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CORRECTION OF TRAJECTORY EXECUTION ERRORS IN HSM USING A MIRROR APPROACH

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Abstract. This paper focuses on contouring errors appearing during the execution process each stages of the process (CNC interpolation, feed drives). The so-called CEC Contouring Error Compensation) method which stands for a temporal mirror approach is developed in this paper. The modification of the trajectory setpoint so that the executed actual trajectory matches the CAM trajectory proves to be efficient as contouring errors are significantly decreased.

Keywords: Contouring errors, compensation, feed drive, trajectory.

1 INTRODUCTION

Within the context of High Speed Machining, the machining process is complex as it involves several stages. Starting from a CAD model built from geometrical and functional specifications, the tool trajectory is calculated during the CAM stage. The tool path, defined as a set of points expressed in the chosen format [Langeron et al., 2004], is transmitted to the CNC unit, whose role is to translate this calculated tool path into a set of axis commands (called reference axis commands). These commands are followed by the axis motion tracking control and feed drive servo dynamics. The movement between the tool and the part is generated at the end of the execution process. Finally, the last stage is the actual cutting process giving the machined part. Due to the numerous errors accumulated at each stage of the process, the machined part presents geometrical errors as regards the geometrical model. However, it is generally difficult to separate each source of errors unless a complete modeling of the machine is performed [Altintas et al., 2005]. Such a model may allow the prediction of the nature of errors and their importance in the final geometrical deviations. Nevertheless, a complete model is difficult to establish, and authors generally focus on one or more sources of errors only [Lavernhe et al., 2008]. This paper focuses only on execution errors associated to the machine structure and its CNC. Our objective is to propose an identification method of those errors followed by the minimization of such errors using a mirror approach also called the *Contouring Error Compensation method* (CEC method). The CEC method relies on the modeling of the feed drives.

2 EMPHASIS OF EXECUTION ERRORS

2.1. Illustration

Execution errors gather errors resulting from the interpolation stage, those generated by the feed drives and those associated to the machine tool geometry. The paper enhances the importance of errors generated by the feed drives, and the necessity to correct them. Let us consider the flank milling of a sharp corner using a cylindrical tool whose radius is equal to

the corner radius (Figure 1 – left). Due to kinematics limits, the trajectory is necessarily rounded to pass the discontinuity at high feedrates

. Indeed, Figure 1 clearly highlights that follow-up errors (gathering interpolation and feed drive errors) can be neglected for low programmed feed rate (0,1 m/min), whereas those errors are significant when the programmed feed rate is higher (10 m/min). This effect is actually clearly visible on the simulated machined surface: geometrical deviations observed can reach 30µm for the high velocity whereas it does not exceed 5µm for the low one.

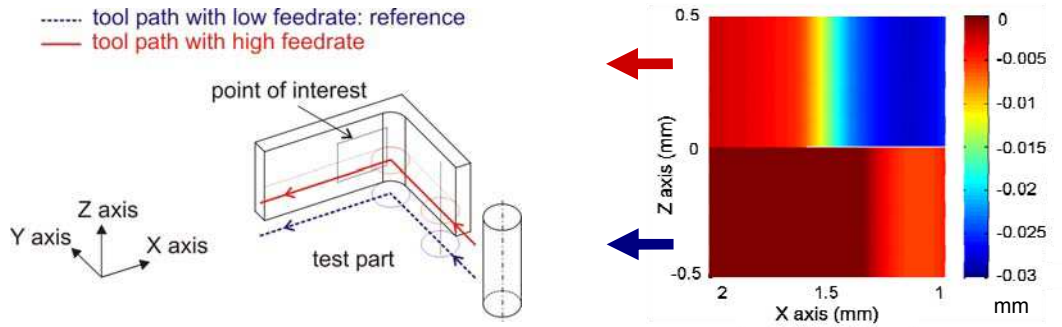


Figure 1; Tool trajectories and cartography of geometrical deviations

In the next, we propose a method to correct execution errors. Actually, the decrease in follow-up errors involves decreasing the geometrical deviations onto the part surface. The method takes advantages of a model of the feed drives previously assessed and described in [Prévost et al. 2010] predicting the feed drive errors. For each axis, the input of the model is the setpoint calculated by the interpolator and transmitted to the axis cards, denoted by the *position setpoint* (PS). The main outputs of the model are the *simulated axis positions* (SP), giving a good estimation of the actual axis positions, the simulated velocity (SV) and the simulated motor current (SMC). The next section is dedicated to the definition and the mode of calculation of the execution errors.

