Experimental evaluation of errors during five axis High-Speed Machine tool motion

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EXPERIMENTAL EVALUATION OF ERRORS DURING FIVE AXIS HIGH-SPEED MACHINE TOOL MOTION

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ABSTRACT

The paper presents a method to evaluate the effect of servo-error, quasi-static geometric error and dynamic geometric error on volumetric errors at the tool center point under high speed and high dynamic load.

The interpolator output signals and the machine encoder signals are recorded and compared to evaluate the contouring errors resulting from each axis follow-up error. The machine encoder signals are also compared to the actual tool center point position as recorded with an in-house non-contact measuring instrument to evaluate the total geometric errors. A method is proposed to decompose the geometric errors in two categories: the quasi-static geometric errors independent from the speed and the dynamic geometric errors, dependent on the programmed feed rate and resulting from the machine structure deflection during the acceleration of its axes.

The evolution of the respective contributions of contouring error, quasi-static geometric error and dynamic geometric error is evaluated and a relation between programmed feed rate and dynamic error is highlighted.

INTRODUCTION

High speed machining is known to reduce machining time and improve surface quality due to its particular cutting process [1]. Five axis machining, with its ability to control the tool orientation with respect to the workpiece, leads to productivity improvement.

From the numerical model of a part to the generated tool path to machine it, several approximations are made leading to a loss of accuracy. During the execution of the tool path, a machine axis is subject to follow-up errors, leading to orientation and position errors of the tool [1]. Also the machine structure, in its quasi-static state, suffers from link and motion errors causing position and orientation errors of the tool [2]-[5]. Moreover, thermal variations of the machine are another source of errors [6].

When programmed feed rate and actual velocity increase, as is usual during the high-speed machining process, the dynamic solicitations of the structure become higher causing inertial forces due to the acceleration of the different parts of the machine. It may result in some alterations of the machine geometry, causing further tool position and orientation errors [7].

A method to evaluate the contributions of error sources to the Cartesian volumetric errors at the tool center point (TCP) for a five axis machine tool at different programmed feed rates is described in this paper. The method is based on a single setup, and the non-contact measuring instrument used allows measurement even at the highest programmed feed rate.

First, the error sources considered and the principle of the decomposition method are presented. The experimental setup is described and finally, the results gathered for different feed rates are given and discussed.

PRINCIPLE OF THE METHOD

A. Error sources

The Cartesian volumetric error is defined as the three components of the vector from the theoretical position of the TCP relative to the workpiece frame to its actual position. They are decomposed into the contribution of three error sources:

- the effect of follow-up errors of the axis drives, later called contouring errors [8] and written δ_c;
- the quasi-static geometric errors of the machine, which include link and motion errors and thermal drift, written δ_{qs};
- the dynamic geometric errors, resulting from the machine structure deflection under dynamic load, written δ_d.

The evaluation of those three error sources can help quantify the relative impact of dynamic errors to the total volumetric errors, and the relevance of associated models for corrective actions.

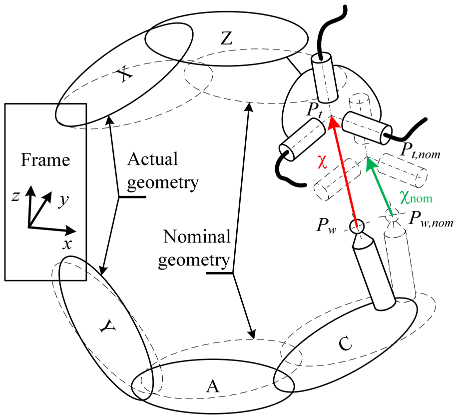

Fig. 1: Schematic view of the volumetric error

B. Measurement technique

The nominal position of the tool center point relative to the workpiece is evaluated with the nominal direct kinematic transformation (DKT) of the machine fed with the controller inputs of the machine.

$$\chi_{nom} = P_{t,nom} - P_{w,nom} = DKT(C,A,Y,X,Z) \qquad (1)$$

The actual position of the tool relative to the workpiece is evaluated with a newly re-designed non-contact sensor called CapBall, developed in house and based on earlier work [5], which measures the position of a ball mounted on the machine table relative to the TCP.

