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MACHINE TOOL

Simulation and verification of parametric numerical control programs using a virtual machine tool

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Abstract A parametric computer numerical control (CNC) program was developed to make a test complex surface on a vertical milling machine equipped with an external fourth rotational axis. Parametric programming was used in order to get higher flexibility of the manufacturing process. The ball-end milling process was simulated and verified in a virtual model of the machine tool developed with the module integrated simulation and verification of the product lifecycle management software of Siemens NX7®. After that, the real process was carried out on the shop floor to machine the test surface. This demonstrates that the virtual machine tools are an effective resource to simulate and verify the performance of machining processes controlled by CNC parametric programs. The possibility of accurately simulating the parametric CNC program reduces the risk of its implementation and enables a more frequent use of this efficient feature of contemporary CNC machine tools.

Keywords Virtual machine tool · Parametric programming · CAD/CAM · Ball-end milling · Multi-axis machining

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1 Introduction

A computer numerical control (CNC) system consists of a computer, power electronics components, such as motor amplifiers and electronic circuits, and servo actuators [1]. The computer control unit receives ISO standard NC-programs that describe the tool path geometry, tool number, feed and spindle speed at each path segment [2].

A virtual machine tool is a simulation tool of the CNC system that involves virtual modeling of the machine tool kinematics and feed drive dynamics, update of the workpiece geometry as the material is removed, and motions of the drives and auxiliary units, such as tool and pallet changes. In short, the rigid body motion of the machine tool and the CNC functions must be predicted as the workpiece is produced in order to achieve a virtual CNC system [3].

Generally, the CNC program is generated in a CAD/CAM environment, and then the virtual machine tool allows the geometric update of the workpiece as the tool cuts the material at each NC block. In addition, the solid model of the machine tool, its multi-axis kinematics and the location of fixtures can be displayed in the CAD environment [3, 4].

Parametric programming, as a feature of modern CNC machines, has the potential to bring higher efficiency to manufacturing industries. Parametric programming is a G/M code programming in which axis position (x, y, z, a, etc.), feed and speed functions can be specified by a parametric expression. Similar to computer programming languages such as Pascal or C, computer-related features such as variables, arithmetic, logic statements and looping are available in parametric programming. Although parametric programming has the potential to increase the flexibility of CNC operations, it is one of the least frequently utilized features of CNC machines [5].

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Parametric programming has the ability to generate general-purpose programs, including variables in computer programs written in BASIC or C. By changing the variable values within a general purpose program, it is possible to generate new programs for a variety of work pieces. Parametric programming can be used to generate programs for extremely complicated shapes and geometry. Since parametric programs allow complex arithmetic calculations to be performed within the program, there is almost no limit for the geometric shapes that can be machined. Any shape that can be mathematically defined can be described and machined using a parametric program (with a Macro command) [6].

When a CNC program is generated with a conventional CAM software, sequences of trajectories with a large number of code lines are generated [7]. This is because such software often ignores advanced programming utilities provided by the controllers, such as parametric programming (macro), canned cycles, feature pattern symmetry aids (rotation, mirroring), etc. [8]. In an example presented in [5] the average number of NC instructions for machining a family of parts is 82 lines, while the number of NC instructions in the corresponding parametric program is 38 lines. Parametric programming allows designing process algorithms in which the programmer can apply his personal expertise. Despite the potential of parametric programming to increase process flexibility, its use is infrequent because standard CAM software automatically generates DIN/ISO CNC code but not a parametric code. Thus, parametric programming is more costly and requires that the CNC programmers have a higher skill level. This fact is especially relevant in the cases of complex parts and machine tools with more than three axes.

In this work, a complex test surface was designed to be machined by ball-end milling process on a vertical machining center equipped with an external fourth rotational axis. The CNC program to machine the test surface was produced by a machining expert using parametric programming. The CNC program was simulated and verified in a virtual model of the machine tool developed with the ISV (Integrated Simulation and Verification) module of the Siemens NX7® software. Finally, the manufacturing process of the surface was carried out in the actual vertical machining center Leadwell V-20 with satisfactory results.

2 Materials and methods

2.1 Test surface and work material

The surface designed for the test is the concave surface of the workpiece shown in Fig. 1. The work material was a Ti-6Al-4V alloy cylinder with 70 mm diameter and 20 mm thickness. Due to the geometry of this workpiece, for its manufacturing, a machine tool with a rotational axis is more suitable than a three axis machine.

