

Evaluation of computer-aided manufacturing software accuracy for high precision machining

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Abstract

This article describes the investigation of the ability of WORKNC® Computer-Aided Manufacturing (CAM) software to generate sound toolpaths for high-precision machining. This study is being conducted in the scope of Radio Frequency Quadrupole (RFQ) manufacturing for Proton Induced X-ray Emission (PIXE) detector. By default, CAM software is configured to obtain a good compromise between accuracy and calculation time. Nevertheless, for greater accuracy, these default parameters must be tweaked. The machining of the modulations on the PIXE RFQ, which involves a shape tolerance of 10 μm , is used as a case study. The software parameters and milling strategies are evaluated in regard to the toolpath accuracy. The investigation of the successive data transformations has permitted a significant improvement of the toolpath accuracy generated by the software compared to results obtained prior to this study. The best practice that allows high-precision machining using WORKNC® is presented.

Manufacturing (CAM), Machining, Accuracy

1. Introduction

The manufacturing industry meets constantly increasing challenges both in terms of quality and part complexity. The emergence of Computer-Aided Design (CAD) software has facilitated the design of parts with complex geometries. Although the kinematics of the machines offers great flexibility, programming toolpaths to machine such surfaces can be challenging without the use of a software. Nowadays, Computer-Aided Manufacturing (CAM) is widely used in the industry. It allows the computation of toolpaths for the machining of complex shapes using multi-axis kinematic, permitting to improve the surface quality [1]. CAM integrates the CAD files into the manufacturing process for a consistent stream of information all along with the design, manufacturing, and metrology. Nevertheless, the data from CAD undergoes conversions and geometric transformations during its processing in the software. The efficiency of the toolpath computation is one of the most challenging problems in the design of CAM software [2-4]. By default, it is configured to obtain a good compromise between accuracy and calculation time. For greater accuracy, default parameters must be tweaked. The purpose of this study is to assess the ability of WORKNC® (version 2020.0) to fulfill CERN requirements in terms of toolpath accuracy and give the best practice for high-precision machining.

1.1. Case study

This study is being conducted in the scope of Radio Frequency Quadrupole (RFQ) manufacturing for Proton Induced X-ray Emission (PIXE) detector. In the CAD model, the vane tips of the RFQ are generated using a spline. Since this surface is complex, CAM is used for the roughing as well as for the finishing of the vane tips [5]. The finishing of the modulation, which is studied in this article, is performed with a shape milling cutter and using only 2 of the 5 axes of the machine. This shape has to be

machined very precisely to accelerate the particle beam with the least possible losses. For this reason, the shape tolerance on the modulation is $\pm 5 \mu\text{m}$ [6]. The tests that are discussed in this article have been conducted on the most critical portion of the lower major van of the PIXE HF-RFQ module 1 (see **Figure 1**), containing the minimum radius of curvature of the modulation.

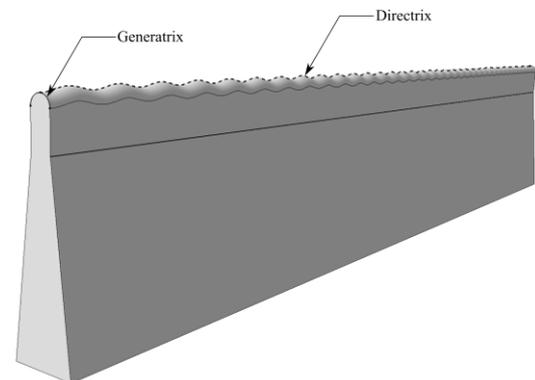


Figure 1. The studied portion of the PIXE RFQ modulation

2. CAM workflow and methodology

During the design phase of the PIXE RFQ, a finite element method (FEM) software is used to optimize the shape of the modulation. The FEM software produces a list of points, which are interpolated in the CAD software using a spline to generate the profile of the modulation. This section describes various workflows that permit to produce equivalent milling toolpaths for the finishing of the vane tips as well as the methodology used to assess the data processed by the software.

2.1. Various CAM workflow to produce milling toolpaths

For 2- and 3-axis milling, WORKNC allows to work either from a curve or from a 3D model (see **Figure 2**). CAD models can be imported in the STandard for the Exchange of Product (STEP)

format or directly in the specific CAD software file format. From this point, the model is converted into a mesh, which is used to generate a toolpath using CAD model-based strategies. It is also possible to use a mesh-sectioning feature to extract a section curve from the mesh, and use it to generate the toolpath using a curve-based strategy. Another workflow consists of importing directly a list of points in the CAM software, and generate a toolpath from it. In both cases, the toolpath is composed of a list of tool positions and orientations, which are converted into machine axes positions with linear and/or circular interpolations during the post-processing step.

