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The use of a laser tracker and a self-centring probe for rotary axis verification

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Abstract

This paper presents a small collection of tests related with the analysis of a rotary axis according to ISO 230-7 but introducing two alternative equipments briefly explaining each method. The disadvantages of the methods in which the movement of a rotary axis engages the translational axes of a Machine Tool are expressed, which leads to the proposed study. The errors of a rotary axis are described as established in standards and the measurement procedures carried out in the tests for verification of a rotary indexing table, based on the use of a self-centring probe and a laser tracker, are explained. Also, the necessary elements setup for measurement are described. Then, the followed calculation process of the measured errors is explained in detail. Finally, the results of the most significant errors obtained from the test measurements are presented.

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Keywords: Geometric Verification; Rotary axis; PIGE; Complex Instruments.

1. Introduction

The identification of the geometrical errors present in the rotary axis of a machine tool (MT) is a subject that has generated different studies, such as [1, 2]. However, nowadays it continues being of interest in the dimensional metrology field [3], mostly because of the difficulty of distinguishing the actual rotary axis error value from errors the linear axes are adding when involved.

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Regarding a 5 axes MT, 12 Position Dependent Geometrical Errors (PDGE) caused by inaccuracies in the components of the axis , and 8 Position Independent Geometrical Errors (PIGE) due to assembly imperfections [4] can be found. Recent researches propose several methods that aim its identification [4-6], such as ISO standard 10791 [5] that describe non-loaded or quasi-static measures for the central line of a rotary axis and [7], where the R-Test has been used to identify the location errors of rotary axes. Measuring methods like cone frustum [2, 8], machining test [10] and touch-trigger probes [11] have been proposed for the measuring of the geometric errors in a 5 axis machine tool though double ball-bar methods have become really popular to evaluate the rotary axes [8, 9, 12]. However, most of them only consider the PIGE. After the study of the existing methods it can be concluded that nowadays there is not a single method able to fulfil the verification needs of any rotary axis in a general way, and is clear that the linear axes of the MT are involved depending on the measuring method used for verifying a rotary axis.

This article presents the verification procedure to identify the PIGE of a rotary indexing table using a Linear Displacement Sensor (LDS), a Self-Centring Probe (SCP) and a Laser Tracker (LT) in order to demonstrate the feasibility of using the LT and SCP for verifying an independent rotary axis. The error values calculation are made using a direct method by following the specification of the standard [4].

2. Rotary axis errors

A rotary axis has six degrees of freedom that generate its movement and centring errors, Fig. 1, which can be difficult to distinguish from one another because their effects overlap, as the movement errors are unexpected relative displacements between the workpiece and the tool on the sensitive direction and the centring errors are deviations of the axis on the perpendicular directions, angularly or parallel to the central rotational axis due to structure or to working speed changes.

Current standards [4] describe a conventional method for the calibration of a rotary axis, which involves the use of a cylindrical or spherical reference object used to make the radial, axial and pendulum measure of an axis by means of capacitive, inductive or displacement sensors.

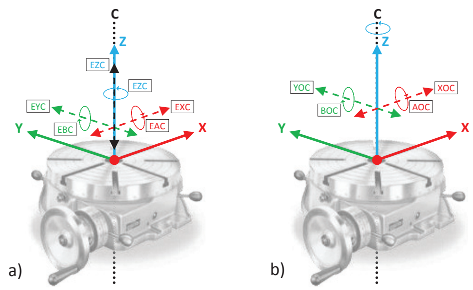

Fig. 1. (a) Movement and (b) Centring errors of a rotary axis.

Clearly, this standard offers certain guidance about the measuring devises to be used, however, since the errors of an axis are directly calculated from its linear deviations in the orthogonal directions, is possible to utilize other measuring devices.

Most of the studies conducted recently used a ball-bar (it is one of the measuring devices now considered in ISO 230-1:2012) in order to identify the geometric errors of a rotary axis in a direct way and not as a volumetric method, such as in the case of using the R-test method, which is more efficient than the ball-bar precisely because it allows the identification of multiple errors. Nowadays, this method is widely used, even if their measurement methodology requires the combination of movement of all axes, rotary and translational, with all the complications that entails.

This paper present the verification of an index table on which the calculation of Position Independent Geometric Errors is performed, opting for a direct identification by following the specifications of ISO 230-7 [4] standard. The study has made possible to analyse the feasibility of using measurement instruments not recommended in the standard such as a self-centring probe or a Laser Tracker. The methodology and the results of the experimental measurements using a LDS, a SCP and a LT are presented.

3. Experimental procedure

The procedure mainly follows the guidance of the ISO 230-7 standard. A series of measurements that allow the calculation of the errors of a rotary axis have been done, taking as a case study a rotary table placed with an inclination of 90 degrees and horizontally aligned with the X axis of a milling machine.

As auxiliary measurement setup, a drill holder is placed in line with the central axis of the rotary table. This holds a rectified steel bar that serves as a measuring surface for the LDS, and at the same time is used to place the reflector whose position measures the LT or the calibrated sphere measured by the SCP. The measurements are made at two axial positions along the measured axis.

