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Measurement-based geometric reconstruction for milling turbine blade using free-form deformation

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ABSTRACT

In aerospace engineering, the combination of hot forming and numerical control milling processes is an effective way to manufacture gas turbine blades nowadays. Due to the shape deviation, it is hard to mill the parts formed by hot forming process to the final nominal shape sometimes. To reduce the rejection rate and save the production cost, a measurement-based approach for geometric reconstruction of final nominal shape using free-form deformation (FFD) is presented in this paper. The original shape was firstly sliced into several cross-sections in its design manner, then each section was modified by FFD based on a set of organized measurement points, and at last the final nominal shape was reconstructed by lofting these modified cross-sections. An iteration process with knot insertion was developed to improve the FFD calculation accuracy. The results were found to be highly encouraging, which validates the feasibility of our proposed geometrical reconstruction method.

1. Introduction

Hot forming processes such as forging, casting and creep forming, are widely used in manufacturing complex structural parts in aerospace application, which can reduce material costs and improve machining efficiency [1–4]. However, they cannot directly meet the high accuracy requirement of some key parts such as gas turbine blades and blisks. Thus, they are often followed by numerical control (NC) milling to ensure the final accuracy of these parts [5–8]. That is, the output of the hot forming process is the input of the NC milling process.

A critical barrier has been encountered in the NC milling of these output parts that they were different from each other because of low forming accuracy. Moreover, some formed parts cannot be milled to the final nominal shape due to large shape deviation. For reducing the rejection rate and saving the production cost, the nominal geometrical shape should be reconstructed [9,10]. In this paper, we investigate the problem of geometrical reconstruction of final nominal CAD model for milling gas turbine blade using free-form deformation.

The main contributions of our work are:

- We consider the geometrical reconstruction of gas turbine blade as a problem of shape modification with multiple measurement points. A least squares minimization approach regarding point-pair displacements was adopted.
- We describe the geometrical shape of gas turbine blade in non-uniform rational B-splines (NURBS) formats. Free-form deformation (FFD) was used to modify the lattice control points to update the NURBS shape. An iteration process of FFD calculation was developed to improve the calculation accuracy by knot insertion.
- The NURBS shape of the gas turbine blade was reconstructed in its original design manner. The NURBS shape was sliced into several cross-sections. Each cross-section was reconstructed first and then the final shape was lofted by these modified cross-sections.

The rest of the paper is organized as follows. In Section 2, some related works on geometrical reconstruction and FFD are described. Section 3 details the geometric reconstruction approach for milling gas turbine blade. Implementation of the proposed approach is given in Section 4. Results of a case study are depicted in Section 5. Finally, conclusions and outlook are presented in Section 6.

2. Related work

2.1. Geometrical reconstruction for gas turbine blade

In general, the geometrical reconstruction of gas turbine blade contains three typical phases, which are scanning, point processing and surface reconstruction [11]. A mesh or point cloud data of the

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three-dimensional (3D) shape are achieved in the scanning and point processing. In the surface reconstruction, a patch or a set of curves is created firstly based on mesh or point cloud data, and then parametric surfaces are fitted into the segments considering the constraints of continuity along the boundaries. Gao et al. [12] digitized the blade to polygon 3D model and loaded this scanned polygon model into the reverse engineering software of Polyworks for the blade tip reconstruction. Lange et al. [13] achieved a three-dimensional point cloud of the measured blade using structured light, then exacted the section outlines from the point cloud, and finally reconstructed the blade model. Yilmaz et al. [14] utilized a 3D non-contact measurement method to digitize the blade and developed an adaptive approach to reconstruct the deposited blade tip surface. Lin et al. [15] scanned the forging blade with a coordinate measuring machine (CMM) and adaptively reconstructed a surface model to solve the disconnection problem between the actual surface of the blade and the theoretical model around the leading edge and tailing edge. Piya et al. [16] and Wilson et al. [17] used the sectional gauss concept to extract Prominent Cross Section (PCS) from an airfoil mesh of a blade and employed the reverse engineering technology to reconstruct the geometry of turbine blades. Gromann and Juttler [18] generated a trivariate B-spline parametrization of turbine blades from measurement data generated by an optical scanner.

It is obviously that previous works firstly required a large point cloud scanned or probed from the turbine blade and then reconstructed the model from these points, which is time-consuming and very labor intensive. Besides, for the same type of turbine blades with different shape deviation, this complicated procedure needs to be repeated again and again. In this study, we attempt to find a more quick and convenient approach which reconstructs the turbine blade model by modifying the nominal CAD model according to a small number of measurement points.