The test surface was generated in a CAD system through the partial revolution of the elliptical section with 12.00 × 8.00 mm semi axes shown on the left side of Fig. 2; the resulting test surface is shown on the right. As a condition for machining the surface, the rotational axis of the machine tool must coincide with the axis of the cylinder that represents the raw material. The manufacturing test performed consisted of carrying out the machining roughing process, leaving 0.25 mm of stock allowance for the finishing process. More precisely, the roughing cut was programmed over the surface of an elliptical section with 11.75 × 7.75 mm semi axes.

Equation 1 represents the parametric form of an ellipse with center (h, k) in the x–y plane, where a is the semi-major axis, b is the semi-minor axis, and α is the eccentric anomaly. For any point on a curve in the x–y plane, the curvature κ is defined by Eq. 2 [9] and the radius ρ of curvature is the inverse of the curvature κ.

$$x = h + a\cos\alpha;\; y = k + b\sin\alpha;\; \textit{where} \quad \alpha = \tan^{-1}\left(\frac{a(y-k)}{b(x-h)}\right) \tag{1}$$

$$\kappa = \frac{|y''x' - x''y'|}{(x'^2 + y'^2)^{3/2}} \tag{2}$$

One of the main problems with machining complex surfaces using multi-axis machine tools arises when a concave and a convex surface are engaged [10]. In the machining of the proposed concave test surface, this condition appears because the selected cutting tool is a convex ball-end mill. A condition to avoid interference in the machining of a concave surface is that the radius of the cutting tool must be smaller than the radius ρ of curvature of the surface in all the points over the cutting tool trajectory. Interference, as shown in Fig. 3, will be produced if a cutting tool with a radius bigger than the radius of curvature of the surface is used [11]. Table 1 shows ρ for several points, from the edge to the center (x axis on Fig. 2) of the elliptical section that generates the test surface. From the results in Table 1, a tool with a radius less than or equal to 8.09 mm is adequate for machining the proposed test surface.

2.2 Parametric numerical control program

By means of Eq. 3 [9], at any point of the elliptical profile, the coordinates of a second point that determine the normal unit vector of the profile in the analyzed point can be found. The center of the circle that represents the cutting