2.2. Calculation of contouring errors

Considering ideal machine geometry, link and motion errors (statics as well as dynamics effects) are neglected [Zagarbashi et al. 2009]. As a result, tool tip positions match axis positions, and execution errors only result from the combination of interpolation errors and feed drive errors. Two types of errors can be used to describe the deviations between the reference tool trajectory and the effective one: tracking errors or contouring errors. Tracking errors between the position setpoint and the actual axis positions are due to the servo controller dynamics. Let us take the example defined in Figure 2; the reference trajectory is in black (continuous line), and the actual trajectory is defined as a set of points ($P_1, \dots, P_i, \dots, P_n$).

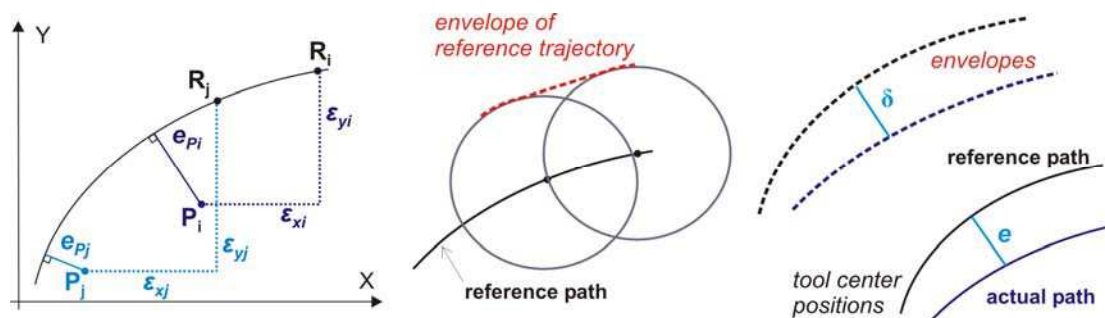


Figure 2; Tracking and contouring errors

The tracking error is directly linked with time and is calculated axis by axis, as $\varepsilon_{Xi} = X_{Ri} - X_{Pi}$, where R_i is one point of the reference trajectory, and P_i is the actual position at the considered time. Therefore, the global tracking error is defined by $\|\overline{P_i R_i}\| = \sqrt{\varepsilon_{xi}^2 + \varepsilon_{yi}^2}$. Contouring errors in multi-axis motion control systems are due to tracking errors of each individual servo drive. The contouring error, e_{pi} , is defined normally at the reference trajectory (Figure 2), and is generally considered to be the most relevant as regards geometrical deviations on the surface [Peng et al. 2007]. Indeed, geometrical deviations δ result from the deviations between the envelope of the tool movement and the designed surface. As seen in Figure 2 – left, those errors correspond are quite equivalent to contouring errors in the case of trajectories free from discontinuities ($e \sim \delta$).

In order to evaluate contouring errors, the algorithm developed in [Erkorkmaz et al. 2006] attempting to find the shortest orthogonal distance between the reference tool path and the actual one is adopted in the present work. In particular, this algorithm is also used to calculate the interpolation errors denoted e_1 (between the calculated trajectory and the position set point (PS) as well as the feed drive errors (between the position set point PS and the simulated *tool tip position* (SP)) denoted e_2 .

3 OPTIMIZATION USING THE CEC METHOD

As a matter of fact, a first approach to reduce contouring errors is to reduce them indirectly by attempting to reduce axis tracking errors. A second approach is to reduce directly contouring errors. These kinds of methods imply an evolution of the control architecture and require open controller units [Sencer et al. 2009]. Other approaches developed in [Tsai et al., 2008] rely on the adaptation of the setpoint trajectory and the federate.

