CONTRIBUTION FOR THE MANUFACTURING OF SCULPTURED SURFACES WITH HIGH-SPEEDS BASED ON NEW METHODS OF TOOL PATH INTERPOLATION

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Abstract. *In spite of the growing use of sculptured surfaces in new products, the manufacture of this surface type presents countless limitations related to machine time and the product surface quality. Because of this, there is a constant search for the manufacturing process optimization through the evolution of the several level by involved technologies, such as: numeric control, cutting tool, CAD/CAM Systems, etc.. However, as this manufacturing process involves the use of all those technologies and, for being different technologies, it presents different of technological development, there is a natural technological limitation represented by the technology with smaller evolution degree. With that, this paper has the purpose of analyzing and developing support to the substitution of the tool path representation segments of straight line (Linear Interpolation) for mathematical models capable to represent curves (Spline Interpolation), developing thus, the technology of the tool path representation.*

Keywords*: Sculptured Surfaces; Tool Path Interpolation; CAD/CAM Systems*

1. INTRODUCTION

The new functional and aesthetic demands when developing a product, linked to the evolution on the CAD (Computer Aided Design) Systems towards the modeling and manipulation of sculptured surfaces, stimulate the higher insertion of the geometric representation through sculptured surfaces.

Currently, such surfaces may be found in products with functional requisites, such as, aerodynamic components applied in the aeronautic industry, surgical prosthesis and components with optical characteristics (Choi and Jerard, 1998), or products with aesthetic requisites for customer satisfaction, such as products in the automotive and electronic sectors. For them, the geometric representation through sculptured surfaces is used as a factor to the launching of new products.

Because of this fact, there is the search for technological advancements in manufacturing of sculptured surfaces that may be able to increase the process efficiency, mainly when talking about the milling of molds and dies. This process presents high demand by automotive, aeronautical and electronic industries.

Among such technological advancements, the HSC (High Speed Cutting) Technology has shown the highest contributions towards the improvement on this manufacturing process' efficiency, mainly because it shows, as features, the high rate of material removal, manufacturing time reduction and high surface quality, as well as a continuous search for increases in the active speed throughout the process (Schulz, 1996).

During the nineties, most of the mold and matrix industries in Germany, Japan and the USA intended to invest in the development of the application of HSC Technology in their manufacturing processes (Fallböhmer *et al.*, 1996).

As a consequence, the statistical report of the German machines tool industry in 2005 (WDW, 2005), presented the HSC Technology as a trend in the fabrication processes, as well as in developing machines tool. Besides, the report also shows as a trend the development of technologies that work as supports and propel the HSC Technology, such as high-performance numeric controls, integration of the CAD/CAM/CNC chain in the manufacturing process, direct actuation systems (linear motors), etc.

Among the several technologies involved in the HSC Technology, the tool path generated by the CAM System gives the manufacturing process characteristics directly related to the machining time and final quality. Through the tool path, one may propel or limit the HSC Technology application in the manufacturing of high-speed molds and dies.

As a reflex of the importance of the tool path in the HSC Technology, in 1996, the mold and dies companies from Japan, Germany and the USA that were starting the application and development of the HSC Technology, highlighted the generation of the tool path in CAM Systems as the most important technology to be developed in the future (Fallböhmer *et al.*, 1996).

Normally, due to the mathematical simplicity and user-friendly characteristics, the tool path represented by straight-line segments (Linear Interpolation) became a standard in the industrial environment (Lartigue *et al.*, 2001; Hsu andYeh, 2002).

However, the dynamic demands in the process resulting from the application of the HSC Technology result in several dynamic limitations at executing the tool path with Linear Interpolation, mainly regarding the machining feed and the geometric model accuracy (Lartigue *et. al.*, 2004; Han *et al.*, 1999; Helleno and Schützer, 2006).

Han *et al. (1999)* highlight the feedrate limitation because of the numeric control processing capacity for interpreting and processing the great amount of information blocks (Look ahead) coming from the usage of Linear Interpolation in complex surfaces.

Arnone (1998) approaches this very problem relating the Numeric control processing time and the segment size of the tool path. Regalbuno (2004) and Stroh (2005) presented, in their studies, the feedrate limitation because of the acceleration variation coming from the inclination angle between the straight lines segments.

Lartigue et al. (2001) approaching the subject of complex surface milling in five-axis machining centers, checked the same problems while using the Linear Interpolation for representing the tool path in complex surfaces.

The feedrate variation, observed in these cases, will have a negative influence over the machining time and the product's surface quality, resulting in a technological limitation at manufacturing complex surfaces with high speeds. Because of this, the study of new interpolation methodologies of tool path is paramount.

