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Virtual compensation of deflection errors in ball end milling of flexible blades

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ABSTRACT

The deflections of highly flexible turbine blades and slender end mills lead to tolerance violations during milling. This paper presents a digital simulation and compensation model for blade machining operations. Stiffness of the blade at the cutting zone is updated as the metal is removed without re-meshing using a computationally efficient sub-structuring technique. The cutter–workpiece engagement is evaluated by considering the deformations of both end mill and the blade under the cutting loads. The estimated deformations are compensated by modifying the tool path coordinates. The model has been experimentally verified in ball-end milling of a blade whose dimensional errors have been reduced from ~70 μm to ~10 μm.

1. Introduction

The current research trend is to digitally model the machining operations, and optimize them in virtual environment before conducting costly physical trials. A comprehensive review of the virtual machining research, which consists of modelling cutter–workpiece engagement (CWE), cutting forces, machine and machining dynamics, simulation and optimization of machining operations can be found in CIRP key note paper [1]. This paper focuses specifically on the accurate ball-end milling of integrally bladed rotors, which is mostly affected by the quasi-static deflections of highly flexible thin-walled blades and the slender tools. Currently, the dimensional errors are measured after a machining trial, and the tool path is modified to compensate the errors iteratively until the tolerance of the blade is satisfied. It is desired to develop the mathematical model of the process leading to prediction and compensation of deflection errors digitally to eliminate the costly machining tests.

Tool deflection errors are either controlled indirectly by constraining the cutting forces through feedrate scheduling [2,3], or by modifying the tool path [4]. Varying flexibility of the part along the tool path and changing tool–workpiece engagements due to the deflections of the tool and the part have not been considered. There have been studies to predict the deflections of the thin-walled parts in milling, where the static stiffness of the blade changes with the material removal. Biermann and Kersting [5,6] compared Finite Elements (FE), particle and oscillator based methods to predict the flexible workpiece deflections. These models are applicable for the analysis of a small portion of the workpiece due to the required complex mesh modifications and re-meshing. Budak et al. [7] combined FE with a structural modification technique to predict the structural dynamics of flexible parts. Koike et al. [8] updated the static stiffness of the in-process workpiece, and minimized the static deflections of a cantilevered beam by orienting the cutting forces in the direction having the highest stiffness. Instead of using computationally prohibitive re-meshing based methods, Tuysuz and Altintas [9] modelled the initial workpiece in FE only once, and analytically updated its static and dynamic stiffness as the material is removed by developing a substructuring method.

In this paper, a comprehensive virtual model of dimensional form errors and their compensation in ball-end milling of thin-walled blades are presented as outlined in Fig. 1. The article is organized as follows. The cutting force and cutter–workpiece engagement models for a rigid blade machining system are briefly overviewed in Section 2. The stiffness of the blade is updated analytically as the material is removed along the tool path (Section 2.1). The cutter–workpiece engagement boundaries are updated by considering both the tool and workpiece deflections induced by cutting forces (Section 2.2). The deflection errors are predicted and compensated by modifying the tool path in Section 3. The proposed form error reduction has been experimentally demonstrated in ball-end milling of a sample blade in Section 4, and the paper is concluded in Section 5.

2. Modelling of dimensional surface form errors

NC program for blade milling is assumed to be chatter free, and the objective is to estimate and compensate the static deflection errors imprinted on the blade surface as (Fig. 1). The time invariant static stiffness of the slender end mill is modelled as a cantilevered elastic beam divided into disk elements along its axis. The blade is meshed into discrete tetrahedral elements having the same nominal height of tool's discrete disk elements, and used to predict the time varying stiffness changes. First, the cutter–workpiece engagement (CWE) is estimated by assuming both parts as rigid using MACHpro^{TM}-Virtual Machining System [1]. The distributed cutting force vector $\boldsymbol{F}_q$ applied at each tool-blade

