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A QUICK TEST FOR DIAGNOSING POSITIONING ERRORS IN CNC MANUFACTURING

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Abstract. *The manufacturing processes executed by machine tools have the working accuracy as their common performance requirement. The CNC controls the movements of each machine axis under disturbances from the manufacturing process and from the machine itself, generating positioning errors. This paper discusses a procedure to estimate and forecast the positioning errors observed in open CNC machine centers. The procedure is intended to minimize the efforts for the machine diagnostics through the use of internal CNC functions, without external monitoring of machine movements. Tests were executed using circular trajectories with different feedrates. Positioning information from the machine CNC were compared with the machine coordinates to derive the observed errors. Sample-tests were replicated to yield the modeling and the validation of observed positioning errors as a function of used feed rates. Results show a quick test capable of diagnosing positioning errors to be used in planning CNC operations for parts manufacturing.*

Keywords: *CNC Manufacturing, Quick Test, Contour error, Modeling*

1. INTRODUCTION

The dimensional precision of a manufactured part depend on the positioning capability of the machine used in its manufacturing, as well as the kinematic, thermal and dynamic behavior, which usually are identified as error sources. Therefore the total dimensional error can be split up for simulation to help identifying important error components in cutting operations.

The contour error is characterized by the orthogonal distance between the trajectory of set point and the one actually performed by the machine under those error sources, whose main components in the CNC control loop are the following error of each axis, gain's mismatches of controllers, time constant of each machine axis and external influences such as friction, cutting forces, inertia, etc. [1].

Schmitz et al [2] studied practical cases to evaluate the contribution of geometry, thermal errors, cutting forces and contour errors on the total error of manufactured parts. Contour errors were recorded under different feedrates and using a grid encoder, and a contribution of 18% from the contour errors on the total error budget was reported.

Uhlmann et al [3] used monitoring techniques, modeling and simulation to analyze the influence of different error sources on milling operations of complex surfaces. The authors show contributions of contour errors up to 80% of the total observed errors, depending on the chosen feedrate and on the manufactured geometry.

Based on the described results it would be a good practice to determine the maximum admissible contour error for the particular workpiece and developing modeling and simulation tools to forecast contour errors in tool path planning. However, the interactions among different error sources as well as the inherent uncertainties in their measurement tend to increase the difficult in identifying the individual contributions of simultaneous error sources.

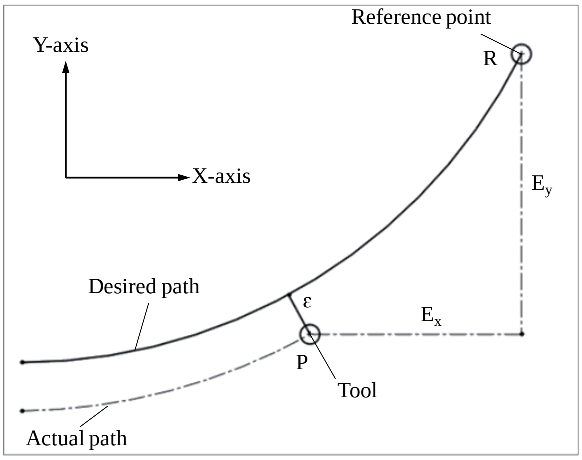
The simulation of contour errors in a virtual CNC includes modeling of the machine kinematics and the dynamic of feed drives, besides the assumptions of rigid bodies for the moving machine parts. Besides, some CNC functions must be used to implement tools for forecasting of contour errors [4-6].

Due to the wide range of topics and the natural complexity of this process, in this work the modeling of the machine's controller and feed drives are considered in an initial step to measure and forecast contour errors when milling of circular trajectories. To do so, a quick test was developed to measure the contour error in shop floor applications without extensive measurement and experimentation.

2. LITERATURE REVIEW

2.1 The contour error

The servo-control has a characteristic called servo lag, which is inherent to all feedback controls. The servo loop uses the difference between the programmed position and the actual machine position, measured by the machine sensors to feed back the control system. This difference constitutes the inherent difficulty to reach the programmed target in each machine axis, being one of the main sources of contour error; see Figure 1 for details [1].



ε: Contour error
Ex, Ey: Axial errors
R: Reference position
P: Actual tool position

Figure 1: Contour error in a circular trajectory [1].

