Optimization of Rotor Assembly Process of Rotor Initial Unbalance of an Aeroengine Gas Generator

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Abstract: The rotor initial unbalance of an aeroengine gas generator of turboshaft engine seriously affects rotor assembly process. To reasonably optimize rotor assembly process, the effect analyses of rotor initial unbalance of single disc and combined discs on rotor dynamic characteristics are firstly implemented in respect of the dispersity of rotor initial unbalance. It is found that the most important factors contributing to rotor vibration are the unbalances of the first stage compressor disc and the second stage turbine disc. However, reducing the mass of two discs conflicts with the control of the whole gas generator rotor balance resulting from the unbalance increase of single components. Thus, we further analyze the key control factors of affecting rotor initial unbalance, and give the strict control measures of centrifugal impeller runout in the assembly process by adjusting the angle of central tie rod axis. The purpose of this measures to make the assembly process simpler and more effective for timely controlling rotor initial unbalance. The efforts of this study validate that the proposed method is workable for the rotor tightened by a central tie rod and possesses the significant meaning of practical application in engineering.

Key words: turboshaft engine; initial unbalance; assembly process; gas generator rotor; control technique

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0 Introduction

Typical gas generator rotor system of turboshaft engine comprises three stages of axial compressors, one stage of centrifugal impeller and two stages of axial gas turbine rotor. The gas generator rotor is supported by 1-0-1 structure, assembled by curvic couplings centering and central tie rod with segmented retightening measure. For the central tie rod, the ratio of length to radius is to 15. In this case, the bearing before compressor is ball bearing and the bearing after gas turbine is rolling bearing. The structural diagram of gas generator rotor is shown in Fig. 1. The datum plane of rotor balance locates on the convex platform before blade-root of the first stage bladed disc and the fixed bolt of second stage gas turbine baffle. The allowable unbalance levels of each rotor component and sub-rotor system are approximately in [2 g·mm, 4 g·mm] as well as 12 g·mm (front) and 16 g·mm (back), respectively. Under the effect of numerous parts, the unbalance of rotor system is so excessive in quantity and dispersity that 50 test values distribute in the range [180 g·mm, 500 g·mm]. It is very easy to induce the excessive unbalance of single part and the vibration of whole-body aeroengine due to excessive material elimination of rotor parts and too large balance weight, catering for the requirement of repeatedly disassembling for faulty aeroengine[1]. What is more, the scrap of aeroengine parts emerges due to the reduction of materials and induces the efficiency decrease of aeroengine dynamic balance[2]. Therefore, it is urgent to reasonably control the initial unbalance of rotor system.

The objective of this paper is to find the critical controlling points of rotor initial unbalance in assem-

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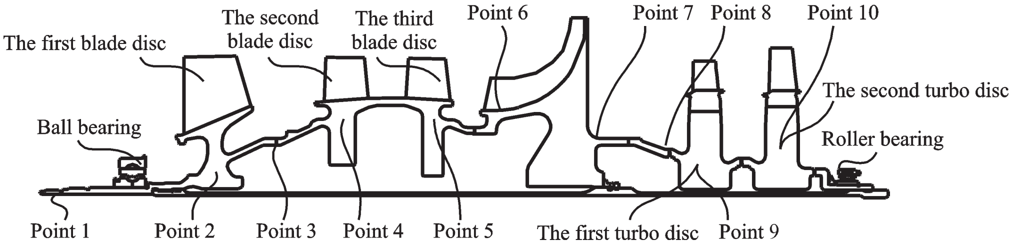

Fig.1 Schematic diagram of an aeroengine rotor

bly process, and to optimize the assembly technique and design quantitative standards, by analyzing main factors which affect the rotor initial unbalance.

1 Affecting Factors of Initial Unbalance

Initial unbalance of one component is often induced by manufacturing error and uneven material. It is impractical to further improve the allowable unbalance level of a single rotor part from technology and economy perspectives. The initial unbalance of rotor system is the vector sum of allowable unbalance values for many stages and additional unbalance values induced by eccentric assembly.