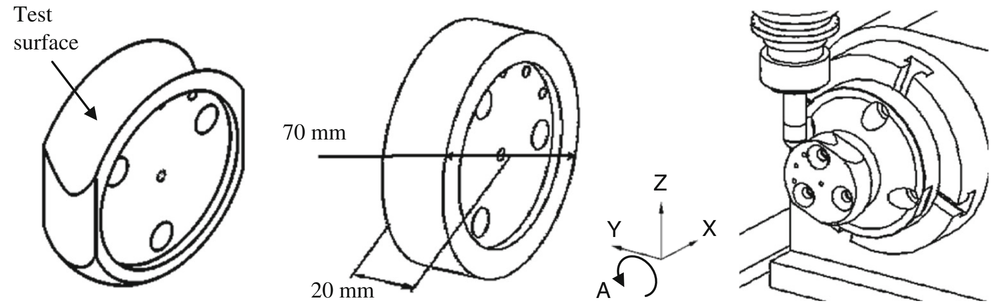


Fig. 1 Test surface, dimensions of raw material and workpiece setup

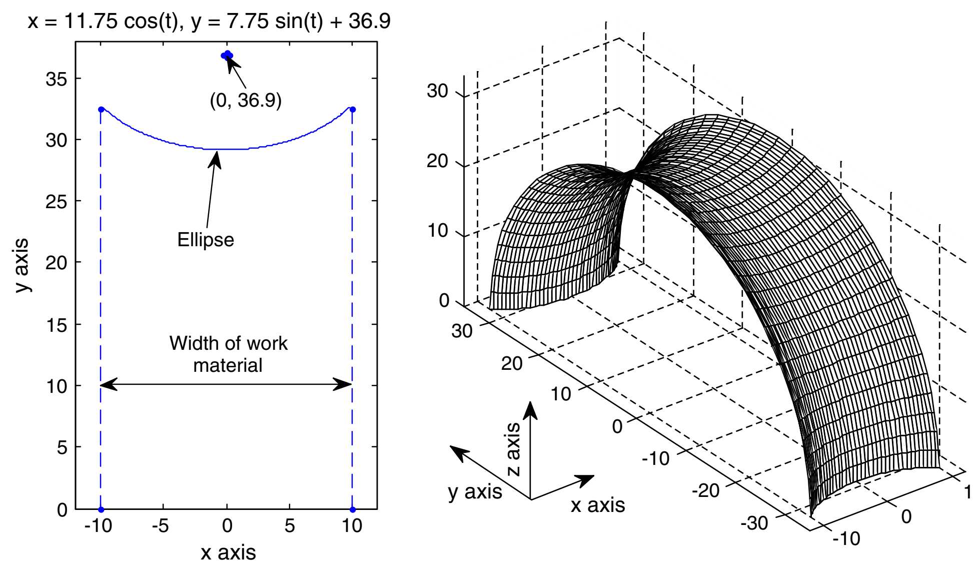


Fig. 2 Elliptical section (*left*) and test surface generated by its rotation around *x axis* (*right*)

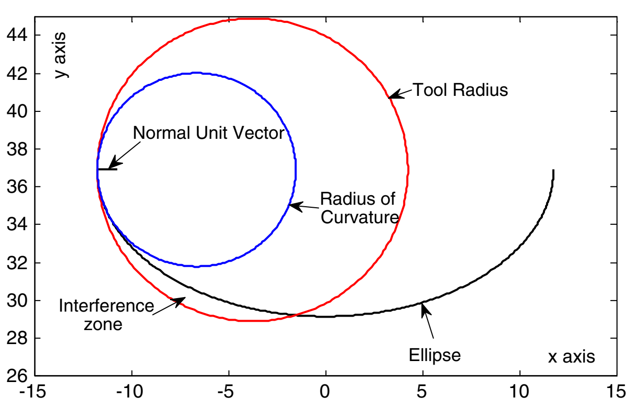


Fig. 3 Interference between the cutting tool and the machined profile geometry

Table 1 Radius ρ of curvature over the elliptical section of the test surface

x (mm)	y (mm)	α (rad)	κ (mm^{-1})	ρ (mm)
−10.0	32.830	3.69438	0.12362	8.090
−9.5	32.339	3.77077	0.11207	8.923
−9.0	31.917	3.83985	0.10269	9.738
0.0	29.150	4.71238	0.05613	17.814

tool must be aligned with this normal vector to program the cutting tool positioning in the radial direction.

$$N = \left(\frac{-y'}{\sqrt{x'^2 + y'^2}}, \frac{x'}{\sqrt{x'^2 + y'^2}} \right) \quad (3)$$

The general strategy used in the parametric CNC program consisted on positioning the tool sequentially with a radial depth of cut of 0.5 mm over the elliptical profile (Fig. 4a). The rotation of the fourth axis of the machine tool generates the feed movement to produce the cutting process. The ball-end mill was positioned with a fixed inclination angle $\theta = 45°$ (Fig. 4b, c). The parametric CNC program, written for the Fanuc 0MD controller of the machine tool, is shown in Fig. 5.

2.3 Cutting tool, machine center and virtual machine tool

From the results in Table 1, a ball-end mill with 8.00 mm radius can be used to do the roughing cut of the test surface. The selected cutting tool was a Kyocera RDFG16FR16.0 mm ball-end mill. In order to do the rough machining of the test surface, the cutting parameters given

