Simulation Techniques in CAD-CAM Processing by Milling of Surfaces on NC Machine-Tools

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Abstract: - The paper presents theoretical and practical-applicative aspects on some methods for the NC simulations using the CATIA v5 software, Machining module. An application is proposed for the milling procedure to process complex surfaces (plane and complex sculpture surfaces). Some practical optimization criteria are used, such as: correct choose of the machine-tool, type and durability of the cutting tools, paths and division patterns of the stock left for machining, optimum cutting parameters (cutting speed and feed speed), efficient use of the machine-tool, reduction of the machining time, precision conditions etc. The paper contains images and numerical data obtained from simulations allowing to draw conclusions regarding the possibilities to optimize the generation of complex surfaces whose generating and directing curves are not defined analytically.

Key-Words: - CAD-CAM, machining parameters, NC manufacturing simulation, optimization criteria, CATIA

1 Introduction

To develop the processing steps for a mechanical part on a NC machine-tool involves generation of control data, stored in a predetermined sequence in a specific ControlPanel equipment [7].

The main stages are: 3D representation of the part, setting the technological operation sheet, choice of the working parameters, choosing the strategy of division patterns of the stock left for machining, simulation processing, generation and checking the NC program.

These programs can be generated directly on the machine-tool, the operator writes the necessary instructions using the available interface or by using a CAD-CAM program and a virtual model of the piece [4].

Defining the piece in a CAD environment is used as the entry data to generate the NC program with a complex existing programming languages. Thus, the simulation is justified to optimize the process because CAM programs elaborate and list the NC machine code. Each processing program for the part, compatible with the machine-tool, consists of a sequence of sentences written in a logical sequence based on a specific syntax.

The machine-tool command is provided by the numerical control equipment (NCE), designed especially for the following types of machine-tools: lathes, milling, grinding, hobbing machines [8]. Their complexity is determined by the number of numerically controlled axes and precision processing [11].

The machine-tools, by their kinematics structure, execute simple and precise movements (rotation \( R \), translation \( T \)) in relation to the numerically controlled axes [5], [8]. The correct assessment of these axes is imposed by standards and recommendations.

The axes of coordinates are assigned to couples of translation (guideways) and/or rotation of the machine [6]. The trajectories that define the generated surfaces result from the combination of two, three or more simple movements, with determined speeds.

On the modern CNC equipments the user may program, in addition to coordinates, other geometrical information regarding the compensation of tools’ wear (lengths and diameters).

Thus, it is possible to make various corrections on: the dimensions, the wear of the cutting edge [2], the amount of deformations, the level of tool’s vibrations, and of the vibrations appeared in the fixture devices clamping the part on the machine-tool [1] etc.
2 Initial Conditions

In the current analysis it is used a machine-tool of vertical processing center (MCV) type, 5-axis (3 translations and 2 rotations) numerically controlled. The CAM processes on the machine-tool are simulated in the CATIA v5 working environment, along with the cutting tools, toolholders, and necessary fixture devices.

The process parameters consist of the cutting regimes, the tools paths in the processing movements etc.

By simulation there were analyzed the generation of the part’s surfaces based on different ways of dividing the stock left for machining. Also, the processed surfaces’ roughness parameters $R_a$ may be geometrically evaluated.

A simplified representation of the machine, its axes and its mobile units are presented in Fig. 1.

The X, Y and Z axes assure movements for feed and/or positioning on the longitudinal (LS), transversal (TS) and vertical (VS) directions, shown on figure. The TS slide is equipped with a tilting rotary table having independent rotation motions on the A and C axes. The cutting tool T is fixed in the main shaft MS, part of the mobile assembly VS.

Choosing of the machine-tool and of the milling head was determined mainly by the numerically controlled axes number and positions, the stroke lengths, the diameter of the rotary table, the range of the spindle speeds, of the feed speeds, of the quick motions, the dimensions of the working space etc. Also, it was taken into account the positioning accuracy and repeatability of the machine, the collisions avoiding and the stability of the cutting process [10]. It is recommended that, during the processing, the tool rotation axis at any point of the machined surface to be perpendicular to the tangent to the generated trajectory.

