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Chatter free tool orientations in 5-axis ball-end milling

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ABSTRACT

Dies, molds and parts with complex free form surfaces are usually machined with ball end mills on 5-axis CNC machining centers. This paper presents automatic adjustment of tool axis orientations to avoid chatter along the tool path. The process mechanics and dynamics of ball end milling are modeled in cutter-workpiece engagement coordinate system. The structural dynamics of tool and workpiece are transformed to cutter-workpiece engagement coordinates by considering the tool path and the kinematics of the machine tool. The stability of the 5-axis ball end milling is modeled at each tool path location, and the chatter free tool axis orientations are searched iteratively using Nyquist criterion while avoiding gouging limits. The tool path, i.e. cutter location (CL) file, is updated to generate chatter free, 5-axis ball end milling of the parts. The proposed algorithm has been experimentally proven in 5-axis ball end milling tests.

1. Introduction

Ball end milling is commonly used in finish milling of dies, molds, impellers, turbine blades and other parts with complex sculpture surfaces. The tool axis direction is always constant in 3 axis machines, but can be oriented to avoid collision and zero speeds at the tool tip on 5-axis machine tools. This paper presents a method to predict tool axis orientations to avoid chatter in 5-axis ball end milling of parts with free form surfaces.

There has been significant research reported in 5-axis milling, but mainly on tool path generation and collision avoidance as summarized by Lasemi et al. [1]. The tool path generation and collision avoidance methods are based on wokpiece geometry and machine configuration, hence the physics of machining are not considered. Recent research efforts considered the servo drives, contouring errors, and the kinematics of 5-axis machine tools. Sencer et al. [2] modeled the contouring errors as a function of tool tip, tool orientation, path curvature and servo dynamics. Beudaert et al. [3] and Yuen et al. [4] optimized the tool orientation to generate smooth tool paths while avoiding to violate the torque limits of all drives in 5-axis machines.

The process related research in tool axis orientation considers the static and dynamic flexibilities of the workpiece and tool. Lazoglu et al. [5] optimized the tool orientation to constrain the static deflections of tools and parts perpendicular to the finish surface. Although significant research has been reported in the stability of machining operations [6], there has been a very limited effort reported in optimizing the tool orientation to avoid chatter in 5-axis ball-end milling of free form surfaces. Ozturk et al. [7] modeled the influence of tool's tilt and lead angles of the tool on the stability of 5-axis ball end milling operations. They used both zero order and multi-frequency stability solutions [6] to generate stability lobes as a function of tool's lead and tilt angles. However, the engagement and the FRF directions vary with the change of tool orientation along the tool path. The chatter free tool path planning requires the identification of most optimal tool orientation and depth along the curved, 5-axis tool path, which is presented in this paper.

The frequency response functions (FRF) of the machine and workpiece are assumed to be measured in their stationary coordinate systems. The relative FRFs between the tool and part are transformed to moving tool-part engagement coordinates where the ball end milling process stability is modeled. The tool-part engagement conditions, feed direction and kinematics of the machine tool are considered in constructing the stability equation in frequency domain. The rotary drive positions of the machine which determine the tool axis orientation are searched to achieve chatter free, stable cutting conditions along the tool path. The proposed method is experimentally validated with 5-axis ball end milling tests.

Henceforth, the paper is organized as follows. The dynamics of ball end milling system is modeled in engagement coordinate

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Nomenclature

WCS	workpiece coordinate system
ECS	engagement coordinate system
MCS	machine coordinate system
ECS_m	modified engagement coordinate system
ϕ_{st}^l, ϕ_{ex}^l	entry and exit angle of the engagement map of axial disk element l
z_{bottom}^l, z_{top}^l	bottom and top z value of the engagement map of axial disk element l
$\phi_j(z, t)$	radial immersion angle at time t and elevation z from the tool tip
$\kappa(z)$	axial immersion angle at elevation z from the tool tip
$g(\phi_j)$	unit step function that determines whether the tooth is in or out of cut
K_{rc}, K_{tc}, K_{ac}	oblique cutting force coefficients in radial, tangential and axial directions, respectively
Δz	height of differential axial disk elements
$h_d(t)$	dynamic chip thickness
$\Delta \mathbf{q}_E$, $\Delta \mathbf{q}_{E_m}$	relative dynamic displacement between the tool and workpiece in ECS and modified ECS, respectively.
$\Delta \mathbf{q}_M$, $\Delta \mathbf{q}_{MW}$	dynamic displacement of tool in MCS and WCS, respectively.
$\Delta \mathbf{q}_W$	dynamic displacement of workpiece in WCS
$\Delta \mathbf{q}_{W_t}$	relative dynamic displacement between the tool and workpiece in WCS
$\mathbf{n}(\phi_j(z, t))$	surface normal vector at cutting edge
$\mathbf{A}(\phi_j(z, t))$	directional matrix
$\mathbf{A}_0$	average of directional matrix
$\mathbf{F}_E$, $\mathbf{F}_M$, $\mathbf{F}_W$	dynamic cutting forces in ECS, MCS and WCS, respectively.
$\mathbf{\Phi}_E$	relative FRF between the tool and workpiece in ECS
$\mathbf{\Phi}_M$	FRF of the tool measured in MCS
$\mathbf{\Phi}_W$	FRF of the workpiece measured in WCS
$\{\vec{P}_W, \vec{O}_W\}$	original tool tip coordinate and orientation vector, respectively.
$\{\vec{P}_{Wm}, \vec{O}_{Wm}\}$	modified tool tip coordinate and orientation vector, respectively.
θ_A, θ_C	angular positions of A and C axis, respectively
$\mathbf{R}_{E-W}$	rotational transformation matrix from ECS to WCS
$\mathbf{R}_{Em-W}$	rotational transformation matrix from modified engagement coordinate system ECS_m to WCS
$\mathbf{R}_{MW}$	rotational transformation matrix from MCS to WCS
$\mathbf{R}_{Em-E}$	rotational transformation matrix from modified engagement coordinate system ECS_m to ECS
$[x_m \;\; y_m \;\; z_m]^T$	Cartesian coordinate of a vertex in ECS_m
$[R_0 \;\; \phi_m \;\; \kappa_m]^T$	Spherical coordinate of a vertex in ECS_m

