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AUTOMATIC TOOL SELECTION AND FEEDRATE ADAPTATION FOR ROUGHING SCULPTURED SURFACES

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ABSTRACT
Sculptured surfaces used in the design and manufacture of molds, dies are machined on 3 or 5-axis milling machines. Generally, the final part is obtained in three stages: roughing, semi- roughing and finishing. In the roughing stage, the goal is to remove the most material from the initial workpiece as rapidly as possible by using generally a large flat end mill tool. In the classical approach, the NC part programmer, based on his experience, chooses the number of tools with their dimensions and fixes the cutting conditions from existing tables. In this paper, we present a systematic methodology that permits, from the NURBS surfaces to rough on 3-axis CNC milling machines, firstly to select automatically for each cutting plane the optimal flat end mill tool from a database of tools, and secondly to calculate the optimal feedrate for each tool movement by considering the removed volume, tool dimensions, allowable cutter deflection, spindle speed and material of the workpiece.
Key words: Tool Selection, Feedrate, Adaptation, Sculptured Surface, Roughing.

1. INTRODUCTION
Free form parts used in the design and manufacture of molds, dies …etc. are machined on 3 or 5 axis milling machines. To machine these surfaces, many aspects must be taken into account: surface definition, machining parameters, tools …etc. Different problems related to the machining of free form surfaces have been considered by researchers [1-6]. Among the fields of research are the optimization of the machining by the selection of the optimal tools and the optimal cutting conditions in order to reduce the machining times and the costs [7-9]. Generally, three stages are required to obtain the final part: roughing, semi-roughing and finishing. In the roughing stage, the goal is to remove the most material from the initial workpiece as rapidly as possible, by using generally a flat end mill tool, on sequential horizontal cutting planes and keeping only a small thickness of material for the next stages. In the classical approach of tool path generation, the NC part programmer, based on his experience, chooses the number of tools to be used with their dimensions and in the same time fixes the cutting conditions (feedrate and cutting speed) for each tool from existing tables and then uses the simulation to verify the absence of interferences. This work is tedious and depends on the surface geometry and the skill of the programmer. In this paper, we present a systematic methodology that permits, from the NURBS surfaces to rough on 3-axis CNC milling machines using flat end mill tools, firstly to select automatically for each cutting plane the optimal tool from a database of tools that avoids the interferences and secondly to calculate the adaptive feedrate for each tool movement by considering the volume of the removed material, tool dimensions (length and radius), allowable cutter deflection, spindle speed and material of the workpiece. The proposed methodology reduces the preparation times, the machining times and the costs and increases the productivity and the tools life.

2. OPTIMAL TOOL SELECTION FOR ROUGHING SCULPTURED SURFACES

It should be noted that in our work we have used the NURBS formulation to represent the machined surfaces due to their important properties relative to other formulations. The following sections describe the necessary steps for selecting the optimal flat end mill tools.

2.1. Triangulation and optimum number of triangles

To select the optimal tool and to simplify the calculation of the intersection points between a set of horizontal planes (cutting planes) and the theoretical surfaces, each surface must be triangulated. In this work, we have used the uniform triangulation with the determination of the optimum number of triangles in each direction (*u*-direction and *v*-direction) that verify a set of constraints in order to reduce the total number of triangles and thus the calculation and the required memory. The imposed constraints are fixed by the user and are for each triangle: the maximum length of each segment (d_1), the maximum distance between the medium of each segment and the theoretical surface (d_2) and the maximum distance between the center of gravity of the triangle and the theoretical surface (d_3).