Consequently, the interpolation methods of tool path are reconsidered when generating the NC Program and their studies have been approached by several authors through the research of new interpolation methods for tool path (Lartigue *et al.*, 2004; Rangarajan and Dornfeld, 2004; Altintas and Erkorkmaz, 2003; Yau and Kuo, 2001; Cheng *et al.*, 2002).

Among these new methodologies, the Spline Interpolation, in which the tool path is represented by curve segments based on mathematical models (Mahon and Browne, 1993), allows a tool path which is soft and precise, creating a solution at machining with the HSC Technology (Lartigue et al., 2004; Erkorkmaz and Altintas, 2001; Cheng *et al.*, 2002).

1.1. CAD/CAM/CNC Chain

The manufacturing process in sculptured surfaces is based on the usage of the CAD/CAM/CNC Chain, in which a geometrical model containing the product conception is transferred to the CAM System. In this step, the manufacturing data will be inserted, such as raw material dimensions, machining strategies and technological parameters so that the tool path is calculated and simulated. In this moment, the tool path will be represented by a native file, known as CLDATA (cutter location data file) (Mahon and Browne, 1993). This file contains the coordinates in the Cartesian plane of the tool path.

This native file may be recognized only by the CAM System in which it was generated, and, for not being in the programming language ISO 6983, it is not interpreted by the CNC, (Choi and Jerard, 1998). In most cases, an additional module, linked to the CAM System, known as post-processor, will be the responsible for changing the native file into an NC Program, with the language appropriate for the CNC.

Figure 1 illustrates the integration of the CAD/CAM/CNC Chain in the manufacturing of sculptured surfaces.

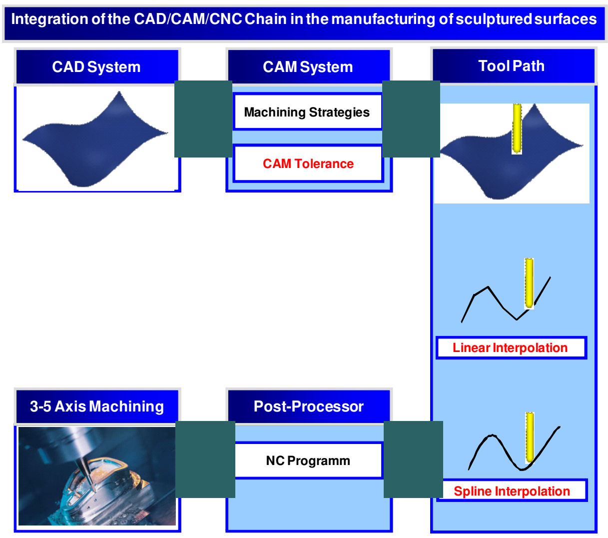

Figure 1. Integration of the CAD/CAM/CNC chain in the manufacturing of sculptured surface.

In traditional manufacturing, in which the demands on the feedrate are significantly less, the tool path interpolation methods were disregarded as a resource for the CAM Systems. This turned linear interpolation into the standard due to its mathematical simplicity and ease of use for the programmer.

However, with the application of HSM Technology where the demands on the feedrate are higher, the linear interpolation method begins to create various limitations, primarily in relation to the rate of machining and the accuracy of the geometric model. This has resulted in the reconsideration of the utilization of tool path interpolation in the generation of the NC program (Lartigue *et al.*, 2004; Altintas and Erkorkmaz, 2003; Yau and Kuo, 2001).

Figure 2 illustrates the federate behavior in function of the increase in programmed feedrate obtained in an experiment at the Laboratory for Computer Application in Design and Manufacturing (SCPM/UNIMEP). In these tests the NC program was generated using linear interpolation.

Observe that for a programmed feedrate of up to 1.000 mm/min for the tool machine and tested numerical command, the real feedrate remains constant along the entire geometric model and with the same programmed value. However, as the programmed feedrate increases, the variations of the real feedrate become more pronounced in the more complex areas of the geometric model.

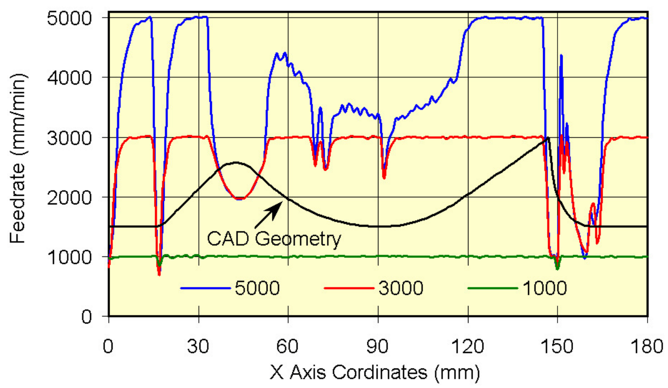

Figure 2. Feedrates behavior using linear interpolation

Due to this, the study of new tool path interpolation technologies has become fundamental. Among the existing methodologies, this article will evaluate the Linear and Spline interpolation.

