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Analysis of tool orientation for 5-axis ball-end milling of flexible parts

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ABSTRACT

This article investigates the effects of lead and tilt angles in 5-axis ball-end milling of flexible freeform aerospace parts by considering process mechanics. In current CAM technology, tool posture is determined by geometrical analysis only. However, in high-performance 5-axis milling, not only the geometry, but also the mechanics of the process is critical. Therefore, a new and comprehensive mechanics-based strategy is proposed for selection of tool postures considering process parameters such as cutting force, torque, part vibration, and surface quality. Effectiveness of the proposed strategy is validated by conducting experiments on 5-axis ball-end milling of flexible freeform structures.

1. Introduction

In today's competitive world, there is a significant demand for high-performance 5-axis milling of flexible parts in the aerospace industry. In the current state of the art of CAM technology, tool postures (lead and tilt angles) in 5-axis milling are determined only by geometrical concerns and the mechanics of the process has not been included yet. Ignoring the mechanics of the process may lead to the risks of suboptimal performance, such as undesired forces, tool/workpiece deflection, excessive vibration, poor surface quality, longer machining cycle time and relatively higher machining costs especially for freeform parts such as turbine blades, blisks and impellers. Nowadays, only geometry-based analysis for the selection of tool postures is not sufficient for competitive machining industries. In order to explore the full potential of 5-axis machining for higher performance, current selection strategy of tool orientation must be enhanced by considering mechanical constraints of the process.

Significant amount of research has been dedicated to gouge-free and geometry-based tool posture identification [1,2]. On the other hand, little research has been conducted to illustrate the effects of tool posture on mechanical parameters. Some studies considered the effects of tool orientation on wear [3], scallop height, workpiece accuracy, surface roughness [4] and the chatter stability [5]. The effects of tool orientation on multi-axis ball-end milling cutting forces were modeled in the frequency domain analytically using the convolution integration technique in rigid part machining [6]. Cutting forces for multi axis ball-end milling were modeled numerically in the time domain for rigid parts and did not focus on the effects of tool posture [7]. As indicated in all above-mentioned studies, 5-axis ball-end milling of freeform parts is challenging due to the fact that there are nonlinear relations between tool orientation and mechanical parameters of the process.

Despite all the research work have been carried out in this field, up to today, there is still a lack of mechanics-based strategy that is able to predict the ideal tool posture in 5-axis milling of flexible workpieces. Therefore, the aim of this article is to investigate the effects of lead and tilt angles on cutting force, torque, deflection and surface quality in 5-axis ball-end milling of flexible parts such as turbine blades. The novelty of the proposed strategy lies in presenting a mechanics-based reference map that suggests the appropriate tool orientation considering above-mentioned parameters. The effectiveness of the approach is demonstrated experimentally.

2. Effects of tool orientation on ball-end milling mechanics

A cutting force model for 5-axis ball-end milling developed already [7] is utilized here to estimate the cutting force and torque at each cutter location (CL) point. Fig. 1 depicts 5-axis ball-end milling of a flexible freeform part. In this figure, l and t represent lead and tilt angles respectively. dF_a, dF_t and dF_r are, respectively, the force components in axial, tangential and radial directions. $\psi(z)$ is the zenith angle and R is the nominal radius of the tool.

The differential cutting force components can be calculated as:

$$\begin{aligned} dF_{t,j}(\theta_j,\psi(z)) &= K_{tc}h(\theta_j,\psi(z))db(z)+K_{te}dS(z) \\ dF_{r,j}(\theta_j,\psi(z)) &= K_{rc}h(\theta_j,\psi(z))db(z)+K_{re}dS(z) \\ dF_{a,j}(\theta_j,\psi(z)) &= K_{ac}h(\theta_j,\psi(z))db(z)+K_{ae}dS(z) \end{aligned} \qquad (1)$$

where, θ_j, $db(z)$, h and $ds(z)$ are, respectively, the current angular position of cutting edge, the chip width, the instantaneous chip thickness and the length of cutting edge for a discrete disk j shown in Fig. 1b and c. K_{tc}, K_{rc} and K_{ac} are cutting constants and K_{te}, K_{re} and K_{ae} are edge constants in tangential, radial and axial directions, respectively [6,7]. The differential cutting forces in tool coordinate frame $(X_tY_tZ_t)$ are transformed to workpiece coordinate frames $(X_wY_wZ_w)$ as shown in Fig. 2a to determine the normal cutting force along the normal axis (Z_w) that cause deflection of the part due to