The Cartesian volumetric error is expressed by the difference between the actual and the nominal position of the tool center point relative to the workpiece, as depicted in Fig.1.

C. Decomposition of the Cartesian volumetric error

The contouring error can be evaluated by recording the machine controller inputs and encoder actual values and comparing the relative position of the tool and the workpiece from the two points of view.

At low velocity, the dynamic geometric errors can be considered as negligible because the dynamic load is low with respect to the usual high stiffness of machines. Thus, the errors measured at a low programmed feed rate can be defined as the quasi-static geometric errors.

The errors appearing when the programmed feed rate and the machine velocity increase are due to alteration of the machine structure under dynamic load and are called the dynamic geometric errors. They can be evaluated by measuring the total geometric errors along a single trajectory at different programmed feed rate and removing the quasi-static geometric error contribution.

Fig. 2 summarize this decomposition: from the interpolator output, the nominal position of the TCP relative to the workpiece is successively modified by cumulating the contouring errors from the controller (δ_c), the quasi-static errors from the machine tool structure (δ_{qs}) and the dynamic errors from dynamic loads on the structure (δ_d). The resulting position is the actual one measured by the CapBall instrument.

Hence, Eq. (2) propose a model to express the error occurring between the interpolator and the actual position of the tool relative to the workpiece.:

$$\chi - \chi_{nom} = \delta_c + \delta_{qs} + \delta_d \qquad (2)$$

The following section describes how each contribution is calculated.

MODEL FOR ERROR CONTRIBUTIONS

A. Contouring error

The effect of follow-up errors on volumetric errors is defined as the contouring error by Sencer *et al.* in [8].

The recording of the encoder values of each axis of the machine allows calculating χ_{enc} representing the volumetric difference from the encoders' point of view. This way, the contouring error is given by eq. (3).

$$\delta_c = \chi_{enc} - \chi_{nom} \qquad (3)$$

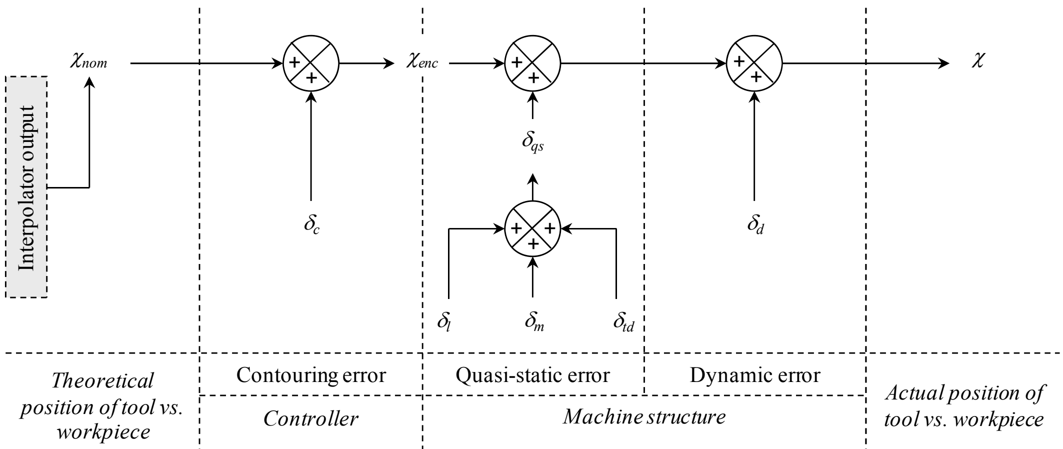

Fig. 2: Decomposition of the error into contouring error δ_c, quasi-static geometric error δ_{qs} and dynamic geometric error δ_d.

