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Technical Paper

Improving a real milling machine accuracy through an indirect measurement of its geometric errors

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ABSTRACT

Traditional verification techniques, based on direct measurement of machine tool errors to improve accuracy, will gradually be replaced by technology based on indirect measurement techniques, reducing significantly the maintenance and verification time required. Within these techniques, the laser tracker is highlighted as a measurement system.

This paper presents all the verification processes on a real milling machine, studying the principal steps and influence factors, such as the kinematic model of the machine tool, the influence of the verification points distribution, convergence criteria, the defined identification strategy and the compensation procedure. The adequacy of the mathematical compensation provided by this method is validated using traditional verification methods based on a laser interferometer and new ones based on a laser tracker.

1. Introduction

The productivity and accuracy of machine tools (MTs) are important aspects in a competitive market. By measuring a number of points, verification allows characteristic information to compensate the influence of an MT's geometric errors and improve its accuracy.

The influence of geometric errors can be measured individually or collectively. The direct measurement of errors has been widely used in the verification of MTs and compensation of measurement coordinates machines (CMMs) [1]. These characterization techniques analyse the errors of each axis independently, taking into consideration the kind of axis of movement as ISO 230-1 [2], regardless of the kinematic model of the machine and the motion of other axes. Verification has been considered rigid body behaviour, as in Donmez et al. [3] and Chen et al. [4]. However, new studies are based on non-rigid behaviour to describe the error structure of the CMM [5]. New geometric error measurements use different laser interferometer techniques based on diagonal displacement, such as in Chen et al. [6], Okafor et al. [7] and Yang et al. [8], taking into consideration thermal influences also.

However, the manufacturing sector is currently shifting to indirect measurement in order to reduce the verification time required, especially in MTs with a long range of movement [1]. Indirect measurement produces a global correction of the MT workspace based on multi-axis movement and its kinematic model. Based on rigid-body behaviour, Lin et al. [9] assigned the origins of the joint frames at the physical joint to evaluate the volumetric error of multi-axis MTs, and Barakat et al. [10] presented error modelling and CMMs. Using this, volumetric verification (VV) uses indirect measurement with measurement systems such as a ball bar or laser interferometry to obtain approximation functions of each geometric error of the MT. Interest shown by different industrial sectors has resulted in several researches being focused on improving this innovation. Fan et al. [11] designed a new application of a 3D laser ball bar; Linares et al. [12] studied the influence of the measurement procedure using multilateration techniques to improve the MT's accuracy; Zhang and Hu [13] defined a new method based on three-point measurement using a laser tracker (LT) to determine the geometric error of the MT based on multilateration techniques; Wang et al. [14] determined rotary axis errors using multi-stations; Rahman and Mayer [15] used their own MT to determine its error and improve itself; Mehrdad and Mayer [16] used a machining test to validate the verification process; Aguado et al. [17] developed an identification parameter technique to improve MT accuracy using indirect measurement and a synthetic data generator, Aguado et al. [18] studied the influence of different parameters in identification parameters results including the LT in the MT kinematic model, Aguado et al. [19] determined the measurement strategies to determine the volumetric error in multi-axis MTs using an LT, analyzed

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the efficient used of identification [20]. Moreover, as presented by Soori et al. [21], these errors have also been included in virtual machining models.

Verification techniques have evolved in the area of software MT control systems too. Traditionally, to improve the accuracy of MTs, compensation tables of their control software were used. Currently, new compensation methods are being implemented, modifying the numerical control code in real time or using post-processing of CNC programs. Lechniak et al. [22] developed one of the first offline software compensation bases; Choi et al. [23] implemented an on-machine measurement with a touch probe to compensate for geometric errors; Gui et al. [24] created software error compensation via numerical control programme reconstruction; Gui et al. [25] developed a new method to improve the error on MTs with a Siemens 840D CNC system, and Khan and Chen [26] developed software based on an error table which interprets the axis function through a cubic spline technique and synthesis modelling of an MT. In addition, control software designers such as Siemens, Fagor and Heidenhain are daily incorporating new modules, using functions obtained in the verification process, to compensate directly for geometric errors.

However, one of the most relevant questions of this process is how to validate the adequacy of verification results, and in what conditions verification should be carried out to obtain the best results. To solve that question, this paper presents all verification processes, studying their principal steps and influence factors, such as the kinematic model of the machine tool, the influence of verification point distribution, the defined convergence criteria, the identification strategy and the compensation procedure. These are studied using a real milling machine with three linear axes. To validate the adequacy of the results obtained during nonlinear optimization, a traditional verification method based on a laser interferometer as the measurement system and new methods based on a laser tracker are used.