2.2. Determination of contours and offset contours

We suppose that the distance between two consecutive cutting planes (depth of cut) is constant and is fixed by the user and the intersection points are calculated between the triangles and each horizontal plane. The determination of the contours and the associated offset contours passes by theses steps:

1. Calculate the intersection points between the triangles and the horizontal plane.
2. Calculate the approximate unit normal vector if the intersection point is not a vertex using the mean values of the parametric coordinates of the vertices of the segment (u_1, v_1) and (u_2, v_2).
3. Construct all the contours from the intersection points. It should be noted that for a plane we can find many contours and each contour can be closed or opened.
4. Using the projection of the unit normal vector on the horizontal plane (XY) at each intersection point, the tool radius "R" and the stock allowance "ε", each contour is offset by a value equal to the sum of "R" and "ε".

2.3. Optimal tool selection

To rough the surface, we have used direction parallel strategy in One-Way and Zig-Zag. With this strategy, the user must introduce the direction of the tool movements and the distance between two consecutive paths or the percentage of tool diameter. Giving these parameters, the intersection points between the set of parallel segments in the given direction and the offset contours are determined and the machining segments are localized. For machining, we start by the linear movements along the machined segments and then we constraint the tool to pass along the offset contours in order to obtain a good surface. To determine the optimal tools for each plane we proceed as follows: we take the largest tool from a database of tools and then we determine the offset contours and the machined segments. After this, for each tool movement, we verify if there are points of the contours inside the geometry generated by the tool. If this is the case, we choose a small tool and the same steps are repeated until absence of interferences and thus an optimal tool is found. In the end, a set of optimal tools are found and we have integrated the possibility to use all tools or to select a reduced number.

3. FEEDRATE ADAPTATION

The machining times of free form surfaces is very important and depends on many parameters such as tool dimensions, feedrate, machining strategy …etc. and in this work we consider the feedrate after that the optimal tools are selected. The amount of removed material changes constantly for each tool displacement and therefore it is necessary to adapt the feedrates. To determine the cutting conditions two methods can be used "volumetric method" and "vector force method" and in this work the first method is used. For this method, the power P (watt) required to cut the material is given by [8]:

$$P = K \times MRR \qquad (1)$$

Where K is a constant that depends on the workpiece material [10] and MRR (mm^3/min) is the metal removal rate. The cutting speed V (mm/min) is calculated from the rotational speed N (rpm) and the tool diameter D (mm). The cutting speed V and the tangential cutting force F_t are given by:

$$V = \pi \times D \times N / 1000 \quad (2)$$

$$F_t = P / V \quad (3)$$

To control the tool deflection, a maximum deflection δ is fixed by the user and the tool is considered as a beam of length L and diameter D_{eff}=0.8×D and the tangential cutting force is applied at its extremity. The deflection δ is determined from the beam bending formula:

$$\delta = (F_t \times L^3)/(E \times I) \quad (4)$$

Where E is the modulus of elasticity of the tool material and I is the moment of inertia.

The adaptation of the feedrate for the roughing machining necessitates the following steps:

1. Generate a set of triangles on the upper face of the workpiece.
2. Set the constant parameters D, N, δ, E and K.
3. Calculate the constants D_{eff}, I, F_t, V, P and MRR in this order.
4. For each tool machining displacement ΔL:
   - Calculate the removed volume RV.
   - Calculate the optimal time t_{opt} required for this displacement by:

$$t_{opt} = RV / MRR \quad (5)$$

   - Calculate the optimal feedrate F_{opt} for this displacement by:

$$F_{opt} = \Delta L / t_{opt} \quad (6)$$

In the end of this process, an optimal feedrate is associated for each displacement which permits to fix the cutting forces and thus prevent tool breakage (increasing tool life) and damage of workpiece.