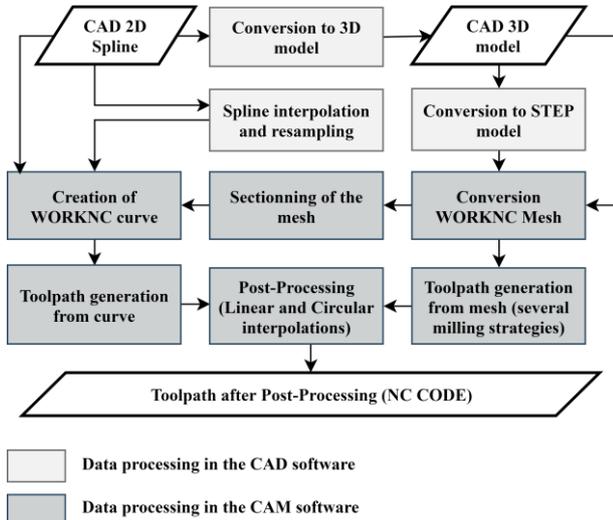


Figure 2. Flow chart of the CAM workflows to produce milling toolpaths.

In most cases, the CAM software computes the point of Cutter Contact (CC) between the tool and the part (see **Figure 3**), and applies an offset to generate the positions of the Cutter Location (CL). In some strategies, it is also possible to generate toolpaths with cutter compensation: the strategy generates the positions of the CC points and not the CL points. In this case, the machine has to calculate the compensation and the CAM software is not responsible for the offset computation.

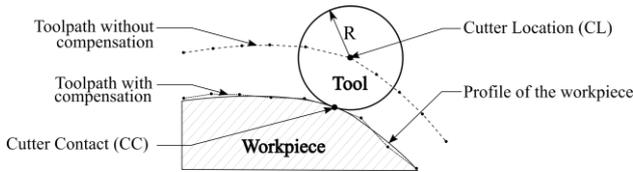


Figure 3. Representation of the position of the cutter location and cutter contact points

2.2. Global methodology for CAM software evaluation

First, baseline data is established to allow the evaluation of the results from the CAM software. The loss of accuracy at each step of CAM workflows described above as well as the general accuracy is evaluated using the case study. Not only the toolpath points are evaluated, but also the error due to the linear interpolation between these points. In the context of the machining of the PIXE RFQ, the maximum allowable amplitude of the error on the toolpath is set to 1.50 μm from peak to peak such that it remains below 15% of the tolerance to be respected after machining. The results are discussed not only in terms of accuracy but also in terms of workflow efficiency, and adaptability to workshop use.

3. Method used to assess data from CAM software

To avoid introducing errors using software to assess the data, python algorithms are used, for which both the accuracy and computation method are controlled.

3.1. Definition of the reference curves

As mentioned above, the points exported from the FEM software are interpolated in the CAD software to generate a spline. This spline is used as a directrix to generate the modulation shape, the profile of the shape tool being the generatrix (see **Figure 1**). Some tests have shown that data undergoes several transformations in the CAD software also. The implication is that the spline and the resulting 3D model do not fit perfectly together. For a better consistency of the results, two different references have been defined. The first reference is defined by polynomial interpolation of a list of points from the spline. This reference is used for workflows involving directly the points from the spline. The second reference is defined by the interpolation of a list of points projected on the surface of the 3D model and is used to evaluate data from workflows involving the CAD model. The projection of the points on the surface has been computed and verified using two different CAD software. The points exported from the FEM software have a constant spacing in the longitudinal direction of 0.1 mm. Since the polynomial interpolation function defining the curve is of class C^1 , and that the spacing of the points is small compared to the curvature (the ratio is greater than 18), the radius of curvature can be considered a constant between each couple of consecutive points. In this case, the error due to the linear interpolation ϵ of the points from FEM simulation can be approximated geometrically using **Equation 1**, where ρ_{min} is the minimum radius of curvature of the curve and s is the longitudinal spacing of the points. In the future, this model can be used to assess quickly the accuracy of a list of points regarding linear interpolations.

