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Kinematic behaviour modeling of the axes of a machining center in high speed milling

B.Gassara^{1,2 a}, G.Dessein^{2,b}, M.Baili^{2,c}, M.Hbaieb^{1d} and W. Bouzid Saï^{1,e}

¹ Unité de Génie de Production Mécanique et Matériaux, ENIS, route Soukra Km 3,5-B.P. 1173-3038 Sfax-Tunisie

² Université de Toulouse ; INPT/ENIT ; Laboratoire Génie de Production; 47 avenue d'Azereix, BP 1629, F-65016 Tarbes Cedex, France

^a bassem.gassara@enit.fr, ^bgilles.dessein@enit.fr, ^cmaher.baili@enit.fr, ^dmhbaieb@yahoo.fr, ^ewassilabouzid@yahoo.fr,

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Abstract. In the context of high speed milling “HSM”, the feed rate does not always reach the programmed value during the machining process which implies an increase of machining time and non compliance with the programmed feed rate. This phenomenon leads to productivity issues and an underestimation of the cost of machining for the industry.

The aim of this study is to identify the kinematic behaviour of the machine tool during any type of discontinuity between linear and circular contours in different combination by taking into account the specific machining tolerances. In order to achieve this, a model of the law of the axes motion and the actual trajectory at discontinuities is necessary. This method is based on the subdividing of the trajectory into elementary geometries according to the type of interpolation (circular or linear). The proposed method can estimate the cycle time with a maximum error of 5% between the actual and the prediction cycle time.

Finally, an experimental study was carried out on a high speed machine. It is based on elementary tests in order to analyze the axes behavior during any type of discontinuity and to validate the developed models.

Introduction

The growing competition in the market continues to evolve the standards of quality. The requirements to reduce time and costs are always higher. This gave birth to new processes and production techniques including the High Speed Milling “HSM”. This machining process is the most used method in industry and where the cutting speed can reach values of five to ten times higher than those used in conventional machining [1]. However, the important feed rates and accelerations of the axes solicit the structure of the machine, its digital servo drives control and its numerical control. The response of the machine in these conditions is different from imposed feed rate and trajectory. For example, the actual machining time is often very high compared to the time estimated by the CAM software. Indeed, the feed rate does not always reach the programmed speed during a machining process [2, 3, 4].

The generated tool path can be expressed using linear and circular interpolations. At points where different interpolations meet, there is often a discontinuity in curvature or in tangency. At the points of discontinuity, the movement of the axes slows down in order to respect the maximum values of acceleration and Jerk for each axis which results in an increase in the cycle time.

In this context, several works have been interested to adapt the tool path to rapid piloting of the machine. So, two models for smoothing the trajectory were distinguished. The first is meant to approximate the trajectory by a polynomial function [5]. The second is based on the addition of a

For motion along the tool path, the acceleration phase is composed of 3 zones (Fig. 1b). The deceleration time is given by the following expression:

$$T_{dec} = T_A + 2T_{J1}$$

Where: T_{J1} and T_A are respectively, the time when the feed rate is controlled by a maximum value of the jerk and the time when the feed rate is controlled by a maximum value of acceleration.

Feed rate for a linear interpolation. In linear interpolation, the limitation of the feed rate is essentially due to the cycle time interpolation of the numerical control unit (NCU), the programmed feed rate and the block length.

The feed rate authorized by the NCU ($V_{lin\ m}$) is given by:

$$V_{lin\ m} = \min(V_{icy}, V_{Lb}, V_{fprog}) \quad (1)$$

$$\text{With: } V_{icy} = \frac{L}{T_{cy}} \quad (2)$$

V_{Lb} is a function of the block length and the machine kinematic parameters (jerk and acceleration). This limitation will take place when the sum of the length of acceleration and deceleration is bigger than the length of a block L_b .

Feed rate for circular interpolation. For circular interpolation, the feed rate is limited by three kinematic parameters of the axes (acceleration, jerk and maximum feed rate) and the radius value of a circular interpolation R_i .

