

Research on the Measurement Uncertainty of Blade Surface Measured by Coordinates Measuring Machines

Y. Z. Li^{1,a}, G. H. Zhang^{1,b}, Z. S. Liu^{1,c}, H.Y. Huang^{1,d}, S. Y. Kang^{2,e} and Y. F. Peng^{3,*}

¹School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

²Xiamen Jimei Vocational Technology Educational School, Xiamen 361022, China

³Xiamen University, Xiamen 3610005, China

Abstract

The purpose of this paper is to investigate the measurement uncertainty of blade surface by coordinates measuring machines (CMMs). In the past, the measurement of blade surface by CMMs is usually measured in the vertical mode, of which the measuring probe is normal to the surface. In this paper, a rotation mode, of which the measuring probe of CMMs is not collinear with the normal of the blade surface, is presented and its feasibility is explored in measuring the blade surface. The measurement uncertainty of rotation mode by CMMs is also examined. It is found that the measurement uncertainty of the blade back is superior to that of the blade basin. Furthermore, the uncertainty at the blade bottom is inferior to that of the blade tip. The reason may be that the measurement accuracy is closely related with the surface curvature at different parts of the blade.

Keywords: CMMs; Measurement uncertainty; Probe; Blade

Introduction

Turbine blade has been applied in an extraordinary wide range fields, such as the aviation, aerospace, automotive, energy and other industries [1]. As one of the most important parts of turbine machinery, surface quality and manufacturing precision of the blades directly impact the turbine performance, efficiency and service life. Thus the profile measurement of turbine blade is very important during the blade machining procedure. However, it is difficult to measure and establish the profile measurement of turbine blade because of its complicated shapes and space twist angles of the blades. Therefore it needs an appropriate and accurate measurement method for the turbine blade profile measurement.

There are numerous researches about the blade measurement [2]. The most commonly measurement method applies in the profile measurement of turbine blade is the coordinate measuring machines (CMMs) because it is capable of measuring the profile with complex structure [3]. The disadvantage of CMMs is that the measurement efficiency is slow and easy influenced by the environment. Then it needs a more appropriate method to meet the needs of fast detection and on-site measurement and replace the CMMs to meet the fast development of production. Then some optical measurement methods, such as optical measurement methods with the characteristics of non-contact like optical theodolite [4], three-dimensional photography [5], laser interferometry [6,7], and the laser triangulation method [8], are gradually applied in the profile measurement of turbine blade. The commonly characteristics of the optical measurement are that they have better detection accuracy but shorter scanning range than CMMs, which results they fit the measurement of the roughness and micro-structure of blade surface. In most of the actual circumstances, the measurement of blade mainly focuses on the size and shape of the blade. This means that the CMMs is still the preferable tools for the measurement of blade. Furthermore, the measurement accuracy of CMMs increases rapidly and even ups to be micrometer scales. It can also reach even sub-micron order of magnitude accuracy if the high precision measuring probe is adapted. For example, Savio used CMMs measuring turbine blades, and the uncertainty is about 5-10 μm [9]. The shape of the impeller is complex, and the space between two adjacent blades is narrow, and even there might be a geometric overlapping

between the blades. So it is difficult to measure with the traditional methods. A 3-axis CMMs (refers to 5-axis CMMs), together with a dividing head with two rotational axes, can undertake the complicated measurement [10]. It is common and reliable to apply the 5-axis CMMs in the turbine blade profile measurement today.

There are many factors influence the measurement result of CMMs. Therefore, it is necessary to examine the measurement uncertainty of blade by CMMs. The determination of measurement uncertainty of CMMs is a complex and burdensome task. Among the precision metrology, there a large quantity researching works concerning on the analysis and compensation of CMMs [11,12]. There are also some works discussing the measurement uncertainty of CMMs, such as the sampling strategy [13,14]. The application versatility that allows CMMs to inspect a wide range of features and part types makes the CMMs in evaluating the measurement uncertainty to be a multifaceted problem. Furthermore, the research on measurement uncertainty is now increasingly focusing on the measurement of freeform surface by CMMs with the development of modern engineering technology [15,16]. Currently, the vast majority of CMMs measurements have no rigorous uncertainty budget. Though the blade can also be looked as a type of freeform surface to some extent, it has its own characteristics, such as the space twist angle and varied curvature of the cross-section profile. But related work on turbine blade is seldom found to our knowledge. So, the explosive application of turbine blade is still hindered by a lack of international standards and traceable measurement technologies for conducting reliable quality control of manufactured blade surface. Thus, it is indispensable to do some work about the measurement uncertainty of blade by CMMs.