$$\epsilon = \rho_{min} - \sqrt{\rho_{min}^2 - (s/2)^2} \quad (\text{Equation 1})$$

In the case of the PIXE RFQ, the minimum radius of curvature is 1.709 mm, which gives a maximum theoretical error of $\pm 0.73 \mu\text{m}$ on the modulation (0.72 μm was found using a numerical algorithm). This value is almost 15 % of the tolerance to be respected after machining, and does not include the errors due to the computation CL point. For this reason, the curve has been resampled with 5000 points along the CAD spline, giving a spacing of 0.0316 mm, and a maximum error of $\pm 0.07 \mu\text{m}$. The differences between the reference curve and the CAD spline were minimized using cubic polynomial interpolation. The maximum error is 0.001 μm , which is negligible and permits to validate the definition of the reference curve.

3.2. Evaluation of the distance between a point and the reference curve

The assessment of the accuracy of the mesh, software features, and toolpaths consists in the computation of the distance between points and a reference curve. As mentioned above, the reference curve C is computed using a cubic polynomial interpolation function f of the list of n points

$$P_i = \begin{pmatrix} x_i \\ y_i \end{pmatrix}, i \in \llbracket 1, n \rrbracket.$$

Since the sequence

$$x_i, i \in \llbracket 1, n \rrbracket$$

is strictly monotonically increasing, x is used as a parameter to define the curve C as follows:

$$C(x) = \begin{pmatrix} x \\ f(x) \end{pmatrix}.$$

The tangential vector \hat{T} to the curve C is a unit vector in the direction of the velocity vector and is defined as

$$\hat{T}(x) = \frac{1}{\sqrt{1+f'(x)^2}} \cdot \begin{pmatrix} 1 \\ f'(x) \end{pmatrix}.$$

Since the normal vector \hat{N} is perpendicular to the tangential vector \hat{T} ,

$$\hat{T}(x) \cdot \hat{N}(x) = 0 \Rightarrow \hat{N}(x) = \frac{1}{\sqrt{1+f'(x)^2}} \cdot \begin{pmatrix} -f'(x) \\ 1 \end{pmatrix}.$$

From here, it is possible to define the line L in the direction of $\hat{N}(x)$ passing through $C(x)$ using the parameter t as shown in the following equation:

$$L(x, t) = C(x) + t \cdot \hat{N}(x).$$

An optimization algorithm is used to solve numerically the equation

$$L(x, t) = \begin{pmatrix} x_i \\ y_i \end{pmatrix},$$

which is obtained for $x = (x_s)_i$ and $t = (t_s)_i$ (see **Figure 4**). In this method, the precision of the algorithm is controlled since the solution lies in a disk of radius R_ε around the point P_i . While $(x_s)_i$ defines the position of the projection on the reference curve, $(t_s)_i$ is the distance between the point and the curve.

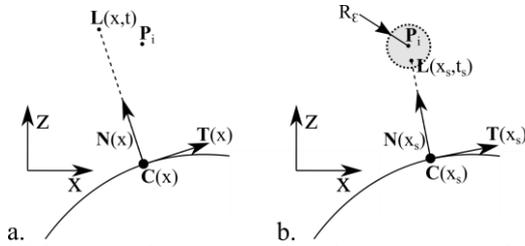


Figure 4. Representation of vectors and points used for the point-curve distance computation algorithm.

Since this method only permits to find a local solution, the choice of the initial guess is important. In our case, the initial guess for the algorithm is $(x = x_i, t = 0)$. Since the expected error is well below the minimum radius of curvature (below 0.6 % of ρ_{min} if errors up to 0.02 mm are considered), the local solution is the global solution. For this study, a computational tolerance of 10^{-8} mm is chosen.

3.3. Computation of the machined profile from a two-dimensional toolpath without radius compensation

When evaluating the results of a strategy without radius compensation, the toolpath, which corresponds to CL points, has to be assessed against the profile of the part. For this reason, an algorithm is used to compute the theoretical machined profile. The algorithm developed here supports the linear and circular interpolations. The simplest algorithm would consist of computing the normal vector to the curve and applying an offset of the value of the radius in this direction. Nevertheless, this method is not suitable if, at a given point, the curve is convex and the radius of curvature is smaller than the offset value because cusps are generated.