The approach we propose, the Contouring Error Compensation (CEC) method can be applicable for any type of trajectory (2D and 3D), and whatever the description format (linear or B-spline). The method, based on the setpoint trajectory adaptation, could be likened to a mirror-type approach [Suh et al., 1996]. The CEC method is illustrated in Figure 3 through the example of a 2D continuous curve. Obviously, it can be transposed in 3D and for 5-axis trajectories by including geometrical transformations. In the figure, the black curve is the CAM trajectory, the red curve is the setpoint trajectory and the green one is the actual trajectory. The method attempts to modify the setpoint curve so that the actual trajectory matches the CAM trajectory. For this purpose, the points of the setpoint curve must be moved of a distance equal to $-e_T$, where e_T is the total execution error defined as the sum of the interpolation error and the feed drive error. The main difficulty is that errors are not geometrical but must be linked with time. Therefore, the deviation noted $e_T(ti)$ is the total deviation between actual trajectory and the CAM trajectory at the time ti . As the method is based on a time approach, the point R_{ii} of the setpoint trajectory corresponding to the time ti is moved to R'_{ii} so that:

$$\overline{R_{ii} R'_{ii}} = \overline{-e_T(ti)} \quad (3)$$

The difficulty is now to transpose this method to sampled trajectories considering that set points are delivered by the CNC with a sample period of $T_{\text{sampling}} = 6\text{ms}$. Moreover, in the proposed approach the actual trajectory is simulated using the algorithm detailed in [Prévost et al. 2010]. It is thus necessary to generate the simulated points with the same sampling period than that of the setpoint trajectory. Then, as illustrated in Figure 3 – right, the new set points are easily determined since to each discrete point R_i of the setpoint trajectory corresponds a

point P_i belonging to the simulated trajectory. As a result, the new point R'_i at the sampling time t_i is given by:

$$\overrightarrow{R_i R'_i} = -\overrightarrow{e_T(i)} \quad (4)$$

Therefore, the CEC method involves that the new setpoint trajectory has the same number of sampled points than the previous one; this implies a same execution time of the trajectory ($N.T_{\text{sampling}}$, where N is the number of sampled points and T_{sampling} is the sampling period of the NC). Obviously, after the compensation, the trajectory execution has to be checked in terms of velocity, acceleration, jerk and current, in order to be sure that physical limits of the machine are respected. Once the new setpoint is calculated using the CEC method, the new simulated tool positions are evaluated [Prévost et al. 2010].