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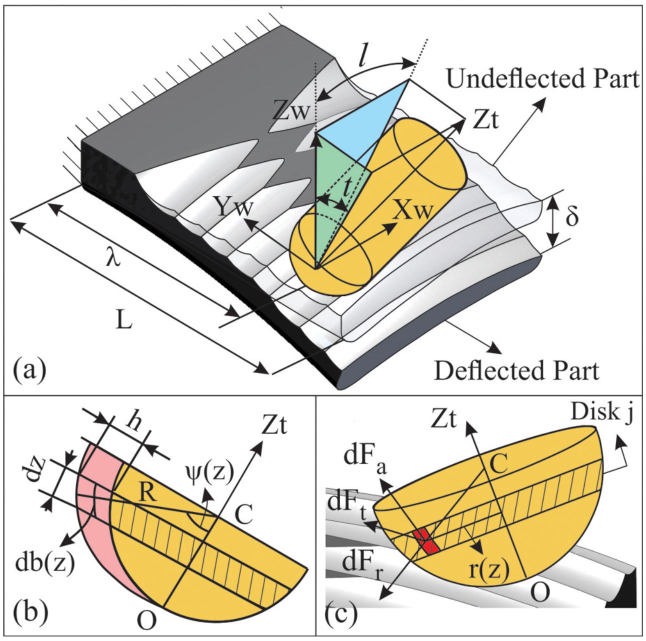

Fig. 1. (a) Tool posture in 5-axis ball-end milling of a flexible part, (b) Instantaneous chip thickness, (c) Differential force components.

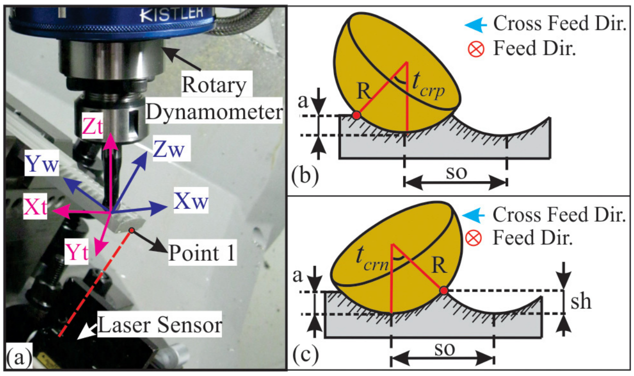

Fig. 2. (a) 5-axis milling of flexible cantilever workpiece (airfoil blade) (b) Critical positive tilt angle, (c) Critical negative tilt angle.

the bending as given below:

$$\begin{bmatrix} dF_{xw}\\ dF_{yw}\\ dF_{zw}\end{bmatrix} = [T]^{-1}[A]\begin{bmatrix} dF_r\\ dF_\psi\\ dF_t\end{bmatrix}$$
$$[A] = \begin{bmatrix} -\sin(\psi)\sin(\theta) & -\cos(\psi)\sin(\theta) & -\cos(\theta)\\ -\sin(\psi)\sin(\theta) & -\sin(\psi)\sin(\theta) & \sin(\theta)\\ \cos(\psi) & -\sin(\psi) & 0\end{bmatrix} \qquad (2)$$
$$[T] = \begin{bmatrix} \cos(l) & 0 & \sin(l)\\ \sin(t)\sin(l) & \cos(t) & -\sin(t)\cos(l)\\ -\cos(t)\sin(l) & \sin(t) & \cos(t)\cos(l)\end{bmatrix}$$

Differential cutting torque can be determined by local radius $r(z)$ and differential tangential force (Fig. 1c) as the following;

$$d\tau = r(z)\cdot dF_t \qquad (3)$$

The differential cutting force and torque in Eqs. (2) and (3) are integrated along cutter-workpiece engagement domain defined by a solid modeler kernel to find the total cutting force and torque [7]. The flexible workpiece shown in Figs. 1a and 2a is modeled as a cantilever beam. The maximum static deflection of flexible part along Z_w at point 1 can be determined from;

$$\delta = \frac{F_{zw}\lambda^2}{6EI}(3L-\lambda) \qquad (4)$$

L and λ are the length of the flexible part and the distance of the tool from the fixture as shown in Fig. 1a. E and I are the elastic modulus and the area moment of inertia determined numerically.

