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Integrated Dexels Geometric Model and Predictive Force Model for Feedrate Optimization in 03 Axis Milling Machine

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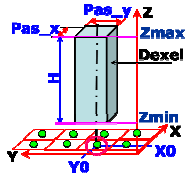
Abstract. Machining of sculptured surfaces engender abrupt variations in cutting forces, excessive tool deflections and undesirable vibrations and therefore poor surface finish. To reduce these problems and to have a stable machining it is more indispensable to select the appropriate cutting conditions. The aim of this paper is to propose an approach for determining the optimum feedrates along tool path during finishing of sculptured surfaces with ball end tools on 03-axis CNC milling machines using a predictive mechanistic model of cutting forces. Its steps are :1) approximation of the workpiece geometric model by dexels, 2) localization of the contact zones between tools and workpiece using machining simulation, 3) prediction of the cutting forces, 4) optimization of the feedrates and 5) updating of the machining program « G-Code ».

Introduction

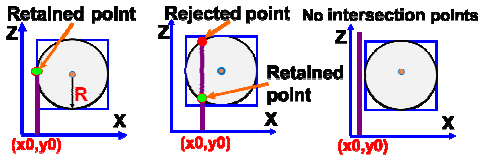
When machining sculptured surfaces, contact regions (tools-surfaces) and cutting forces vary continuously and abruptly along the tool path due to their complex geometry causing excessive tool deflections, undesirable vibrations and poor surface finish. To reduce these drawbacks, it is more useful to vary the feedrates during machining to limit the cutting forces to a safe level. In this research field, many researchers studied the influence of the cutting conditions on the behavior of machining. In reference [1], a model is developed to predict cutting forces applied to ball end mill by considering several parameters. In [2], geometric and mechanistic milling models are integrated to predict cutting forces and feedrate scheduling for five-axis machining. In [3], feedrate for three axis machining is selected by combining geometric and mechanistic models. In [4], an octree-based NC simulation system is developed for end milling to optimize the machining conditions using a mechanistic model. The aim of this paper is to propose an approach for optimizing the feedrates, for each tool displacement along the tool path, while finishing sculptured surfaces on 03-axis CNC milling machines using ball end mill tools by integrating a geometric model based on dexels and a mechanistic force model.

Proposed Approach

Creation of the Dexel Model. Dexels are used to approximate solid parts by material columns parallel to Z-axis. The creation of these dexels passes by calculating the center of each dexel (X0, Y0) using steps *pas_x*, *pas_y* and the dimensions of the raw part. The intersection between a vertical line passing by its center and triangles permits to calculate its extremums points Z_{min} and Z_{max} (Fig. 1.a).
Milling Simulation. This step simulates the removal material for the finishing operation using ball end mills for any machining strategy after adding a stock allowance to each dexel. The simulation permits to determine the intersection points between ball end mills and dexels for each tool position by considering three cases (Fig. 1.b). After calculating the intersection points, the dexels heights are updated.



a. Dexel parameters.



b. Cases of intersection between a line and a sphere.

Fig. 1. Dexels parameters and intersection cases between vertical line and sphere.

Contact Region Localization. The determination of the contact regions between tools and surfaces for a tool position passes by these steps:

- *Tool segmentation*: consists in subdividing the engaged part of the tool limited by the extreme values Z_{min} and Z_{max} of the intersection points into a set of discs with the same thickness for each tool position (Fig. 2).
- *Affectation of points to discs*: the intersection points associated to each disc are determined based on the Z coordinates of the intersection points and the limits of the discs. Next, the position angle for each point is calculated according to the X-axis (Fig. 3).
- *Creation of the contact regions for each disc*: the entrance angle and the exit angle associated to each region are calculated from the discs points. The affectation of the intersection points to the contact regions is done by testing the difference of the position angles for two successive points according to a calculated angle θ (Fig. 4).

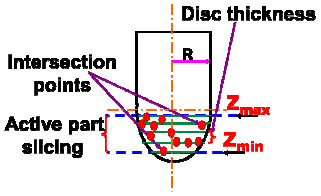


Fig. 2. Tool active part segmentation.

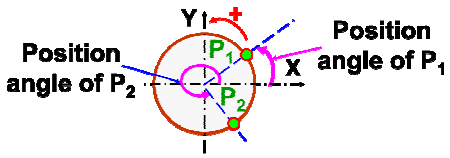


Fig. 3. Position angle of points.