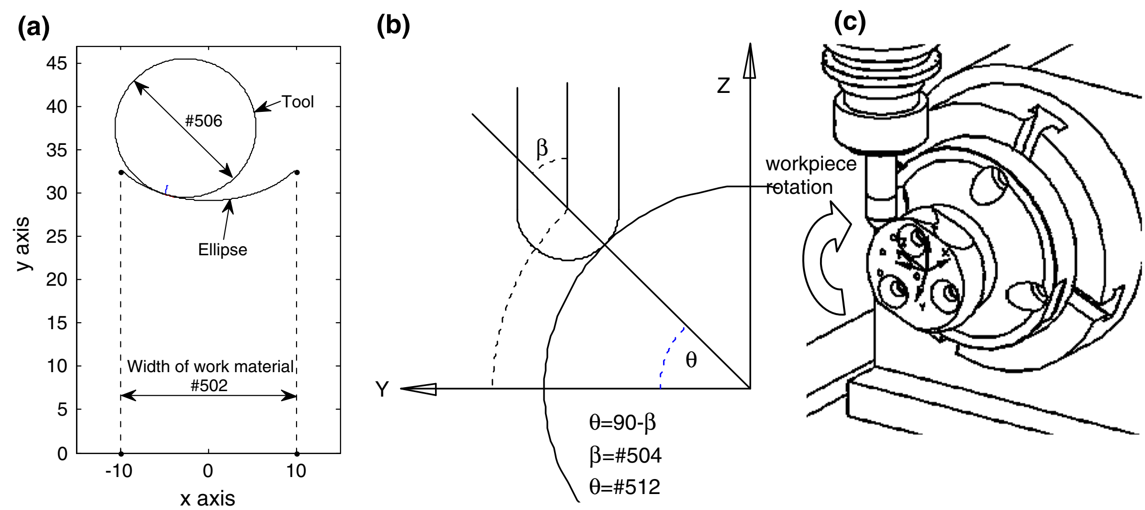


Fig. 4 **a** Ellipse profile and cutting tool, **b**, **c** positioning of the cutting tool. *Symbol* (#) represents the parametric variables used

Fig. 5 Parametric CNC program for machining the test surface

```
(Concave surface rough)
(Variables definition)
(#501=Work material Dia. mm)
#501=69.85
(#502=Work material width mm)
#502=20
 (#504=Beta angle Degrees)
#504=45
(#505=Radial depth of cut mm)
#505=0.5
(#506= Tool diameter mm)
#506=16
(#507=rpm tool)
#507=2750.
(#508=feed rate mm/min)
#508=250.
(#509=tool position)
#509=8.
#503=#506/2
#510=#501/2
#511=#502/2
#512=90-#504 (Teta angle)
#513=-80-#504
#514=#513+160
#100=#510+20
#110=-#511 (x start)
(Machine configuration)
G80G40G49G21G17
G91G28Z0
M41
G28X0Y0A0
G90G59
M6T#509
M3S#507
G00X0Y0A0
G43Z#100H#509
(Elliptic surface algorithm)
N10
(Ellipse "y" coordinate)
#111=-2*SQRT[144-
#110*#110]/3+36.9
#112=3*#111-110.7
#113=2*#110
(Eccentric anomaly)
#114=ATAN[#112]/[#113]
#115=SIN[#114]*SIN[#114]
#116=SIN[#114/2]*SIN[#114/2]
#117=SQRT[5*#115+4]
(Normal unit vector)
#118=[4*#116-2]/#117
#119=-3*SIN[#114]/#117
(Center tool in the x-y plane)
#120=#110+#118*#503
#121=#111+#119*#503
(Rotation Matrix)
#122=#121*COS[#512]
#123=#121*SIN[#512]-#503
X#120 Y#122
A#513
Z#123
G1A#514F#508
G0Z#100
#110=#110+#505
IF[#110GT#511]GOTO40
GOTO10
N40G91G28Z0M9
G28X0.Y0.M5
M41
G28A0
M40
G90
M30
```

by the ball-end mill manufacturer for titanium alloys were used: 60 m min^{-1} cutting speed, 0.10 mm feed per tooth and 0.50 mm radial depth of cut.

The machine tool used was a Leadwell V-20 vertical machining center with 8,000 min^{-1} maximum spindle speed and 5.5 kW power. This machine has the stiffness, accuracy and repeatability characteristics of a general-purpose machining center in agreement with the test certificate supplied by the manufacturer. The machine center was equipped with a fourth rotational axis Golden Sun CNC-151R with 22 min^{-1} maximum rotational velocity, 225 Nm maximum torque and 0.001° positioning precision. The Fanuc 0MD controller of the Leadwell V-20 machine tool controls the four axes available. Figure 6 represents the developed virtual model of the machining center, including the fourth axis and all the assembly accessories. A virtual emulator of the Fanuc 0MD controller, available also in the ISV system, was associated to the mechanic model.

3 Results and discussion

The machining process was first simulated on the virtual machining center and afterwards executed on the real machining center of the shop floor. Figure 7 shows an image of the simulation of the CNC parametric program on the virtual machine tool. To carry out the simulation process, the "simulate machine code file" function that allows loading the G code from a plain text file was used. Subsequently, the simulation and verification were done effectively using the ISV module.

