SMOOTHNESS OPTIMIZATION OF 5-AXIS HIGH-SPEED FLANK MILLING TOOL PATHS

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Abstract: This work deals with the optimization of 5-axis flank milling tool paths regarding the geometrical deviations and the trajectory smoothness. Our approach consists in integrating the energy of deformation of the tool path as a smoothness parameter in tool path computation. The resulting tool trajectory minimizes a compromise between geometrical deviations and smoothness in the part coordinate system. In order to assess smoothness in the machine coordinate system, an estimation of the minimum machining time is calculated accounting for the machine tool kinematical limits. Finally the proposed approach is assessed through experimental investigations.

Keywords: CAD-CAM, high-speed machining, 5-axis flank milling, tool path smoothness, geometrical deviations

1 INTRODUCTION

The use of 5-axis flank milling within the context of High Speed Machining (HSM) allows the increase in material removal rate and is now widely used to machine complex parts such as turbine blades, ship propellers or impellers. Since most of the surfaces of these complex parts are non developable ruled surfaces or free-form surfaces, the challenge is to minimize overcuts and undercuts [Rehsteiner 1993]. In some cases, minimizing interferences leads to oscillatory trajectories which may involve process inefficiency during machining.

We have experimentally shown the interest of considering a smoothness criterion to enhance machining efficiency [Pechard et al. 2009]. Indeed, in most cases, the tool path is smoother as the energy of deformation associated decreases. As a result, the feedrate is higher and machining time shorter. Nevertheless, experimental results also highlighted that the tool path smoothness is enhanced to the detriment of the minimization of geometrical deviations. A compromise has to be made between both criteria accounting for the functional requirements.

The method developed consists in finding the smoothest tool trajectory respecting the geometrical requirements. Our approach is based on the concept of the Machining Surface (MS) [Duc et al. 1999]. This concept provides a continuous model of the tool path instead of an organized set of points and vectors. In 5-axis flank milling, the Machining Surface is a ruled surface, locus of the tool axes (Figure 1).

However, during machining a smooth trajectory in the part coordinate system (PCS) is not necessarily smooth in the machine coordinate system (MCS) considering the structure of the machine tool and the kinematical characteristics of the joints. In the present paper, we propose to establish the concordance between the prediction of a smooth motion via the energy of deformation and the actual behaviour during machining. The approach relies on the analysis of the kinematical constraints generated by the tool movement along the trajectory resulting from the kinematical limits of each machine tool axis. Such an analysis leads to an estimate of the

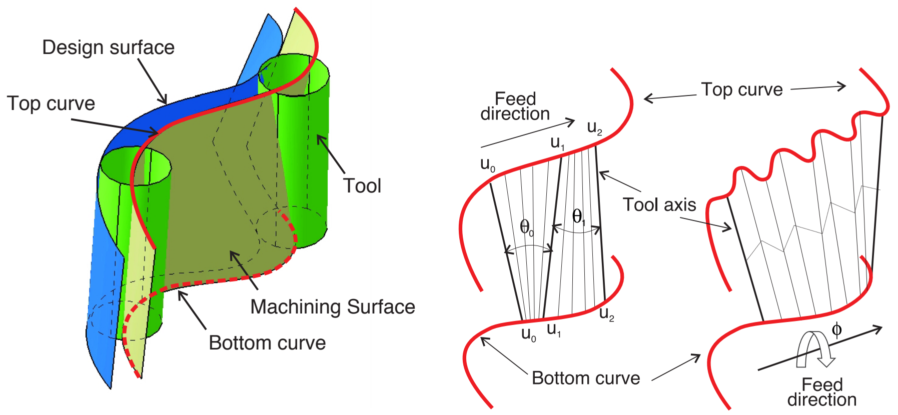

Figure 1: (a) The Machining Surface; (b) Pitch and roll angles

maximum feedrate the tool can reach. After a presentation of our method to optimize both the smoothness and the geometrical deviations, an application is proposed through the machining of an impeller. Results are then analysed in the PCS as well as in the MCS.