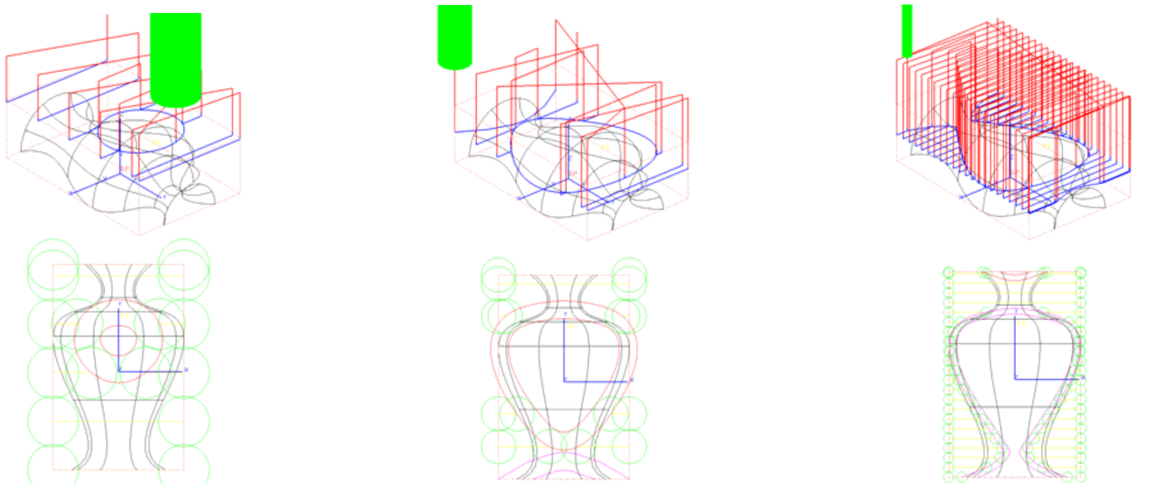
4. SOFTWARE DEVELOPMENT AND RESULTS

To automate the selection of the optimal flat end mill tools and to adapt the feedrate for each tool movement, we have developed an MS Windows software using the C++ Builder and the graphics library OpenGL [11]. In this software, the user introduces the main parameters: tools dimensions, depth of cut, percentage of the diameter, sweeping method, machining direction, criteria of triangulation, workpiece material, rotational speed and maximum deflection. After this, the software selects firstly the optimal tool for each cutting plane. We have integrated the possibility to use all selected tools or to choose a restricted number of tools. Secondly, the software calculates the adapted feedrate for each tool displacement and lastly generates the machining program.

To demonstrate the effectiveness of the proposed methodology, we have considered the NURBS surface represented by figure 1.a. The dimensions of this surface are 160mm×102mm×51mm. For this example we have considered the following parameters: number of triangles in each direction of the surface is fixed to 100, depth of cut is equal to 2mm, percentage of the diameter is equal to 10, the machining is done in One-Way and the direction of machining is parallel to the X axis. With these parameters, 26 cutting planes are found and all contours are represented by figure 1.b. The software selects 11 tools from a data base of tools with the radius of the largest one is equal to 20mm and the radius of the smallest one is equal to 3mm and the total machining time is nearly 11 hours. When the smallest tool is used, the machining takes nearly 40 hours which is very important compared to the optimal time. The figure 2 shows the contours, the offset contours, the tool positions and the tool path for three different cutting planes with different tool dimensions.

a. NURBS Surface. *b. Calculated contours.*

Figure 1. Considered surface and the calculated contours.



a. Plan n°1, R=20mm. *b. Plan n°12, R=13.5mm* *c. Plan n°14, R=4mm.*

Figure 2. Generated tool path for three different planes.

After this, the feedrates are adapted off-line for each tool displacement where the results depend on the workpiece material with the same parameters. The total machining time can increase or decrease because it depends on the initial fixed tools feedrates and workpiece material but the tool life is increased. It should be noted that the execution time depends on surface complexity and dimensions, depth of cut, number and dimensions of tools in the database and the CPU of the computer.

5. CONCLUSION

In this paper, we have presented a systematic methodology that permits, from CAD models of surfaces to rough on 3-axes CNC milling machines with direction parallel machining strategy and flat end mill tools, the automation of the selection of the optimal tool for each cutting plane and the adaptation of the feedrates for each tool displacement. The proposed methodology reduces considerably the preparation times, the machining times, the costs and increases the productivity and the tools life.

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