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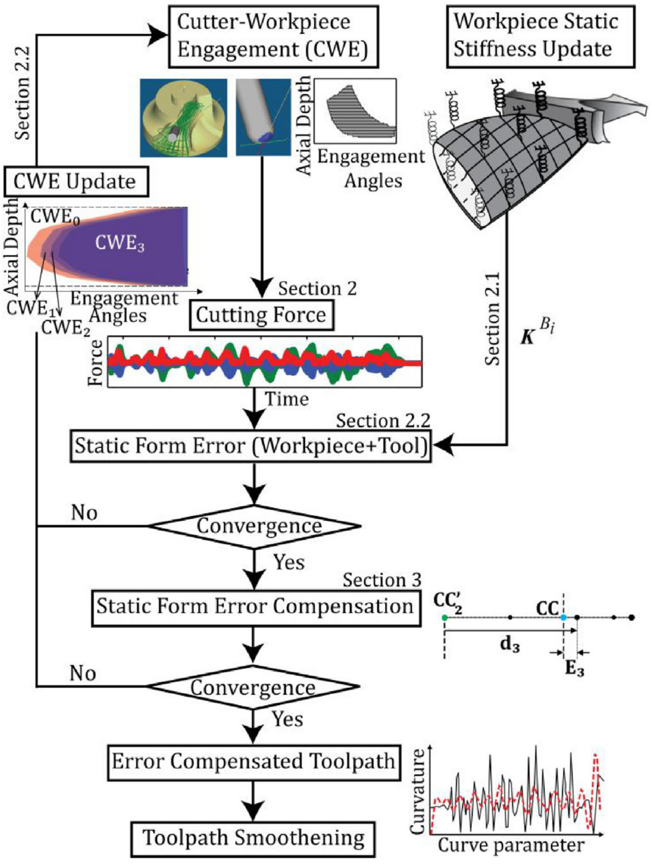

Fig. 1. Overall flow chart for the proposed scheme.

element along the contact zone is evaluated as:

$$\boldsymbol{F}_q = K_q h(\phi, z)\boldsymbol{d}(\phi, z)dz \quad (1)$$

where K_q denotes the cutting force coefficients in three directions (q ∈ (x,y,z)), $\boldsymbol{d}(\phi, z)$ is the directional factors matrix obtained from the projection of tool edge forces into Cartesian directions, and $h(\phi, z)$ is the chip thickness at the contact zone of the disk element with the height dz and the angular immersion (ϕ). The details of the milling force computation are well known and can be found in Ref. [1]. The deflection vector ($\boldsymbol{x}$) of each element on the tool and blade are solved from the following set of linear equations iteratively to avoid numerical instabilities,

$$\boldsymbol{K}\mathbf{x}_q = \boldsymbol{F}_q \quad (2)$$

where $\boldsymbol{K}$ is the stiffness matrix. While the cutting forces and the deflections can be evaluated with the well-established knowledge, the challenge is to consider the variation of the small radial engagements caused by the deflections of flexible tool and blade. Also, the blade's stiffness matrix varies as the material is removed, and its conventional computation by updating the geometry and remodelling in FE is computationally prohibitive to be used in practice. The authors developed a computationally efficient, general sub-structuring method to predict the dynamics of time varying, thin-walled structures without updating geometry and remeshing as presented in Ref. [9]. The computational cost is reduced from O(n^4) [10] to a linear form of O(n) with the proposed approach. In the blade example with 1500 cutter locations (CL), the computation is reduced from 13.5 s to 1.95 s per CL point. The method has been adopted to predict the stiffness matrix of the blades in ball-end milling as follows.

2.1. Blade stiffness update

Stiffness matrix of the blade blank B_0 is initially computed using a standard FE method. The removed volume A_i between two successive tool path locations ($i-1$) and i ($i = 1 \ldots k$) is defined as a substructure, and its stiffness contribution within the in-process blade B_{i-1} is directly cancelled by coupling a fictitious substructure having the same geometry but the opposite stiffness of the removed material A_i (Fig. 2). The stiffness of the workpiece B_i is automatically updated without re-meshing, which reduces the computation time. The time-dependent static stiffness of B_{i-1} is modified by adding the fictitious material (A_i) as

$$\boldsymbol{K}^{B_i}(t) = \boldsymbol{K}^{B_{i-1}}(t) + \left(-\boldsymbol{K}^{A_i}(t)\right) \quad (3)$$

