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# Process simulation integrated tool axis selection for 5-axis tool path generation

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ABSTRACT

In 5-axis tool path generation the tool axis is usually selected based on the workpiece geometry only, ignoring its effects on the process and machine tool motion. In this paper, a process simulation integrated tool axis selection approach is proposed to adjust the tool axis vectors in an already generated 5-axis milling path for improved process in terms of cutting forces, stability and machine tool motion. The part surface data, required to re-calculate the tool axis, is extracted from the existing path. The proposed approach is demonstrated on a representative case.

## 1. Introduction

5-Axis milling is widely used in machining of parts with complex geometries in high value manufacturing industries such as nuclear, aerospace and automotive. Use of ball end mills increases contouring capability, where the tool posture is varied along the tool path to overcome geometrical constraints. This causes cutter-workpiece engagement boundaries (CWEB) vary along the tool axis and throughout the tool path [1,2]. As the mechanics and dynamics of cutting are closely related to the CWEB, the tool posture has significant effects on the cutting performance.

Tool path generation for 5-axis milling of free form surfaces has been studied for the last decades [3,4], where selection of tool posture is subject to several concerns. Collisions and gouges have to be avoided [5] and smooth machine tool motion should be sustained [6]. Additionally, process stability is of great importance and low cutting forces are preferred [7,8]. Current CAM packages consider only collision and gouging in tool posture selection. However, the tool postures meeting such kinematic concerns may not guarantee process stability and lowered cutting forces, which can be achieved by adjusting the tool posture. On the other hand, selection of tool posture according to stability and cutting force analysis only, may not sustain smooth machine tool motion. Thus, process mechanics, dynamics and machine tool motion should be considered concurrently in tool posture selection for improved process performance and part quality.

Geometrical simulations were integrated with tool path generation as the first attempt to improve 5-axis milling. Leu et al. [9] developed a geometrical verification approach for 5-axis milling, compatible with generalized APT tool definition. Lauwers et al. [10] used NC simulation in tool path generation to adjust the tool posture to avoid collisions. Tool posture significantly affects the rotary axes motion. In a recent study, a graph based approach was developed to minimize rotary axes displacements [6]. It was shown that the rotary axes motions can be robustly smoothed by adjusting the tool posture. Later, developments in modeling of 5-axis milling enabled the use of process models in selection of cutting parameters for ball-end milling [11–13]. The first integrated virtual machining system [2] was developed for 3-axis milling [14] to select process sequence and parameters using physical process models. Recently, the effects of tool posture on the mechanics and dynamics of the cutting process were emphasized in two studies. Shamoto et al. [7] proposed chatter stability index to optimize tool posture for increased stability in turning. Layegh et al. [8] on the other hand, investigated the effect of tool posture on 5-axis milling of flexible parts. They showed that consideration of cutting force, and part vibration in tool posture selection lead to improved process performance. In the literature, majority of the studies focus on tool path generation for a known surface rather than adjusting the tool postures for an already generated 5-axis milling cycles. Besides, use of process models in tool posture optimization for a whole tool path has not been studied, which requires integration of process simulations with tool path generation. In this paper, as the first time in the literature, a novel tool posture optimization approach is proposed for already generated surface milling cycles. The part surface location and normal vector data is extracted from the tool path file using a novel geometrical technique [15]. Chatter stability, cutting forces and machine tool motion are considered in optimization of the tool postures along the tool path.

## 2. Simulation of 5-axis milling

In 5-axis milling, the cutter location (CL) and orientation with respect to the part surface vary along the tool path. Thus, the cutting depth, $a$, step over, $s$, lead angle, $l$, and tilt angle, $t$, and

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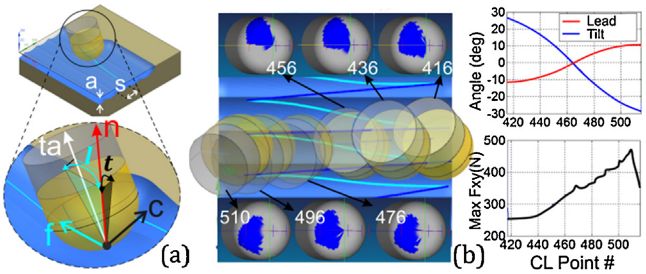

**Fig. 1.** 5-Axis milling, (a) cutting parameters, (b) variation of CWEB.

hence the CWEB vary at each CL point as shown in Fig. 1, requiring process simulation to identify the feasible tool postures.

### 2.1. Mechanics and dynamics

A previously developed process simulation approach [1] is utilized in this paper. The cutting parameters are analytically extracted [1] to identify CWEB. The cutting forces are simulated using mechanistic model and the stability limits are calculated in frequency domain [1]. The cutting force coefficients are calculated through orthogonal to oblique transformation.

### 2.2. Characterization and simulation of machine tool motion

In this paper, machine tool motion is considered in tool posture selection through simulations in order to avoid jerky rotary axis motions and significant slowdown of the feed rates leading to increased actual cycle time. Simulation of machine tool motion and response time requires the jerk, acceleration, and feed limits to be known, which are obtained experimentally using two setups. The first setup involves high resolution short distance displacement sensor with ±5 mm measuring range as shown in Fig. 2a. Laser interferometer was used in the second setup to measure axis motions in longer blocks. The linear and rotary axes were individually commanded to move 5 mm and rotate 1°, respectively. The motion limits are then extracted from the measured displacement data. The feed profiles of the linear axes for a representative test are plotted in Fig. 2b. It can be seen that the feed limit is 0.055 m/s, at which the measured feed saturates. By such an experimental approach the mass inertia effect and unideal conditions of the axes are included in the identified limits.