The chosen machine-tool has the following technical characteristics: rectilinear movements, max., on axes $X = 800$ mm, $Y = 600$ mm, $Z = 500$ mm, circular movements, max. $A = -110^\circ$ ... $110^\circ$ and $C = 360^\circ$, spindle speed max.: 15000 rpm, the power of the main electric engine: $P_n = 12$ kW, the torque $M_c = 53$ Nm, the power of the electric engines for the feed/positioning movements: X-axis and Y-axis: 4 kW, Z-axis: 5.5 kW, machining feedrate max.: 6000 mm/min and rapid feedrate: 30000 mm/min, tool magazine: number of tools: 24, tool changing time: 2 s, chip-to-chip time: 5 s, the toolholder cone type: HSK; NC system: Sinumerik 840. Some of the features listed are inserted into the Numerical Control tab (Fig. 3) available for selection of the NC equipment in the CATIA Machining module [4].

The sizes of the used stock are $120 \times 120 \times 35$ mm, made from a high alloyed steel material (HB=250), clamped with a special fixture device on the machine-tool’s rotary table RT.

The part is represented in Fig. 2 as a 3D model, having a prismatic form and it is provided with cavities and prominences.

The part surfaces (S1-S9) can be processed by simulation in the CATIA v5 CAM environment after an analysis in terms of shape, size and disposing of the machined surfaces.

Fig. 1.

The part surfaces (S1-S9) can be processed by simulation in the CATIA v5 CAM environment after an analysis in terms of shape, size and disposing of the machined surfaces.

Fig. 2.

Fig. 3.
In order to establish the technological system [3], there are defined the cutting tools and the necessary fixture devices for the application of the machining processes. These data are inserted in the CATIA program during the simulation phases of each processing operation for the technological process. The fixture devices and the toolholders are not defined by default in the program, but they are taken into account by the user when choosing a surface of the part that will not intersect the feed/positioning movement paths of the tool. Also, the simulation is possible to avoid collisions, especially in the case of movements on A and C axes [5], [6]. The CATIA v5 program allows the user to define the cutting tools, offering many options (corresponding to the technological process).

For the stock’s material there are selected tools from specialized catalogs. For this application, the cutting tools are provided with ISO P20 inserts (Coromant Catalogue steel milling grades) [12]. The user can determine the main features/code for each tool: diameter and length of the active part, total length, diameter and shape of the toolholder, number of teeth, the tool type for the corresponding surface shape and for the applied technological process etc. For the current analysis, in the paper are presented some data regarding the characteristics of each cutting tool: material and form of plates, cutting edges geometry, constructive angles of the tool’s edge, recommendations of use etc.

For example, Fig. 4 shows some data inserted in the appropriate fields available in the CATIA v5 program referring to the tool CoroMill 245.

### 3 Stages and Results of the CAM Simulation

The part’s shape analysis and the number of processing surfaces, noted on the part 3D model (Fig. 2), indicate, as necessary, several technological processes: rough face milling (S4), rough contour profile milling (S1, S2, S3), semi finish complex milling (S1, S2, S3, S5, S6), finish complex milling of the surfaces previously processed.

#### 3.1. Stages, processing and tool paths

In this paragraph are presented the milling processes of the surfaces whose generating and directing curves are not defined analytically. Figure 5 shows successively the following processing sequence: face milling 120×120 mm, depth 2 mm, in one pass (5, a.), external contour profile milling 120×120 mm, depth 20 mm, in four passes on the depth of the stock left for machining (5, b.), external contour profile and cavities semi finish milling, strategy Spiral (5, c.). For the finishing milling process, it is used the Zig-Zag strategy [4], [13], in 5 axes, on two directions (5, d. and 5, e.). The first direction is on the X axis and the second on the Y axis, with repositioning between two consecutive paths. Some figures have a small detail image for a better understanding of the generated tool trajectory.
Table 1. Data of the simulation process