The feed rate ($V_{cir\ m}$) authorized by the NCU is given by:

$$V_{cir\ m} = \min(V_{fprog}, V_{Lb}, V_J, V_{Am}, V_{icy}) \quad (3)$$

The feed rate V_{Am} corresponding to the limitation of the acceleration is given by [6]:

$$V_{Am} = \sqrt{R_i A_m} \quad (4)$$

The feed rate V_J corresponding to the limitation of jerk is given by [6]:

$$V_J = \sqrt[3]{J_m R_i^2} \quad (5)$$

In circular interpolation, the programmed feed rate V_{fprog} depends on the nature of the circular shape machined: convex or concave. For a concave circular shape, we can use on Sinumerik 840D NCU correction of the feed rate by using the normal correction profile with constant feed (CFIN¹ on NCU Sinumerik 840D) [10]. In this case, the programmed feed rate becomes:

$$V'_{fprog} = \frac{R_p - R_{tool}}{R_p} V_{fprog} \quad (6)$$

R_p is the workpiece curvature radius and R_{tool} is the tool radius.

Feed rate of crossing on a continuity in tangency. At a tangency of continuity (discontinuity in curvature), the NCU slows down the movement of the axes in order to respect the maximum acceleration and jerk values for each axis.

- Continuity in tangency between circular and linear interpolation (point N as shown in Fig. 1a) [7]:

$$V_{jcN} = \sqrt{R_{Ci} C} \text{ et } C = J_m \delta t \quad (7)$$

- Continuity in tangency between two circular interpolations (point M as shown in Fig. 1a):

$$V_{jcM} = \sqrt{\frac{R_i R_{Ci} J_m \delta t}{R_i + R_{Ci}}} \quad (8)$$

¹ Instruction of correction the feed at inside curvature of Sinumerik language

Geometric modeling of continuities in tangency. The path generated by the CAM software/Mastercam is discretized into several elementary blocks according to the type of interpolation (linear and circular). A discontinuity in curvature or tangency at points where different blocks meet tends to slow down the feed rate and thereafter increasing the cycle time. The rate of change depends on the orientation angle γ_i between two consecutive interpolations (Fig. 2). With i Varies from 1 to n and n is the total number of block.

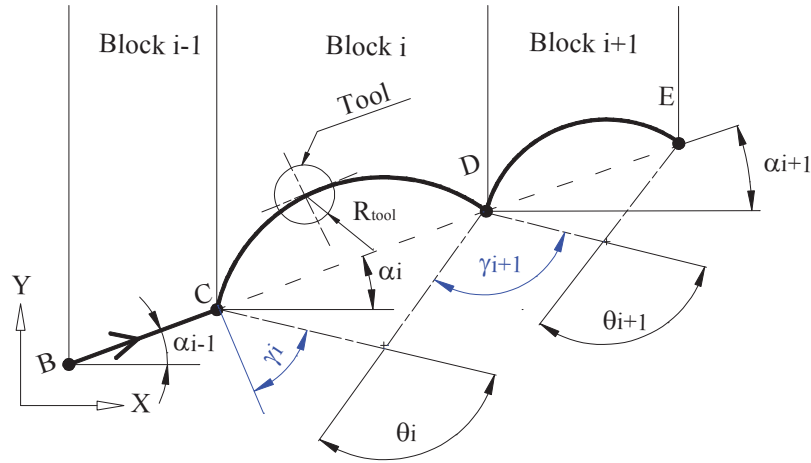


Fig. 2: Discretization of the tool center path

The equation of the orientation angle γ_i for the tool path is depended on the type of interpolation (linear or circular).

The equations of the orientation angle γ_i for linear and circular contours in different combinations are presented in table 1.

Table 1: Calculation of the orientation angle according to the type of interpolation

Connection Between	Equation of γ_i	Connection Between	Equation of γ_i
G1G1	$\alpha_i - \alpha_{i-1}$	G2G3	$\frac{\theta_{i-1}}{2} - \frac{\theta_i}{2} - \alpha_{i-1} + \alpha_i$
G1G3	$\frac{\theta_i}{2} + \alpha_{i-1} - \alpha_i$	G3G2	$\frac{\theta_i}{2} - \frac{\theta_{i-1}}{2} - \alpha_{i-1} + \alpha_i$
G3G1	$\frac{\theta_{i-1}}{2} + \alpha_{i-1} - \alpha_i$	G2G2	$\frac{\theta_{i-1}}{2} + \frac{\theta_i}{2} - \alpha_{i-1} + \alpha_i$
G1G2	$\frac{\theta_i}{2} - \alpha_{i-1} + \alpha_i$	G3G3	$\frac{\theta_{i-1}}{2} + \frac{\theta_i}{2} + \alpha_{i-1} - \alpha_i$
G2G1	$\frac{\theta_{i-1}}{2} - \alpha_{i-1} + \alpha_i$		