1.2. Linear Interpolation

In linear interpolation, the CAM system determines the tool path through the interpolation of straight line segments that best adapt to the tolerance range of the CAM system (see Figure 2). These straight line segments are represented by the G01 command of the ISO 6983 programming language. Because linear interpolation uses straight line segments to represent the tool path, it has a simpler mathematical representation than other methods. For this reason it has become the most popular method for representing tool paths.

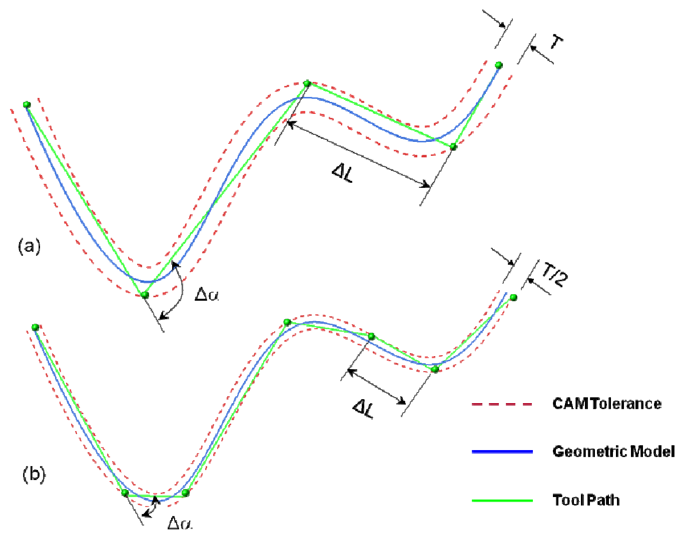

Figure 3. Tool path in function of CAM Tolerance.

As show in Figure 3:

- the increase or reduction in the CAM Tolerance results, respectively, in increases or reductions in the (ΔL) segment size used for representing the tool path;

- The increase or reduction in the CAM Tolerance results, respectively, in increases or reductions in the inclination between the ($\Delta\alpha$) segments of the tool path. This characteristic, like its influence over the manufacture of sculptured surfaces, is evident in studies performed by Stroh (2005) and Regalbuno (2004).

1.3. Spline Interpolation

In the Spline interpolation, differently from what happens with the Linear Interpolation, the tool path is represented by a set of segments of B-Spline Curves (C0, C1,.., Cn) and straight lines.
The B-Spline Curve uses, in its representation, a mathematical model based on the Blending Function (Basis Spline), which presents the Bernstein Basis as a special case. The mathematical representation of a B-Spline Curve may be observed in the Eq. (1).

$$P(t) = \sum_{i=1}^{n+1} B_i N_{i,k}(t) \tag{1}$$

Equations (2) and (3) define the Blending Function (Basis Spline) for the B-Spline Curve.

$$N_{i,1}(t) = \begin{cases} 1 \;\; para \;\; x_i \le t \le x_{i+1} \\ 0 \;\; para \;\; demais \;\; casos \end{cases} \tag{2}$$

$$N_{i,k}(t) = \frac{(t - x_i) N_{i,k(t)}}{x_{i+k-1} - x_i} + \frac{(x_{i+k} - t) N_{i+1,k-1}(t)}{x_{i+k} - x_{i+1}} \tag{3}$$

Thus, in the manufacturing of sculptured surfaces, the CAM System may determine a path for the most mollified tool, within the limits of the CAM Tolerance range, as shown on Figure 4 (Erkorkmaz and Altintas, 2001; Cheng *et al.*, 2002).

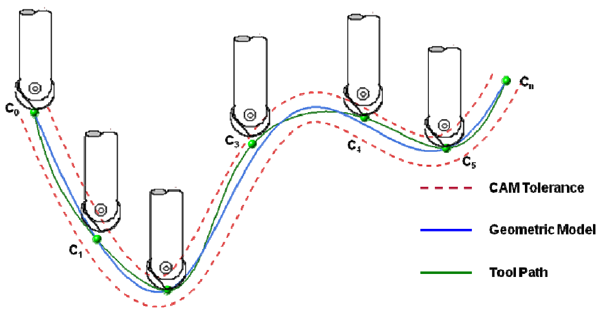

Figure 4. Representation of the interpolation by curves.

