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
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 envelope [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]:

\[ E_{XX} = E_{XX0} + E_{XX1} \cdot \Delta x + E_{XX2} \cdot (\Delta x)^2 + E_{XX3} \cdot (\Delta x)^3 + E_{XXb} \cdot (\Delta \theta/\Delta x) \]  \hspace{1cm} (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;
- \( \Delta \theta/\Delta x \) is the backlash coefficient and
- \( \Delta \theta \) 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].](image)
Each axis is modeled as a nominal link (the nominal axis location), a nominal motion and an erroneous motion (the error motions) using the polynomial representations of each of the six error motions.

Hence, the pose of Z-axis relative to the foundation frame, for example, is as presented in equation (3).

\[
\begin{align*}
&J_{T_{Zj}} = [F_{T_{Zj}}]^{-1} \cdot [F_{T_{Zj}}]
\end{align*}
\]

where,

- \(J_{T_{Zj}}\) is a 4x4 homogeneous transformation matrix representing the pose of frame \(i\) relative to frame \(j\);
- \(X_i\) is the nominal X-axis frame before motion;
- \(X\) is the X-axis frame after nominal motion by axis command \(x\) and
- \(X'\) is the predicted X-axis frame after the action of the error motions, represented by an ordinary polynomial as in equation (1).

A Jacobian can be generated from such a model describing the sensitivity of the observed volumetric deviations to the machine error parameters and artefact and tool setup errors:

\[
\begin{align*}
\tau &= JP
\end{align*}
\]

\(\tau\) is a column matrix representing the volumetric errors at each \(m\) balls and the scale bar length reproduction error;

- \(P\) is a column matrix including the error motions coefficients, balls and tool tip position errors and
- \(J\) is the Jacobian matrix.

Given a well-conditioned Jacobian, a solution for the unknowns is calculated using the pseudo-inverse of \(J\), \(J^+\) in the following equation and an iterative procedure using Newton’s method [11].

\[
\begin{align*}
P &= J^+ \tau
\end{align*}
\]

2.4. Validation Criteria

The efficiency of parameter identification is primarily based on the analysis of the Jacobian matrix properties. One of the most important and powerful tools is its conditioning number [14] and rank. The rank must be equal to the number of unknowns to be estimated. In addition, while simulating the proposed probing strategy for the estimation of the simulated error motion coefficient values, the validity of the estimated coefficients is enhanced when the Jacobian has a low condition number.

2.5. Principles of the applied strategy

A calibration strategy consists of an artefact definition, a set of B and C indexation pairs, a list of balls to be probed at each indexations and a list of machine error parameters to be estimated. A Matlab code was specifically written to simulate a measurement strategy so that its effectiveness, at least numerically, can be validated.

The first strategy to be analyzed was one previously used in [15] where a 24 master balls uncalibrated artefact assembled on the machine pallet was measured for seven different indexation set of B and C axes with measuring ranges of -90° to +90° and -270° to +270° respectively, yielding the following BC sets in Table 1. The spindle indexations are used to estimate the x and y offsets of the spindle axis. The scale bar (known distance between balls 1 and 2) is measured once at \(b=0^\circ\).

Table 1. Set of indexations using the previous strategy (24 balls /7 BC indexations).

| Spindle indexation (°) | Artefacts measured (i) |
|-----------------------|------------------------|
|                       | \(b\) \(c\) \(i=1\ldots,26\) |
| 0                     | -90 -180 i=3,...,26 |
| 0                     | -30 -90 i=3,...,26 |
| 0                     | 0 0 i=26 |
| 90                    | 0 0 i=26 |
| 180                   | 0 0 i=26 |
| 270                   | 0 30 i=3,...,26 |
| 0                     | 60 180 i=3,...,26 |
| 0                     | 90 270 i=3,...,26 |

The strategy provides (6x24+1x26+4x1) sets of coordinates, for a total of 522 coordinate observations.

This probing sequence was originally used to estimate only the eight axis location errors, three linear gains and two spindle offsets, modeled using selected zero degree and first degree coefficients of the error motions polynomials, for a total of 13 coefficients among the available total of 180 (6 axes x 6 error motions x 5 coefficients).

| Test | Number of master balls | Number of B and C indexations | Cond J | Number of coefficients | Time (s) |
|------|------------------------|-------------------------------|--------|------------------------|----------|
| 1    | 24                     | 7                             | 2.29E+03 | 72                     | 2.9      |
| 2    | 24                     | 13                            | 2.60E+03 | 76                     | 5.3      |
| 3    | 4                      | 7                             | 6.06E+03 | 52                     | 0.6      |
| 4    | 4                      | 13                            | 3.35E+03 | 76                     | 1        |

In order to enhance the error model by identifying the maximum number of geometric errors, including error motions, different simulation situations are analyzed using the process illustrated in Fig. 2. The results of these tests are presented in Table 2.

The best simulation situation, amongst the ones tested, enabling the identification of a maximum of 76 axis location errors and error motions coefficients (including the spindle offsets) appears to be the last one where the number
of master balls is four and the number of B and C axes indexations is 13. Table 3 lists the estimated errors coefficients while using this strategy.

Fig. 2. Simulation strategy of geometric error coefficients estimation.

2.7. Decoupling of confounded errors

The 4 balls/13 indexations strategy is insufficient to enable the identification of some parameters such as the axial error motion of C axis ($E_{ZC}$) and the radial error motion of B axis ($E_{ZB}$).