From equations presented in table 1, we can distinguish two types of discontinuities in the path according to the value of γ_i . For a discontinuity in curvature (D.c.) $\gamma_i = 0^\circ$, there is a continuity in feed rate. For a discontinuity in tangency ((D.t.) $0^\circ < \gamma_i < 180^\circ$, there is no continuity in feed rate.

In the case of the linear-circular interpolation, the tool path is represented by a linear contour (BC) and a circular contour (CD: radius R_i and center O_i) (as shown in Fig. 3).

The coordinate X_C is given by:

$$X_C = \frac{\cos \alpha_{i-1}}{\sqrt{(X_C - X_B)^2 + (Y_C - Y_B)^2}} + X_B \quad (9)$$

The coordinates of point D are given by:

$$X_D = 2R \sin \frac{\theta_i}{2} \cos \alpha_i + X_C \quad Y_D = 2R \sin \frac{\theta_i}{2} \sin \alpha_i + Y_C \quad (10)$$

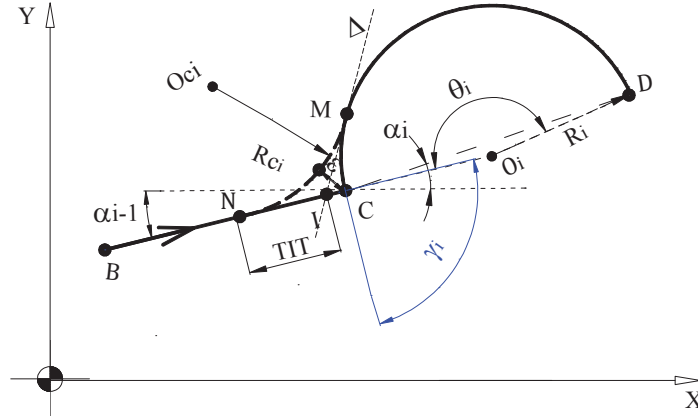


Fig. 3: Elementary path

The tool path presents a discontinuity in tangency located at the point C (as shown in fig 3). This discontinuity in tangency has been replaced by discontinuity in curvature by adding an arc with a center O_{ci} and with a fillet radius R_{ci} .

Firstly, the angles θ_i and α_i are determined using Eq. 9 and Eq. 10. Then, the angle γ_i is calculated. The fillet radius R_{ci} , which depends on the imposed error ε , is calculated by:

$$\left\{ \begin{array}{l} (X_C - X_{O_{ci}})^2 + (Y_C - Y_{O_{ci}})^2 = (\varepsilon + R_{ci})^2 \\ \left| \frac{Y_C - Y_B}{X_C - X_B} X_{O_{ci}} - Y_{O_{ci}} + \frac{Y_B X_C - Y_C X_B}{X_C - X_B} \right| = R_{ci} \\ \sqrt{1 + \left(\frac{Y_C - Y_B}{X_C - X_B} \right)^2} \\ (X_{O_i} - X_{O_{ci}})^2 + (Y_{O_i} - Y_{O_{ci}})^2 = (R_{ci} + R_i)^2 \end{array} \right. = R_{ci} \quad (11)$$

The fillet radius R_{ci} , which depends on the imposed value of TIT^2 , is calculated by:

$$\left\{ \begin{array}{l} TIT^2 = (X_M - X_I)^2 + (Y_M - Y_I)^2 \\ TIT^2 + R_i^2 = (X_{O_i} - X_I)^2 + (Y_{O_i} - Y_I)^2 \\ (X_{O_{ci}} - X_{O_i})(X_M - X_{O_i}) + (Y_{O_{ci}} - Y_{O_i})(X_M - X_{O_i}) = 0 \\ \frac{Y_C - Y_B}{X_C - X_B} X_I - Y_I + \frac{Y_B X_C - Y_C X_B}{X_C - X_B} = 0 \\ R_{ci} = \sqrt{(X_M - X_{O_{ci}})^2 + (Y_M - Y_{O_{ci}})^2} \end{array} \right. \quad (12)$$