The representation of the tool path using this method presents the following characteristics:
- Smaller NC programs in relation to the linear interpolation ones, due to the need of a smaller amount of dots for representing the same path (Lartigue *et al.*, 2001);
- Substitution of the straight line segments by curves, eliminating the problems with the block processing times and acceleration and deceleration peaks;
- Better surface finishing;
- Reduction in the machining time when manufacturing Sculptured surfaces, once the federate behavior is close to the programmed feedrate (Cheng *et al.*, 2002).

2. DEVELOPMENT OF MACHINING TESTS

To investigate the effect of tool path interpolation methodology in the manufacture of sculptured surface, linear and Spline interpolation were used only in the finishing operation with CAM tolerance of 0,05 and 0,005 mm. In all tests the roughing and semi-finishing operations were identical.

The test model used in the machining tests as illustrated in Figure 5. In order to simulate the manufacturing conditions for molds and dies, the manufacturing tests were done in AISI-SAE P20 steel.

The machining was performed in two machining centers , which present the following features: Machine A (Siemens 840D control; 3 Axis; linear drives for acceleration > 2g and 100m/min federate max.; 40.000 rpm motor Spindle); Machine B (Siemens 840D control; 5 Axis; 1g acceleration and 50m/min federate max.; 28.000 rpm motor Spindle).

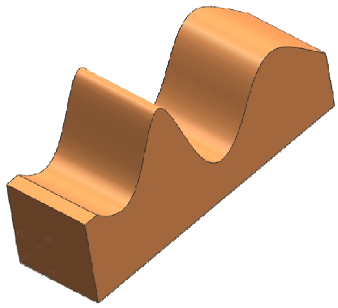

Figure 5. Test model used in experiments.

The interpolation methodologies for the tool path being analyzed during the finishing operation were distributed into machining ranges along the test model, in the following setups:

- Range 1 – Linear Interpolation - CAM tolerance of 0.05 mm;
- Range 2 – Linear Interpolation - CAM tolerance of 0.005 mm;
- Range 3 - B-Spline Interpolation - CAM tolerance of 0.05 mm (CAM A System);
- Range 4 - B-Spline Interpolation - CAM tolerance of 0.005 mm (CAM A System);
- Range 5 - B-Spline Interpolation - CAM tolerance of 0.05 mm (CAM B System);
- Range 6 - B-Spline Interpolation - CAM tolerance of 0.005 mm (CAM B System);

Trying to evaluate a single integration standard between the CAM and CNC systems, the tool path with B-Spline interpolation was generated with different CAM tolerances (0.05 and 0.005 mm) and CAM Systems (CAM A and CAM B Systems).

Because high-speed machines tool are equipped with the Siemens 840D command, it will not be possible to check the integration of these CAM systems with other types of CNC controls.

For checking the influence of the B-Spline interpolation over different characteristics of dynamic conditions, the experiments are performed in two machining centers with two conditions of federate (2.500 and 15.000 mm/min).

As the feedrate limitation in these types of machines is determined by the cutting tool, the behavior curves in feedrate were obtained through cut-free movements. This allowed checking the behavior of interpolation methods in limit feedrate.

3. ANALYSIS OF THE RESULTS

3.1 Analysis of the Tool path

Despite the fact that the test model geometry is unique for all the machining tests, the tool path generation on the CAD/CAM/CNC chain allows tool paths with distinct features according to the methodology adopted.

For this analysis, a simplified tool path was used containing only a single tool course over the geometry of the test model.

3.1.1 Linear Interpolation

Because of the fact that the tool path, in this case, is made of straight-line segments, its analysis is based on the comparison of segment parameters, specifically the size and the inclination.

Figure 6 illustrates the features of the tool paths with Linear Interpolation used in the test model finishing. The test model profile shown in this figure is illustrative and does not contain values identifiable on the graph scale.

From Figure 6 the following results can be noted:

- the tool path with a CAM Tolerance of 0.05 mm presents straight line segments higher than the ones in a CAM Tolerance of 0.005 mm;
- The tool path with a CAM Tolerance of 0.05 mm presents a higher inclination between straight-line segments than a CAM Tolerance of 0.005 mm.