To perform a non-linear trajectory the control-loop inputs are also non linear. For a circular trajectory one has as follows in equation (1), where ρ is the trajectory radius and x, y are the axis set-points defined by equations (2) and (3) [1]:

$$(x-\rho)^2 + y^2 = \rho^2 \tag{1}$$

$$x = \rho(1-\cos\omega t) \tag{2}$$

$$y = \rho\sin\omega t \tag{3}$$

In equations (2) and (3) ω=f/ρ and f is the feedrate on the circular trajectory. Therefore, to track a circular trajectory each machines axis performs a sinusoidal movement at the velocity ω, usually with a phase shift between movements. The phase shift is a function of ω, which makes the contour error also a function of ω [1].
From the above, the contour error in a circular trajectory can be calculated as shown in equation (4), where ξ and ω_n are the damping factor and the eigen frequency of the control loop, respectively [7].

$$\frac{\varepsilon_{ss}}{\rho} = 1 - \frac{1}{\sqrt{1+(2\xi\omega/\omega_n)^2-2(\omega/\omega_n)^2+(\omega/\omega_n)^4}} \tag{4}$$

Equation (4) shows a relationship between the velocity and the contour error. To yield a quick test for shop floor application it is important to investigate the adequacy of a linear model to represent the correlation between the chosen feedrate and the observed contour error.

2.2 Linear regression

The linear model can be expressed by equation (5), where α the intercept, β is the angular coefficient and ε_i is the random error of Y for each sample i [8, 10]:

$$Y = \alpha + \beta X_i + \varepsilon_i \tag{5}$$

Therefore, β is the variation rate of Y on X and α is the minimum observable contour error when the velocity becomes null [8]. Since the evaluation of equation (5) is based on samples of contour errors, it can be rewritten as shown in equation (6) where $\hat{Y}$ is the estimate of Y when measured velocities X_i are used.

$$\hat{Y} = a + bX_i \tag{6}$$

To calculate the model parameters ɑ e b the least square method can be used as follows [8]:

$$b = \frac{Sxy}{Sxx} \tag{7}$$

$$\mathrm{a} = \bar{Y} - \mathrm{b}\,\bar{X} \tag{8}$$

where:

$$Sxy = \sum XiYi - \frac{\sum Xi \sum Yi}{n} \tag{9}$$

$$Sxx = \sum Xi^2 - \frac{(\sum Xi)^2}{n} \tag{10}$$

$$\bar{Y} = \frac{\sum Yi}{n} \tag{11}$$

$$\bar{X} = \frac{\sum Xi}{n} \tag{12}$$

The linear correlation between the variables is expressed by the coefficient shown in equation (13), where Cov |X,Y| is the covariance between X and Y, σ_x^2 is the variance of X and σ_y^2 is the variance of Y [9]:

$$r = \frac{Cov\ |X,Y|}{\sqrt{\sigma_x^2 \sigma_y^2}} \tag{13}$$

As per equation (13) the correlation coefficient varies between -1 and 1, showing stronger correlations when it approaches to | 1 |. It gives a positive or negative correlation depending on the signal of the calculated coefficient. The coefficient of determination (R^2) is the second power of the correlation coefficient (r) and indicates the amount of variation in Y that can be explained by the independent variable X [9].

The above described model and procedures are based in the following assumptions [8]:

a) The average of fitting residuals is zero;
b) The variance of fitting residuals is constant over X;
c) The distribution of residuals is Gaussian;
d) The errors associated with X observations are statistically independent.

3. THE DEVELOPED QUICK-TEST

The discussed quick-test is based on the investigation of contour errors in a 300 mm diameter circle. The procedure shown in Figure 2 was developed to measure the contour error when several feedrates are used in CNC milling. It follows the linear modeling of observed errors against the used feedrates, to derive estimates of mean contour errors under conditions different from those used in the test development. The contour error was determined by subtracting the hypotenuse of axes coordinates (x and y) from the 150 mm programmed radius. Since the developed procedure rely on CNC functions, available in most commercial machine tools, it can be used to estimate contour errors when planning cutting operations for most CNC machine tools.

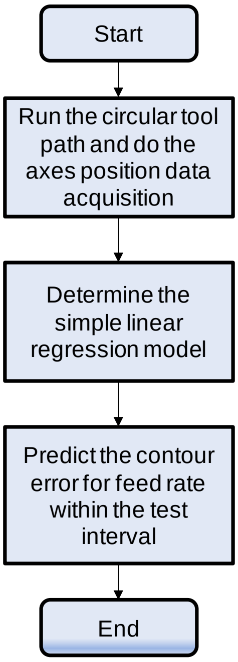


Figure 2: Quick-test flowchart.

The experiments were run in a three-axis vertical machine-center HERMLE (Germany), model C800U, as illustrated in Figure 3, with 800 mm, 600 mm and 500 mm capability in the X, Y and Z directions, respectively. The maximum machine power is 18 kW at 24000 rpm, being equipped with a CNC 840D from SIEMENS, Germany.