²The distance which the rounding block may begin

The machine slowed at the discontinuities in tangency [4, 6, 7]. At this type of discontinuities, the NCU may authorize an advance speed not null if there is an error ε imposed on the trajectory tracking (functional tolerance imposed on part design). In this case, a circular arc is created according to the imposed error ε and the angle of orientation γ_i . To insert the radius of connection at the discontinuities, the rounding function G641 integrated into the NCU and the modal rounding function of RND³ have to be used. For the first, the connection radius value depends on the distance from which or for which the block transition is rounded (TIT). Therefore, the distance must be specified with ADIS function. For the second, the connection radius between the blocks is inserted into the NC programs.

Cycle time modeling

The model developed above allows us to determinate the cycle time T_c taking into account the geometry of the trajectory and the behaviour of the machine.

The cycle time is defined by the following expression:

$$T_c = \sum_{i=1}^n (T_{V_m}(i) + T_{acc}(i) + T_{dec}(i)) \quad (13)$$

With: i , T_{V_m} , T_{acc} and T_{dec} are respectively, the number of elementary interpolation, the cycle time using a maximum feed rate, the acceleration time and the deceleration time.

The different steps to determine the evolution of the feed rate and the cycle time T_c are as follows:

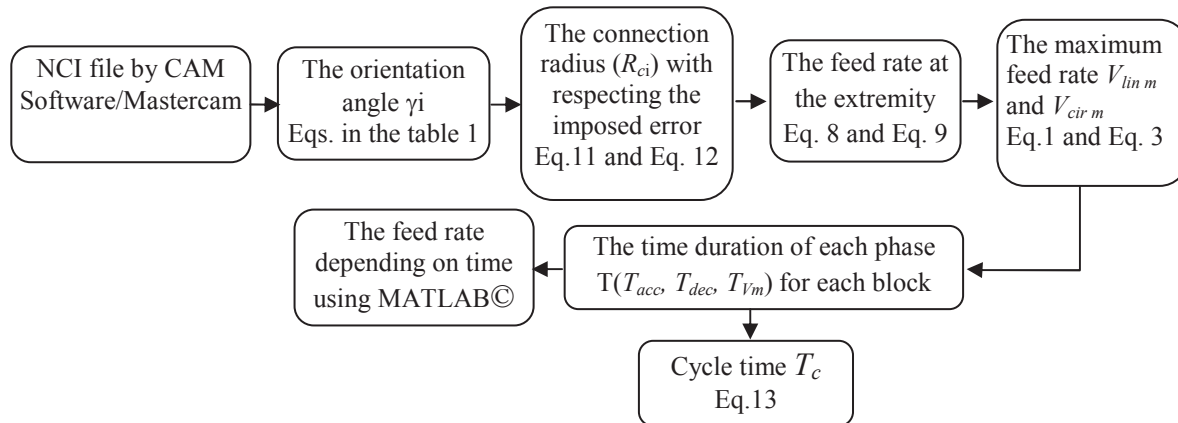


Fig. 4: Modeling steps

Results and Discussion

Based on this study, the impact of the imposed error value on the cycle time, according to the calculation of the feed rate evolution during motion along the tool path can be determined. To validate this study, two tests are performed on a high speed 3-axis machining center with a Sinumerik 840D NCU [10]. The first test enables to determine influence of tool path geometry on the feed rate. The second permits to study the impact of the imposed error value ε on the cycle time. The characteristics of the machine are presented in the following table (Table 2).

Table 2: Characteristics of the machining center HURON KX-10

Huron KX10	
Spindle speed	100 à 24000 tr/min
Maximum feed rate	30m/min
Maximum acceleration	3 m/s ²
maximum jerk	50 m/s ³

³Instruction of rounding the corner of the contour of Sinumerik language

Influence of tool path geometry. To determine the influence of tool path geometry on the feed rate, the circular-linear interpolation for different orientation angles γ_i is considered. The theoretical and experimental feed rate profiles are superimposed on Fig. 5. In this case, the discontinuity in tangency is removed by the addition of a circle arc which is a function of TIT (by using the function G641).