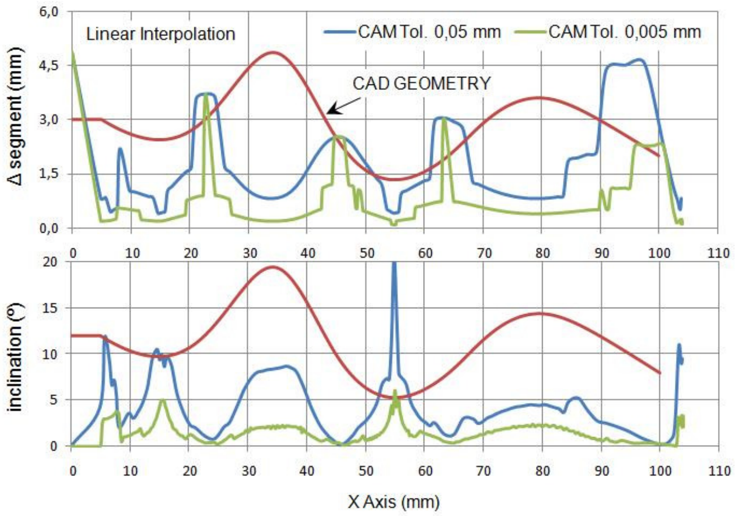

Figure 6. Characteristic of the tool path with Linear Interpolation.

3.1.2 Spline Interpolation

Because of the fact that a tool path based on Spline Interpolation is made up of curve segments, its analysis cannot be based on the same criteria used in the Linear Interpolation, but on the characteristics of the mathematical model of its original curve, such as the blending function and the derivatives of first and second order.

In the CAM A System, it was observed that the tool path with Spline Interpolation and a CAM Tolerance of 0.05 mm is represented by three curve segments, while a tool path with Spline Interpolation and a CAM Tolerance of 0.005 mm is represented by four curve segments.

Differently from the CAM A System, in the CAM B System, in both cases, the tool path with Spline Interpolation is represented by a single curve segment.

3.2 Machining Time

As a comparison effect between the interpolation methodologies of tool path, the Linear Interpolation was used for defining the reference machining time, being indicated as 100% in the discussions to follow.

For the tests performed with a feedrate of 2,500 mm/min, shown on Figure 7, the Spline Interpolations showed a better performance when compared with the Linear Interpolation (reductions between 3 and 22%), mainly for the interpolations generated with a CAM System tolerance of 0.005 mm.

Despite the low feedrate used in these tests, one may observe that the best performance of the Spline Interpolations is evident on usages with the Machine B. This machining center presents dynamic characteristics lower than the Machine A.

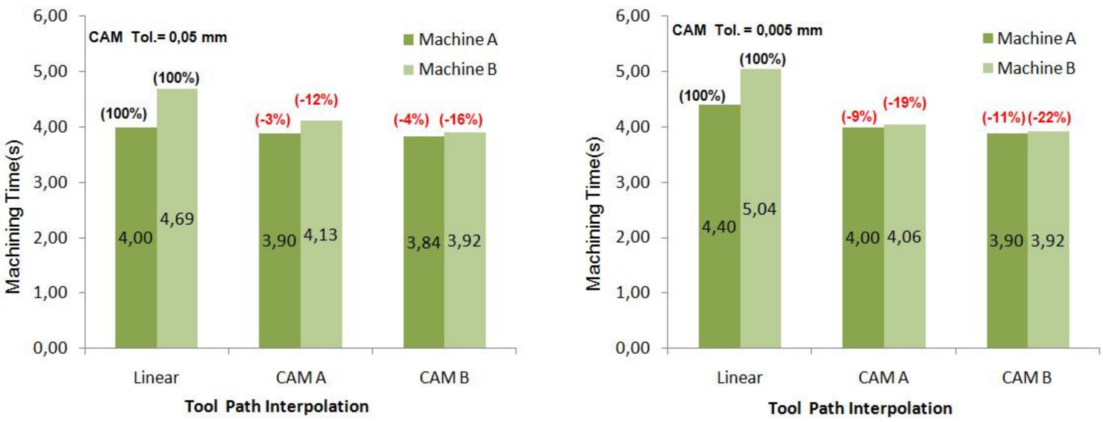

Figure 7. Machining time with feedrate of 2,500 mm/min.

For the tests performed with a feedrate of 15,000 mm/min, as shown on Figure 8, the Spline Interpolation also presented a better performance than the Linear Interpolation (reductions between 46 and 68%).

