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An approach for machining distortion measurements and evaluation of thin-walled blades with small datum

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Abstract Inspection techniques for aero-engine blades are a hot topic in industry. Since these blades have a sculptured surface and a small datum, measurement results may deviate from an actual position. There are few proper approaches compensating for non-uniform distribution errors that are within specified tolerance ranges. This study aimed to develop a meshing structure measuring approach for the distortion of blades via non-contact optical 3D scanning. A rough measurement and a registration procedure are initially adopted to rectify the coordinate system of a blade, which avoids the initial coordinate system errors caused by the small datum. A measurement path with meshing structure is then unfolded on the blade surface. For non-uniform distribution errors, the meshing structure measurement is more visual and clear than the traditional constant height curves method. All measuring points take only 7 min to complete, and the distribution of error is directly and accurately presented by the meshing structure. This study provides a basis for future research on distortion control and error compensation.

1. Introduction

The surface curvature of blades is becoming increasingly complex with the development of high bypass turbofan engines. Such engines require thin blades with high thrust-to-weight ratios to improve sustained performance.[1,2] Inspecting and analyzing machining distortions are indispensable for evaluating processing methods for two reasons: (1) The quality of a machined blade can be judged against its accuracy requirement; and (2) Distortion analysis may provide reasons for blade non-conformity and suggestions for quality improve-

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ment. Since blades constitute a high proportion of an aero-engine and significantly affect its aerodynamic efficiency, rapid measurement and accurate evaluation of machining distortions is critical.[3–5]

Hsu et al.[6] attempted to apply coordinate measurement techniques to a blade section measurement method in order to evaluate blade dimensions and geometric tolerance. They initially determined the coordinate system of a blade and proposed a two-step measurement procedure. An analysis process for blade parameters was discussed and an algorithm related to the optimal positioning of measurement data was then developed. Mansour[7] provided a small number of points for a simulation method via contact 3D scanning while remaining within the allowable deviation. Fu et al.[8] proposed a 3D profile measurement method based on multi-value coding. Their paper mainly discussed the principle of a non-contact 3D profile and generalized a measurement system for blades. A machining distortion is frequently evaluated by investigating bending and torsion deviations between a nominal machined surface and an actual machined surface.[9–11] However, such an evaluation fails to comprehensively analyze issues involving each blade's machined distortion area according to the measurement data, particularly with blades of complex curvatures and small datum.

Non-uniformly distributed errors can still be observed even when bending and torsion deviations are tolerable. The imbalance of rotors, which is caused by non-uniformly distributed errors and scallop heights after machining is one of the main causes of vibration and noise in aero-engines,[12] directly decreasing work performance and fatigue life.[13] Adaptive machining or adaptive repairing of curved blades through geometric reconstruction has been widely adopted.[14,15] Given a small datum or the lack of an assistant datum to help locate a blade, it is difficult to inspect a manufactured surface that best fits a design model. Therefore, a rapid and accurate measurement method should be developed to locate distortions. Existing tools such as the touch trigger probe have several disadvantages, such as slow sampling speed and the radius compensation error of its stylus ball.[16,17] The present study proposes a method for analyzing and evaluating distortions based on non-contact measurements and the shape of a blade. Li et al.[18,19] systematically presented an introduction of simplification, smoothing and parameter extraction with respect to point-sampled blades, and achieved section curve reconstruction and mean-camber curve extraction with the representation of a point cloud. This work promotes the development of optical measuring as applied to blade inspections.

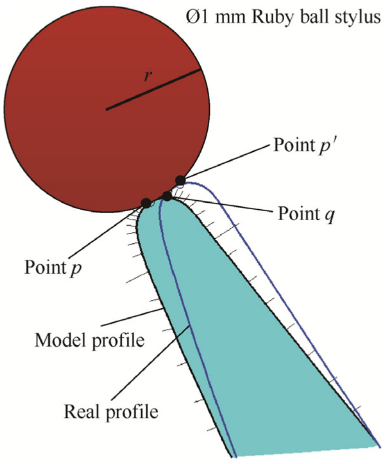

Fig. 1 Deviation of a contact CMM.

The remaining parts of this paper are organized as follows: Section 2 analyzes several problems in existing contact measurement blade inspection techniques by investigating a sharply curved blade with small datum, then presents how high-precision and high-speed data measurements of the blade can be obtained. Section 3 discusses the measurement process of a blade's curved sections and how distortion is accurately inspected in three steps. Finally, a sample blade is validated in Section 4 to demonstrate the overall procedure and to illustrate the necessity and feasibility of the proposed method.

2. Measurement principles of blade distortion

2.1. Problems in blade distortion inspections

2.1.1. Mismatched contact points

The profile and positional error of a cross-section curve are generally used to evaluate blade surface measurements. A blade surface is typically composed of four areas: pressure surface, suction surface, leading edge, and trailing edge. The leading and trailing edges are extremely small and sharp and, with a curvature radius of approximately 0.1 mm, are difficult to measure. When contact coordinate measuring machines (CMMs) are used for blade inspection, the distortion of the workpiece, particularly near the leading/trailing edges, may result in a substantial deviation between the workpiece and the computer-aided design (CAD) measurement model. As shown in Fig. 1, r is radius of ruby ball stylus, point p is the planned position of the measurement path. However, the real contact point is point q, which corresponds to the model profile. This phenomenon leads to the data of point q reflecting the position of point p'. In addition, the contact probe records the center of its ball end. The data used for workpiece localization are the coordinates of the points where the probe is in contact with the workpiece. Compensating for the probe radius also introduces errors during a sharp change in the curvature of a surface. Moreover, a high-precision measurement using a CMM requires scanning in small steps, thus measuring the sheer volume of data points is a time-consuming process.

With the advancement of laser technologies and the improvement of measurement accuracy, non-contact 3D scanners have been successfully applied to surface data acquisition in the industry.[15] Fast and large CCD arrays have been commercially developed for spectroscopic applications. The introduction of CCD arrays is an important breakthrough in range sensors based on 3D active triangulation. Coupled with enhanced processing, these devices have improved range accuracy to 0.01%, which enables the acquisition of huge amounts of data to provide high-quality results.[16] The optical CMM based inspection system has advantages in performing rapid data acquisition, measuring complex (narrow) geometry, and performing global inspections for a component with freeform surfaces.[11,20,21]

2.1.2. Inaccurate location of small datum

Many turbine blades have small, single-ended datum located away from the blade body as shown in Fig. 2. The datum