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Inspection of assembly error with effect on throat and incidence for turbine blades

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ABSTRACT

Turbine blades are the key aerodynamic parts and most widely used in turbomachinery. Rather than working individually, turbine blades are assembled on the rotor of turbomachinery to constitute bladed disks as the basic working units. Therefore, the quality of turbine blade assembly is crucial for guaranteeing the long and safe operation of turbomachinery with good performance. Aiming at this critical issue, two assembly error specifications of turbine blades are firstly defined as Circumferential Indexing Error and Axial Positioning Error, which are key factors affecting the throat and the incidence of turbine cascade. Then, the corresponding feature-based analysis methods are presented in this paper. Finally, the proposed theory and methods are experimentally verified through the bladed disk of a steam turbine rotor. The results demonstrate that the two defined assembly error specifications of turbine blades can be effectively extracted using the proposed methods. The assembly error of turbine blades can be used to evaluate the aerodynamic performance and the operating safety of turbine. Moreover, a guide can also be provided for the subsequent adjustment and correction of turbine blade assembly.
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1. Introduction

Turbomachinery refers to the machines that transfer energy between a rotor and fluid, such as steam turbine, gas turbine and aero engine [1,2]. Like other power equipment, efficiency is the most important performance parameter for turbomachinery and a small change in the efficiency of either turbine or compressor can cause a much larger proportional change in the power output [3]. The influencing factors of efficiency are very complex and can cause various losses. In turbomachinery, the energy transformation is implemented by the interaction between fluid and bladed disks of turbine or compressor. Thus, many factors that cause losses are related to the bladed disks, especially their geometric structure. As the bladed disk is constructed by the assembly of a series of blades on the rotor [4], the geometric structure of bladed disk is mainly determined by the position distribution of blades. Therefore, the assembly of blades can affect the performance of turbomachinery and even lead to mistuning and vibration of bladed disk structure [5]. It is really important safety, cost, and readiness concerns for the operating of turbomachinery [6].

For a machinery or component, the assembly process could inevitably cause the errors of the relative position between its key parts and directly affect the performance. So, the assembly errors should be defined based on the effect on performance and the assembly process of machinery or component. And then, the analysis need to be made to the defined assembly errors. For instance, in a multi-axis machine tool, deviation in the relative position between various linear and/or rotary axes exists and will directly affect the machining accuracy of workpieces [7]. Aiming at this problem, five geometric deviations of a linear axis of machine tool were defined as assembly errors, including three angular errors (pitch, yaw and roll) and two straightness errors along the direction of the other two linear axes. And the five specifications of assembly error were measured using laser interferometer (pitch and yaw), laser tracker (two straightness errors) and gradienter (roll) [8]. Not only mechanical systems, but the same problem are also faced by optical components. Here, the light field camera is taken as another instance. The errors of the relative position between microlens array and the photoreceptor could affect the imaging quality of light field camera. Based on the imaging principle and assembly process, the four assembly errors of microlens array were defined as coupling distance error, translation error, rotation errors and tilt errors. By

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comparing the error image and the standard image of a light field camera using assembly error correction model, the four types of assembly errors were analysed and evaluated based on the change in the imaging quality [9].

For the assembly of blades in turbomachinery (e.g. gas turbine), the related techniques are reported in the patents, which mainly refer to the turbine blade assembly themselves, such as structures, tools, methods and processes. Here, the claims of the representative patents are reviewed. In [10], it is claimed that a plurality of dovetail slots are spaced circumferentially about the rotor disk and each rotor blade is inserted into a respective rotor dovetail slot. In [11], it is claimed that an axial spacing is defined between the rotor blade and the stator vane. In [12], it is claimed that a gas turbine engine rotor assembly comprising a rotor disk and a plurality of circumferentially-spaced rotor blade assemblies coupled to said rotor disk. In [13], it is claimed that the locking plate and the deformable closing plate are designed to fix the turbine blades during engine operation: for one thing, the locking plates are secured in a circumferential direction by the deformable closing plate; for another, the locking plates and the deformable closing plate are both used to prevent the turbine blades from moving in an axial direction. Hence, it can be learned that the circumferential and axial position of turbine blades are very critical and should be strictly controlled in the assembly process. However, the inspection techniques for turbine blade assembly are not referred to in the patents, including the definition and analysis of assembly error for turbine blades.