*Corresponding author: Peng YF, Xiamen University, Xiamen 3610005, China, Tel: +86-592-2187283; E-mail: pengyf@xmu.edu.cn

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In this paper, a study on the measurement uncertainty of blade by CMMs is presented, of which a rotation mode is adapted by 5-axis CMMs to measure the blade. The operation process and sources of uncertainty are analyzed firstly. Then, the measurement experimental result and measurement uncertainty are discussed in detail.

Theoretical Background

The turbine blade is always a typical freeform surface with a space twist angle. The truncated cross-section profiles of blade have their own characteristics at different height. Furthermore, the curvature of the cross-section profile at the same height is varied at different sampling points, which results that the measurement operation of blade needs special sampling strategy and planning. Thus the measurement task of the blade surface becomes a complicated and burdensome work.

In this paper, a novel measurement sampling strategy for blade surface is presented. The measurement operation is performed on 5-axis (3+2) CMMs. The special interest of the measuring strategy is that the discretized points are measured with a measuring probe and head in a rotation mode. The position and gesture of measuring probe is kept normal to the tangent of the cross-section profile at the sampling points, but not collinear to the normal of the measuring points. Based on this principle, the measuring path is automated generated. The measuring strategy is shown in Figure 1. The procedure can be described as:

- (1) To move the measuring arm to a defined position firstly and hold still.
- (2) To rotate the measuring probe to be normal to the tangent of cross-section profile at the sampling point A, and let the measuring head to contact the measuring point A on the blade surface, and then perform the measuring operation.
- (3) To retreat the measuring probe and head to its original position and gesture.
- (4) To move the measuring arm to the next position.

- (5) To rotate the measuring probe and probe to contact the measuring point B and finish the measuring operation.
- (6) To retreat the measuring probe to its original position/gesture again.
- (7) To move the measuring arm to the next position.

It is apparently that this measuring strategy is more flexible in planning the space position for the measuring arm than the parallel mode defined as the measuring probe collinear to the normal of cross-section profile at the measuring point. This method also offers many measuring path options for the measuring operation of the complex freeform surface.

There are many factors influence the measurement task, which includes geometrical error, thermal deformation, sampling strategy, measuring path, measuring speed and approaching distance. The influence factors generally can't be accurately quantized in a mathematical expression and also can't be controlled in an idealized way, which results the measurement uncertainty in CMMs. The measurement uncertainty is related to all the influence factors. Due to the complicated relationship of the error source, it is hardly to explain every error component in detail. Furthermore, the influence factors are interacted each other. The advisable method to cope with those influence factors is to consider them as a whole thing and decompose them onto every movement axis at a defined measurement point. If the blade is examined on a 5-axis CMMs, the comprehensive errors of the influence factor on the CMMs' error of indication in a sampling point A can be illustrated as in Figure 2 on the condition that the separate influence factors are assumed to be uncorrelated, which is

$$\begin{aligned}
 \begin{bmatrix} ex(A) \\ ey(A) \\ ez(A) \end{bmatrix} &= \begin{bmatrix} xpx(A) \\ xty(A) \\ xtZ(A) \end{bmatrix} + \begin{bmatrix} ytx(A) \\ ypy(A) \\ ytz(A) \end{bmatrix} + \begin{bmatrix} ztx(A) \\ zty(A) \\ zpz(A) \end{bmatrix} \\
 &+ M_1 \begin{bmatrix} xrx(A) \\ xry(A) \\ xrz(A) \end{bmatrix} + M_2 \begin{bmatrix} yrx(A) \\ yry(A) \\ yrz(A) \end{bmatrix} + M_3 \begin{bmatrix} zrx(A) \\ zry(A) \\ zrz(A) \end{bmatrix} + M_4 \begin{bmatrix} ywz(A) \\ xwz(A) \\ xwy(A) \end{bmatrix} \quad (1) \\
 &+ M_5 \begin{bmatrix} wru(A) \\ wrv(A) \\ wrw(A) \end{bmatrix} + M_6 \begin{bmatrix} uru(A) \\ urv(A) \\ urw(A) \end{bmatrix}
 \end{aligned}$$

Where $M_1, M_2, M_3, M_4, M_5, M_6$ are matrices of weights depending on the design and operation characteristics of the 5-axis CMMs, the stylus used and the space coordinates of point A.