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of the technological process</th>
<th>Cutting tool [12]</th>
<th>Process parameters*</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( t_m )</td>
</tr>
<tr>
<td>1</td>
<td>Rough face milling (fig. 5, a)</td>
<td>Face mill with 5 teeth, CoroMill 245/GC 1025, ( K_r = 45^0 )</td>
<td>( D_1 = 62.5, D_c = 50, a_p = 1, a_e = 25, h_{cx} = 0.15, f_z = 0.21, v_c = 170, n_c = 1041, v_f = 1100, P_c = 1.5, M_c = 14, Q = 27 )</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>External contour profile rough milling (fig. 5, b)</td>
<td>Profile milling cutter with 5 teeth, CoroMill 300/1030</td>
<td>( D_1 = 42, D_c = 32, a_p = 5, a_e = 10, h_{cx} = 0.12, f_z = 0.12, v_c = 120, n_c = 909, v_f = 630, P_c = 2.1, M_c = 14, Q = 32 )</td>
<td>2.98</td>
</tr>
<tr>
<td>3</td>
<td>External contour profile and cavities semi finish milling (fig. 5, c)</td>
<td>Ball nose end mill with 2 teeth, CoroMill 216/P, GC 2040, Main inserts E-M</td>
<td>( D_1 = 10, r_c = 0.3, l_2 = 160, a_p = 3, a_e = 4, h_{cx} = 0.05, f_z = 0.05, v_c = 180, n_c = 6250, v_f = 625, P_c = 0.5, M_c = 0.8, Q = 8 )</td>
<td>12.45</td>
</tr>
<tr>
<td>4</td>
<td>External contour profile and cavities finish milling, X axis, repositioning on Y axis (fig. 5, d)</td>
<td>Ball nose end mill with 2 teeth, CoroMill 216/P, GC 2040, Main inserts E-M</td>
<td>Variant I: ( D_1 = 10, a_p = 0.2, a_e = 2, h_{cx} = 0.015, f_z = 0.015, v_c = 180, n_c = 20460, v_f = 614, P_c = 0.4 )</td>
<td>20.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Variant II: ( D_1 = 10, a_p = 0.2, a_e = 2, h_{cx} = 0.015, f_z = 0.015, v_c = 125, n_c = 14000, v_f = 420, P_c = 0.3 )</td>
<td>21.2</td>
</tr>
<tr>
<td>5</td>
<td>External contour profile and cavities finish milling, Y axis, repositioning on X axis (fig. 5, e)</td>
<td>Ball nose end mill with 2 teeth, CoroMill 216/P, GC 2040, Main inserts E-M</td>
<td>Variant I: ( D_1 = 10, a_p = 0.2, a_e = 2, h_{cx} = 0.015, f_z = 0.015, v_c = 180, n_c = 20460, v_f = 614, P_c = 0.4 )</td>
<td>21.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Variant II: ( D_1 = 10, a_p = 0.2, a_e = 2, h_{cx} = 0.015, f_z = 0.015, v_c = 125, n_c = 14000, v_f = 420, P_c = 0.3 )</td>
<td>22.16</td>
</tr>
</tbody>
</table>

*\( D_1 \) (mm) – tool diameter, \( D_c \) (mm) – cutting diameter, \( l_2 \) (mm) – tool length, \( a_p \) (mm) – cutting depth, \( a_e \) (mm) – working engagement, \( h_{cx} \) (mm) – chip thickness, \( f_z \) (mm) – feed per cutting edge (mm), \( v_c \) (m/min) – cutting speed, \( n_c \) (rot/min) – spindle speed, \( v_f \) (mm/min) – feed speed, \( P_c \) (kW) – cutting power for removal of chips, \( M_c \) (Nm) – cutting torque, \( Q \) (cm³/min) – metal removal rate, \( t_m \) (min) – machining time, \( t_t \) (min) – total time.

Position of the tool axis from the machined surface is obtained on the machine-tool by orienting the part with movements on the A axis. The simulation spreadsheet data are shown in Table 1 with reference to: tools, trajectories, cutting and generation parameters and, also, the required processing time (\( t_m \) – machining time and \( t_t \) – total time).
3.2. Results

Applying the simulation methods resulted the parameters given in Table 1. Inserting these calculated parameters in a practical case in a CAM program on the real milling machine-tool having \( n_{\text{max}} = 15000 \) rpm is not possible to comply in variant I for the processings 4 and 5 (finish millings in table 1) in which the calculated spindle speed \( n_c = 20460 \) rpm exceeds this maximum value. Thus, for the finish millings the user must choose a lower spindle speed value, 14000 rpm, and the simulation process parameters \( v_c \), \( v_f \) and \( P_c \) are recalculated (variant II).