2 GEO5XF APPROACH

The minimization of the geometrical deviations guarantees the respect of the geometrical specifications. In the present approach, we use the least-square criterion to minimize the geometrical deviations. For each point of the design surface, the geometrical deviation e_k^2 between the design surface and the machined surface is computed as described in [Lartigue et al. 2003] leading to:

$$G_{dev} = \sum_k e_k^2 \tag{1}$$

In addition a minimum energy criterion is considered to account for tool path smoothness. The expression of the energy of deformation used is the one proposed by Wang et al. [Wang et al. 1997]. As the Machining Surface $S(u,v)$ is a ruled surface, the surface energy of deformation is defined by:

$$E_{def} = \iint_D \left(\left| S_{uu} \right|^2 + 2 \cdot \left| S_{uv} \right|^2 \right) dudv \tag{2}$$

The ruled surface $S(u,v)$ is defined by two B-spline curves $Cb(u)$ and $Ct(u)$ as follows:

$$S(u,v) = (1-v) \cdot Cb(u) + v \cdot Ct(u) \tag{3}$$

Thus giving:

$$E_{def} = \iint_{u,v} \left(\left|(1-v) \cdot Cb''(u) + v \cdot Ct''(u)\right|^2 + 2 \cdot \left|Ct'(u) - Cb'(u)\right|^2 \right) dudv \tag{4}$$

With such an expression, the evolution of the pitch and roll angles of the rules is considered during the deformation of the MS thanks to S_{uv} and S_{uu}. The first term of E_{def} with the second derivatives $Cb''(u)$ and $Ct''(u)$ represents the roll angle evolution and the second term with the first derivatives $Cb'(u)$ and $Ct'(u)$ represents the pitch angle evolution (Figure 1).

This yields to the objective function to be minimized:

$$W = \alpha \cdot G_{dev} + \beta \cdot \Delta E_{def} \quad (5)$$

where α and β are adjustable parameters as geometrical deviations or smoothness is preferred.

In general, the energy of deformation will increase during the optimization because the initial machining surface will be stretched and twisted in order to reduced the geometrical deviations. As the objective is to minimize this variation, the Single Point Offset algorithm (SPO) [Liu 1995] is used since it generates smooth tool paths. Then, the initial MS is determined by least square approximation with energy minimization of the directrix curves [Park et al. 2000] computed by the SPO method. Given this initial MS with low energy of deformation, we do not minimize the energy of deformation of the MS E_{def} but the variation of energy ΔE_{def}. Let S be the initial MS and $(S + \Delta S)$ the MS after displacement of the control points. The variation of the energy ΔE_{def} can be expressed in function of the energy of the initial surface as:

$$\Delta E_{def} = E_{def}(S + \Delta S) - E_{def}(S) \quad (6)$$

In order to obtain a linear system, we make the following assumption:

$$\Delta E_{def} = E_{def}(\Delta S) \quad (7)$$

The optimization consists in minimizing the function W relatively to the displacement of the control points of both the bottom and the top curves, δCb_l and δCt_m. This leads to solve a linear system of $3 \cdot (n_1 + n_2)$ equations where n_1 and n_2 are the number of control points of the bottom and top curves respectively:

$$\frac{\partial W}{\partial Cb_i, Ct_i} = 0 \quad (8)$$

3 SMOOTHNESS IN THE MACHINE COORDINATE SYSTEM

Although the smoothness criterion is defined in the part coordinate system, we propose to compare the variation of energy of deformation and the smoothness in the machine coordinate system. From a qualitative point of view, smoothness in the MCS is related to the geometrical derivatives of the joint movement [Castagnetti et al. 2008]. The idea is to calculate the limitations of the effective feedrate given by the velocity, acceleration and jerk limits of each machine tool axis considering the tool path geometry [Sencer et al. 2008]. Hence, we are able to propose an indicator of the smoothness in the MCS defined by an estimation of the machining time. The machining time is calculated by evaluating the maximum feedrate $\dot{s}$ that can be reached by the machine tool along the path. This work is done in the phase plane $(s - \dot{s})$ with s the path displacement $s \in [0, L]$, and $\dot{s}$ the feedrate.