Because of the measurement uncertainty, the measuring points are always misaligned as shown in Figure 3. The distance between the programmed point A and measured point A' is the so-called measurement error \bar{e}_A , which is

$$\bar{e}_i = \bar{r}_A - \bar{r}_{A'} = \begin{bmatrix} ex_i(A) \\ ey_i(A) \\ ez_i(A) \end{bmatrix} \quad (2)$$

Which \bar{r}_A denotes the distance vector of point A and $\bar{r}_{A'}$ is the distance vector of contact point A' by measuring head according to the measuring strategy. The operation condition of CMMs is always uniformly unstable, and the measurement results changes at different measurement round. In order to evaluate the feasibility of the measurement strategy of the rotational mode, it is necessary to examine the measurement uncertainty of blade surface with 5-axis CMMs.

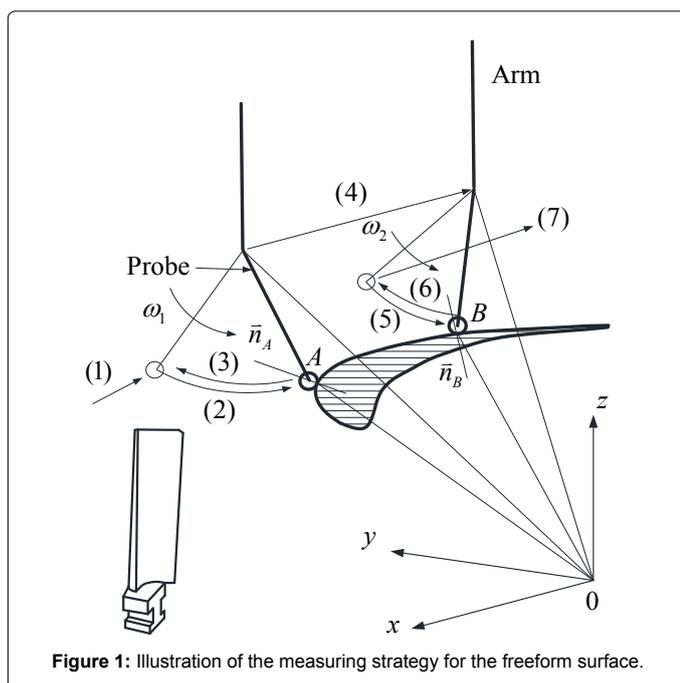
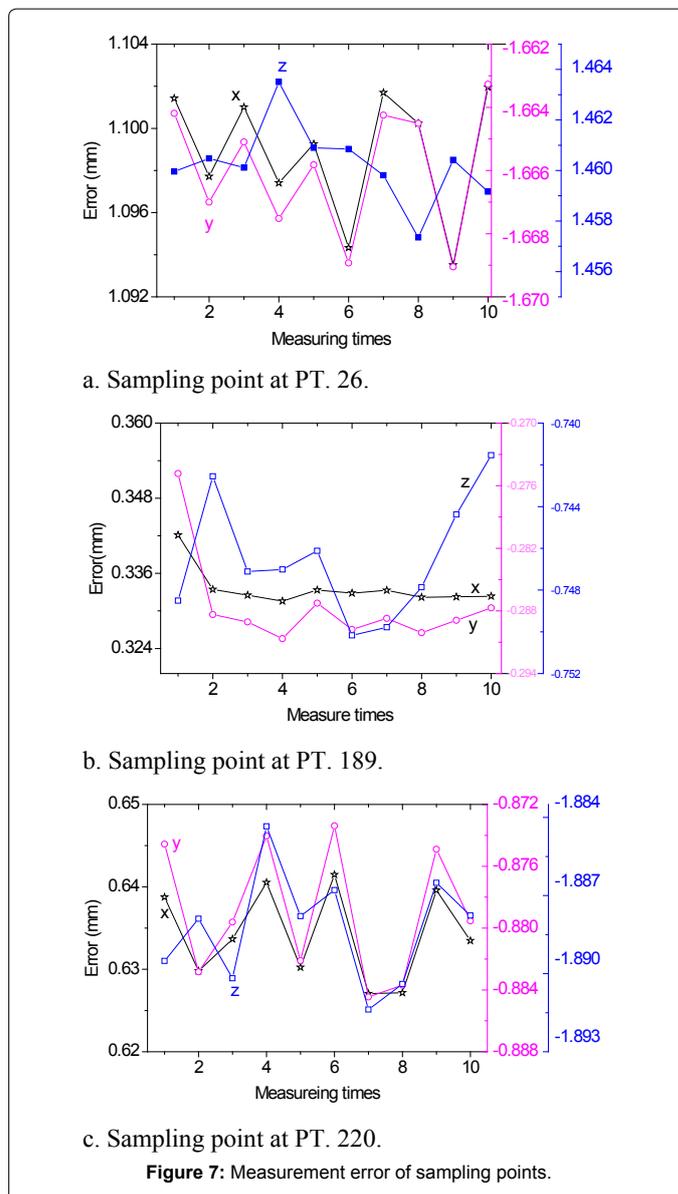
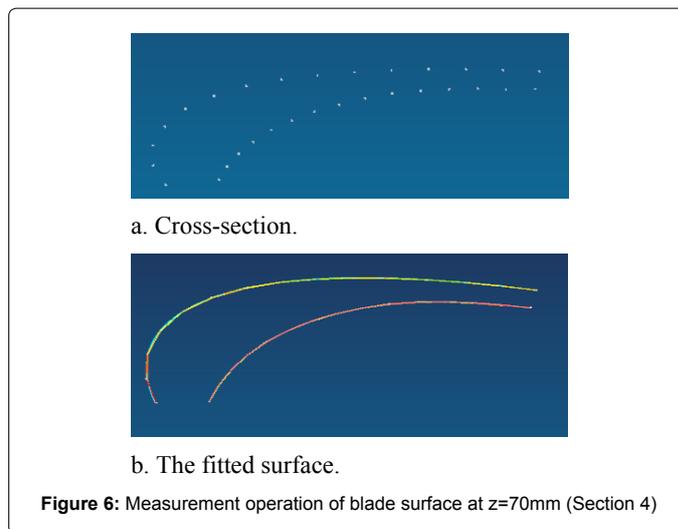
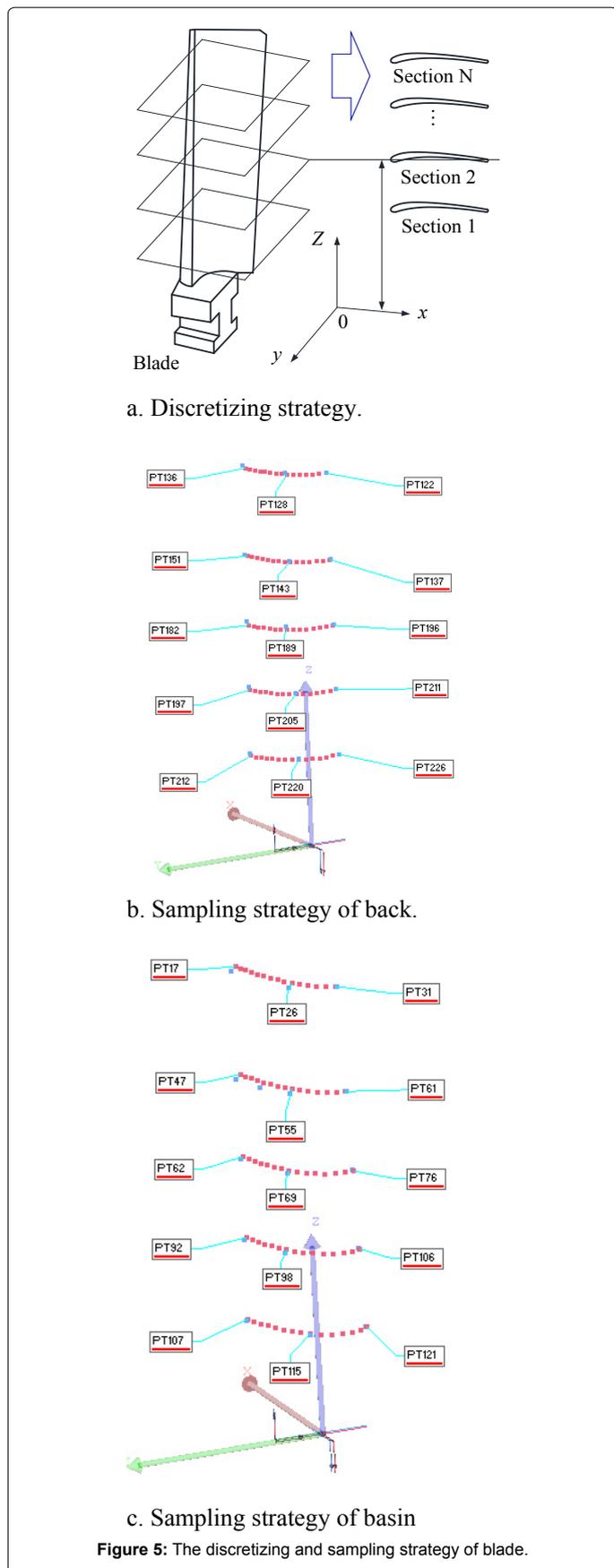
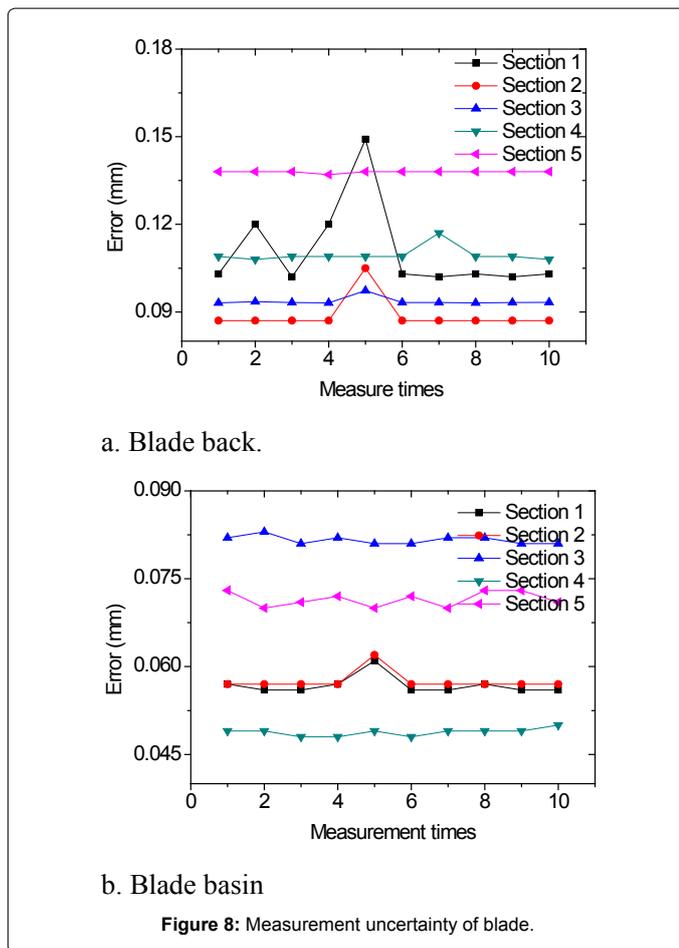


