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Axis location errors and error motions calibration for a five-axis machine tool using the SAMBA method

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Abstract

Positioning accuracy is one of the most important factors influencing a machine tool's ability to manufacture parts meeting the required tolerances. Thus, regular check-ups followed by geometric compensation or mechanical adjustments are necessary to prevent accuracy degradation on such machines. This paper presents an enhanced measurement strategy to extend the capability of the Scale and Master Balls Artefact (SAMBA) method to the estimation of not only the axis location errors but also error motion parameters modeled as ordinary polynomials. This indirect measuring method uses on-machine probing of a scale enriched uncalibrated master balls artefact to gather observations of the machine volumetric behaviour. The analysis of the kinematic model and its associated Jacobian matrix which characterizes the sensitivity of the volumetric errors, as detected by the SAMBA method, to the axis location errors and error motions provide the mathematical basis for the probing strategy design. The simulation and experimental results presented demonstrate the contribution of the applied strategy in enriching substantially the machine tool error model.

Keywords: Metrology; Machine tools; Measurements; Simulation; Calibration

1. Introduction

Five-axis machine tools are widely used in industry due to the manufactured part complexity and the need to meet tight tolerances while achieving high productivity. Such machines have three prismatic and two rotary axes, which allow the simultaneous and continuous control of the tool orientation and position with respect to the workpiece.

The machine tool performance is defined mainly by its volumetric accuracy and repeatability [1] which are affected by dynamic, thermal, load and geometric error sources.

The geometric errors, classified as quasi-static errors, are inherent to the machine structure and its components and are considered as one of the main sources of inaccuracy.

They are classified into two groups [1, 2]:

- Axis location errors: describe the position and orientation of successive (prismatic and rotary) axes.
- Error motions: describe the axis motion deviation from nominal.

The presence of these errors on a machine tool has a major impact on the accuracy of manufactured parts by inducing volumetric errors.

The latter are characterized by a deviation between the actual and desired tool position and orientation relative to the workpiece. Consequently, it is essential to conduct regular calibration tests and compensate those errors numerically or mechanically.

In the literature, the calibration methods are classified into direct (using for example laser interferometry or straightedges) and indirect ones. Direct methods are aimed at the determination of a particular error motion or axis location error. However, they require multiple setups to be measured. Although they offer the most reliable way to obtain error values, great care must be taken to avoid

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contamination of one error type by other errors that are also present on the machine. Indirect methods are less demanding experimentally but sophisticated error separation models are required. Schwenke *et al*. [1] and more recently Ibaraki and Knapp [3] reviewed the main indirect measurement methods to measure the volumetric errors for five-axis machine tools and estimate the geometric error parameters. Some methods use pre-calibrated artefacts [4, 5] while others depend on large numbers of measurements of a single artefact at different indexations of the rotary axes and on mathematical models accounting for the effect of axis location errors on the measured volumetric errors within the machine work envelop [6, 7].

Indirect methods are generally required to model error motions so that the number of unknown variables used to build the model is kept as small as possible while allowing realistic representation of the actual errors. It has been shown that polynomials of degree three to four and harmonic functions are appropriate mathematical tools in describing the machine prismatic axes behavior [8-10].

As for axis location errors, Mir *et al.* [11] concluded that eight axis location errors, excluding spindle location, is a minimal and complete set in defining a five-axis machine tool geometry and ran simulations using a telescoping magnetic ball-bar. Later, they established that some of the zero degree and first degree error terms of the polynomials used to model the motion errors could be retained in the model to represent the axes location errors [12].

This paper introduces a probing strategy for use with the SAMBA probing method and a polynomial modeling in order to identify not only the axis location errors but also a maximum number of motion errors on a five-axis machine tool.

Thus, the second section of this work introduces the nominal kinematic and polynomial modeling of the axis location errors and error motions of a five-axis machine tool followed by the actual probing strategy applied in order to estimate those parameters according to the validating criteria. The analysis behind the decoupling of confounded error is also presented. Based on the theoretical results, an improved probing strategy and artefact configuration are proposed which are considered as test time reducing and geometric error coefficients identification enhancing. The experimental aspect of this theory is introduced in the third section.

2. Error modeling and identification

In this section, a probing strategy is presented in order to estimate all potentially identifiable error parameters, for the third degree polynomials, used to model the error motions, when using a single stylus length for the probing of a SAMBA, to gather observations on the machine volumetric behaviour.

2.1. Polynomial representation

The modeling of axis location errors and error motions of a five-axis machine tool is carried out using ordinary polynomials of third degree. A fourth term is added to the mathematical equation expressing the backlash error. This model will allow taking into consideration, while analyzing the machine behaviour, the slow variation of error motions throughout the axis motion range [9].

Equation (1) describes, for instance, the polynomial modeling of the positioning error in X-axis [2]:

$$E_{XX} = E_{XX0} + E_{XX1} \cdot x + E_{XX2} \cdot x^2 + E_{XX3} \cdot x^3 + E_{XXb} \cdot (\dot{x} / |\dot{x}|) \quad (1)$$

where,

- E_{XX} is the normalized representation of the linear positioning error motion of the X-axis;
- E_{XX0} , E_{XX1} , E_{XX2} and E_{XX3} are the polynomial coefficients in an increasing degree order;
- E_{XXb} is the backlash coefficient and
- $\dot{x}/|\dot{x}|$ is the sense of the motion, used to reach that position.

2.2. Kinematic modeling

The kinematic model describes the relative position between a reference ball rigidly connected to the table and the stylus tip of the touch trigger probe, rigidly connected to the spindle.

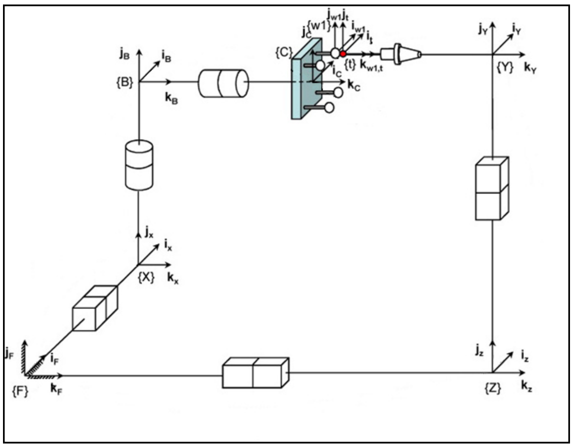

Fig. 1. Nominal kinematic model of a five-axis machine tool with WCBXFZYT topology [13].

Fig. 1 illustrates the studied serial machine tool whose topology is WCBXFZYST. W, F, S and T denote the workpiece, foundation, spindle and tool, respectively. C, B, X, Y and Z are the machine rotational and prismatic axes.

2.3. Mathematical modeling

The mathematical description of the machine tool forward kinematic model uses homogeneous transformation matrices as described in equation (2). It can predict the position of the stylus tip relative to each ball considering all axis location errors and error motions.