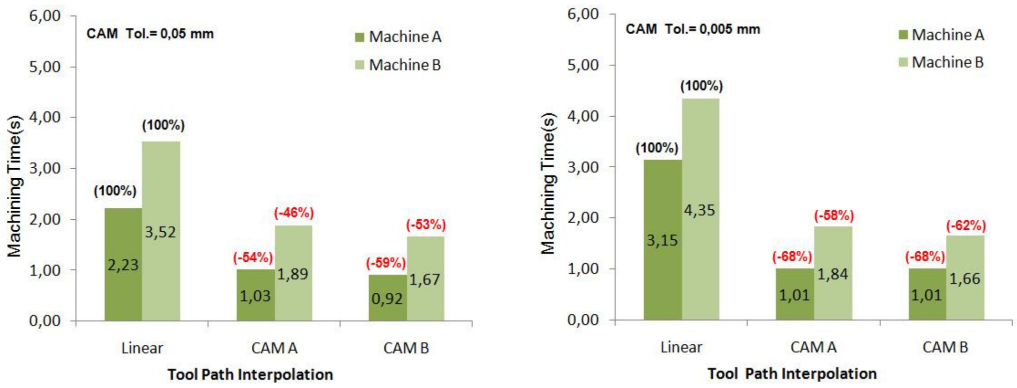

Figure 8. Machining time with feedrate of 15.000 mm/min.

With the comparison between the variation on machining times in relation to the interpolation methodology on the tool path and the machining center used in the tests, one may observe that:

- in the low feedrate applications where the dynamic demands are lower, the benefits of the Spline Interpolation are more evident in the machining center with lower dynamic characteristics, that is, the application limitations of the Linear Interpolation for describing paths of complex surfaces are less evident in a machining center with a high dynamic performance;
- the usage of higher feedrates and, consequently, higher dynamic demands, proves the better performance of the Spline Interpolations over the Linear Interpolation;

Besides, one may observe through

Figure 9 and Figure 10 the effect of tolerance in the CAM System in different feedrates and machining centers. In this case, the interpolation with a CAM tolerance of 0.05 mm was used as reference machining time, being thus indicated with the value of 100%.

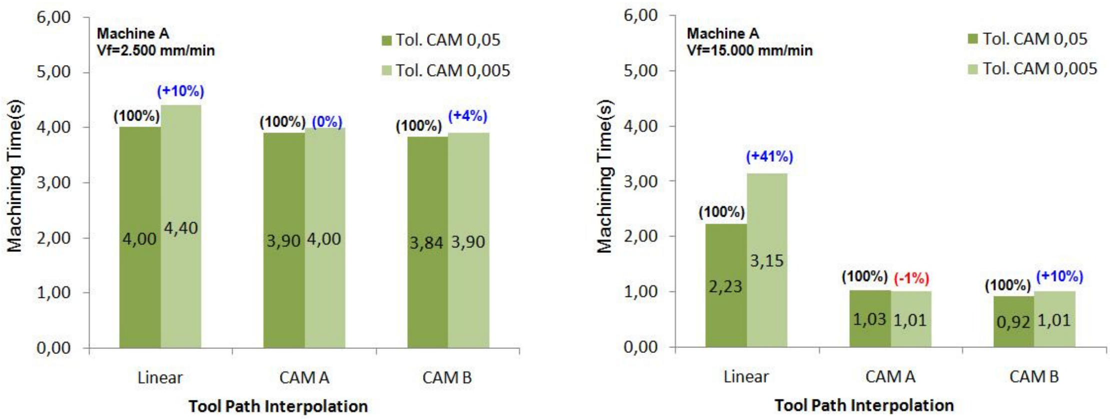

Figure 9. Effect of the CAM tolerance on the Machine A.

One may notice that the tolerance variation in the CAM System presents a significant effect for the Linear Interpolation in both machining centers. The machining time increases with the reduction of the tolerance in the CAM System, that is, the higher segmentation on the tool path results in an increase in the machining time.

With the exception of the CAM B Spline Interpolation in the Machine A, in which one observes some increase in the machining time with the reduction in the tolerance in the CAM System, the other Spline Interpolations do not present significant variations in the machining time because of reductions in the tolerance.

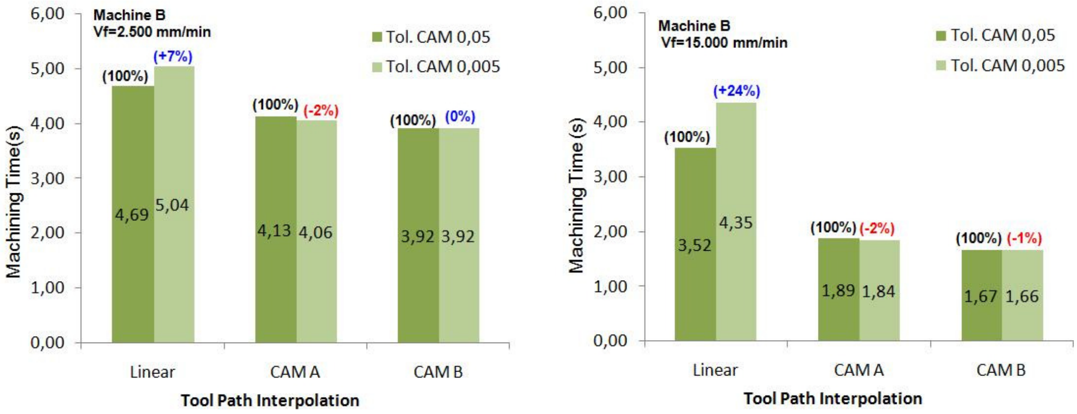

Figure 10. Effect of the CAM tolerance on the Machine B.