To reduce the initial unbalance of rotor, rotation angle method is commonly adopted to adjust the angular position of all stages of discs, with the assist of optimization algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), and so on. In fact, the eccentric distance of all assembled discs has large deviation comparing to the theoretical zero values, so that the adaption of the existing optimization algorithms[3-5] is too low to control initial unbalance. In other words, it is impossible to reduce the initial unbalance of rotor as only considering the unbalance angle degree of each component in assembling rotor system without regard to the control of jump after assembly[6-7]. In this case, it is necessary to precisely measure the jump of all components and accurately orient the angle direction of initial unbalance of single part[6-7]. The requirement leads to the improvement of manufacture and checkout for factory and the difficulty of production cost control. Therefore, this study is to reduce the rotor initial unbalance by controlling the assembly quality (featured by jump value) of one component or some components in respect of test data.

The influencing factors of rotor initial unbalance in assemble process[8-9] include as follows:

(1) Unbalance of single component

The vector sum of single components' unbalance seriously influences rotor initial unbalance[3].

(2) Runout of curvic couplings (end-tooths)

The runout of a well-balanced component has little effect on the initial unbalance. However, the runout of component's curvic couplings mating surface has a great influence on the initial unbalance of the rotor[10]. When the eccentricity of components resulting from the curvic coupling runout is 0.005 mm, the amount of induced unbalance is $3.5\ \text{kg}\times 0.005\ \text{mm}=17.5\ \text{g}\cdot\text{mm}$ which is much larger than the residual unbalance $2\ \text{g}\cdot\text{mm}$ of single component.

(3) Processing quality of screw-thread in central tie rod

The central tie rod is an elongated shaft, and contains three screw-threads which distribute on the front, middle and back of the central tie rod. It is required that the runout of the middle diameter of each thread relative to the rotating center of the part is no more than 0.05 mm. But the measurement of the real runout value is indeed difficult. When the coaxiality of the threads of central tie rod is poor and is not parallel to the axial line of the curvic couplings of rotor part, the central tie rod will sways, and the back end of the central tie rod exists structural interference which is presented by the increased tightness of parts assembly that is illustrated in Fig.2. This interference reversely affects the centering accuracy of curvic couplings and significantly influences rotor initial unbalance.

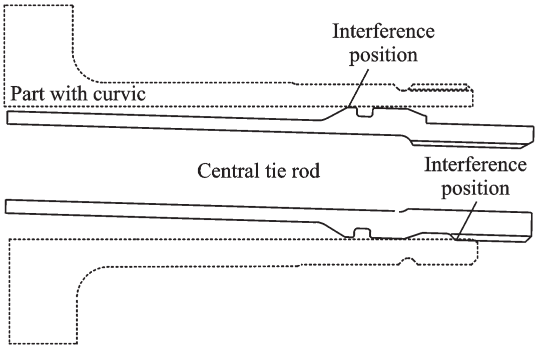

Fig.2 Schematic diagram of interference after the center tie rod swaying

(4) Influence of rotor pre-tightening

The type of rotor is segmental pre-tightening and its preload control has specific requirement that the preload of rotor dynamic balance is consistent with that of assembly[9,11]. The automatic curvic couplings are not fully utilized by once pre-tightening. Besides, strong randomness of components' concentricity easily causes large rotor eccentricity.

2 Effect Analysis of Discs' Unbalances on Rotor Dynamic Characteristics

To control rotor initial unbalance, the rotation angle method[3] is usually used to adjust the relative position of two components unbalance. In respect of 50 times assemblies and dynamic balance checks, however, the approach is found to hold strong randomness and cannot obtain obvious effect since the concentricity influence of components' assembly. To find the key factors of controlling rotor initial unbalance, the effect degree is discussed using vibration response when the rotor system has only one unbalanced disk.

2.1 Effect analysis of single component initial unbalance

Assuming the residual unbalance value of all the assembled disks is less than 2 g·mm and the rotor assembly is completely concentric without any additional unbalance, the displacement responses of the combined rotor are calculated and the results are shown in Figs.3—4. The amplitude variation of rotational speeds for different points under many stages of discs are described in Figs.5—8. Herein, the distributions of 10 points along the rotor are shown in Fig.1.