The controller input signals must be carefully synchronized with the actual encoder values to evaluate the effect of the follow-up errors on the volumetric errors at the tool tip.

B. Quasi-static geometric error

The *quasi-static* geometric error, expressed by δ_{qs} in eqs. (2) and (4), is defined as the geometric error independent of the machine velocity. It is decomposed into three sources:

- the effect of link errors that represents the axis to axis location errors of the machine, written δ_l;
- the effect of motion errors of each axis, written δ_m;
- the thermal drift of the machine, written δ_{td}.

$$\delta_{qs} = \delta_l + \delta_m + \delta_{td} \qquad (4)$$

The effect of link errors is modeled according to [3], and the values the machine link errors are identified with a method adapted from [5]. Then, for any pose of the machine, the modeled volumetric error due to link errors can be calculated, leading to the construction of δ_l while gathering the modeled error for each point of the trajectory.

The effects of motion errors are generally defined by continuous and smooth mathematical functions [4] [9]. The effect of the motion errors along an experimental trajectory is evaluated by running the trajectory at low programmed feed rate. This initial measurement leads to the thermal reference state of the machine. Also, at low programmed feed rate, the dynamic loads are low compared to the stiffness of the machine, leading to the hypothesis of negligible dynamic geometric error: $\delta_d = 0$. Thus, eqs. (2)-(4) can be transformed to eq. (5):

$$\delta_{m,mes} = \chi - \chi_{enc} - \delta_l \qquad (5)$$

The measured $\delta_{m,mes}$ is curve-fitted with polynomial functions of the curvilinear abscissa along the trajectory. The identified polynomial functions are finally used to model the effect of the motion error on the trajectory δ_m, independently of the speed. Finally, for other experimental trajectories, the effect of thermal drift is modeled by an offset: the execution of an experimental trajectory lasts less than 20 *s*, so the variation of the drift during this period was not considered significant. The drift offset is evaluated by the mean value of the total volumetric error minus the effect of link and motion error (eq. (6)):

$$\delta_{td} = mean\,[(\chi - \chi_{enc}) - \delta_l - \delta_m\,] \qquad (6)$$

The quasi-static geometric error δ_{qs} is modeled by the sum of δ_l, δ_m and δ_{td} (eq. (4)). Its value does not depend on the speed along the trajectory.

C. Dynamic geometric error

The dynamic geometric error, expressed by δ_d in eq. (2), is here defined as the errors occurring when programmed feed rate, and also dynamic forces on the machine structure, increase. The dynamic error results from geometric alterations of the machine components under dynamic forces such as deflection of the machine structure.

Eqs. (2)-(4) allow to express the dynamic geometric errors δ_d as the contribution that does not show at low speed, in eq. (7):

$$\delta_d = (\chi - \chi_{nom}) - (\delta_c + \delta_{qs}) = (\chi - \chi_{enc}) - \delta_{qs} \qquad (7)$$

EXPERIMENTAL SETUP AND RESULTS

This study was carried out on a Huron KX8-five five axis machine tool. This machine has a WCAYFXZT structure, with a 45-degree-tilted A rotary axis. It is equipped with a Siemens Sinumerik 840D Powerline numerical command unit.

The experimental trajectory includes a sharp corner to generate high accelerations of the machine axes with high programmed feed rates.

The motion of each axis is programmed with linear interpolation, and all the axes are synchronised. The machine is commanded in joint space to provide the sought dynamic solicitations.

The experimental trajectory is executed at different programmed feed rates, from 1000 *mm/min* to 18 896 *mm/min*.