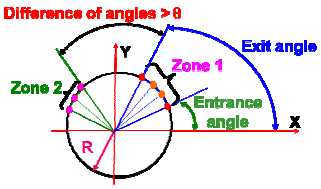


Fig. 4. Contact regions for a disc.

Cutting Forces Prediction. The proposed approach uses a mechanistic force model to predict the cutting forces for each tool position. The differential cutting forces components tangential dF_t, radial dF_r and axial dF_a in a local cartesian system corresponding to an infinitesimal element edge length of the tool are given by [2]:

$$\begin{cases} dF_t = K_{tc}(h_a)^{-p1} h(\phi,z)\,dS \\ dF_r = K_{rc}(h_a)^{-p2} h(\phi,z)\,dS \\ dF_a = K_{ac}(h_a)^{-p3} h(\phi,z)\,dS \end{cases} \quad (1)$$

Where h_a, $h(\phi,z)$ and dS are respectively the average thickness of the chip, the instantaneous thickness of the chip and the edge cutting length [3]. K_{tc}, K_{rc}, K_{ac}, p_1, p_2 and p_3 are constants determined experimentally. In a local cartesian system, cutting forces for an angular position ϕ are:

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = \begin{bmatrix} -\sin\phi\sin\kappa & -\cos\phi & -\sin\phi\cos\kappa \\ -\cos\phi\sin\kappa & \sin\phi & -\cos\phi\sin\kappa \\ -\cos\kappa & 0 & -\sin\kappa \end{bmatrix} \begin{bmatrix} dF_t \\ dF_r \\ dF_a \end{bmatrix}. \quad (2)$$

The prediction of the cutting forces for a tool position passes by these steps:

- For each disc and for each contact region, subdivide it into a set of points with a constant angular increment. For each point corresponding to a position angle ϕ:
  - Calculate the average and the instantaneous chip thickness h_a, $h(\phi,z)$ and the cutting edge length dS. Then, calculate the differential cutting forces dF_t, dF_r, dF_a and the cutting forces dF_x, dF_y and dF_z.
  - Sum all the cutting forces to obtain the cutting force for the considered region.
  - Sum all the cutting forces to obtain the cutting force on each disc.
  - Sum all the cutting forces for all discs to obtain the resultant cutting force.

Feedrate Optimization. To obtain a better stability of the cutting process and having an improved surface topography, cutting forces are fixed constant to an acceptable value using a mechanistic cutting forces model. For this, an iterative approach is developed to adjust feedrates (Fig. 5).

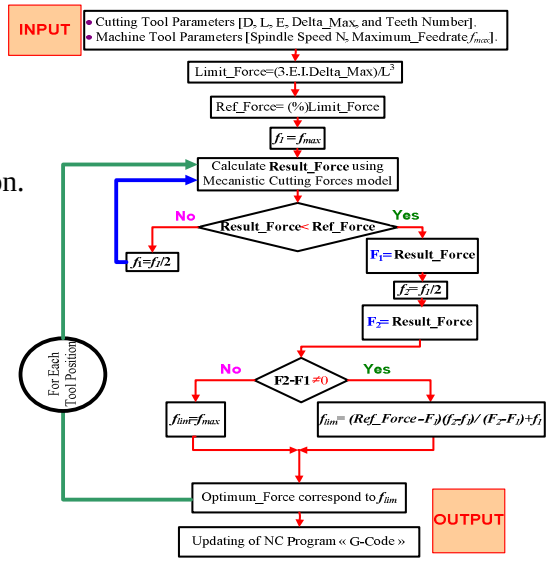


Fig. 5. Flowchart of the feedrate optimization.

This approach is divided in two parts:

➢ **Part 1:** Calculate the optimized feedrates based on the maximum tool deflection:

➲ Calculate the *limit* and *the reference cutting forces Ref_Force*. Then for each point of the tool path:

♦ Determine the first feedrate f_1 iteratively giving a cutting force F_1 less or equal to the *limit cutting force* by starting from the maximum machine feedrate.

♦ Calculate the second feedrate f_2 using f_1 and the associated cutting force F_2.