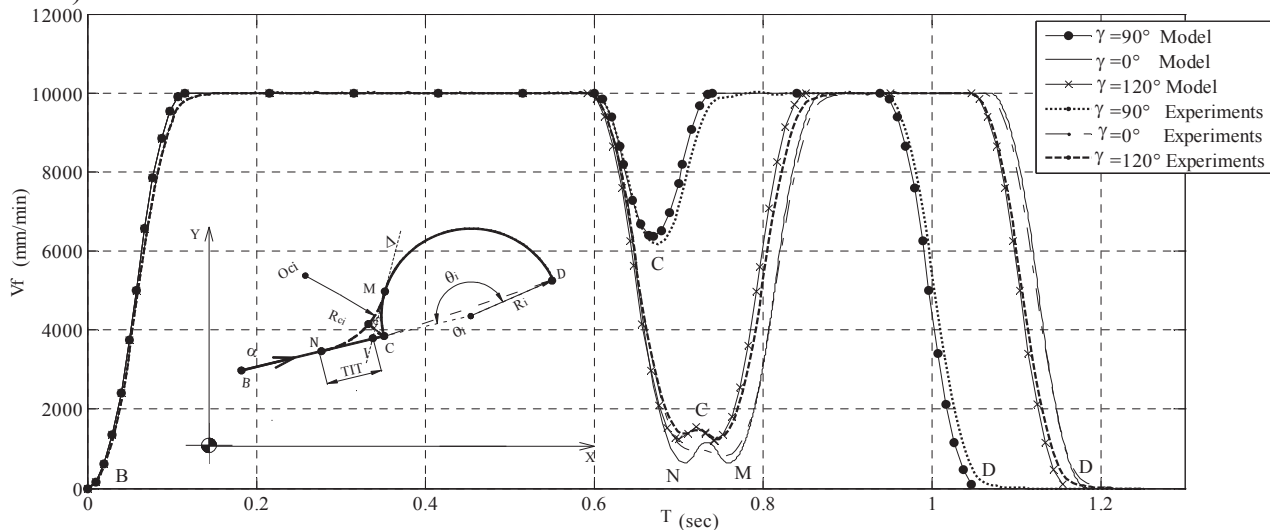


Fig. 5: Theoretical and experimental feed rate profiles for different values of γ_i ; TIT=0,5mm; BC=100mm and Ri=50mm

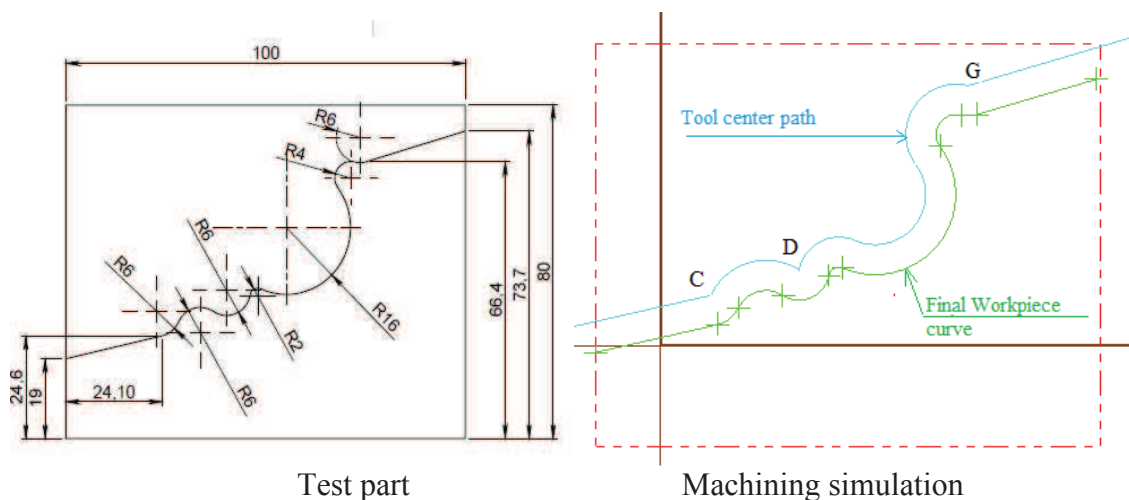
The feed rate at a discontinuity crossing (Fig. 5) is maximum for an angle $\gamma_i = 90$ (curvature discontinuity), then it decreases for other values of the angle γ_i (0° et 120°) corresponding to a discontinuity in tangency.