Let $q(s) = [X(s)Y(s)Z(s)A(s)C(s)]^T$ be the vector defining the position of the 5 joints of the machine tool. Velocities, accelerations and jerks of the joints are expressed by the following equations:

$$\dot{q}(s) = \frac{dq(s)}{dt} = \frac{dq(s)}{ds}\frac{ds}{dt} = q_s(s)\dot{s} \quad (9)$$

$$\ddot{q}(s) = q_{ss}(s)\dot{s}^2 + q_s(s)\ddot{s} \quad (10)$$

$$\dddot{q}(s) = q_{sss}(s)\dot{s}^3 + 3q_{ss}(s)\dot{s}\ddot{s} + q_s(s)\dddot{s} \quad (11)$$

The three vectors $q_s(s)$, $q_{ss}(s)$ and $q_{sss}(s)$ are the geometrical derivatives of the trajectory in the joint space, they are thus easily computable. Note that their expressions are related to the derivatives of the Machining Surface which are minimized in the functional W.

Considering the physical limits of the axis in velocity, acceleration and jerk:

$$|\dot{q}| \leq V_{max}^{axis} \quad ; \quad |\ddot{q}| \leq A_{max}^{axis} \quad ; \quad |\dddot{q}| \leq J_{max}^{axis} \quad (12)$$

The equations (12) should be solved recursively because of the link between $\dot{s}$, $\ddot{s}$ and $\dddot{s}$. But neglecting the last terms of the equations we can find a good approximation of the upper limit of $\dot{s}$ in a close form (13).

$$\dot{s} \leq \min\left(\frac{V_{max}^{axis}}{|q_s|} \quad ; \quad \sqrt{\frac{A_{max}^{axis}}{|q_{ss}|}} \quad ; \quad \sqrt[3]{\frac{J_{max}^{axis}}{|q_{sss}|}} \right) \quad (13)$$

4 EXPERIMENTAL INVESTIGATIONS

The example concerns the flank milling of an impeller blade (Figure 2) on a 5-axis machining center with a RRTTT (A/C) structure. Two different tool paths have been computed using the Geo5xF approach: the first one emphasizes the geometrical deviation (least-square minimization of the geometrical deviations) and the second one the smoothness of the trajectory (minimization of energy of deformation). For each trajectory, two different formats of interpolation are tested: BSpline native curves and classical linear format. The first one allows the explicit calculation of the geometrical terms whereas for the second one the G^1 discontinuities have to be taken into account. Table 1 displays for each trajectory the values of overcuts and undercuts, the energy variation, the estimated machining time, and the actual machining time collected after air cutting.

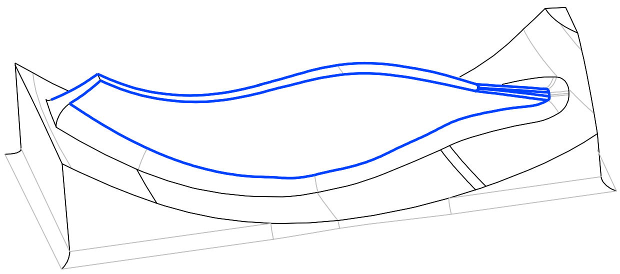

Figure 2: Test surface

Impeller	Under.(mm)	Over.(mm)	Energy(mm^{-2})	Estim. time(s)	Mach. time(s)
Min Deviation	0.13	-0.39	9820	G1: 19.5 BS: 7.3	G1: 23.45 BS: 9.3
Min Energy	0.54	-1.06	868	G1: 10 BS: 3.5	G1: 12.02 BS: 6

Table 1: Results of Geo5xF method

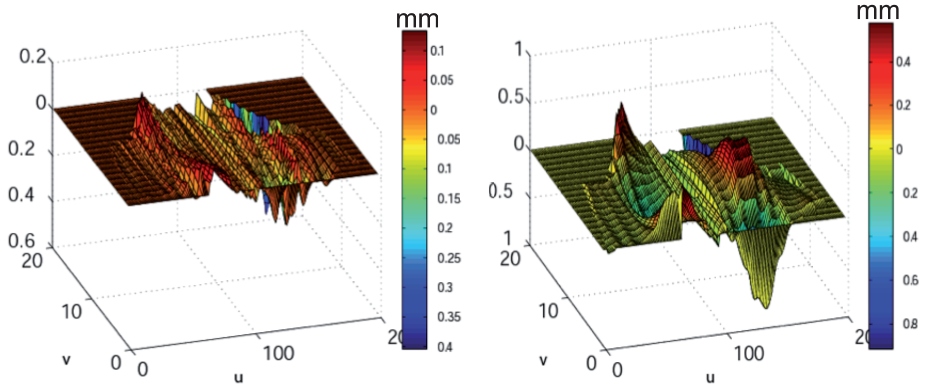

Figure 3: N-buffer simulations (left: min deviation ; right: min energy)

