Analysis of Dynamic Characteristics of a Propeller Blade Subjected to Large Material Removal in Milling

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***Abstract*—A propeller blade, as a typical example of low-rigidity components, is prone to chatter and deformation in machining process, especially when large material removal is applied. In order to foresee the problems and then optimize the process, identification of the dynamic behavior of the workpiece is of great importance. This paper studies the dynamic characteristics of the workpiece in the machining process from plate to propeller blade using Finite Element Method. The results show that the time-varying natural frequencies of the workpiece decrease gradually at the beginning steps of the process due to the influence of material removal, and increases afterwards influenced by the geometry of the blade.**

***Index Terms*—surface machining, propeller blade, whirling, dynamic characteristics**

I. Introduction

Propellers are a type of mechanical fans that convert rotational motion into thrust. To this end, a propeller employs a number of aerofoil-shaped blades that are geometrically constructed out of functional free-form surfaces. The curved and slender shape of the blades plays a prominent role in their propulsive performance. Nevertheless, it also endows the blades with typical characteristics of thin-walled components.

Blade machining is recognized as an intractable task due to the low-rigidity and geometrical complexity of the workpiece. The related literature shows intensive research has been conducted with respect to blade modeling and tool path generation [1]-[3]. Usually blade components are shaped by 5-axis milling process using end mills. This is quite an established approach with acceptable precision and surface finish, although it is not wholly satisfactory because the machine tools are usually quite expensive and the tool path algorithms are very complicated. In recent years, researchers also worked on alternative ways for machining blades or blade-like components, for example, ref. [4] proposed to use circular disk mill cutters, and [5] and [6] examined the feasibility of blade whirling. While these approaches prove more cost-effective, the larger material removal rate in the process makes the product quality more liable to deformation and vibration due to the low-rigidity of the workpiece and the dynamic characteristics of the process.

Accurate dynamics characterization is the precondition for prediction of the machining process [7]. In recent years, time-varying dynamic characteristics corresponding to material removal during the machining process have gained much attention. Previous work pointed out that the influence of the material removal on the dynamic characteristics of the workpiece was not negligible [8], [9] and the dynamic characteristics in different stages of machining would affect chatter stability especially in thin-walled workpiece machining [9], [10].

Generally, impact hammer test and shaker test are the most common methods for identifying dynamic parameters [11]. Kuljanic [12] compared four types of sensors (rotating dynamometer, accelerometers, acoustic emission and electrical power sensors) and picked out the optimal muti-sensor system for chatter singles. Iglesias [7] provided a method called SMFE(sweep milling force excitation) procedure that allowed obtaining the FRF (frequency response function) by using the actual machining force under real cutting condition. And ref. [13] presented a methodology for prediction of time-varying dynamics by using the FRF only once.

However, it is not straightforward in some cases to conduct an impact hammer test and capture the dynamic responses of the in-process workpiece, because the workpiece and cutting tools are usually in complex multi-axis moving or rotating condition. Numerical methods are effective alternatives in view of the difficulty of the application of online measurement during the real machining situation. Bartosz [14] established a way for precise determination of the varying FRF by utilizing

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modal analysis based on workpiece acceleration measurement during machining. Kersting [15] evaluated the time- and position-dependent dynamics in five-axis NC milling process of thin-walled component. Biermann [16] presented a simulation system considering the geometry and regenerative workpiece vibrations during the five-axis milling process. Budak [9] used the cutter location(CL) files to determine the removed elements at each tool location and predicted the in-process blade workpiece dynamics based on a structural dynamic modification scheme by using FEM model of the initial workpiece.

This paper aims to identify the dynamic characteristics of the propeller blade workpiece subjected to large material removal through numerical simulation. In order to estimate the dynamics of the in-process propeller blade workpiece considering the material removal effect and the blade geometric character, the machining process is divided into several steps, each corresponding to a strip of the workpiece.

II. Modal Analysis of Propeller Blade Workpiece in Process

A propeller blade can be produced through machining out of a piece of raw material. Usually a cuboid-shaped piece of material which is similar to the blade component in size is used as the raw workpiece and the milling is carried out along the tool path pre-defined as shown in Fig. 1. For a certain position on the blade, the overall vibration could be simplified to linear superposition of oscillations corresponding to the harmonic components of excitation.