By analyzing the five-axis machine tool kinematic modeling, it is noticed that the inability to estimate some of the errors is the result of their being confounded with each other as shown in Table 4.

The first two confounded situations are due to the linear relation between the indexations of B and C axes during the probing operation. As shown in Fig. 3, the B and C pairs are on a straight line so that one is a linear function of the other. Therefore, a set of 17 indexations of B and C axes is simulated by giving a careful consideration to breaking the relationship between the B and C axes set of indexations.

The generated results allow the identification of $E_{ZC}$ and $E_{CB}$ error motions in addition to the backlash error related to the two rotary axes. Regarding $E_{EBZ}$, $E_{EAY}$ and $E_{EBY}$ location errors, it is found that the angular errors are confounded with the linear ones due to the use of a single probe stylus length. Using two different tool lengths could eliminate these interdependencies.

Table 4. Causes of the confounded errors.

| Location errors | Definition | Causes |
|-----------------|------------|--------|
| $E_{ZC}$        | Axial error motion of C-axis | Coupled with the radial error motion of B-axis in Z-direction ($E_{ZB}$) |
| $E_{CB}$        | Tilt error motion of B-axis around C-axis ($E_{C}$) | Coupled with the angular positioning error motion of C ($E_{EC}$) |
| $E_{EBZ}$       | Angular error motion of Z-axis around B-axis (yaw) | Coupled with the straightness error motion in X-axis direction ($E_{EXZ}$) |
| $E_{EAY}$       | Angular error motion of Y-axis around A-axis (yaw) | Coupled with the positioning deviation of Y-axis ($E_{EYY}$) |
| $E_{EBY}$       | Angular error motion of Y-axis around B-axis (roll) | Coupled with the straightness error motion in X-axis direction ($E_{EXY}$) |
| $E_{ECY}$       | Angular error motion of Y-axis around C-axis (pitch) | Stylus tip alignment with the tool frame Z-axis |

Fig. 3. Relationship between B and C axes indexations.

Compared with the 4 balls/13 indexations strategy, the proposed strategy (4 balls/17 indexations) based on non-linear sets of rotations of B and C axes during the probing sequence has decreased significantly the condition number of the Jacobian matrix (from 2.35E+03 to 720.26) versus increasing the number of estimated errors coefficients from 76 (including the spindle offsets) to 84 (including the two spindle offsets and the two backlashes of B and C axes). The additional coefficients are shown in bold in Table 3 which does not list the backlashes of B and C axes that are estimable with the proposed strategy too.
3. Experimental aspect

3.1. Measurement method

A reconfigurable uncalibrated master balls artefact (RUMBA) [13] enriched with a double ball scale bar, to form a scale and master balls artefact (SAMBA) is used to gather observations of the machine volumetric behaviour [15].

![Fig. 4. Scale and master balls being probed with a MP700 Renishaw probe on a Mitsui Seiki HU40-T machine tool.](image)

The machine’s own touch trigger probe sequentially measures all accessible balls of the artefact at a number of rotary axes indexations. The RUMBA artefact uses individual stem mounted balls screwed directly into the machine table.

The SAMBA method has been proven numerically to estimate the eight axis location errors, the translational offsets of the spindle axis and the three positioning linear error gains of a five-axis machine tool [13, 15].

3.2. Measurement results

The SAMBA test is carried out on a HU40-T horizontal five-axis machine tool using an MP700 Renishaw probe while performing the indexation set of the proposed strategy (4 balls and 17 indexations of B and C axes). The test lasts 1.7 h and yields 51 ball centre measurements. The data analysis of the estimated parameters while predicting the machine behaviour for 76 and 84 parameters coefficients is presented in Table 5.

![Fig. 5. Cartesian volumetric errors unexplained by the estimated machine model for 76 and 84 parameters coefficients respectively in mm (errors 10,000σ).](image)
Fig. 5 shows the residual volumetric errors in the machine table frame. The mean volumetric error norm unexplained by the estimated machine model decreases from 3.61 μm to 2.62 μm and the maximum volumetric unexplained error from 10.1 μm to 5.22 μm when identifying 76 and 84 parameters coefficients respectively (spindle offsets included).

4. Conclusion

In this paper, the SAMBA method is used for data gathering and the rotary axes indexation strategies are studied by performing tests on a Matlab simulator, analysing the resulting estimation Jacobian condition number and by conducting experiments on a laboratory machine. This approach has proven to be advantageous while assessing geometric errors and avoiding interdependency which affects the condition number of the Jacobian.

A new rotary axes indexations set is proposed in order to enrich the geometric error model of the five-axis machine tool by identifying a maximum of axis location errors and error motions parameters based on a third degree ordinary polynomial modeling with backlash. It was established that the presence of confounded error coefficients was the result of a linear relationship between the previously used B and C axes indexations set as opposed to being an intrinsic limitation of the SAMBA method.

The proposed probing strategy enables the identification of 84 axis location errors and error motion coefficients compared to the previous one where only 13 coefficients were initially identified. The previously used strategy was found in this study to be suitable for a maximum of only 76 parameters which does not fully exploit the potential of the SAMBA method.

One of the purposes of the suggested strategy is also to reduce the number of master balls required to measure the errors in the machine volume versus increasing the indexation set of the B and C axes. This can reduce the measuring time and consequently the lost production time.

Future work is focusing on generating, by numerical simulation, an optimized probing strategy taking into account the number of master balls, their location on the machine pallet, the sequence of B and C axes and the necessary time for the calibration process in order to meet industrial requirements.

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