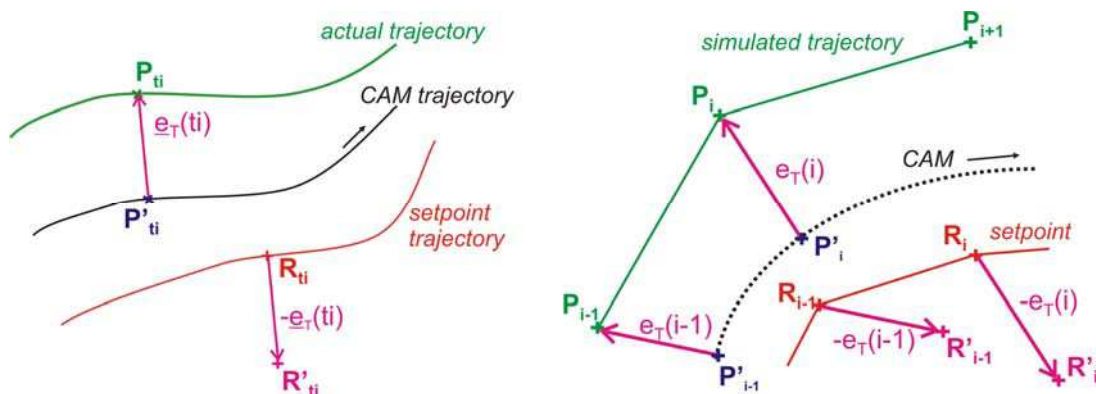


Figure 3; Contouring error compensation method

4 APPLICATIONS

4.1. Application 1 – Smooth B-Spline

The following example illustrates the method. It concerns the machining of a planar cubic B-spline curve (defined by the control points CP , and the knot vector U) with a programmed feed rate V_f equal to 10 m/min (Figure 4). The machining program is executed using the B-spline format. For the milling operation, the tool is always located inside the curve; the material is on the left of the tool during execution.

$$CP = \begin{bmatrix} -100 \\ 0 \end{bmatrix}, \begin{bmatrix} -50 \\ 0 \end{bmatrix}, \begin{bmatrix} -50 \\ 50 \end{bmatrix}, \begin{bmatrix} 0 \\ 50 \end{bmatrix}, \begin{bmatrix} 50 \\ 0 \end{bmatrix}, \begin{bmatrix} 50 \\ -50 \end{bmatrix}, \begin{bmatrix} -100 \\ -50 \end{bmatrix}$$

$$p = 3$$

$$U = [0 ; 0 ; 0 ; 0 ; 1/3 ; 1/2 ; 2/3 ; 1 ; 1 ; 1 ; 1]$$

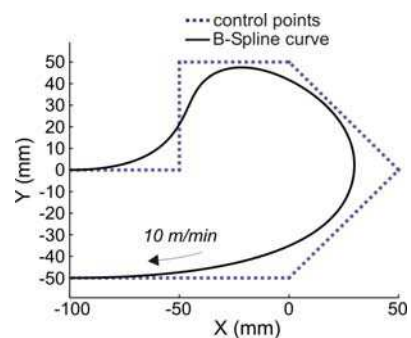


Figure 4; The B-Spline curve definition

Figure 5 displays execution errors: the red curve stands for the interpolation errors e_1 , the green curve stands for the feed drive errors e_2 and finally the blue curve represents the total error e_T . Peaks appearing at abscissas 100 and 175 mm exactly correspond to axis direction

inversions. The CEC method is applied. Figure 5 presents errors before compensation (left) and after compensation (middle).

First, we can notice that, errors e_2 between the simulated tool tip position and the setpoint trajectory are the same after and before compensation. This can be explained by the fact that the reference trajectory is a B-Spline without C^2 discontinuities. The solicitations on the servo drives are not strong enough to significantly change the shape of error distribution. On the contrary, the interpolation errors e_1 are totally changed and become larger than before. Actually, the error distribution becomes symmetrical about the feed drive errors.

The algebraic sum of e_1 and e_2 coincides with e_T and is quite null (Figure 5 – right), unless for the particular points corresponding to axis inversion. Indeed, maximal errors can reach $70\ \mu\text{m}$ before compensation and fall down to $2\ \mu\text{m}$ ($5\ \mu\text{m}$ in the critical zones of axis inversions). However, if results are very satisfactory in terms of trajectory geometry, it remains necessary to assess the axis behaviour. This assessment is performed through the estimation of the maximum simulated current and jerks after compensation which are very close to those before compensation.