To inspect the assembly accuracy of turbine blades and improve the performance of turbomachinery, the theory of assembly error for turbine blades is studied in this paper. Based on the characteristics of assembly and structure of bladed disks, two specifications of assembly error of turbine blades are defined as the description for the positioning error of turbine blades along circumferential and axial direction. They can change the throat and incidence of a turbine cascade and lead to losses of turbomachinery. And the corresponding analysis methods are also presented to inspect the assembly accuracy of turbine blades.

This paper is organized as follows: In Section 2, two critical specifications of assembly error for turbine blades are defined, with the detailed analysis of related causes and effects on the throat and incidence of turbine cascade. The corresponding analysis methods of assembly error are then presented in Section 3. In Section 4, experimental results of several examples are provided and analysed to verify the effectiveness of proposed methods for the inspection of defined assembly error of turbine blades. Finally, Section 5 concludes this paper and outlines the suggestions for future work.

2. The definition of assembly error for turbine blades

In this section, the assembly of turbine blades are briefly described and analysed. Then, two specifications of assembly error for turbine blades are defined, with the analysis of effects on the throat and incidence of turbine cascade.

2.1. Assembly of turbine blades

In turbomachinery, the turbine can be designed as two different structures according to the direction of fluid flow: the axial-flow turbine whose rotation axis is parallel to the direction of flow and the radial-flow turbine whose rotation axis is perpendicular to the direction of flow. Among them, the axial-flow turbine is most widely employed using a compressible fluid, especially for heavy duty turbomachinery. In the study of this paper, the axial-flow turbines are selected as the research objects. As an aerodynamic component, turbine blade is typically composed of three main parts: aerofoil surface, blade tip and blade root, as shown in Fig. 1.

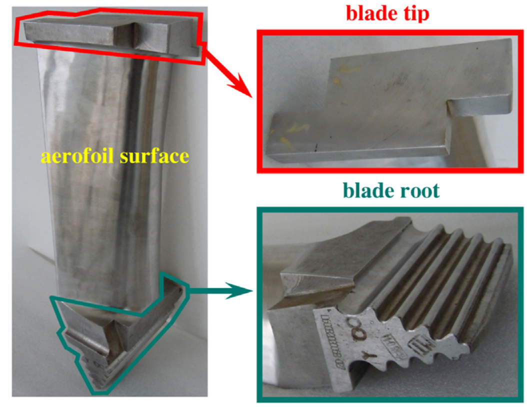

Fig. 1. Steam turbine blade.

Fig. 2. Fitting between blade roots and slots on rotor disk.

The aerofoil surface of a turbine blade is a free-form shaped part that interacts with fluid to implement energy transformation. The blade root is used to fix the turbine blade on the rotor. Among all types of shapes, the fir-tree shape is the most widely used design for a blade root, just as the steam turbine blade shown in Fig. 1. This type of root allows for different expansion rates between disk and turbine blade while still holding the turbine blade firmly against centrifugal loads [14]. Moreover, the blade tip is often used to form the shroud structure, which can reduce the vibration and tip leakage loss of bladed disks.

As shown in Fig. 2, by the fitting between blade roots and corresponding slots on the disks of the rotor, the turbine blades can be assembled on the rotor. And the assembled turbine blades are often distributed uniformly along the circumferential direction of a rotor to form a series of bladed disks, as shown in Fig. 3.

The compressor, another key component of turbomachinery, has a similar structure to the turbine. And they simply operate in reverse during energy transformation [15]. Therefore, the related theory and methods of assembly error for turbine blades could also be applied to compressor blades.

2.2. Specifications of assembly error for turbine blades

In addition to the assembly process, turbine blades and rotor disk both have machining error. Positioning error of the assembled turbine blades may exist not only relative to the rotor but also among turbine blades.

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