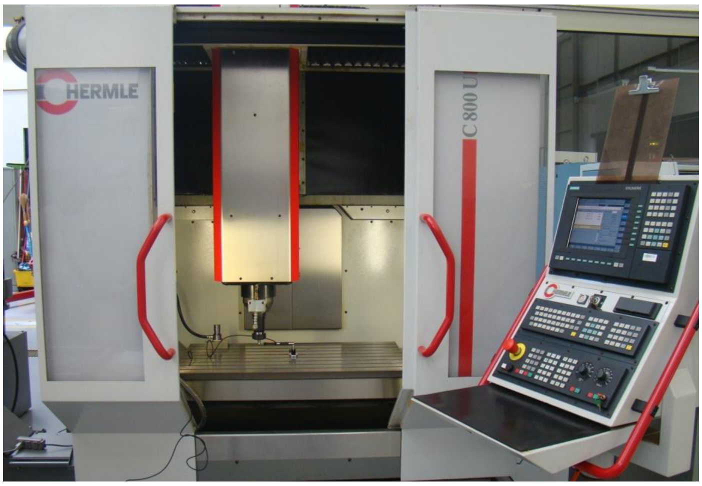


Figure 3: HERMLE C800 U vertical machine center.

The circular trajectory with 150 mm radius was planned using X-Y interpolations in both directions, clockwise and counterclockwise. The center of the test circle was set at the center of the machine table and feedrates of 1000, 3000, 6000, 15000 and 25000 mm/min were used. Three samples were gathered for each used feedrate and tested direction to create replicates for statistical analysis. Data was collected using a SINUCOM-NC software from SIEMENS.

The experiments were run without material removal to focus the developed test only on the machine's controllers and feed drives. As already described, this approach was used as an attempt to produce a simple test with a linear model capable of describing the relationship between the observed contour error and the used feed rate.

It is worth mentioning that the developed test uses the machine scales for positioning measurements to allow modeling the same information already used in the feedback of the machine control systems.

4. TEST RESULTS AND MODEL VALIDATION

The Table 1 shows the mean contour error associated with the feedrates and the movement directions used in each test.

Table 1: Mean contour error, feedrates and movement direction.

	Mean contour error [mm]	
Feedrate [mm/min]	Clockwise	Counterclockwise
1000	0,0100	0,0070
3000	0,0091	0,0091
6000	0,0099	0,0099
15000	0,0142	0,0143
25000	0,0205	0,0205

Table 1 initially shows an average increase of 3 µm in the observed contour error when directions clockwise and counterclockwise were used at 1000 mm/min. Even under this variation for the particular feedrate used in the experiment, the usability of the proposed quick test and the adequacy of a linear model have being demonstrated as discussed below.

The sample shown in Table 1 has being used to calculate the model coefficients as per equations (7) and (10), together with the correlation coefficient given in equation (11), resulting in α = 0,007469 mm; b = 0,000001 mm/(mm/min) and R^2 = 0,964485. From a practical standpoint, α is the static positioning error observed in the machine axis and b is the ratio of counter error increase for every 1 mm/min of increase in the used feedrate.
Figure 4 shows the estimated linear relation between the mean contour error and the used feedrate.

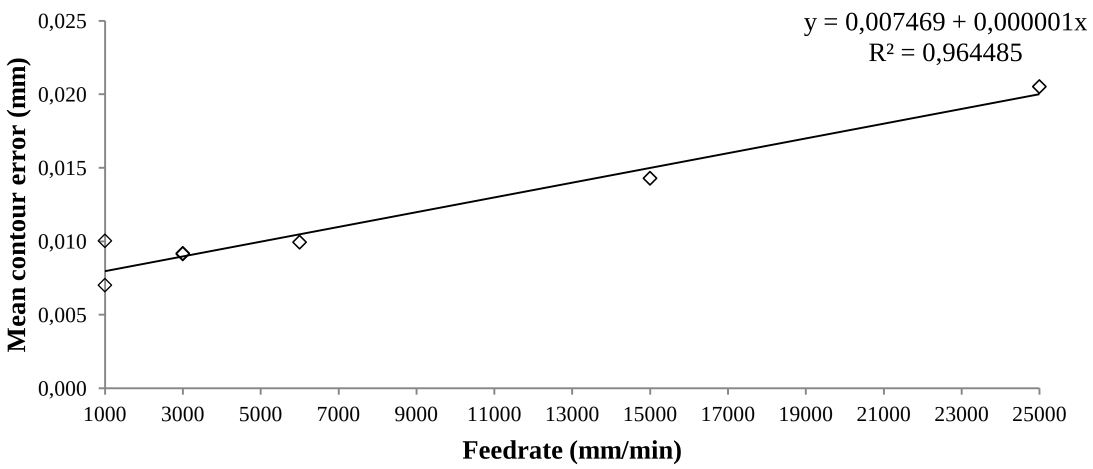


Figure 4: Regression model for the mean observed feederate.