Figure 1: Illustration of the measuring strategy for the freeform surface.





root of the blade is always much bigger than that of the blade tip, which can be seen in Figure 8. The uncertainty of the fitted error at section 1 is the biggest one. This may attribute to that the blade surface is a twisted one, and the distortion extent is more serious for the cross-section at the root of blade surface, of which the distortion may result the poor measurement and fitting error. While at the tip of the blade, the cross-section profile is less twisted, and the error influence factors of measurement is relatively less, which may improve the measurement result and therefore the better fitted error. The third is that the fitted error's uncertainty of the back's cross-section is big than that of the basin's cross-section. The reason may be thought as that the curvature of the back varies a lot, especially near the leading edge, while it varies much gently for the basin surface, which can be seen at Figure 6. Then it may need much longer measurement path and operation for the measuring of the blade back, which may result more error accumulation and thus the worse uncertainty. Therefore, in order to improve the uncertainty of fitted error both for the back and basin, the future work should focus more attention on the reasonable measurement and sampling strategy, especially for the blade back.

Conclusions

In this paper, the measurement uncertainty of blade surface measured by CMMs was examined. The measurement method of blade was performed on a 5-axis Zeiss CMMs with a novel rotation mode. The examination and analysis reveals that the measurement uncertainty of sampling coordinates shows a stable trend. And the fitted error's uncertainty of the cross-section also exhibits a small

amplitude fluctuation. The uncertainty of fitted error decreases when the cross-section goes from the bottom to the blade tip. The fitted error's uncertainty of blade back is much serious than that of the blade basin. The reason may be because the profile's curvature varies at different parts which cause different measurement results and error. This research shows that the rotation mode can be used to measure the blade with complex surface shape, but the more future work should be paid on the sampling and measuring strategy to cope with the surface curvature variation.

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