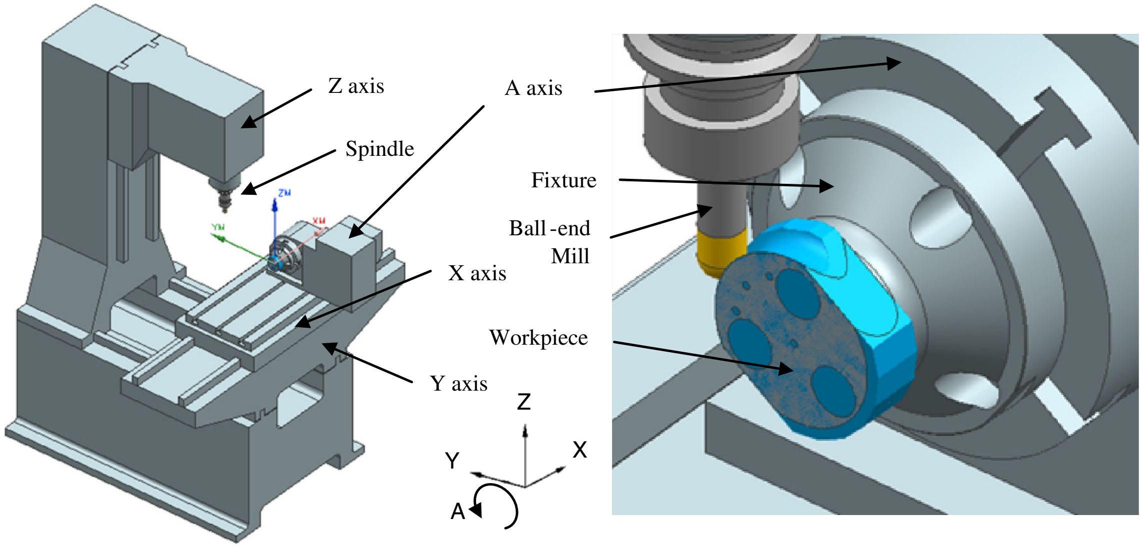


Fig. 6 Virtual machine tool built in NX7 PLM software

Fig. 7 Simulation of the CNC parametric program on the virtual machine tool

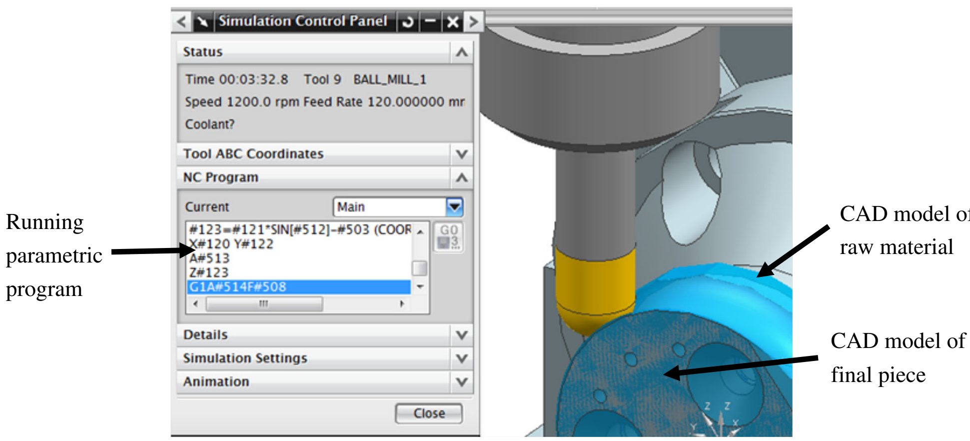


Fig. 8 Checking of the stock allowance material (*left*) and real machined test surface (*right*)

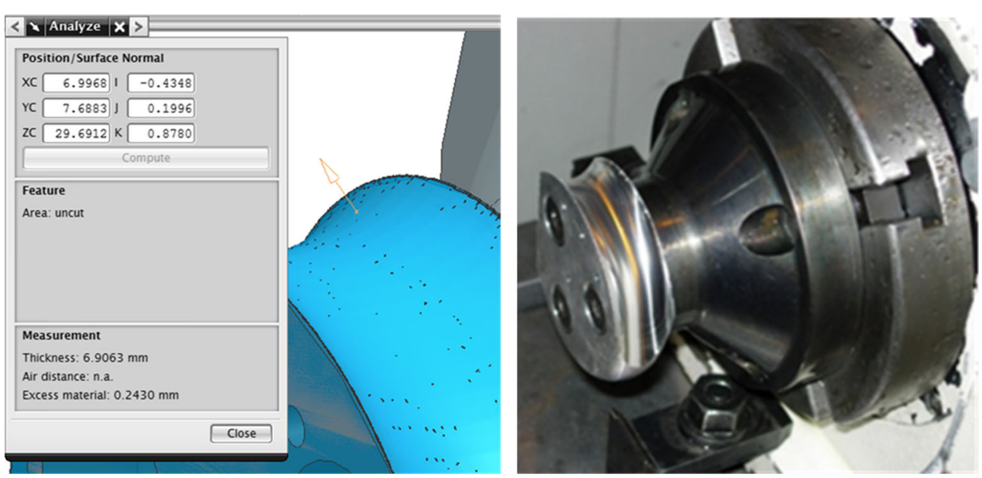
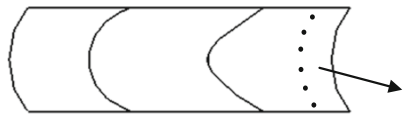