3. Effects of tool orientation on the cutting force waveforms and on the forced vibration of a flexible part

Changing tool orientation in 5-axis ball end milling directly affects the instantaneous tool-workpiece engagement region. Therefore, magnitudes and waveforms of cutting forces, as well as forced vibration amplitudes of flexible parts are affected by tool posture. In the cases when the tool tip is in contact with the workpiece, the cutting process would be less interrupted which in turn reduces the magnitude of the tool and workpiece oscillations because of the lower fluctuation of cutting forces. However, due to the fact that cutting speed at the tip of the tool is zero, having the tip in contact causes poor surface quality and significant ploughing forces [8]. In order to solve this problem, all the possible discrete lead and tilt angle pairs, which make the tool tip in contact with the workpiece are determined from engagement model. Then, the tool tip was adjusted marginally to be located outside of the tool-workpiece engagement domain. It is experimentally proved in Section 4.1 that this strategy leads to pseudo-constant cutting force magnitudes with lower fluctuations on the waveforms and therefore lower forced vibration on the flexible parts.

In order to prevent the tool tip from contact with the workpiece, the critical positive and negative tilt angles (t_{crp} and t_{crn}) should be considered based on Fig. 2b and c as the following;

$$t_{\text{crp}} = \cos^{-1}\left(1-\frac{a}{R}\right);\, t_{\text{crn}} = -\tan^{-1}\left(\frac{so}{2(R-a)}\right) \qquad (5)$$

The critical lead angle l_{cr} can be calculated as;

$$\begin{aligned} l_{\text{cr}} &= -\cos^{-1}\left(\frac{R-sh}{R\cos(t)}\right) \text{ for } t_{\text{crn}} \le t \le 0\\ l_{\text{cr}} &= -\cos^{-1}\left(\frac{R-a}{R\cos(t)}\right) \text{ for } 0 \le t \le t_{\text{crp}}\end{aligned} \qquad (6)$$

where a, sh and so are respectively depth of cut, scallop height and step over.

4. Simulation and experimental validation

The effects of tool posture on the magnitudes and waveforms of cutting force, torque as well as on the forced vibration of the flexible part and the quality of machined surface are investigated. The experimental setup is shown in Fig. 2a. The cutting force and torque were measured using a Kistler 9123C rotary dynamometer. Deflection of the workpiece was measured at point 1, which is located at the tip of the workpiece, using a Keyence LK-H052 laser displacement sensor with 0.025 [μm] repeatability and ±0.02% linearity. All of the simulation and experimental cases were designed for Al 7050 blocks with 98 × 38 × 10 [mm^3] dimension. A two fluted ball-end mill with the diameter of 12 [mm] was used in all cases. Other cutting parameters are indicated in Table 1. Experiments were designed and conducted in Mori Seiki NMV 5000 DCG 5-axis vertical machine.

Table 1
Cutting parameters in ball-end milling of the flexible airfoil parts.

Operation	Roughing	Semi-finishing	Finishing
Depth of cut [mm]	1	0.6	0.15
Step over [mm]	5.8	1.4	0.35
Spindle speed [rpm]	2500	3500	4500
Feedrate [mm/min]	250	350	500

4.1. Effect of tool posture on cutting force waveforms

The effects of the tool posture on the engagement domain and on the cutting force waveforms and magnitudes are investigated. Feasibility of the proposed strategy presented in Section 3 is illustrated with an example in Fig. 3. The cutting forces were acquired while 5-axis milling of the airfoil blade shown in Fig. 2a. Spindle speed, feedrate and depth of cut were respectively 2500 [rpm], 250 [mm/min] and 1 [mm].

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