3.3 Analysis on the Feedrate

The analysis on the feedrate for different interpolation methodologies of the tool path obtained with the Machine A is shown on Figure 11.

As it may be observed in these figures, the feedrate varies in the test model geometry with different characteristics between interpolation methodologies of the tool path. For all the situations, the Linear Interpolation presented the highest speed variation, and this variation is aggravated with the 0.005 mm CAM System tolerance.

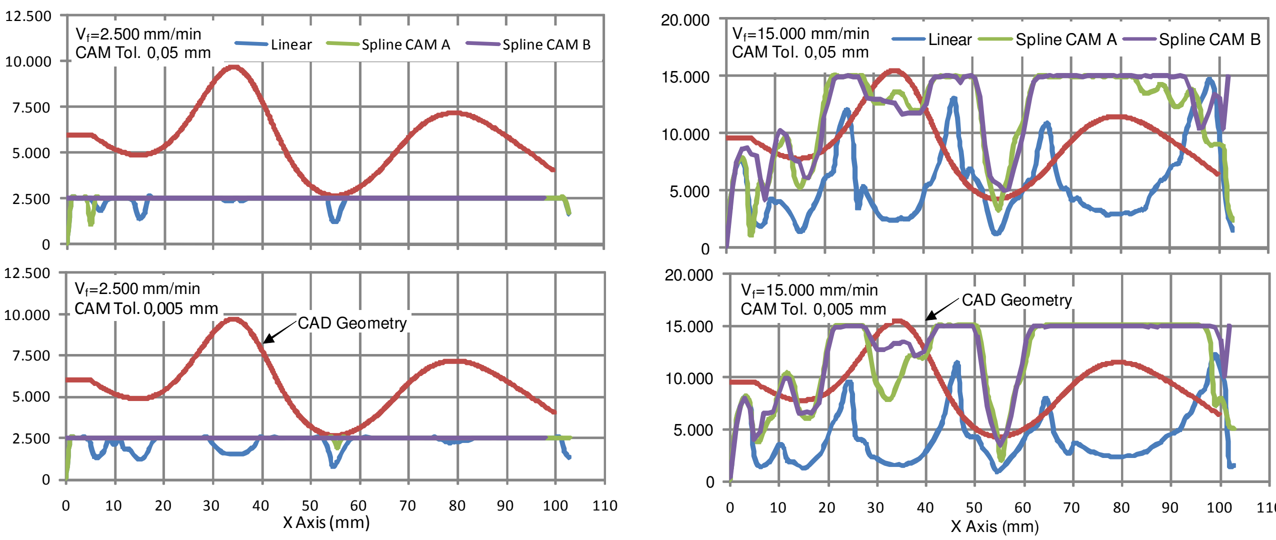

Figure 11. Feedrate Behavior – Machine A (Vf =2.500 and 15.000 mm/min).

For the Spline Interpolations (Spline CAM A and Spline CAM B) one may observe that the feedrate presents a performance superior to the Linear Interpolation, mainly in high-speed conditions. It is also observed that there are critical regions in the geometry that result in a feedrate lower than the programmed one.

Besides, one may observe that the Spline Interpolation generated by different CAM systems (Systems CAM A and B) presents a distinct behavior in some regions of the test model geometry.

Figure 12 illustrate the feedrate for different interpolation methodologies of the tool path obtained with the Machine B.

Through these figures, it is observed that the tests performed with the Machine B presented the same characteristics shown by the Machine A. Nonetheless, because of lower dynamic characteristics, the real feedrates presented a higher variation.

Comparing both machining centers with high feedrates (see Figure 11 and Figure 12) one observes that, in the Machine A, the feedrate reaches the programmed feed values for some time. In the Machine B, the feedrate is always lower when compared to the programmed feedrate.