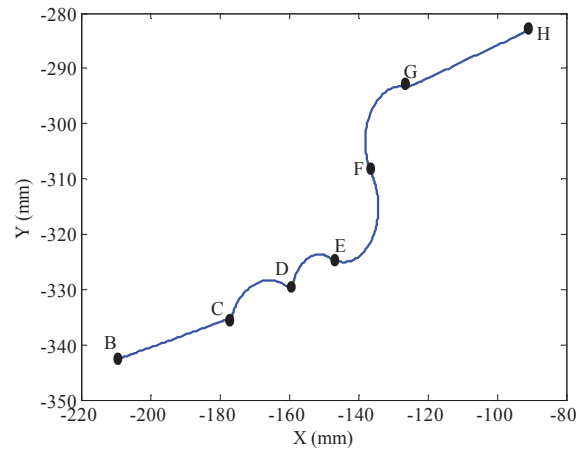
Impact of the imposed error value on the cycle time. To determine the impact of the imposed error value ε on the cycle time, the tool path shown in Fig. 6 is modified by adding arcs at the discontinuities located at points C, D and G with different error values (detailed on table 3). This tool path is composed of five blocks; i varies from 1 to 5.

These tests were developed in the experimental and theoretical studies.

Table 3. Geometry of the trajectory for different tests

Error ε [mm]		0.03	0.1	0.3	0.6	1
Point C	R_{C1} [mm]	0.27	0.91	2.99	6.89	14.11
Point D	R_{C2} [mm]	0.04	0.13	0.41	0.91	1.77
Point G	R_{C5} [mm]	0.89	3.31	14.08	55.21	436

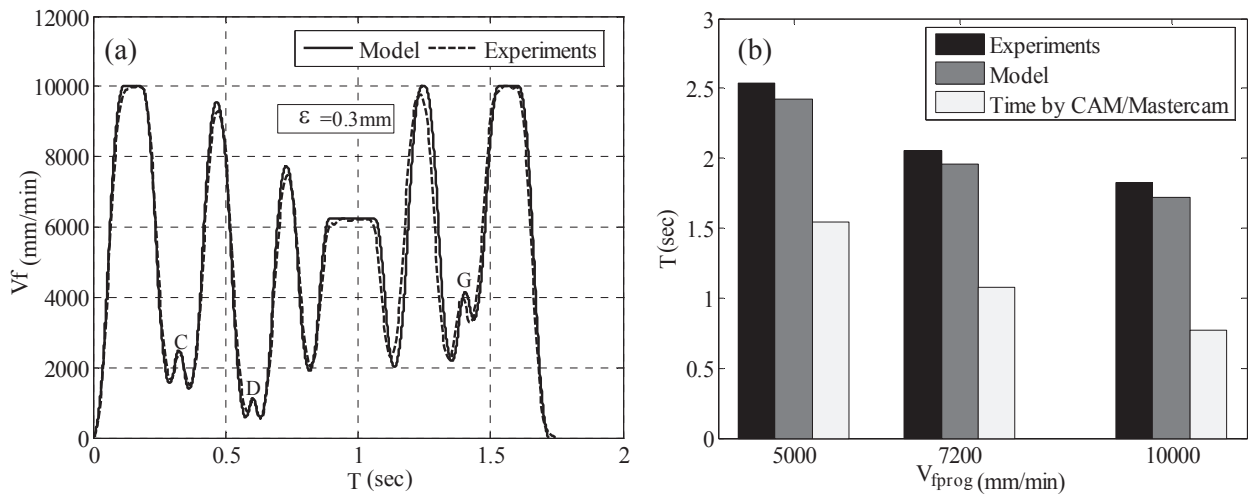




Tool center path

Fig. 6: Simulating machining of a work piece with a tool diameter 12 mm

Fig. 7 shows respectively the experimental and theoretical feed rate for an error value equal to 0.3 mm (a) and the histogram of actual, simulated and calculated time by the CAM software (b).