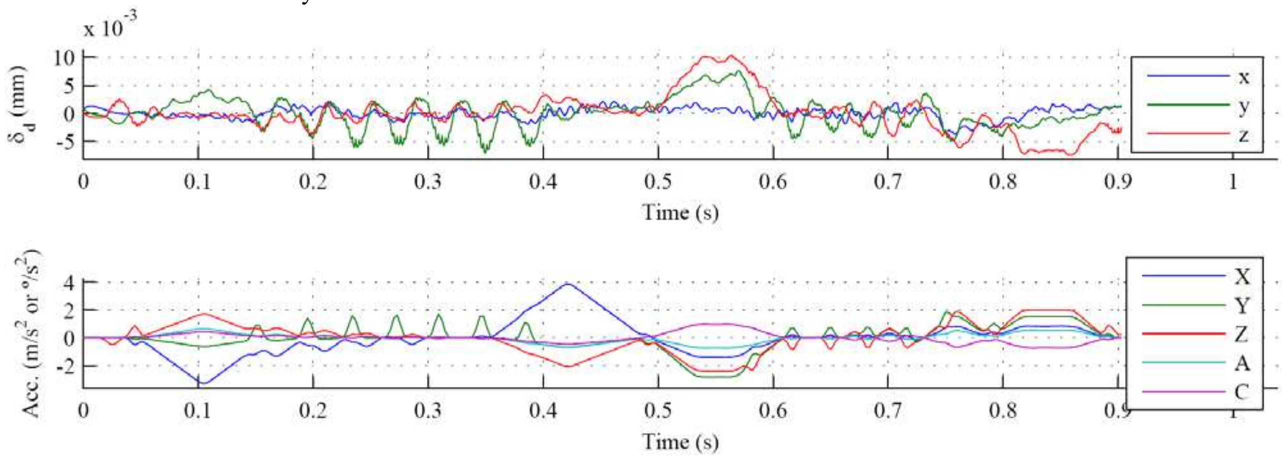

Fig. 3: Evolution of δ_d and acceleration for a programmed feed rate F = 18 896 *mm/min*

Table 1 : Mean percentage value of the norm of the total volumetric error for the tested programmed feed rate

F (mm/min)	$\delta_{c,\%}$	$\delta_{qs,\%}$			$\delta_{d,\%}$
		$\delta_{l,\%}$	$\delta_{m,\%}$	$\delta_{td,\%}$	
1 000	1,1	86,9	11,4	0,0	0,6
5 832	3,9	82,6	10,8	1,1	1,5
18 896	9,5	72,8	9,5	3,3	4,8

For each programmed feed rate *F*, the mean value of the norm of each identified error source is calculated (Table 1). It allows evaluating the evolution of the respective contribution of each source while *F* varies. The quasi-static geometric error is, by definition, independent from the programmed feed rate, but its relative contribution decreases when *F* increases: as expected, contouring error and dynamic geometric error increase with the speed along the trajectory. The dynamic errors are nearly negligible at low programmed feed rate but it is about half the magnitude of the contouring error when *F* increases.

Fig. 3 shows the evolution of the dynamic geometric errors along the trajectory executed at F = 18 896 *mm/min*. The accelerations of the machine axes are also plotted. It was noticed that the linear interpolation mode of the machine generates accelerations peaks at each block transition. Those acceleration peaks are responsible for sudden dynamic loads and dynamic geometric errors.

CONCLUSION

The high-speed machining context requires high accelerations from the machine. Under those dynamic loads, the machine structure may no longer follow a rigid body behaviour. The new method presented in this paper allows to measure the volumetric error at the tool tip, and to evaluate the contribution of the dynamic geometric errors.

The experiments at high programmed feed rates have been made possible by the use of a non-contact measuring instrument: the CapBall. The CapBall was re-designed to increase its stiffness for more reliable measurement under high dynamic loads.

According to the presented model of error sources and the performed experiments, the dynamic errors can reach nearly 5% of the total volumetric error, when considering the mean value of the norm under the condition of the experiment.

Finally, the main interest of this experimental work is to propose a method to evaluate dynamic errors directly at the tool tip. It can be a powerful mean to validate models for the dynamic behaviour of the structure with in-situ measurement. It has been shown that the linear interpolation generates acceleration and dynamic errors peaks. The influence of the NC interpolation and controller command law on dynamic errors can also be investigated with this method.

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