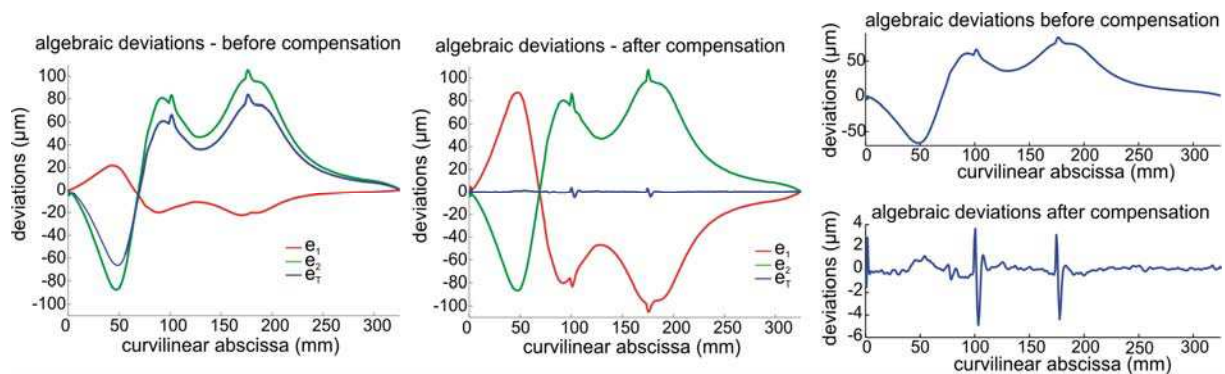


Figure 5 Errors for the BSpline 2D trajectory

4.2. Application 2 - Sharp corner

This application concerns the sharp corner presented in Figure 1. A difficulty is introduced here with the discontinuity at the corner tip at the two segment intersection of the CAM trajectory (black curve in Figure 6a). In order to ensure the corner machining with a minimal slowdown, the smoothing of the CAM trajectory is performed by the CNC interpolators leading to the setpoint trajectory (red curve in Figure 6a) located inside the corner tip. The rounding, linked with the programmed federate, is not negligible as the deviations e_1 are up to $17\ \mu\text{m}$ (Figure 6b). The total error reaches $30\ \mu\text{m}$, which is consistent with the geometrical deviations obtained on the part (see Figure 1). The CEC algorithm is directly applied leading to the optimized setpoint (figure 7c) which gives afterwards the new simulated positions.

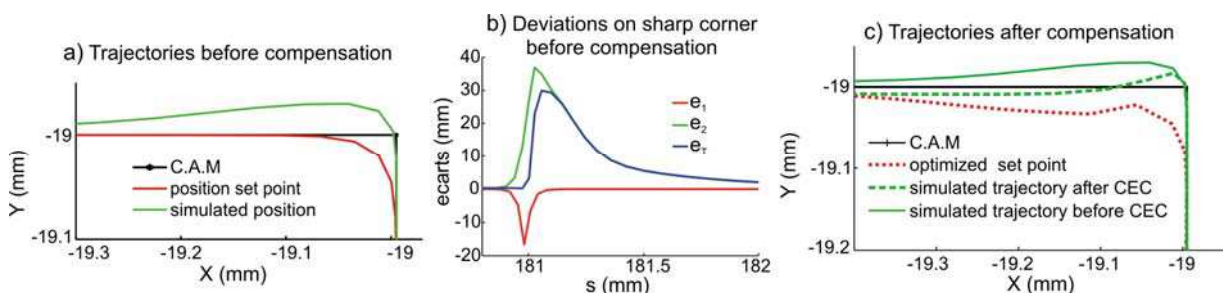


Figure 6; Sharp corner machining

The global deviation e_T is reduced by twice but is not null. Actually, the CEC method is applied considering that the CAM trajectory is the target, which can never be reached. Unfortunately, the machine tool could only machine such geometry with an absolute stop. In order to apply the CEC method, a slight modification of the CAM trajectory has to be performed to remove the tangency discontinuity.

5 CONCLUSION

Many sources of errors can impact the final geometry of a machined part in the case of HSM. One main source of these errors is imputable to the execution process. Considering the machine tool geometry as perfect (statics, dynamics and thermal effects are not taken into account), a method, called the CEC method has been developed aiming at contouring error compensation. Total contouring errors (between the actual trajectory and the CAM trajectory) result from the combination of the CNC interpolator errors and the servo-drives errors. The CEC algorithm relies on the modification of the trajectory setpoint generated by the CNC so that the actual trajectory matches the CAM trajectory. First results prove that this algorithm is efficient for regular trajectories removing contouring errors quite well. However more investigations have to be conducted concerning singular trajectories with discontinuities as sharp corners. Nevertheless, the CEC method is promising for execution error removing.

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