where t is time, $\boldsymbol{K}^{B_{i-1}}(t)$ and $\boldsymbol{K}^{B_i}(t)$ are the static stiffness of B, respectively. The negative stiffness matrix of removed material A_i is $-\boldsymbol{K}^{A_i}(t)$. FE nodes of B_{i-1} and A_i are classified as the interface at the assembly zone and the internal nodes, each having three translational degrees-of-freedom (DOF). The force equilibrium for the blade structure at tool path location $i-1$ (B_{i-1}) is expressed as,

$$\boldsymbol{K}^{B_{i-1}}(t)\boldsymbol{x}^{B_{i-1}}(t) = \boldsymbol{F}^{B_{i-1}}(t) + \boldsymbol{r}^{B_{i-1}}(t) \quad (4)$$

where $\boldsymbol{x}^{B_{i-1}}$, $\boldsymbol{F}^{B_{i-1}}$, and $\boldsymbol{r}^{B_{i-1}}$ are the displacement, cutting force, and internal structural coupling force vectors, respectively. The coupling force $\boldsymbol{r}^{B_{i-1}}$ acts on the interface DOF of the fictitiously added substructure $-A_i$ due to coupling to the main blade body. Similarly, Eq. (4) can be written for the substructure $-A_i$ using the stiffness matrix of the substructure A_i as,

$$-\boldsymbol{K}^{A_i}(t)\boldsymbol{x}^{-A_i}(t) = \boldsymbol{F}^{-A_i}(t) + \boldsymbol{r}^{-A_i}(t) \quad (5)$$

The displacement compatibility and force equilibrium are applied to couple the blade body (Eq. (4)) and the fictitious material (Eq. (5)) at its DOF, i.e. $\boldsymbol{x}^{B_{i-1}} = \boldsymbol{x}^{-A_i}$ and $\boldsymbol{r}^{B_{i-1}} = -\boldsymbol{r}^{-A_i}$, when the tool is at path location $i-1$. The coupled set of equations gives the updated stiffness matrix ($\boldsymbol{K}^{Bi}$) of the blade after the metal A_i is removed,

$$\boldsymbol{K}^{B_i} = \boldsymbol{T}^T \begin{bmatrix} \boldsymbol{K}^{B_{i-1}} & 0 \\ 0 & -\boldsymbol{K}^{A_i} \end{bmatrix} \boldsymbol{T} \quad (6)$$

where $\boldsymbol{T}$ is the transformation matrix satisfying the coupling compatibility and equilibrium for B_{i-1} and $-A_i$. The mathematical details of the sub-structuring process including structural dynamics can be found in Ref. [9] for the general case. Recursive implementation of Eqs. (4)–(6) along the tool path leads to the updated static stiffness of the thin-walled blade as the material is removed, which is used for prediction of the workpiece deflections along the path.

2.2. Cutter workpiece engagement (CWE) update and deflection calculation

The surface errors are calculated by superposing the deflections of the tool and the workpiece at the blade–cutter contact points. CWE is discretized along the tool axis (z) and iteratively updated by modifying each discretized disk's entry, θ_1, and exit, θ_2, angles using the calculated combined tool and workpiece deflection (d) until the deflections converge. Possible three cases in iterations are defined in Fig. 3 where R_z is the local radius on the ball part of the tool at elevation z from the tool tip. For the cutter disk elements with differential height dz, CWE is transformed into the workpiece coordinate system, and the mesh elements containing the exit points

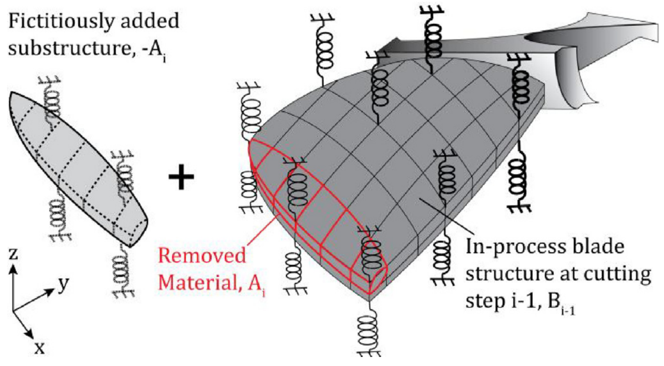

Fig. 2. Coupling of the fictitious substructure.

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