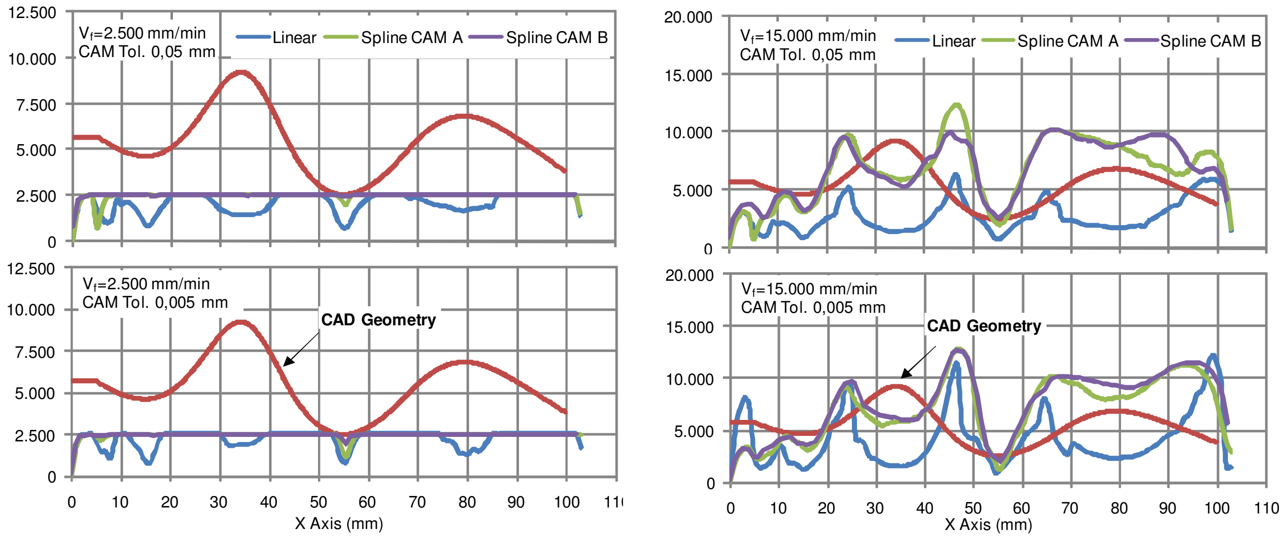

Figure 12. Feedrate Behavior – Machine B (Vf =2.500 and 15.000 mm/min).

4.CONCLUSION

Through the analysis on the generation of the tool path with Linear Interpolation by the CAM System, it was checked that the lower the CAM tolerance, the higher the number of straight line segments in the tool path. Nonetheless, the increase in the number of straight-line segments results in lower sizes of segments and inclinations between them.

Despite the fact that the geometric model of the test model is unique, the generation of the tool path through the Spline Interpolation presented distinct characteristics regarding the adopted CAM tolerances and the used CAM Systems.

The paths generated by the CAM A System were represented by a set of curve segments, and the reduction in the CAM tolerance caused some increase in the number of segments and, consequently, shorter segments.

The paths generated by the CAM B System were, for both CAM tolerances, represented by a single curve segment.

The machining time showed that the paths with Spline Interpolations presented values lower than the ones with Linear Interpolation, mainly in high feedrates. Likewise, the machining times obtained with the Machine A (higher dynamic capacity) presented lower values when compared with the Machine B for all the studied paths.

Among the tool paths with Spline Interpolation, the paths represented through a single curve segment (paths generated in the CAM B System) presented a lower machining time when compared with the paths represented by several curve segments (paths generated in the Unigraphics CAM System).

The reduction in the CAM tolerance had a negative influence only over the machining time of paths with Linear Interpolation, not having influenced the ones with Spline Interpolation.

The feedrate behavior along the test model showed that, in the manufacturing of complex surfaces, independently on the programmed feedrate value, the real feedrate varies due to the geometry characteristics, the tool path representation, the dynamic characteristic of the tool machine and the CNC (machine response time - MRT).

As it happened with the machining time, once they are directly related, the paths with Spline interpolation presented a better behavior when compared with the ones with Linear Interpolation. The average accelerations were also higher in the Spline Interpolations.

In the Linear Interpolation, the rate behavior is related to the size of the programmed segment, with the segment inclination and with the machine response time (MRT). Because of this, the Machine A (MRT=0.003 s) machining center presented a better behavior when compared with the Machine B (MRT=0.007 s).

Among the tool paths with Spline Interpolation, the paths represented by a single curve segment presented a better feedrate behavior when compared with the ones represented by several curve segments.

The feed and acceleration rates' behavior presented similar to the first and second-order derivatives in the tool path. Besides, in the regions represented by junctions between Spline curve segments, there was a marked reduction in the rate.

Thus, despite the fact that the Spline interpolation suffers with problems of integration between the CAD/CAM/CNC chains, the gains obtained with some modifications in this type of interpolation showed that, with some improvements in this integration, this kind of interpolation might really be a solution in the manufacturing of high-speed complex surfaces.

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