The adequacy of the obtained linear model is sustained by the mentioned correlation coefficient, whose statistical significance was verified at the 5% level by the Analysis of Variance shown in Table 2.

Table 2: ANOVA.

	DF	SQ	MQ	F calc	F
Regression	1	0,000199	0,000199	217,2546	0,0000004
Residuals	8	0,000007	0,000001		
Total	9	0,000207			

The ANOVA shown in Table 2 is based upon the following hypothesis.

- For H_0: β = 0, there is no evidence to accept the linear relation between the observed contour error and the used feedrate;

- For H_1: $|\beta| > 0$, the linear relation between the observed contour error and the used feedrate cannot be rejected; therefore, it is accepted.

The ANOVA provides F_{cal} = 217,2546, while the reference F_{tab} = 5,32 using the significance level α = 5% and the degrees of freedom $\varphi_1 = 1$ and $\varphi_2 = 8$; see Table 2 for details. Since $F_{cal} > F_{tab}$ the null hypothesis H_0 is rejected and the discussed linear model is accepted at the adopted significance level. The residuals analysis shown in Table 3 was used for verifying the model assumptions.

Table 3: Residual analysis.

Sample	**Radial error (y_i) [mm]**	**Estimated radial error ($\hat{y}_i$) [mm]**	**Residuals (y_i - $\hat{y}_i$) [mm]**
1	0,0100	0,0079	0,0021
2	0,0070	0,0079	-0,0009
3	0,0091	0,0089	0,0002
4	0,0092	0,0090	0,0002
5	0,0099	0,0104	-0,0005
6	0,0099	0,0104	-0,0005
7	0,0143	0,0150	-0,0007
8	0,0143	0,0149	-0,0006
9	0,0205	0,0200	0,0005
10	0,0205	0,0200	0,0005

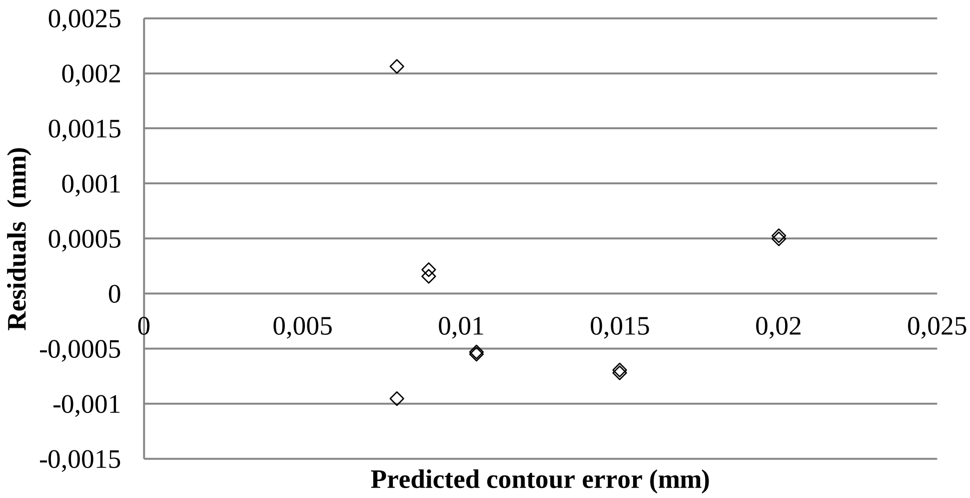


Figure 5: Non-standardized residuals for the adjusted model.

Table 3 and Figure 5 show small residuals with nearly random distribution, except for the feedrate of 1000 mm/min as pointed out before. From this analysis the linear model and the associated experimental procedure is validated for forecasting contour error within the investigated feedrates.

5. CONCLUSION

This paper shows a quick-test developed to forecast contour errors in milling operations of circular trajectories, using simple experimental techniques.

Results show the expected increase of the observed mean error with the increase of used feedrates. The derived linear model allows using the complete test in tool path planning.

Although the test can be replicated for any CNC milling machine, the discussed results are restricted to circular trajectories and do not include influences from the cutting process or the machine dynamics.

The needed experiments to gather data are simple and do not require expensive instrumentation, since the positioning errors of the machine are measured with conventional sensors already installed in the machine. Due to the use of machine sensors it also does not require signal conditioning.

Future work is planned to extend the tested circular radius and a further step will be done to investigate non-circular trajectories.

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8. RESPONSIBILITY NOTICE

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