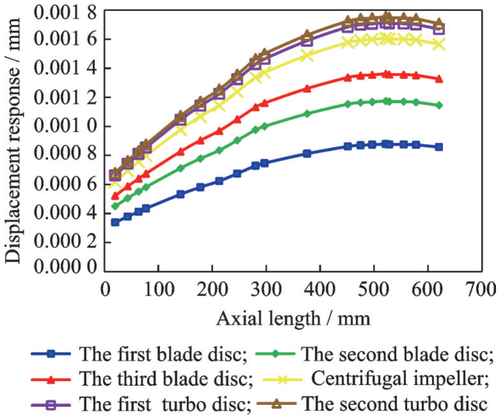

Fig.3 Displacement responses of rotor at the speed that is higher than the first order critical speed

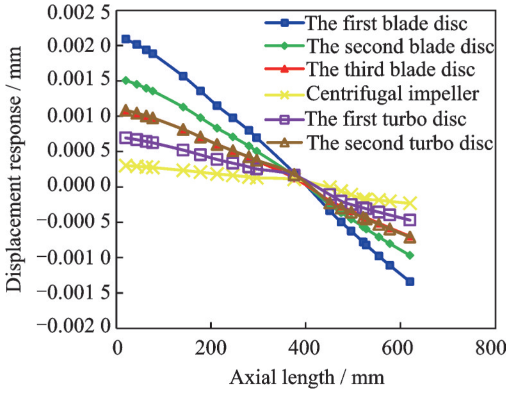

Fig.4 Displacement responses of rotor at the speed that is higher than the second order critical speed

As revealed in Figs.3—8, the displacement responses of the first stage rotor of the turbine are the highest and those of the first stage disk of the axial flow are the lowest at the speed that is higher than the first order critical speed; the displacement responses of the first stage disk of the axial flow are

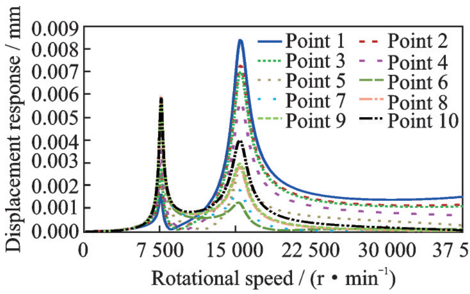

Fig.5 Displacement responses with rotational speed of 10 points along the rotor (Unbalance in the first bladed disc)

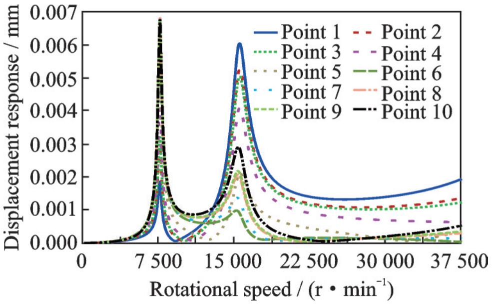

Fig.6 Displacement responses with rotational speed of 10 points along the rotor(Unbalance in the second bladed disc)

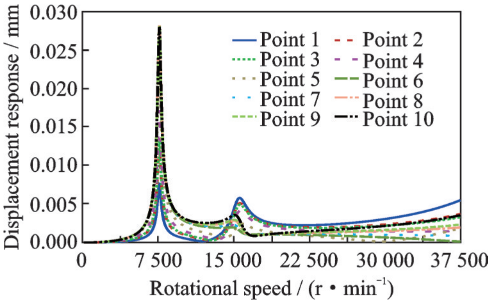

Fig.7 Displacement responses with rotational speed of 10 points along the rotor (Unbalance in centrifuge impeller)

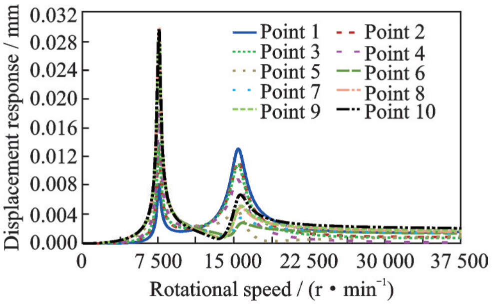

Fig.8 Displacement responses with rotational speed of 10 points along the rotor (Unbalance in the first turbo disc)

the highest, and those of the centrifugal impeller are the lowest at the speed that is higher than the second order critical speed.

