm, which has better global solving capacity and computational efficiency than traditional genetic algorithm. For MIGA, each population is divided into evolutionary groups (the islands) and the populations are separated to generate diverse solutions, which improve the global search ability and convergence ability [19, 20].

Pointer Optimizer is an intelligent automation specialists provided by Isight, with which the information of design space is captured and four optimization algorithms are composed to generate the best optimization strategy automatically. The four optimization algorithms are linear simplex algorithm, sequential quadratic programming (SQP), downhill simplex and genetic algorithm [18].

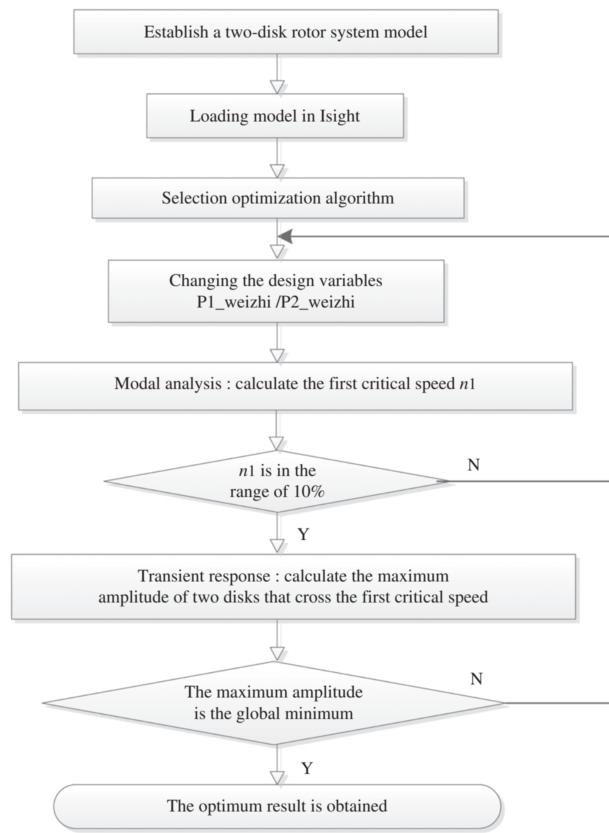

Figure 12: Flowchart of optimization.

Optimization result

The optimization results with the three optimization methods are shown in Table 2. The maximum amplitude

Table 2: Optimization results of the positions of the two disks.

	P_{1_weizhi} (m)	P_{2_weizhi} (m)	a_1 (10^{-4} m)	a_2 (10^{-5} m)	n_1 (r/min)	Calculation numbers	Optimization results
Prototype	0.1255	0.451	1.19219	7.951	3,092		
EVOL	0.1255	0.494	1.157	1.903	3,150	101	a_1 −2.95% a_2 −76.07%
MIGA	0.127	0.493	1.1835	1.427	3,296	1001	a_1 −0.73% a_2−82.05%
Pointer	0.132	0.478	1.156	3.812	3,168	37	a_1−3.0% a_2 −52.06%

of disk 1 crossing the first-order critical speed and the maximum amplitudes optimized with different algorithms are shown in Figure 13. The maximum amplitude of disk 2 crossing the first-order critical speed and the maximum amplitudes optimized with different algorithms are shown in Figure 14. According to Table 2, Figures 13 and 14, the maximum amplitudes of the two disks crossing the first-order critical speed decreased after optimization in the case of 2,780 r/min$\leq n_1 \leq$3,400 r/min, which realized the purpose of optimization.