2.2. Free-form deformation

Free-form deformation(FFD) is a well-established technique for editing CAD model, used to deform two- or three-dimensional geometrical entities [19]. This technology was firstly proposed in 1986 by Sederberg and Parry [20], in which surface primitives of any type or degree can be deformed based on trivariate Bernstein polynomials. In 1990, Coquillart [21] extended this technology and proposed a highly interactive and intuitive modeling technique for designers and stylists. Kobayashi and Ootsubo [22] proposed a new method of free-form deformation by using triangular mesh in 2003, in which an original shape of polygonal mesh or point-cloud is deformed by a control mesh. Direct manipulation of free-form deformations (DFFD) was first proposed by Hsu et al. [23], which allows a user to control a deformation of an object directly. Th FFD technology has been successfully applied in sheet metal forming [24], 3D printing [25] and auto industry [26].

3. Methodology of reconstructing nominal CAD model

3.1. Problem statement

This paper focuses on a problem of geometric reconstruction of nominal CAD model in NC milling turbine blades, which has been formed to a near net-shape by a hot forming process, i.e., forging, casting and superplastic forming. By undergoing multiple heat cycles, the near net-shape suffered some shape deviation compared to the original design shape, which results in a critical problem in NC milling process. As known, for machining complex surface parts involving turbine blade, computer-aided manufacturing (CAM) technology is necessary for multiple-axis tool path generation. The nominal CAD model is indispensable for tool path generation. Basically, the near net-shape of the blade has a small amount of allowance to be milled. The shape deviation induced in the hot forming process makes it impossible to mill the blade to its final nominal CAD model. Fig. 1 schematically presents the relationship between the actual shape hot forming (HF), nominal shape before and after milling (BM and AM). Ideally, the actual HF shape should be the same with the nominal BM shape if there is no deviations. In fact, the final nominal BM shape cannot be enveloped totally by the actual HF shape, which means that the HF blade cannot be milled to the final nominal AM shape.

3.2. Solving methodology

To solve this problem, one way is to improve the hot forming accuracy and another is to reconstruct the final nominal AM shape. This paper attempts to find a solution by reconstructing the final nominal AM shape. Fig. 2 shows the methodology of geometric reconstruction proposed in this paper. The nominal BM CAD model was first sliced into 2D cross-sections and measurement points were generated from each cross-section. On-machine measurement was used to acquire shape point data of each cross-section. The measurement operation was performed twice with the same planned measurement points. The measured points from the first operation were used to match with nominal CAD shape to find the appropriate position. The second operation with the updated position was performed to build the point-pairs for the calculation of FFD volume. According to the distances between point-pairs, the FFD volume of each cross-section was calculated. To evaluate the FFD calculation accuracy, the deformation error (d) was analyzed. If d was greater than the threshold value ε, the FFD volume was iteratively calculated again. Otherwise, the calculated FFD was applied to each cross-section of final nominal AM shape. Finally, the final nominal AM 3D shape was reconstructed by lofting deformed 2D cross-sections. In this paper, the number and distribution of the measurement points are well planned in order to ensure calculation accuracy. Actually, this approach also can solve the case of incomplete point cloud if the accuracy loss is ignored.

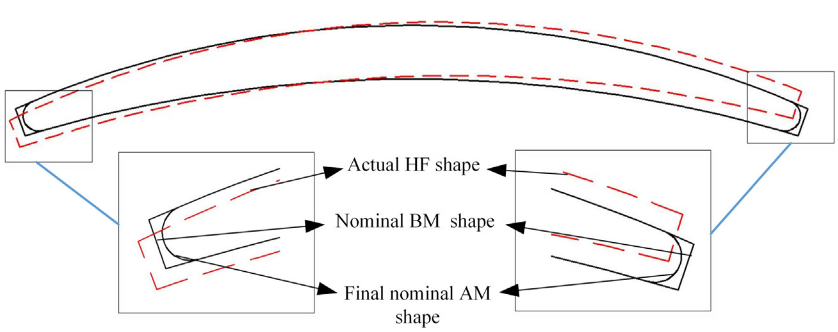

Fig. 1. Schematic of three cross-sections on a blade: actual HF shape, nominal BM shape and AM shape.