2.2 Effect analysis of single component unbalance variation

We assume that the mass of the six disks in rotor system are 0.5, 1.0, 1.0, 3.5, 1.5, and 0.5 kg, and the allowable unbalance is 0, and the existing eccentricity e between the geometric center of the assembled single component and the rotating center of the rotor is shown in Fig.9. Herein, the eccentricity is defined by the runout difference of components before and after assembly. If the eccentricity is 0.005 mm, the additional unbalances ($m \times e$) are 2.5, 5, 5, 17.5, 7.5, and 2.5 g·mm, respectively. In this case, the displacement responses of the combined rotor are obtained as shown in Figs.10—11.

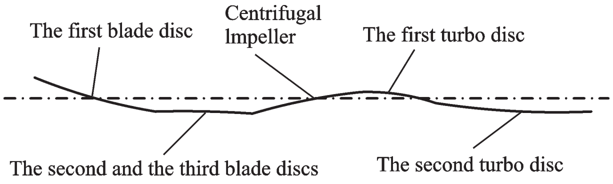

Fig.9 Schematic diagram of the eccentricity of six disks relative to rotational center

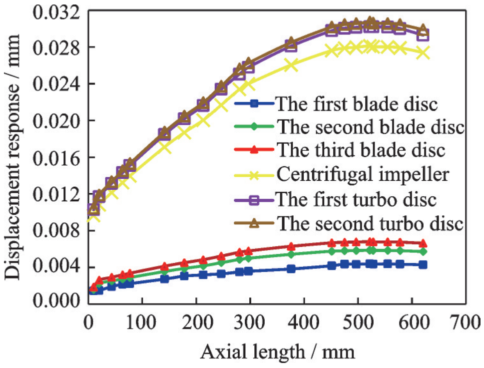

Fig.10 Displacement responses of rotor with additional unbalance at the speed that is higher than the first order critical speed

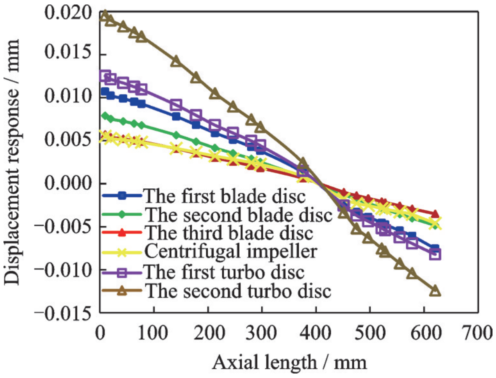

Fig.11 Displacement responses of rotor with additional unbalance at the speed that is higher than the second order critical speed

As shown in Figs.10—11, the displacement responses of the first stage rotor of the gas turbine are the highest, and those of the first stage disc of the axial flow are the lowest, at the speed that is higher than the first order critical speed. The displacement responses of the first stage disk of the axial flow are the highest and those of the centrifugal impeller are the lowest at the speed that is higher than the second order critical speed. Besides, the displacement responses of the gas turbine rotor are the highest at the speed that is higher than the first and second order critical speeds.

3 Key Parameter Analysis of Initial Unbalance Control

To reasonably control the initial unbalance of gas generator rotor, it is necessary to analyze and verify the influence of various factors on the rotor initial unbalance, and then to determine the most influential component as the key control factor in assembly.

3.1 Effect of single component initial unbalance

As illustrated in Section 2, the unbalances of both the first-stage bladed disk of the axial flow and the second-stage disk of the gas turbine should be controlled, to ensure the minimal assembly influence of gas generator rotor on the rotor dynamic characteristics. Moreover, the unloading position of the combined rotor balance is located at the two disks. It should be noted that the unloading and weighting are strictly controlled in engineering because they can reduce the unbalance of the whole rotor and increase the unbalance of single component. Obviously, unloading and weighting are one irreconcilable contradiction and need to be reasonably weighted.