2. Kinematic model and volumetric error modelling

The MT kinematic model symbolizes the flow of movements of serial kinematic structures. Ideally, these structural components and their axes of movement have no errors; however, each axis of movement has six errors per axis and an error for each pair of associated axes (squareness). Assuming the restrictions and researches presented below, the position of the tool relative to the piece can be determined mathematically as a function of the movement of the machine. Several studies have been carried out: Slocum [27] and Duffie and Bollinger [28] presented homogeneous transformation matrices between axes based on the rigid body hypothesis and geometric errors; Wenjie [29] used these as a systematic approach for the geometric error modelling of MTs; Schwenke et al. [1] showed how the kinematic chain of an MT must be created in relation to its structural configuration; Rahman and Mayer [15] measured intra- and inter-axis errors in the kinematic model of the MT using a touch trigger as the measurement system; and Khan and Chen [26] developed a systematic method to obtain the kinematic model of an MT with five axes of movement.

The kinematic model of the machine tool to be verified is *XFYZ*, where the *X* axis drives the worktable and *Y*/*Z* are combined to actuate the tool. The laser tracker occupies the position of the piece in the kinematic model of the machine. Therefore, the rotational matrix and translation vector, obtained by least squares fit, that relate the coordinates system of the MT and LT must be included in the model (Fig. 1).

The equation of movements that relates the nominal coordinates of the MT with the measured coordinates of the laser tracker through MT geometric errors and MT characteristics is presented in Eq. (1).

$$\overline{X_{LT}} = \overline{R_{LT}^{-1}}(\overline{R_X^{-1}}(\overline{R_y}(\overline{R_z}\,\bar{T} + \bar{Z}) + \bar{Y} - \bar{Z}) - \overline{T_{LT}}) \tag{1}$$

$\overline{T_{LT}}$ represents the translation vector between the coordinate system of the machine CSO and the laser tracker CSLT.

$$\overline{T_{LT}} = \begin{pmatrix} oX_{LT} \\ oY_{LT} \\ oZ_{LT} \end{pmatrix} \tag{2}$$

$\overline{R_{LT}}$ represents the Olinde–Rodrigues matrix θ between the CSLT and CSO around a unitary vector $u = (u_x, u_y, u_z)$, where $u_x^2 + u_y^2 + u_z^2 = 1$.

$$R_{LT} = \begin{pmatrix} \cos(\theta) + \mu_x^2(1-\cos(\theta)) & \mu_x\mu_y(1-\cos(\theta) - \mu_z\sin(\theta) & \mu_x\mu_z(1-\cos(\theta) + \mu_y\sin(\theta) \\ \mu_x\mu_y(1-\cos(\theta) + \mu_z\sin(\theta) & \cos(\theta) + \mu_y^2(1-\cos(\theta)) & \mu_y\mu_z(1-\cos(\theta) - \mu_x\sin(\theta) \\ \mu_x\mu_z(1-\cos(\theta) - \mu_y\sin(\theta) & \mu_y\mu_z(1-\cos(\theta) + \mu_x\sin(\theta) & \cos(\theta) + \mu_z^2(1-\cos(\theta)) \end{pmatrix} \tag{3}$$

$\overline{X_{LT}}$ are the coordinates of a machine point measured with the laser tracker.

$$\overline{X_{LT}} = \begin{pmatrix} X_{LT} \\ Y_{LT} \\ Z_{LT} \end{pmatrix} \tag{4}$$

$\bar{T}$ is the offset of the tool.

$$\bar{T} = \begin{pmatrix} x_t \\ y_t \\ z_t \end{pmatrix} \tag{5}$$

$\overline{R_k}$ represents the rotational error matrix in axis k of the tool with $k = x, y, z$.

$$\overline{R_k} = \begin{pmatrix} 1 & -\varepsilon_{z,k} & \varepsilon_{y,k} \\ \varepsilon_{z,k} & 1 & -\varepsilon_{x,k} \\ -\varepsilon_{y,k} & \varepsilon_{x,k} & 1 \end{pmatrix} \tag{6}$$

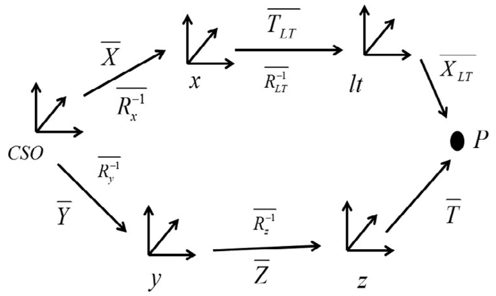

Fig. 1. Kinematic model of MT *XFYZ* with laser tracker.