With EVOL, the maximum amplitude of disk 1 fell 2.95% and the maximum amplitude of disk 2 decreased by 76.07% after 101 calculation times. With MIGA, the maximum amplitude of disk 1 fell 0.73% and the maximum amplitude of disk 2 decreased by 82.05% after 1,001 calculation times. With Pointer, the maximum amplitude of disk 1 fell 3.0% and the maximum amplitude of disk 2 decreased by 52.06% after 37 calculation times. Compared with other algorithms, MIGA obtained the best optimization performance of disk 2 but the worst optimization performance of disk 1 with the maximum calculation amount. Pointer algorithm got the best optimization performance of disk 1 with the minimum calculation amount but the worst optimization performance of disk 2. EVOL algorithm achieved the relative optimal solution after 101 calculations and showed the significant optimization performance of the two disks. That was the relative optimal global solution that could be obtained in a short period of time with EVOL algorithm. In a word, the global optimization algorithms only evaluated design point without the calculation of the gradient of any function and could obtain the global optimal solution, which avoided the focused search in local area.

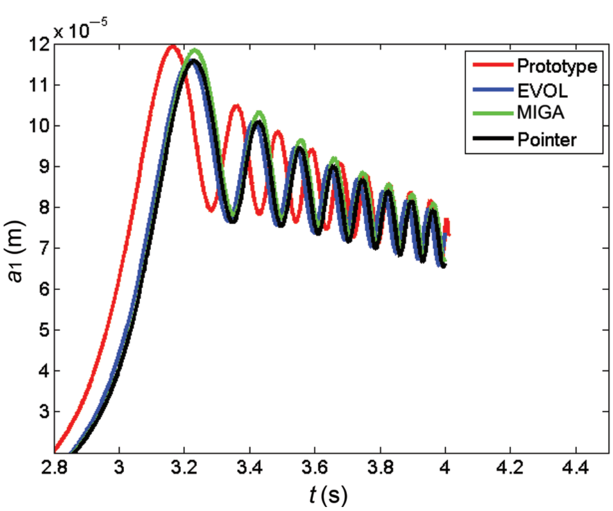

Figure 13: Optimization results of disk 1.

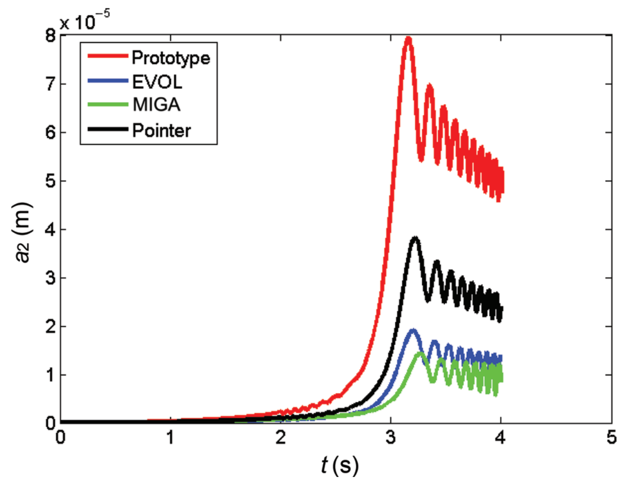

Figure 14: Optimization results of disk 2.

Conclusions

The mechanics model of the two-disk rotor system under the aero-engine support structure of typical 1-0-1 was established and the mode, humorous response and transient response at acceleration condition were analyzed with ANSYS. The positions of the two disks were designed and optimized by the optimization platform

Isight integrated with finite element software ANSYS. The maximum amplitudes of the two disks crossing the first-order critical speed decreased with three different optimization algorithms under the condition of a certain constraint of the first-order critical speed. With MIGA, the maximum amplitude of disk 1 fell 0.73% and the maximum amplitude of disk 2 decreased by 82.05%, which obtained the best optimization performance of disk 2 but the worst optimization performance of disk 1 with the maximum calculation amount. With Pointer, the maximum amplitude of disk 1 fell 3.0% and the maximum amplitude of disk 2 decreased by 52.06%, which got the best optimization performance of disk 1 with the minimum calculation amount but the worst optimization performance of disk 2. The relative optimal global solution could be obtained in a short period of time with EVOL algorithm. The optimization method established in this paper could provide the reference and guide to improve the design efficiency and reliability of aero-engine rotor.

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