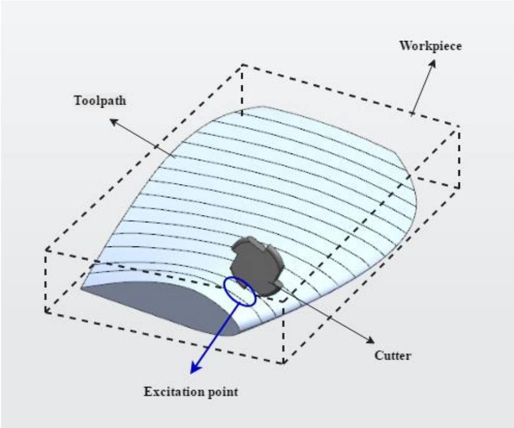

Figure 1. Blade machine schematic

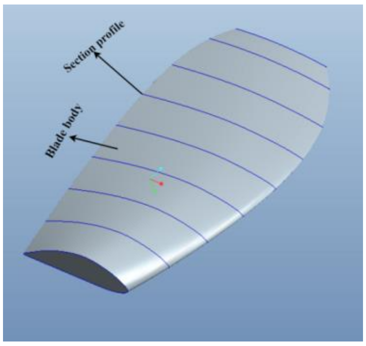

Figure 2. CAD model of propeller blade

Blades are defined by a series of cross-section profiles and several radial locations [17], [18]. In this paper, a propeller blade approximately 150mm long is chosen as the object of analysis. It is modeled based on 9 section profiles, which are each described by 34 data points. The established objective blade model is illustrated in Fig. 2.

To obtain the natural frequencies of the blade workpiece corresponding to the material removal during the machining process, the workpiece is divided into strips considering the geometric feature and simulation is carried out respectively.

A rectangular plate with geometric dimensions 200mm×108mm×20mm is selected as the original workpiece, with a cylinder on one end and a center hole on the other for the sake of clamping. Huge amount of material needs to be removed during the machining process due to the obvious difference in volume between the rectangular plate and the desired blade geometry.

To identify the dynamic characteristics of the workpiece during the material removal process, numerical analysis is conducted. The portion of the original workpiece to be machined is divided into 15 strips arranged in order of material removal. Each strip is 10mm wide and further separated into 6 chunks as shown in Fig. 3. In this way the workpiece is marked off into 90 zones to be machined.

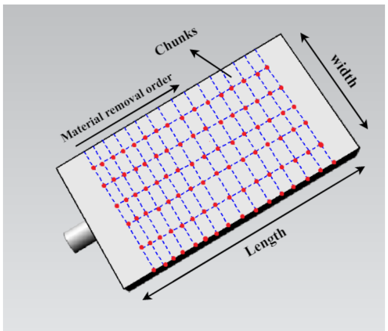

Figure 3. Discretization of the original workpiece

A commercial software package is used to construct the 3D model of the workpiece. The instantaneous geometry of the workpiece at each strip is modeled based on Boolean operations.

These geometrical models are then imported into a finite element analysis software package. For convenience we suppose that the workpiece is made of general material Cooper Alloy with its density, Young`s modulus and Poisson`s ratio being constantly 8300kg/m^3, 11GPa and 0.34 respectively, regardless of the stages of material removal.

The boundary conditions of the workpiece are as follows: two fixed constraints are exerted to the cylinder and center hole at each end of the workpiece mentioned above to mock up the clamping conditions. Solid partition type 10 nodes tetrahedral units (solid187) was selected for the model grid partitioning. The meshing size is set to default by the software. The amount of mesh varies with each individual, for example, there are about 1833 elements and 3643 nodes in the model of step15.

Modal analysis is then implemented in the above-mentioned environment by importing the 90 models built corresponding to the machined chunks of the workpiece. The data of results is managed in MATLAB and illustrated in Fig. 4, Fig. 5, and Fig. 6. Fig. 4 displays the general distribution of the first order frequency of the workpiece that varies with the workpiece being machined chunk after chunk. Further, cubic fitting of these data is shown in the Fig. 5, in which we can see that the natural frequencies descend gradually with the material removal process at the beginning steps, however, as the material removal continues, a peak appears. Furthermore, through the natural frequencies distribution contour map illustrated in Fig. 6, it can be drawn that the variation of natural frequencies corresponding to the chunks with material removed of every strip is slight at the second half of machining strips but drastic changes at the first half stage.