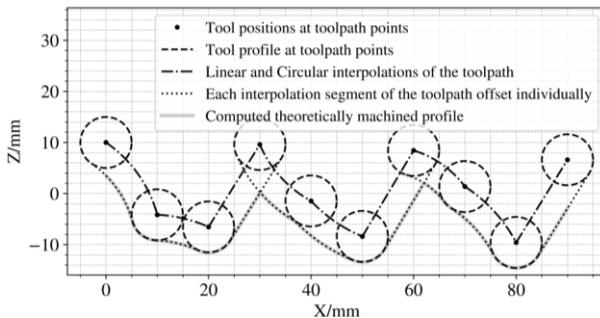


Figure 5. Representation of the offset algorithm on a randomly generated toolpath.

A better approach is to compute the envelope generated by a circle having the same radius as the tool, and whose center can move along the toolpath [7]. For a numerical implementation of this algorithm, the computation is not efficient because it involves discrete positions of the circle. For this reason, a hybrid approach permitting an exact solution is used. The profile is computed using the tool shape only on the toolpath points while linear and circular interpolation are offset mathematically (see **Figure 5**).

4. Evaluation of software features and toolpath computation

4.1. Evaluation of the mesh accuracy

When a part is imported into the software, the geometry is converted into a triangle mesh. The size of the triangles is directly linked to the accuracy of the mesh and to the computation time. In WORKNC, the mesh size can be controlled using the “Tolerance” and “Scaling Factor” parameters. While the smallest tolerance is $\pm 1 \mu\text{m}$, the scaling factor can be used to virtually enlarge the part for calculation, such that the tolerance is divided by the scaling factor. The mesh has been exported as STL and sectioned. For a tolerance parameter of $\pm 1 \mu\text{m}$ and a scaling factor of 10, the error was evaluated to $0.05 \mu\text{m}$ from peak-to-peak for a model in the specific CAD software file format, which is well below the tolerance. Equivalent results were obtained when importing a STEP file, with a maximum error of $0.08 \mu\text{m}$. The same mesh parameters are used for the evaluation of all the features and toolpaths in the following sections.

4.2. Evaluation of curve-based toolpaths accuracy (with and without cutter compensation)

One way to work with curves is to import directly the points in the software. In the case of a toolpath with cutter compensation, the computation of the toolpath should correspond to a simple resampling of the curve to meet the toolpath tolerance criteria. The results obtained for the “tangent to curve” strategy without cutter compensation was $0.50 \mu\text{m}$ for a tolerance of $1.00 \mu\text{m}$ (corresponding to the value of $\pm 0.50 \mu\text{m}$ entered in the software). The same strategy with cutter compensation (corresponding to the “On profile” option) gives better results, with a maximum error of $0.22 \mu\text{m}$ (which is logical because less data transformation is involved). Using the “Minimal compensation” option, which permits to add a smoothing radius in the corners, the accuracy was evaluated to $0.50 \mu\text{m}$ (with a smoothing radius of 0). When programming with a tolerance of $0.20 \mu\text{m}$, the accuracy reached the tolerance value only for the toolpath without cutter compensation (with a value of $0.19 \mu\text{m}$). Although the evaluation of the toolpath was performed only on the portions of the modulation where the tool radius is smaller than the radius of curvature of the curve, some tests showed that the tool is tangent to the curve in two different points when it is not the case, which prevents the tool from penetrating the part geometry.

4.3. Evaluation of the mesh-sectioning feature

To use curve-based strategies, the curve can be obtained by sectioning the 3D model directly in WORKNC. When importing the geometry, the software generates a mesh for the computation and a coarser one for a more efficient visualization. By default, the section is computed with the visualization mesh and is not controlled by any tolerance parameter. Errors over $26 \mu\text{m}$ were generated by this method, which is not sufficient for high-precision milling. To improve the quality of the section, the computation must be performed on the computational mesh. By assessing the mesh section with the “tangent to curve” strategy evaluated in the section above, an accuracy of $1.04 \mu\text{m}$ was achieved, giving a loss of accuracy of $0.54 \mu\text{m}$. Although this method gave better results, the workflow is not efficient since a

specific command line must be used, and the visualization mesh must be hidden while using the function.

4.4. Evaluation of model-based toolpath computation (without cutter compensation)

When considering model-based strategies, the toolpath contains the errors caused both by the meshing (evaluated in 4.1) and the computation of the toolpath itself. With toolpath tolerances of 0.20 μm , 1.00 μm , 2.00 μm , and 10.00 μm , the case study has permitted to evaluate the precision of the toolpaths to respectively 0.90 μm , 0.93 μm , 1.05 μm and 4.68 μm . The tolerance for 0.20 μm is not respected. By importing the points from this toolpath in the CAD software, a value of 0.90 μm was measured for the tolerance of 0.20 μm , which confirms the results obtained with the python algorithm.