To satisfy the requirement of the combined rotor dynamic balance, the weight of the counterweight of turbine disk exceeds the allowable value due to the unloading limitation of the first-stage compressor disk. Although the dynamic balance value of the rotor system meets the requirement of design, the unbalances of the compressor first-stage axial flow disk and the gas turbine second-stage disk are more than 10 times the allowable value of single component, so that the gas turbine rear fulcrum largely vibrates in whole-body aeroengine test. Therefore, it is impractical that the initial unbalances of both the first-stage bladed disk of the axial flow and the second-stage disk of the gas turbine are regarded as key control factors in assembly.

3.2 Effect of curvic couplings runout

In this section, the high and low points of measuring curvic couplings runout are taken as the objective of study. Assembling test with the high point dislocated 180° and 0° are carried out to verify the high and low points of measuring curvic couplings runout. We find that the eccentricity of the rotor can be effectively controlled when high point dislocates 180°. The initial unbalance distribution range of the rotor is significantly reduced by reducing the assembly eccentricity of components with large mass, for example centrifugal impeller. Based on the test, 10 testing values distribute in the range [140 g·mm, 300 g·mm]. Therefore, it is suitable to take the matching of the high and low points of curvic couplings as control factor in assembly.

3.3 Effect of thread processing quality of central tie rod

Typical gas generator rotor of turboshaft engine is assembled by the central tie rod pre-tightening in stages. On the central tie rod, there are three threads and three lug-bosses. The coaxiality between two threads or two bumps or threads and bumps directly affect rotor curvic couplings, and the assembled coaxiality of rotor components, so that the eccentricity emerges. When the central tie rod is completely screwed in the first stage of compressor disc, especially, the verticality of the end face to the diameter for the front thread of the central tie rod greatly influences rotor initial unbalance so that it is difficult to further improve the verticality in the manufacture.

To reduce the influence of thread processing quality, the corresponding adjustment procedures should be added in the assembly process in term of the analysis of comparison. The adjustment procedure is that the eccentricity effect of the central tie rod caused by the top dead of front end (such as retreating at least 30°—60°) can be eliminated by adjusting the axial distance between the central tie rod and the inner hole of the first disk. Meanwhile, centrifugal impeller runout is ensured to meet the design requirements by adjusting the relative position of the central tie rod relative to the centrifugal impeller (through the retreat range of 30°—360°).

Through the monitoring results of outer circle runout of rotor curvic couplings of many gas generator assemblies, it is found that the outer circle runout of the front and rear curvic couplings of the hub axle least affects the initial unbalance, while the outer circle runout of the curvic couplings between primary and secondary and tertiary disks has the greatest effect.

Hence, the angle adjusting process method of the central tie rod can be used as the key control factor in assembly by quantitatively checking whether outer circle runout of curvic couplings between primary disk and secondary and tertiary disks is controlled within [0, 0.01 mm]. This measure can rapidly control the runout of centrifugal impeller more which is consistent with the requirement of single pattern runout, and then control the dispersion degree of initial unbalance of gas generator rotor. The initial unbalance is controlled within the range [80 g·mm, 170 g·mm] through 10 tests.

3.4 Effect of rotor pre-tightening

To fully utilize the self-centering function of curvic couplings, we adjust rotor pre-tightening mode, besides increasing the clearance of the front end of the central tie rod. Conducting the steps of tension—loosening—tension—loosening—tension can eliminate the match randomness of curvic couplings and thread, and well guarantee the assembly consistency of all rotor components and improve the stability of connection, so that the maximum value and dispersion of rotor unbalance can be further reduced by 80%—90%. Therefore, rotor pre-tightening can be considered as one control factor in assembling process.

4 Optimization of Rotor Assembly Process

To make rotor initial unbalance meet design requirements and minimize the eccentricity between the mass center of centrifugal impeller and rotor rotating axis, as illustrated in Fig.5. Through ten dynamic balance checks and four whole-body aeroengine tests, we summarize the main measures of controlling rotor runout and initial unbalance as follows:

(1) Single component dynamic balance and flange runout meet the requirements of pattern.

(2) Install curvic couplings according to 180° dislocation of high runout point.

(3) Adjust the distance between the central tie rod and the inner hole of the first stage of disc to eliminate the eccentricity effect of central tie rod caused by the top dead of front end.

(4) Adjust the relative position of the central tie rod relative to the centrifugal impeller (the retreat range 30°—360°) to ensure centrifugal impeller runout and meet the design requirements.