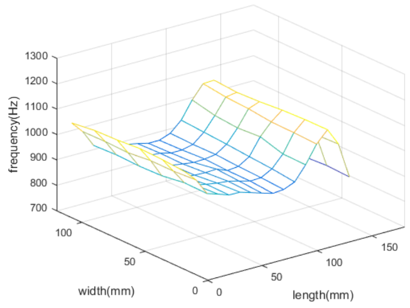

Figure 4. Natural frequencies with chunks removed

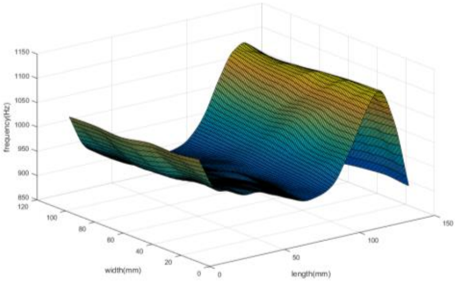

Figure 5. Fitted surface for the first frequencies

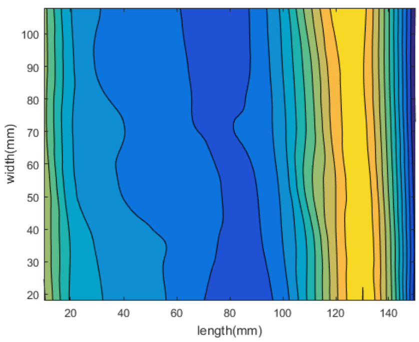

Figure 6. Contour map of 1st frequency

III. Harmonic Response Analysis

Based on the modal analysis, harmonic response analysis is implemented to establish the Frequency Response Function (FRF) for every machining step corresponding to each strip's material removal. For the response, the acceleration signal is selected as the object of analysis. A harmonic force perpendicular to the workpiece plane is applied at the end point on the blade body with the current strip finished. The frequency of the force is set to increase from 500Hz to 2000Hz with a 0.5Hz increment in estimation of the FRF, with the material damping ratio not being taken into account. As shown in Fig. 7, the peaks of the FRFs are zoned on the position-frequency plane which is consistent with the natural frequency results illustrated in Fig. 8. It shows that the natural frequencies in the second half of the machining process are affected more significantly by the removed material of the machined strips. It can be summarized that in machining the first half especially the middle of the workpiece, the material removal of each chunk along a strip produces a large impact on the variation of natural frequencies in width direction. However, at the second half the natural frequencies vary mainly with the removed strips.

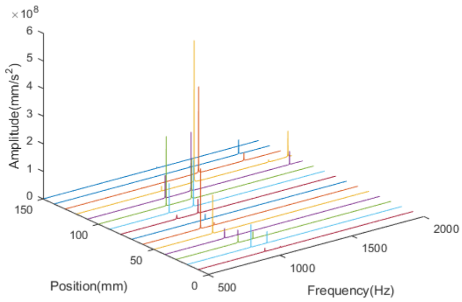

Figure 7. The FRFs of material removal strips

It`s worth noting that the acceleration signal peak values (Fig. 7) and the natural frequencies (Fig. 8) intensify sharply from step 8 to step 12 where the width and the curvature of the blade workpiece enter the stage of rapidly increase. The analysis result shows that the modal shape changes a lot as illustrated in Fig. 9. It is generally perceived that the first order natural frequency of a thin rectangular plate varies monotonously with the material removal in peripheral milling according to ref [10]. In this case, however, the natural frequency decreases firstly due to the material removal and an increasing trend follows from step8 to step12, which is similar to the results presented in ref [9], of which the object model is a turbine blade. The results imply that the particular geometry of the blade, in combination with material removal, may have an influence on its in-process dynamics.

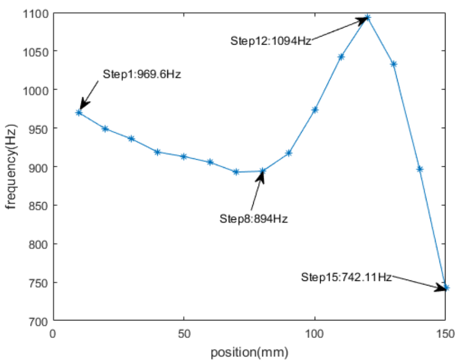

Figure 8. The change rule of 1st order natural frequencies

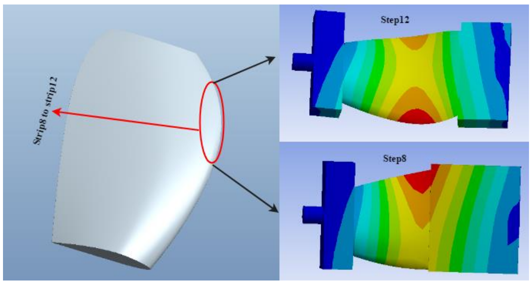

Figure 9. Modal shapes of step8 and step12

IV. CONCLUSION

This paper studied the effects of material removal on the dynamics of in-process workpiece of a propeller blade by using FEM. The FRFs of the workpiece with respect to progression of the machining process were evaluated. The results show the natural frequencies decrease gradually at the beginning steps of the process due to the influence of material removal, but increases afterwards, which implies that the dynamics are influenced not only by the material removal but also by the geometry of the blade. The results also suggest that natural frequency ranges need to be observed to guarantee the stability of the machining process. In this case for example, 885Hz-975Hz is the dangerous frequency range during the first half of machining process while 735Hz-1100Hz is the resonance minefield for the second half.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Luyi Han conducted the research and wrote the paper; Riliang Liu supervised the research and polished the paper. all authors had approved the final version.

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