In machine tool motion and response time simulation, firstly the machine tool axis positions are calculated by post processing [16] the cutter location and postures. Then, the time required for each axis to complete a motion block is calculated considering seven phases of feed profile (see Fig. 2c). Seventeen types of feed profiles are considered for continuity of feed and acceleration.

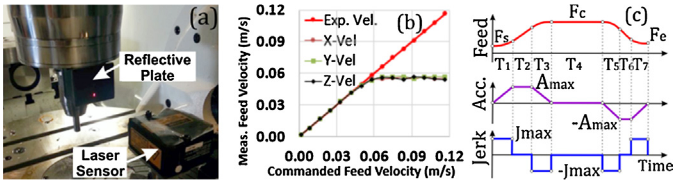

**Fig. 2.** Characterization and simulation of machine tool motion (a) setup, (b) velocity profile, (c) seven phases of feed rate profile.

## 3. Simulation based tool posture selection

In this paper, as the first time in the literature a new approach (see Fig. 3a) is proposed to modify an already generated milling tool path by adjusting the tool posture to achieve the desired stable cutting depth, smooth machine tool motion and lowered cutting forces throughout the tool path. The approach is able to handle the tool paths generated for isoparametric surfaces. The part surface data, required to calculate new tool posture and location, is analytically extracted directly from the CL file [15].

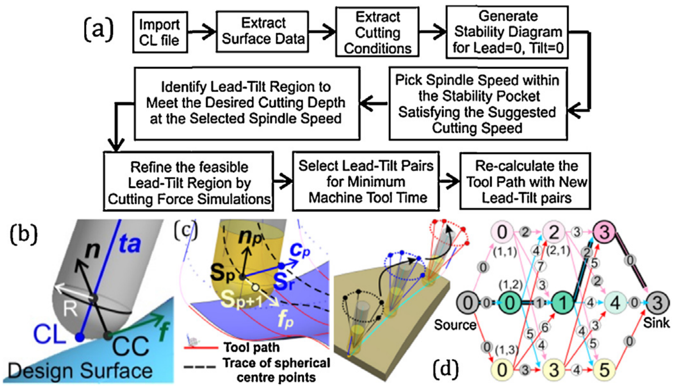

**Fig. 3.** Tool posture adjustment, (a) proposed approach, (b) tool path calculation, (c) extraction of surface data, (d) tool posture network.

### 3.1. Extraction of the part surface data from the CL file

In 5-axis milling tool path generation, at the **p**th cutter contact (CC) point, $\mathbf{CC_p}$, the tool axis vector, $\mathbf{ta_p}$, is calculated by sequential rotation of the surface normal vector, $\mathbf{n_p}$, around the feed vector, $\mathbf{f_p}$, and the cross feed vector $\mathbf{c_p}$, by lead and tilt angles, respectively. Then, the **p**th CL point, $\mathbf{CL_p}$, is derived (see Fig. 3b).

$$\mathbf{ta_p} = [R(\mathbf{c_p}, lead)][R(\mathbf{f_p}, tilt)]\mathbf{n_p} \tag{1}$$

$$\mathbf{CL_p} = \mathbf{CC_p} + R(\mathbf{n_p} - \mathbf{ta_p}) = \mathbf{S_p} - R\mathbf{ta_p} \tag{2}$$

where, $[R(u, \theta)]$ is the rotation matrix around vector $u$ by angle $\theta$.

The inverse solution of Eq. (2) is used to extract the cutter contact points. The surface normal vector is calculated as the cross product of the feed and cross feed vectors, which are calculated between two consecutive spherical center points, **Sp** and **Sp + 1**, and two neighboring spherical center points at the consecutive steps, **Sr** and **Sp**, respectively (see Fig. 3c) [15].

### 3.2. Selection of optimized tool postures

The proposed approach adjusts the tool posture at each CC point to minimize the total machine tool response time subject to stability and cutting force. Such a task resembles solving a shortest path problem for a sequentially connected graph of alternative tool postures (Fig. 3d). Process simulations are used to identify feasible regions of lead-tilt pairs at each CC point. The machine tool response time between the alternative tool postures are calculated as the cost. Then, the minimum cost path in such a graph is found by Djiktra's algorithm [17], implying smooth machine tool motion without axis reversals. This way, the desired stable cutting depth is achieved by adjusting the tool posture along the tool path while sustaining smooth machine tool motion with lowered cutting forces. In Fig. 3d, a representative connected graph for three CC points is shown together with the arbitrary costs. Initially, the cost at the source node is zero. Then, by sequentially moving from the source to the sink, at each CC point the corresponding cost of an alternative node is calculated as minimum of the previous nodes' cost plus the arc connecting it to the previous node. For instance the cost of node (2, 1) is min {(0 + 2), (0 + 4), (0 + 7)} = 2. Then, the shortest path is calculated by backtracking from the sink node to the source nodes as shown by the highlighted arrows in Fig. 3d.

## 4. Determination of feasible region of tool postures

The mechanics and dynamics of milling depend on the CWEB, which varies with the tool posture as shown in Fig. 1b, where the cutting depth and step over are constant but the lead and tilt angles vary. It is seen that the simulated bending force varies significantly. Similarly, tool posture affects stability limits. However, picking a constant tool posture may not be feasible for the part geometry and/or smooth machine tool motion. In this paper, the feasible