system in Section 2. The tool and part dynamics, which change as a function of tool path and machine drive positions, are transformed to engagement coordinate system in Section 3. Chatter free tool orientations are predicted in Section 4. The proposed, chatter free tool axis orientation along the paths are experimentally proven in Section 5, and the paper is concluded in Section 6.

2. Coordinate transformations of vectors for process dynamics

A five axis ball end milling system is shown in Fig. 1. The tool path is generated in a Computer Aided Manufacturing (CAM) software environment using the Workpiece Coordinate System (WCS). The machining process is modeled in Engagement Coordinate System (ECS) where the Z is the tool axis; X-axis is in the tool axis-feed plane, and Y axis is normal to XZ plane. The chip thickness, hence the force distribution along the cutting edges, require the tool-workpiece engagement which is modeled in ECS (shown in Fig. 2). On each cutter location, the engagement of the cutter with workpiece is discretized at each tool location by series of discrete elements along the Z-axis of ECS. Each element has a thickness of Δz with an entry angle (ϕ_{st}) and exit angle (ϕ_{ex}) at each elevation (z). The FRFs of the machine tool and workpiece are needed to predict the relative vibrations between the tool and workpiece along the tool path. The FRF of the workpiece is measured in WCS. The spindle-holder-tool assembly has the most flexibility in ball end milling. Although the low frequency structural modes may change, the FRF of the spindle assembly does not change as the machine configuration varies in 5–axis motions. The FRF of the tool attached to the spindle is measured when the machine is at its home position at the Machine Coordinate System (MCS) as shown in Fig. 1. As the tool orientation changes along the 5-axis tool path, the vibrations must be projected to the tool tip at the ECS in order to predict the dynamic chip loads. The objective is not only to predict the chatter stability of 5-axis ball end milling, but also predict the most stable tool orientations of the ball end mill along the tool path to achieve highest material removal rates.

The geometry of a helical ball-end mill is given in Fig. 3. Due to ball end and helical flutes, the axial depth of cut, radial depth of cut, and the entry (ϕ_{st}) and exit (ϕ_{ex}) angles may change along the tool axis. The tool axis is divided into m number of differential axial disk elements with height Δz along the axial depth of cut. The engagement angles (ϕ_{st}, ϕ_{ex}) are identified by an in-house developed system as shown in Fig. 2 (MACHPRO) for each axial element. The process is defined in ECS where the tool tip position is at the center, and tool axis corresponds to Z_E axis. The stability of 3 axis ball end milling was previously modeled by Altintas at al. [8], and the dynamics of ball end milling is briefly summarized here for an engagement and speed. The cutting forces contributed by the differential axial disk element l at time t are summarized as:

$$\begin{bmatrix} dF_x^l[\phi_j(z,t)] \\ dF_y^l[\phi_j(z,t)] \\ dF_z^l[\phi_j(z,t)] \end{bmatrix}_E = \mathbf{T} \underbrace{\begin{bmatrix} K_{rc} \\ K_{tc} \\ K_{ac} \end{bmatrix}}_{\mathbf{K}_c} \frac{g(\phi_j)\Delta z}{\sin\kappa(z)} h_d(t) \tag{1}$$

where $\phi_j(z, t)$ is the radial immersion angle, $\kappa(z)$ is the axial immersion angle at elevation z from the tool tip. $g(\phi_j) = 1$ when the tooth is in cut, and $g(\phi_j) = 0$ otherwise. Matrix $\mathbf{T}$ transforms the forces from radial, tangential and axial directions to the Cartesian (x, y, z) directions:

$$\mathbf{T} = \begin{bmatrix} -\sin\kappa \cdot \sin\phi_j(z,t) & -\cos\phi_j(z,t) & -\cos\kappa(z) \cdot \sin\phi_j(z,t) \\ -\sin\kappa \cdot \cos\phi_j(z,t) & \sin\phi_j(z,t) & -\cos\kappa(z) \cdot \cos\phi_j(z,t) \\ \cos\kappa(z) & 0 & -\sin\kappa(z) \end{bmatrix} \tag{2}$$

The vector $\mathbf{K}_c$ contains oblique cutting force coefficients in radial, tangential and axial directions, respectively. The dynamic chip thickness ($h_d(t)$) contributed by the relative vibrations between the tool and workpiece in feed (X_E) and normal (Y_E)