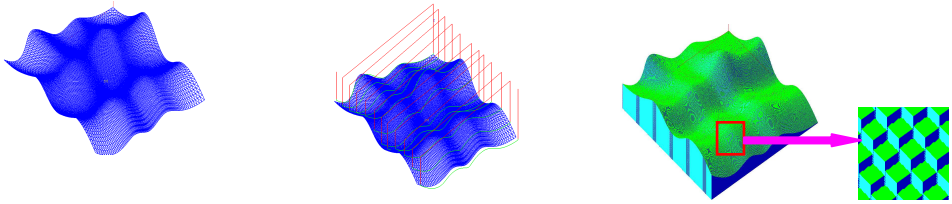
♦ Calculate the *optimized feedrate* f_{lim} using the linear interpolation using the following formula:

$$f_{\lim} = \frac{(\mathrm{Re}\, f\_Force - F_1).(f_2 - f_1)}{F_2 - F_1} + f_1 . \quad (3)$$

➢ **Part 2:** Update the NC program part "G-Code" by replacing the old feedrate by the optimized feedrate for each cutting tool displacement.

Results

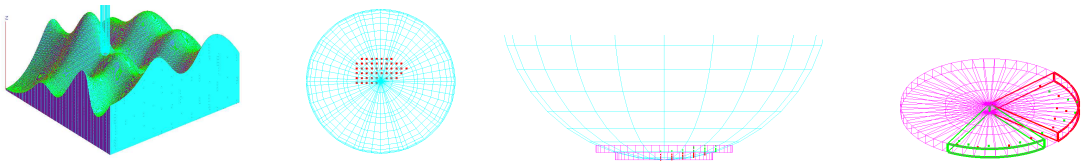
The validation of the approach is performed on an STL model of a sculptured surface (Fig. 6.a) where the dimensions of the raw part are 108mm×108mm×60.12mm. For a ball end mill of a radius equal to 3mm, the generated tool path contains 2260 tool positions (Fig. 6.b). The dexel model is generated by fixing the steps along X-axis and Y-axis equal to 0.2mm (Fig. 6.c).



a. STL Model. b. Machining tool path. c. Dexel model of the sculptured surface.

Fig. 6. STL model, tool path and dexel model.

To simulate the machining, the stock allowance is fixed equal to 0.1mm. Fig. 7.a shows machining simulation where the intersection points between dexels and the tools are calculated for each tool position. Next, the engaged part of the tool into the material is calculated and sliced into a set of discs with the same thickness (0.2mm). Thereafter, from the intersection points, the contact regions for each disc are determined (Fig. 7.b) and (Fig. 7.c).



a. Machining simulation. b. Intersection points. c. Discs and contact regions.

Fig. 7. Intersection points and contact regions for a specific tool position.

Afterward, the resultant cutting forces are predicted for each tool position from these parameters: number of teeth=4, spindle speed=2000rpm, feedrate=500mm/min and the constants are given in [2]. Fig. 8 shows the cutting forces and the feedrates before and after feedrate optimization.

a. Cutting forces along tool path. b. Cutting forces and feedrates variations from tool position 800 to 850.

Fig. 8. Cutting forces and feedrates before and after feedrate optimization.

The limit cutting force is calculated from these parameters: tool Young modulus =210000N/mm^2, maximum tool deflection=0.05mm and maximum feedrate of milling machine=10000mm/min. It is equal to 59.492 N. From the different graphs, several comments can be extricated:

- Before feedrate optimization, the resultant cutting forces present abrupt variations (peaks) along the tool path due to the continuous variations of the surface curvatures (Fig. 8.a).
- After feedrate optimization, the cutting forces are maintained constant (59.492 N) and the feedrates vary along the all tool path (Fig. 8.b).

Once the optimized feedrates are determined, the NC program "G-Code" is updated by replacing the new feedrates in each NC block.

Conclusion

In this paper, an approach for predicting the cutting forces and optimizing the feedrates, during sculptured surface finishing on 3-axis CNC milling using ball end mills, is proposed and implemented. This approach integrates dexels geometric model, milling simulation and mechanistic force model. It permits to obtain a good surface finish and a stable machining. Also, increases tools life and the machine elements. The results show the influence of the surfaces curvatures variations on the contact region between ball end mills and surfaces and consequently on the cutting forces and the importance of feedrates optimization. In perspective, the proposed approach will be extended to predict the cutting forces and to optimize the feedrates for flat end mills and fillet end mills.

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