Fig. 9 Measured stock allowance left by the roughing process and associated deviation



point (up to down)	stock allowance [mm]	deviation [mm]
1	0.263	+0.013
2	0.247	-0.003
3	0.267	+0.017
4	0.281	+0.031
5	0.271	+0.021
6	0.261	+0.011

During the virtual execution of the program, no conflicts or collisions were detected. Once the virtual test surface was obtained, the "analyze" function of the NX7 simulation module was used to compare the surface sculpted in the virtual rough process against the "ideal" surface drafted on the CAD model. As shown on the left of Fig. 8, in this way it was verified that the stock allowance material left by the rough process corresponded to the planned value of 0.25 mm on the entire machined test surface.

After verifying the adequate performance of the machining process in the virtual model, the real surface was fabricated in the machining center of the shop floor. The development of the fabrication process occurred consistently with what was visualized on the simulation, and the test surface was obtained successfully as can be seen on the right of Fig. 8.

The stiffness and accuracy of a machining system is related to the total error of the machining system, this error involves the cumulative effect of several isolated errors that can broadly be classified as: geometric errors of machine components and structures, kinematic errors, errors induced by thermal distortions, errors caused by cutting and dynamic forces, material instability errors, machine assembly-induced errors, instrumentation errors, errors induced by tool wear, fixturing errors and other sources of errors like servo errors of the machine (following errors and interpolation algorithmic errors) [12]. Since all machines are elastic structures at some level of observation, the effect of these static and dynamic forces and influences will be seen in the dimension, form or surface characteristics of a workpiece [13].

A run out of 0.011 and 8.015 mm radius were measured in the ball end mill by using a tool presetting machine Zoller Smile-400. Figure 9 shows the stock allowance material left by the roughing process as determined over six points on the test surface by using measurements with a TESA Micro-Hite 3D coordinate measuring machine (0.001 mm resolution). Also are presented the stock allowance deviations by subtracting the nominal value (0.250 mm) to each measured point. The influence of the stiffness and accuracy of the machining system is evidenced by these stock allowance deviations. A estimation of our technological setup (Fig. 6) stiffness gives a value of 7.2 N μm^{-1}. As can be seen by the deviation values on Fig. 9 and from the above considerations, the simulation results are still valid for the process evaluation of the test surface in the machine tool used.

4 Conclusions

In this work, a specific test surface to be machined was generated in a CAD system by the partial revolution of an elliptical section. To obtain higher manufacturing flexibility, a CNC parametric program was written by a machining expert to manufacture the test surface through a ball-end milling process. The parametric programming feature, available for most CNC controllers, can be more efficient than the standard block to block programming generated by most CAM systems. Parametric programming allows a flexible algorithmic control of the machining process variables, but that implementation of a CNC parametric program to machine a complex surface requires a complete mathematical analysis of the surface.

A virtual machine tool of a Leadwell V-20 machining center, including an external fourth axis was implemented in NX7. The virtual model allowed the simulation of the machining process of the test surface with a high level of realism. This includes the verification of the tool path trajectory and the detection of programming conflicts as well as possible collisions in order to check for errors in the operations sequence. The simulation also permits accurate estimation of processing time, including the cutting tools change and idle movements.

The development of the fabrication process occurred consistently with what was visualized in the simulation, and the test surface was obtained successfully. As shown, the simulation and verification process is possible even for programs developed with the parametric programming technique, thus facilitating the reliable use of this efficient programming feature especially in the case of complex geometries to be machined.

The virtual machine tool implemented is an efficient instrument to simulate and verify CNC programs written manually without CAM assistance, especially parametric programs. Therefore, due to the possibility of simulating the manufacturing process with great realism, the implementation risks are diminished. Eventually, the virtual machine tool also allows reductions of setup time because, even in this stage of the process, it is possible to use it for verification, which makes it possible to avoid the use of costly real resources in trial and error tests.

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