For the optimization by simulation in the CAM environment provided by CATIA there are proposed the following criteria: tools trajectories and the number of passes (division pattern of the stock left for machining), precision and surface quality conditions, processing duration, behavior of the machine-tool in working conditions (power and cutting torque, a low number of sense reversals of feeding motions and positioning), behavior of cutting tool (tool body and tool holder rigidity, vibration level [8], maintaining durability) by a uniform using of the cutting edge.

In the simulation process there were applied different trajectories to obtain the generating and directing curves. The generation of the analyzed surfaces require precise working movements defined according to the strategies adopted for tools paths. Also, there are auxiliary movements: for positioning, for rapid approach and retract, for wear compensation of the tool cutting edge, for changing the tool.

![Fig. 6](image)

CATIA allows the user to set up certain options in relation to these criteria: the tool path is chosen of the following variants: One-way next, One-way same, Zig-Zag, Spiral, Contour only, Concentric and Helical. Also, it is important the milling type: down milling or up milling. The process parameters were choosen, calculated and inserted in the fields of the dialog window (Fig. 6). To simulate the milling of the external contour profile and of the cavities it was used a Ball nose end mill [12], Fig. 7, with two circular plates, the tool diameter is \( \Omega 10 \).

![Fig. 7](image)

Figures 8 show the processing steps of the external contour surfaces and cavities: in Fig. 8, a. the face mill makes a semi finish milling. Fig. 8, b. and Fig. 8, c. present the finish milling on the X axis direction, respectively, the finish milling on the Y axis direction. Fig. 8, d. is a detail with the surface inside the circular cavity after both finishing processings.

The tools marks may be observed on both directions. Figures 8 show the tool movement according to the processing strategies (Spiral for rough milling and Zig-zag for finish millings), and also the tool slope for the finish millings. For these two successive processings there were used the 5-axis machine-tool capabilities.

Changing the tools trajectories, the cutting parameters, choosing different tools etc. aimed at optimizing by simulating the processings. Based on the analysis results of the machined surfaces, the user must consider mainly the variants with the lowest machining time.

Thus, it is possible to process more parts in the appropriate time prescribed for tool durability which gives an increase of operation productivity. Also, the user may choose the variants with a higher machining time, where the cutting tool is in contact longer with the cutting layer, resulting in a lower roughness, but, in the same time, the tool is subject to an intense wear process.

![Fig. 8, a.](image)
3.3. Generation of the part program

After rough, semi finish and finish milling processes by simulation applied on the analyzed part, the CATIA software automatically generate the NC code.

```
N300 T1 M06
N210 G3
N218 G0 G90 G60 G17
N320 G04 Z-2000 X-1000 M3
N330 G04 G07
N340 G03 Z-232.86 V-104.720 2.28 X9000
N360 Z-280
N370 G01 X53.489 V94.739
N380 G3 X53.49 V60.683 Y -150.70 Z -120
N400 G3 X51.977 V60.732 F700
N410 G01 X35.938 V04.237
N420 X65.879 V63.416
N430 G2 X17.587 Z56.532 3-10.317 7-28.085
N450 G2 X18.408 Z53.094 1-28.811 3-10.745
N460 G2 X18.406 Z43.709 3-30.763 30
N470 G2 X18.516 V34.968
N480 G2 X18.232 V-37.975
N490 M06X184.350 V-41.938
```

Figure 9 shows a fragment of the generated code, the lines contain programming data from the processing of the external contour profile and cavities finish milling. Five-axis milling assisted by CATIA v5 provides advanced methods for effective and optimized machining and surface finish.

4 Conclusion

Learning the CAM simulation methodology is an important step necessary to the representation of virtual machine-tools (structural configuration, working space, collision avoidance etc.) and to further simulations on this virtual machine. The items which require further development are: tool path generation, control of simultaneous cutting, selection of proper machining method, tool posture control, post processing.

The ultimate goal of CAM software is to generate the NC program directly from CAD data. Attempts are also being made to machine sculptured surfaces directly from CAD data by introducing a concept of digital copy milling.

References:


