Novel in-situ methodology for geometric error characterisation of rotary axis errors on multi-axis machine tool

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Abstract

Complex mechanical parts with high geometry and dimensional accuracy require multi-axis machining with low volumetric errors. To achieve such precision in the micrometer range, the geometric errors of the machine tool must be correctly identified and compensated. This article proposes a new methodology to measure directly the geometric errors of the rotary axes on machine tool. The methodology consists of a system of several non-contact sensors that are strategically placed around a datum cylinder. This system is held on the machine spindle and remains static over the entire measurement. The relative motion between the sensors and the cylinder is obtained by rotating the table of the multi-axis machine tool. The cylinder could be fast centered and leveled by using micro linear stages. A rotation stage enables to decouple the rotary axis motion from the datum cylinder rotation, consequently carry out methodologies of errors separation associated with multiprobe and multistep methods.

1 Introduction

The manufacture of accurate parts represents a need and a challenge in the industry, machines tools are used for this purpose, nevertheless, these ones have their own defects. Volumetric error is defined as the relative deviation between the actual and the nominal position and orientation of the tool and the workpiece [1]. The sources of these deviations can be various, but the largest contribution is due to quasi-static errors [2]. As part of these, the temperature has a considerable impact, however, most of the errors are due to geometric errors [3-5]. In the case of the rotary axes, these geometrical defects can be classified into six different geometric errors: two radial, two tilt, one axial and one angular positioning error [6]. The identification of these errors is performed through the use of specific tools and procedures. Calibrated artefacts, such as spheres or one and two-dimensional ball arrays are common for the identification in translation axes [7-8]. However, the procedure for rotary axes is more complicated and therefore there are relatively fewer related publications. The use of artefacts such as spheres is common, this is the case of the methodology proposed by [9-10] to identify the radial error or axial error, according to the arrangement of the sensors. The use of cylinders is often applied when characterisation of tilt or radial errors is required [11]. Another approach was proposed by [12] which aims to obtain a complete identification of the six errors of a rotary axis. This system called Dual Optical Path Measurement Method (DOPMM) consists of a motorized rotary stage and a Doppler laser instrument, nonetheless, it is a technically complex methodology. Unfortunately, many of the methods are not able to identify the six errors of a rotary axis or are too complex technically and mathematically.

Due to the use of artefacts to perform the measurement, defects as roundness or incorrect orientation are part of the data obtained and can be incorrectly interpreted as machine errors. Methodologies have been proposed to differentiate between artefact and machine errors. Evans [13] gives an overview of the three types of approaches usually used to handle this type of issue: reversal methods, multistep methods, multiprobe methods.

Reversal methods are techniques that seek to change the sign of an error component. Two measures are performed, nevertheless, between these two measures it is imperative to change the measure setup. It is necessary to mechanically manipulate the artefact and the sensor, rotating both 180°. Due to its mathematical simplicity and theoretically perfect separation, this approach is often considered better than other methods. However, it is technically complicated because ensuring perfect positioning of both the sensor and the artefact is difficult.

Moreover, mechanical manipulation between the two measurements can introduce errors into the measurement results. Multistep methods in contrast to the previous one, requires the manipulation of the artefact only, this will be indexed a number of equally spaced rotations, up to 360° of a complete revolution, while the sensor remains stationary. At first sight, this method seems to be simpler than a reversal, but its accuracy is a function of the number of indexing operations carried out; a higher indexing generates a higher accuracy. Therefore, in order to obtain sufficiently accurate results, a large number of indexations should be performed, which takes time and represents multiple mechanical manipulations of the artefact [14]. Multiprobe method is based on the use of simultaneous measurements from different sensors, usually three. This methodology does not require mechanical manipulation of either the sensors or the artefact, but they must be precisely located in order to ensure good accuracy. However, as Whitehouse depicted in [15] , multistep and multiprobe methods being fundamentally based on Fourier transforms present a critical problem, the harmonics suppressions. Therefore, the choice of the number of indexations for multistep method or the angular distribution of the sensors in multiprobe method becomes extremely important for a correct error separation, due to its close relationship with the harmonic suppression.

This paper is organised as follows. Section 2 explains the basic measurement principle used in the methodology. The conventional multiprobe and multistep methodologies are analysed mathematically in section 3. Then in section 4, the proposed measuring system is presented more in details. An optimisation of the error separation methods is performed in section 5. Finally, last section, gives conclusions and further works.

2 Measuring methodology

The spatial distribution and number of sensors are chosen according to errors that are going to be identified. With a single sensor arrangement oriented perpendicular to the rotary axis of the datum cylinder (artefact), one measurement can reveal the movement of the datum cylinder in the X-Y plane but variations in Z direction could not be obtained. Hence, multiple sensors positioned parallel to the cylinder are employed for this purpose. The data obtained by each sensor is a combination of radial error and tilt error as shown in Figure 1. However, it is impossible to know the contribution of each one. The use of two sensors oriented perpendicular to the rotary axis of the datum cylinder, but separated by a distance d, provides two simultaneous measurement results R_1 and R_2. Two identical variations of both R_1 and R_2 would be interpreted as a radial error. Different measurements between the sensors would indicate the presence of a tilt error. Since d is carefully identified by calibration, the tilt can be calculated by using differential measurement method [1]. This distribution is also used for sensors oriented parallel to the rotary axis of the datum cylinder, to differentiate axial error from tilt error. Strategic positioning of the sensors allows the identification of radial, tilt and axial errors. This paper proposes to take advantage of this principle of pairs of sensors perpendicularly and axially to the datum cylinder to identify tilt, radial and axial geometric errors of machine tool rotary axis.

3 Error separation techniques

The proposed methodology does not require the use of high-quality reference artefacts or even a previous calibration. The implementation of two error separation techniques provides the out-of-roundness defects and deviations due to incorrect orientation of the artefact. A combination between the multiprobe and multistep technique are proposed, which offers a more complete separation of errors. Since, it is performed by two different methodologies, to complement each other in terms of error suppression and reducing to a minimum the mechanical manipulations of the system to change from one technique to another. The technical and mathematical principle of the error separation techniques are presented below.

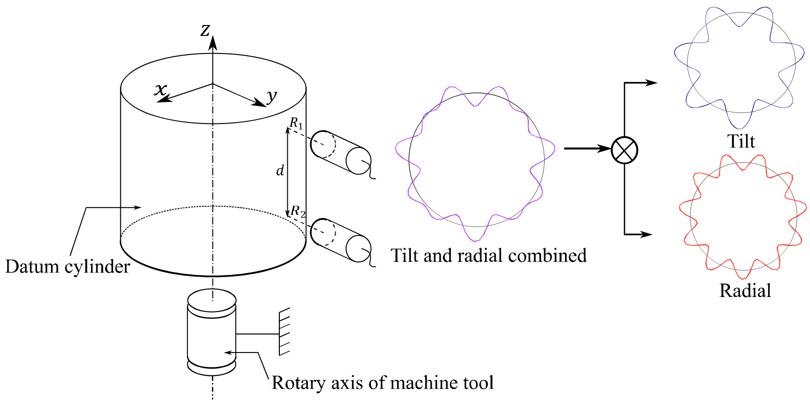


Figure 1 - Potential measurements according to the spatial location and orientation of the sensors

3.1 Multiprobe error separation

In this technique three sensors are oriented at 0°, α and β, all in the same cross section of the artefact as shown in Figure 2. The three simultaneous measurements are mathematically represented as the sum of the artefact roundness error $r(\theta)$ plus the $x(\theta)$ and $y(\theta)$ components of the rotary axis error.

$$\begin{cases} m_1(\theta) = r(\theta) + x(\theta) \\ m_2(\theta) = r(\theta-\alpha) + x(\theta)\,cos(\alpha) + y(\theta)\,sin(\alpha) \\ m_3(\theta) = r(\theta-\beta) + x(\theta)cos(\beta) + y(\theta)\,sin(\beta) \end{cases} \quad (1)$$

It is difficult to extract both the artefact profile or axis error from the three initial equations. To solve the problem, a new equation is defined as the combination of the three measurement results, choosing coefficients a, and b to be able to cancel the machine error contributions.

$$M(\theta) = m_1(\theta) + a\,m_2(\theta) + b\,m_3(\theta) \quad (2)$$

By replacing the system of Equations (1) in (2) one can obtain:

$$M(\theta) = r(\theta) + x(\theta) + a\,[r(\theta-\alpha) + x(\theta)\,cos(\alpha) + y(\theta)\,sin(\alpha)] + \ b[r(\theta-\beta) + x(\theta)\,cos(\beta) + y(\theta)\,sin(\beta)] \quad (3)$$

The Equation (3) can be written as follows:

$$M(\theta) = r(\theta) + a\,r(\theta-\alpha) + b\,r(\theta-\beta) + x(\theta)[1 + a\,cos(\alpha) + b\,cos(\beta)] + y(\theta)[a\,sin(\alpha) + b\,sin(\beta)] \quad (4)$$

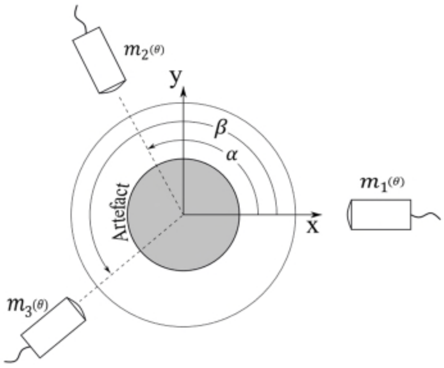


Figure 2 – Schematic diagram of multiprobe method.

In order to suppress the errors of the machine, a, and b must be selected to satisfy the following equations:

$$\begin{cases} 1 + a\,cos\,(\alpha) + b\,cos\,(\beta) = 0 \\ a\,sin\,(\alpha) + b\,sin\,(\beta) = 0 \end{cases} \quad (5)$$

Subsequently, the values obtained for a, and b can be expressed as:

$$\begin{cases} a = \dfrac{sin(\beta)}{sin\,(\alpha - \beta)} \\ b = \dfrac{sin(\alpha)}{sin\,(\beta - \alpha)} \end{cases} \quad (6)$$

Finally, the expression of $M(\theta)$ is:

$$M(\theta) = r(\theta) + a\,r(\theta - \alpha) + b\,r(\theta - \beta) \quad (7)$$

By using the Fourier transformation, $M(\theta)$ and $r(\theta)$ can be expressed as:

$$\begin{cases} M(\theta) = \sum_{k=1}^{\infty} A_k \cos(k\theta) + B_k \sin(k\theta) \\ r(\theta) = \sum_{k=1}^{\infty} a_k \cos(k\theta) + b_k \sin(k\theta) \end{cases} \quad (8)$$

Replacing Equation (8) in Equation (7) gives:

$$M(\theta) = \sum_{k=1}^{\infty} (a_k \varphi_k - b_k \delta_k) cos(k\theta) + (a_k \delta_k + b_k \varphi_k) sin(k\theta) \quad (9)$$

where

$$\begin{cases} \delta_k = b\, sin(k\beta) + a\, sin(k\alpha) \\ \varphi_k = 1 + a\, cos(k\alpha) + b\, cos(k\beta) \end{cases} \quad (10)$$

Subsequently, from Equation (10) and (8) one can obtain:

$$\begin{bmatrix} \varphi_k & -\delta_k \\ \delta_k & \varphi_k \end{bmatrix} \begin{Bmatrix} a_k \\ b_k \end{Bmatrix} = \begin{Bmatrix} A_k \\ B_k \end{Bmatrix} \quad (11)$$

Since, the values of α and β are known, it is possible to calculate a and b by Equation (6). Subsequently φ_k and δ_k can be calculated by Equation (10). The values of A_k and B_k are given by Equation (8), and thus it is possible to obtain the error of the axis $S(\theta)$:

$$S(\theta) = m_2(\theta) - r(\theta) \quad (12)$$

However, if the final matrix is further analysed, it is possible to notice that an incorrect selection of α and β can generate null values of the determinant (harmonic suppression) or very small values of φ_k and δ_k, leading to a poor-conditioning of the matrix and finally to a lower quality error separation. Subsequently, this harmonic suppression problem is inherent to the methodology. Hence, the measurement will be accompanied by the multistep error separation technique.

3.2 Multistep error separation

In the multistep method, the artefact is indexed in equal angular increments φ, meanwhile the sensor remains stationary in the same position. Therefore, each measurement will be composed of the axis error plus the roundness error of the artefact. The error of the artefact will be phase shifted as a function of the θ angle increments of each measurement. This can be represented mathematically as shown in the Equation (13), where $S(\theta)$ is the axis error and $r(\theta)$ is the roundness error.

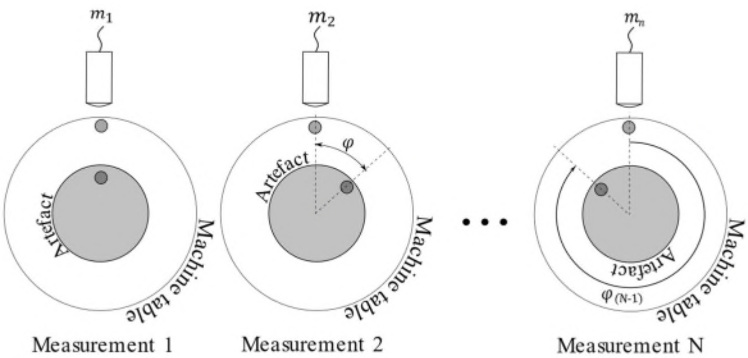


Figure 3 - Schematic diagram of multistep method.

with

$$m_n(\theta) = S(\theta) + r\big(\theta + \varphi(n-1)\big) \; ; \; n \in [\,1; N] \tag{13}$$

By summing each of the N measurements performed and solving for the axis error $S(\theta)$ the following equation is obtained:

$$S(\theta) = \frac{1}{N}\sum_{n=1}^{N} m_n - \frac{1}{N}\sum_{k=0}^{N-1} r(\theta + k\varphi) \tag{14}$$

As in the multiprobe technique, the artefact error can be expressed as:

$$r(\theta) = \sum_{p=1}^{\infty} A_p\, cos(p\theta) + B_p\, sin(p\theta) \tag{15}$$

Substituting this into Equation (14) it leads to:

$$S(\theta) = \frac{1}{N}\sum_{n=1}^{N} m_n - \frac{1}{N}\sum_{k=0}^{N-1}\sum_{p=1}^{\infty} A_p cos\,(\,p\,(\theta + k\varphi)) + B_p sin\,(p(\theta + k\varphi)) \tag{16}$$

Most of the terms of the double summation become equal to zero, so the error of the axis can be approximated as shown in Equation (17). However, there are some terms for which the double summation is not zero and therefore the assumption of Equation (17) is not valid. These terms are the multiples of the number of measurements N. This indicates that the harmonics multiples of N will not be correctly extracted (harmonic suppression).

$$S(\theta) \approx \frac{1}{N}\sum_{n=1}^{N} m_n \tag{17}$$

4 Measuring system

The setup of the measuring system is composed by multiple capacitive sensors which are assembled on a sensor support structure. Capacitive sensors are advantageous for an *in-situ* measurement system because their set up is not voluminous and its calibration is easier to perform compared to other types of sensors. Moreover, as they are non-contact sensors, no disturbances will occur in the measurement due to contact with the cylinder. These sensors are targeting radially and axially to a reference cylinder that is mounted on a mechanical system. The function of the latter is to ensure its correct alignment with the machine rotary axis. In this section the sensors support structure and the alignment system are presented.

4.1 Alignment device

This system allows the displacement in X and Y directions to compensate the misalignment between the axis of the cylinder and the rotary axis that will be characterised as shown in Figure 4(a). Even if the error separation technique identifies this misalignment, a high value can generate radial movements that exceed the measurement range of the sensors, saturating them. Moreover, the software compensation could be not optimal. The system is not equipped with a mechanism to adjust the tilt of the cylinder, however, after characterisation the tilt is not large enough to exceed the measurement range of the sensors, so it can be identified with the error separation process. The use of tilt mechanisms could introduce additional errors to the assembly, as well as increase its height. This complicates its set up on the machine, since the Z-dimension of the machines is a constraint to the dimensions of the measuring system.

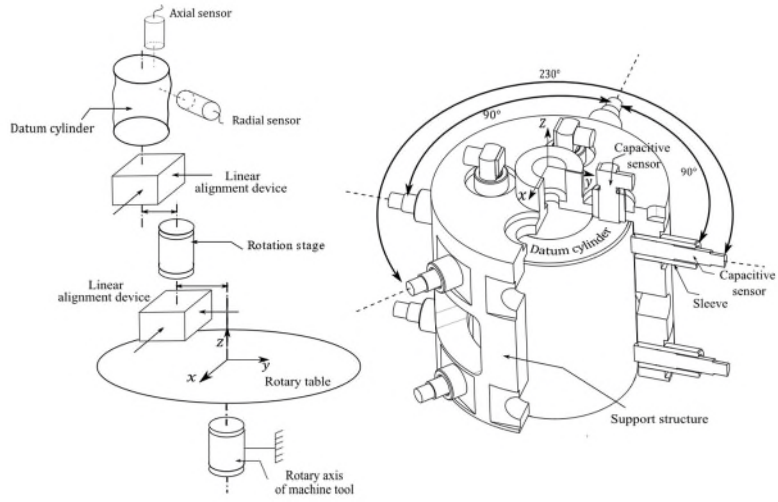
This system also has a rotation stage that allows to decouple the cylinder rotation from that of the machine’s table rotation, this is necessary to perform the indexing required in the multistep technique. This stage is also aligned with the machine's rotary axis to avoid an incorrect motion during indexing.

4.2 Sensors support structure

It’s a cylindrical structure completely surrounding the surface of the reference cylinder. This body fixed on the machine spindle ensures the correct positioning of the sensors. These ones are organised in three sets, two sets of sensors arranged radially in two cross sections spaced by a known distance d. The third group of sensors is disposed axially, targeting to the top of the reference cylinder as shown in Figure 4(b). The support structure has two possible configurations, one to measure errors and another one to separate errors. In the configuration setup to measure axis errors, the radial sensors are oriented at 90°, for both sets of radial sensors as shown in the Figure 4(b). With only two sensors oriented at 0°, it is possible to identify the tilt error in the y-z plane. With a pair of sensors oriented at 90° it is possible to measure the tilt in the x-z plane. The third axially arranged set (Figure 4(b)) identifies the axial and tilt errors as seen in Section 2.

The second configuration involves setting the radial sensors at 0°, 90° and 230° degrees, to optimise the error separation by means of multiprobe technique. The choice of this angular configuration is explained in the following section. The sensors will be inserted into a sleeve with a fine pitch external thread, which is then inserted into the support structure. It allows fine movement between the sensors and the cylinder to adjust measurements with different electronic gains. A lower gain means a smaller measuring range, but at the same time a better resolution.

To reduce noise effects, it is recommended that the sensors and the datum cylinder to be connected to the same ground. For this reason, the structure has a lateral perforation that allows access to the datum cylinder to ensure mechanical and conductive contact during the entire measurement.



(a) (b)

Figure 4 – Locations and orientations of the sensors on the support structure

5 Optimisation of error separation techniques

The selection of the angles that describe the sensors orientations is based on the harmonic suppression shown by the Equations in Section 3. The aim is to reduce the number of suppressed harmonics, especially for low values. Indeed, harmonics over than 20 upr (undulations per revolution) are not common in geometric errors on machine tool or may even be confused with inherent noise of the measurement system, so they can be neglected.

The angular distribution of the three sensors is the same for the two radially arranged sets, being $\alpha = 90°$ and $\beta = 230°$. To select the position of the third sensor, the cylindrical surface of the support is divided into 36 portions, representing increments of 10°. The first sensor is placed at 0°, the second at 90° because this sensor location already exists, due to the configuration for error measurement. The best positions for the third sensor as a function of the suppressed harmonics is calculated in the available positions between 90° and 360°, as shown in the Figure 5. Some configurations are undesirable, such as positioning the third sensor at 270°, because all harmonics would be suppressed. For a location at 260° or 280°, only one harmonic will not be identified. However, it is technically complicated to place one sensor close to another (already positioned at 270°), therefore, the 230° position is chosen. The decision to take 230° as a position will result in the suppression of harmonics 1, 4, 32, but the last one is considerably high, then, their importance would be minimal. Additionally, to minimise the number of suppressed harmonics, the mean of the determinant (Equation 11) is high compared to other configurations, this leads to a better separation of errors.

However, using the multistep technique and an appropriate selection of the indexing angle, it is possible to obtain suppressed harmonics different from those of the multiprobe technique. Choosing an indexing angle of 36° which leads to 10 indexations, the harmonics 10, 20, 30, 40, will not be identified. These are different from those of the multiprobe technique, therefore the results of both techniques would be compensated. The final result is a measure that does not have any harmonics suppressed for the first 20 upr.

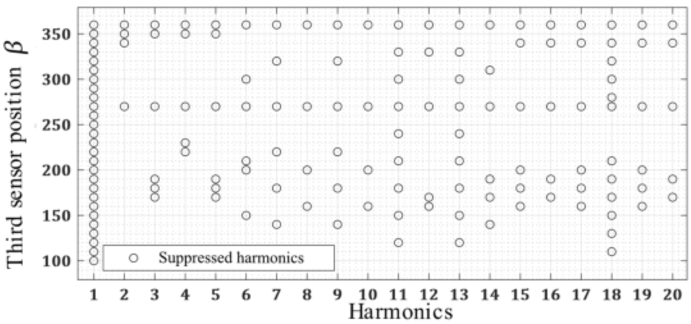


Figure 5 – Suppressed harmonics at different positions of the third sensor with the second sensor at 90°

6 Conclusions and perspectives

This paper presents a new methodology for *in situ* measurement of 5 among 6 errors of a rotary axis by means of a strategic arrangement of the sensors. It consists in an error separation methodology that involves the mutual optimisation of two classical techniques that complement each other. This method leads to a configuration that minimises the number of suppressed harmonics and reduces mechanical manipulations of the system, thus improving the quality of axis error measurement. This methodology is advantageous because it does not require either a high-quality reference artefact nor a metrological environment, since the arrangement of the sensors generates redundancy in order to compare and corroborate the data obtained by different sensors. The measurement system is currently being manufactured; the sensors were calibrated to characterise their behaviour on curved surfaces. In further work the full device will be used directly on HSM600U machine tool equipped with an iTNC530 CNC and IBV6072 modules to duplicate RCN226 Heidenhain encoders. The data recovered from these devices will allow a characterisation of the rotary axis, the identification of geometrical errors, the assessment and propagation of uncertainties.

Acknowledgements

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