A N-Buffer simulation has been computed for both tool paths to assess the geometrical deviation over the part (Figure 3). Regarding effective feedrate, results clearly enhance that the smoothest trajectory is the fastest. In addition, the estimation of the maximum feedrate $\dot{s}$ brings out that the trajectory which minimizes its energy of deformation also minimizes slowdowns (Figure 4). The smoothest tool path generates less acceleration and jerk solicitations on the machine tool. The evaluation of $\dot{s}$ including the jerk constraint givers a good estimation of the maximum feedrate. Moreover, increases of cumulated energy seem to match the acceleration behaviour. However, the machining of the leading edge remains the main difficulty for both trajectories, accelerations and jerk are the limiting factors for the considered machine tool.

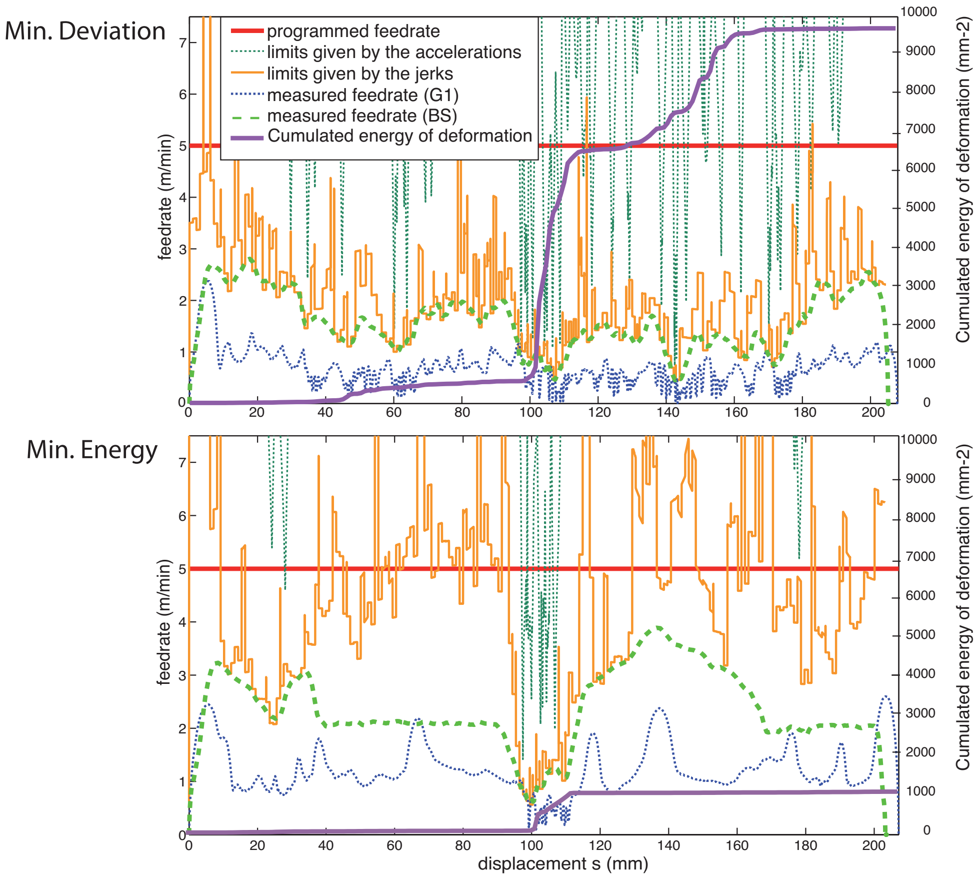

Figure 4: Limitation of the effective feedrate

5 CONCLUSION

In this paper we have presented a method to compute 5-axis flank milling tool paths which allows a compromise between the need for precision and smoothness of the tool path. The tool path smoothness in the part coordinate system is directly linked with the real machining time. Indeed, as the derivatives of the machining surface which are involved in the kinematical constraints equations are minimized the effective feedrate is greater. We also provide an estimation of the maximum feedrate reachable along the path displacement. This estimation computed thanks to the physical limits of the drives may in the future allow us to optimize the tool path directly in the machine coordinate system in the areas where slowdowns appear.

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