4.5. Evaluation of the circular interpolations

As mentioned above, the strategy permits to compute the toolpath, which is composed of the lists of tool positions, and eventually, orientations. The last step after the toolpath computation is the post-processing, which generates a file in the numerical control (NC) programming language of the machine. The toolpath points can be interpolated using circular arcs with a given tolerance. Using circular interpolations permits to reduce the number of lines in the NC file, but the loss of accuracy has to be taken into account for precision machining since this interpolation is done after the toolpath points computation. The accuracy of the toolpath containing circular interpolations was compared to the accuracy of the toolpath containing exclusively linear interpolations. For circular interpolation tolerances of 0.20 μm , 1.00 μm and 2.00 μm , the loss of accuracy compared to the toolpath without circular interpolation has been evaluated to respectively 0.02 μm , 0.30 μm and 1.28 μm . The results are consistent with the tolerance value. Nevertheless, the drawback of using circular interpolation is that the tolerance parameter cannot be changed anywhere else than in the post-processor configuration file.

5. Global workflow tolerance and validation on a test part

5.1. Global workflow tolerance

At each step of the data processing in the CAM software, tolerances are involved. The global tolerance between the input and the output of the software is given by the sum of the tolerance used for the mesh creation, mesh-section, toolpath computation and circular interpolation. The results from each section are summarized in **Table 1**. By combining the obtained results, a global accuracy of 1.00 μm was obtained using the Z-level finishing strategy while respecting the tolerance value. Using prior re-sampling, an accuracy of 0.50 μm was reached by importing directly the points in the CAD software (for a toolpath without tool compensation). This method involves a more complex workflow but permits to improve the results. If using the mesh-section feature on the computational mesh, an accuracy of 1.04 μm was achieved.

	Achieved tolerances (case study)
Mesh computation	0.1 μm (not tested below)
Mesh sectioning feature	0.6 μm (with errors on the "On-curve" strategy)
Strategy : Tangent-to-curve	0.5 μm
Strategy : Z-level finishing	1.0 μm
Circular interpolation	0.1 μm

Table 1. Achieved tolerances in the scope of the PIXE RFQ.

5.2. Machining and measurement of a test workpiece

The most efficient way to use the software is to use model-based strategies. A sample has been machined and measured to validate this workflow. The toolpath used for the machining is the toolpath showed in 4.4, with a tolerance of 1.0 μm . The results of the measurements of the part are given in **Figure 6**.

The part was successfully machined using the model-based strategy, with a tolerance after machining below 4.0 μm .

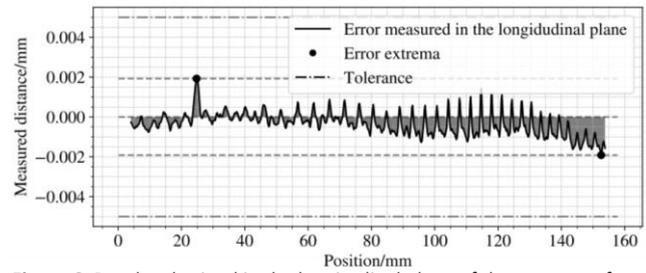


Figure 6. Results obtained in the longitudinal plane of the test part after the machining with a carbide shape mill.

6. Conclusion

In this article, several features and toolpaths from WORKNC CAM software version 2020.0 have been evaluated in the scope of the PIXE RFQ fabrication. By using prior curve resampling, reducing the circular interpolation tolerance in the post-processor, and avoiding the use of the mesh-sectioning feature on the visualization mesh, the accuracy was significantly improved for several different workflows. Using the most efficient workflow (involving the 3D model), a tolerance of 1 μm was achieved on the toolpath, which is 18 times smaller than the tolerance obtained previously using WORKNC. With this toolpath, a test part was machined with a shape accuracy of 4 μm , while 19 μm was obtained without these improvements. This study has permitted to develop a better understanding of the successive data transformations as well as the way to control the global tolerance of the toolpath, which will be very valuable in future projects. The software has demonstrated its ability to produce accurate toolpaths for the machining of high-precision parts for CERN facilities.

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