(5) Adjust rotor pre-tightening form with the steps of tension—loosening—tension—loosening—tension to eliminate the match randomness of curvic couplings and thread, and well keep the assembly consistency of all rotor components and improve connection stability.

(6) Select the reasonable pre-tightening process to ensure the stability and consistency of pre-tightening force[8].

(7) Give the strict quantitative criteria of the runouts of curvic couplings circular and centrifugal impeller at specific locations, which are in accordance with the design requirements.

5 Conclusions

To gain the optimal rotor assembly process, this paper firstly analyses the influences of rotor initial unbalance of single disc and combined discs on rotor dynamic characteristics in respect of the dispersity of rotor initial unbalance and then discuss the key control factors of affecting rotor initial unbalance. Through these investigations, some conclusions are summarized as follows:

As illustrated in the effect analysis of discs' unbalances on rotor dynamic characteristics, (i) the displacement responses of the first stage rotor of gas turbine are the highest and those of the first stage disk of axial flow are the lowest at the speed that is higher than the first order critical speed; (ii) the displacement responses of the first stage disk of the axial flow is the highest and those of the centrifugal impeller are the lowest at the speed that is higher than the second order critical speed; (iii) the displacement responses of the first stage rotor of the gas turbine are the highest and those of the first stage disc of the axial flow are the lowest at the speed that is higher than the first order critical speed; (iv) the displacement responses of the first stage disk of the axial flow are the highest and those of the centrifugal impeller are the lowest at the speed that is higher than the second order critical speed. Besides, the displacement responses of the gas turbine rotor are the highest at the speed that is higher than the first and second order critical speeds. Therefore, the most important factors contributing to rotor vibration are the unbalances of first stage compressor disc and the second stage turbine disc.

From the key factor analysis of initial unbalance control, we find that: (i) it is impractical that the initial unbalances both the first-stage bladed disk of the axial flow and the second-stage disk of the gas turbine are regarded as key control factors in assembly; (ii) it is suitable that the matching of the high and low points of curvic couplings is regarded as the control factor in assembly; (iii) the angle adjusting process method of the central tie rod can be used as the key control factor in assembly to quantitatively check whether outer circle runout of curvic couplings between primary disk and secondary and the tertiary disks is controlled within [0, 0.01 mm]; (iv) rotor pre-tightening can be considered as one control factor in assembling process.

The main measures of controlling rotor runout and initial unbalance are given to make the assembly process simpler and more effective as well as timely control the rotor initial unbalance.

The efforts of this study validate that the proposed method is workable for the rotor tightened by a central tie rod and possesses the significant meaning of practical application in engineering.

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Author contributions Prof. **BAO Youlin** designed the study, provided the core idea, conducted the analysis, interpreted the results. Mr. **LI Lixin** contributed to the rotor optimization and wrote the manuscript. Mr. **CAO Peng** complied the model and contributed to the data analysis. Mr. **HUANG Xinglong** collected the test data. Mr. **LI Ciying** modified the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

基于装配工艺优化的某发动机转子初始不平衡量控制技术

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摘要：某航空发动机转子装配后初始不平衡量分散度大，严重影响了该转子的装配效率。为降低分散度，合理优化转子装配工艺，首先假设转子单个零件装配时完全同心，开展了单个零件不平衡量对转子动力学特性的影响分析。理论分析发现，影响该特性的主要零件是压气机一级盘和燃气涡轮二级盘，需减少其在装配状态的不平衡量。但是，由于转子平衡面也设置在这两个位置，在转子动平衡时需要去料或者配重，这在单个零件不平衡量的控制上是矛盾的。为此，进一步假设单个零件没有不平衡量，但在装配时存在偏心，开展了由偏心引起的不平衡量对转子动力学特性的影响分析。经过分析和试验验证发现，在装配过程中通过调整中心拉杆周向相对位置来控制离心叶轮在装配状态的跳动量，可以降低整个转子初始不平衡量。该装配工艺简单有效，适用于中心拉杆预紧的转子，具有工程实际应用意义。

关键词：涡轴发动机；初始不平衡量；装配工艺；燃气发生器转子；控制技术