**Fig. 7:** Profiles of the theoretical and experimental feed rate (a) and cycle time for different programmed feed rate (b)

These results show a good correlation between experimental and theoretical model of this work. It is noted that the programmed feed rate will not be achieved only for a certain percentage of the total length of the tool path. This percentage depends on the length of the elementary interpolation, the type of discontinuity and the programmed feed rate value. As clearly seen on Fig. 7.b, the time calculated by the CAM software (length / programmed feed rate) underestimates the real machining time. It can be concluded that the importance of this shift should be taken into account during the establishment of the estimated cost. In a HSM context, the actual machining time is particularly dependent on slowdowns axis movement on the paths followed.

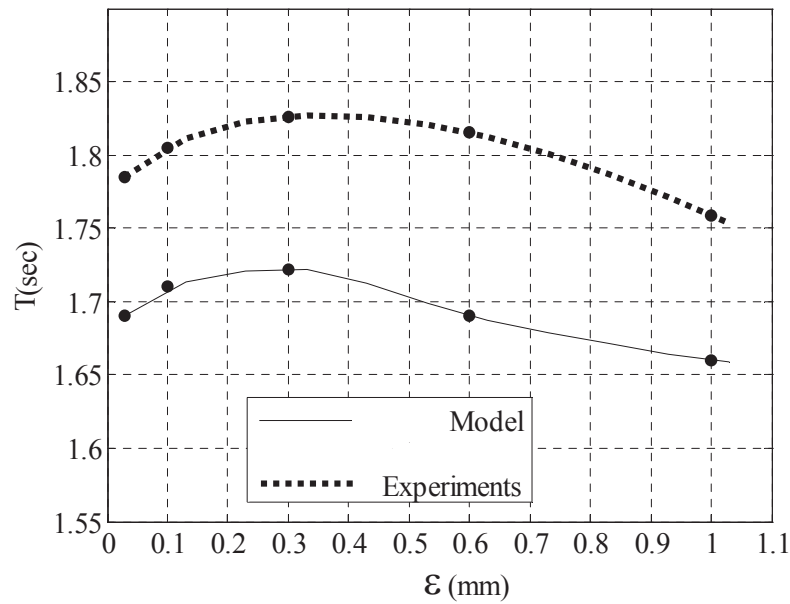


Fig. 8: The impact of the imposed error on the cycle time

Fig. 8 shows the evolution of cycle time depending on the imposed error value between the actual and programmed trajectory. It allows, for example, defining the optimal error value. We note that when the error values increase, the connection radius increases too and subsequently the feed rate of transition. However, this gain in speed does not lead to decrease of the total cycle time. Thus, it is necessary to select the optimal error value. In addition, a small increase in the error value has not a significant influence on reducing the cycle time. This increase will be significant only when the error value ϵ exceeds 0.3 mm.

Fig. 8 shows also that the maximum error between theoretical and experimental results is 5% and this, in a quasi-constant way for all tests.

Conclusion

This work presents a theoretical and experimental study of the evolution of the feed rate in HSM for a tool path discretized into linear and circular interpolation. The study has developed a model describing the behaviour of the axes of machine for any kind of trajectory. In addition, the model developed allows determining the impact of the imposed error value on the cycle time. The theoretical study was elaborated in two parts. The first part is devoted to the modeling of the feed rate with continuity in tangency. However, the second one aims at geometric modeling of continuities in tangency: it consists in calculating the radius between linear and circular interpolations in different combinations with respecting the tolerance imposed by the method office (ϵ).

The experimental study is based on elementary tests to determine the influence of the tool path geometry on the feed rate evolution as well as the impact of the imposed error value. This approach can be generalized to any machining strategy. The comparison between the results obtained by the theoretical model and experimental study demonstrates a maximum error of 5%.

The next step is to develop a calculation interface in order to automate the determination process of the evolution of the feed rate for an imposed error and the estimation of cycle time and production cost. This allows the industry to minimize the reflection time of operators before the establishment of the estimated cost.

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