In order to make a proper comparison of their results, two measurement instruments are used simultaneously so data can be obtained with both systems in the same time frame. Two separate tests are carried out because the reflector and the sphere must be placed at the same point: In the first part, two dial indicators acting as LDS's and a LT are used; in the second part, the same LDS's are used along with a SCP. The specifications of each test are described in the following sections.

3.1 Measurement Setup

Test 1 involves two LDS and a LT. The magnetic base holding the LT reflector ④ is placed in the far end of the rectified steel bar ⑤ used as measuring surface for the LDS ②③ in the axial position 1, Figure 2. Regarding axial position 2, the LT magnetic base ⑤ is placed in the centre of the index table ① by the drill holder and serves as measuring surface for the LDS ②③, Fig. 2.

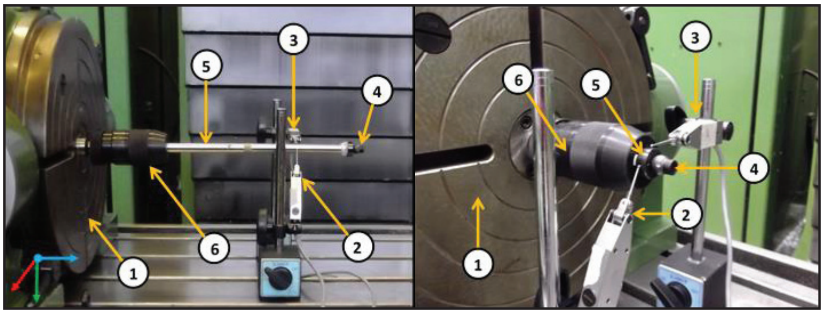

Fig. 2. Test 1 measuring setup in two axial positions.

A specific software (Spatial Analyzer) takes care of obtaining the data from the LT measurements. The 3D coordinates of the measured points are given in a coordinate system (CS) associated to the zero point of every axial position. This CS is constructed relating the base of the index table with the machine working table and the rotary central point. Afterwards the CS is translated to an axial position in order to obtain the measured point coordinates related to the index table position, Fig. 3.

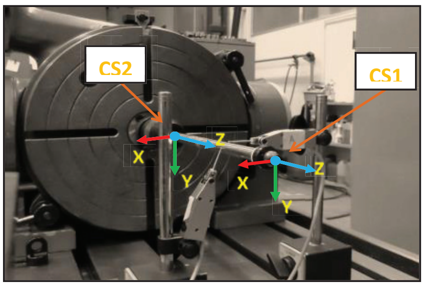

Fig. 3. Test 1 Coordinate Systems (CS).

In Test 2, Fig. 4, a SCP ④ that measures the coordinates of the centre of a sphere placed in each of the two axial positions is used along with the same two dial indicators as LDS. The measuring precision sphere is attached to a magnetic base ⑦ in the far end (axial position 1) of the rectified steel bar ⑤ that serves as measuring surface for the LDS's ②③. The bar is placed in the centre of the index table ① by the drill holder ⑥. The SCP measures the 3D coordinates of the sphere while simultaneously the LDS measures the deviations of the rotary axis. In axial position 2, the magnetic base ⑦ and the attached calibrated sphere are placed directly in the drill holder ⑥. The LDS's ②③ take as measuring surface the edge of the magnetic base.

In both tests the LDS are placed in a lateral position, oriented to the X and Y axis of the second measuring device.

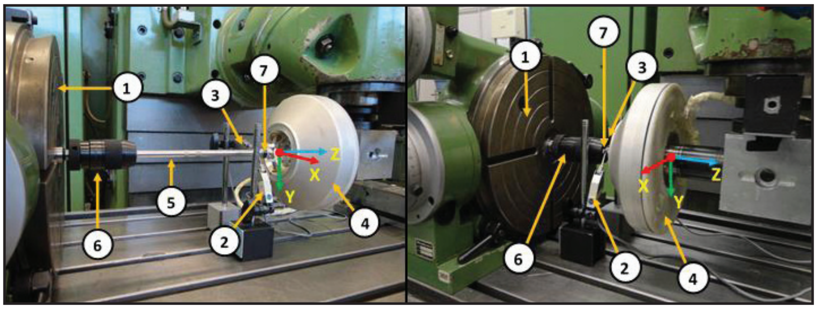

Fig. 4. Test 2 measuring setup in two axial positions.

The measurements in both axial positions are used to calculate the Radial and Pendulum Measurement Error, individually or combined, of the rotary axis C in the X and Y directions of the rotary indexing table. However, this test made only possible to obtain data to calculate the Axial Movement Error with the LT and SCP measurements whose Z coordinates can be used for this. It was necessary to carry out another test to obtain data to calculate this error with LDS's.

In this measurement set up, Fig. 5, a flatness reference standard attached to the centre of the rotary table is used as measuring surface for the LDS. One of them is put in contact with the reference, placing the measuring tip aligned in the very rotary centre so any axial deviations of the indexing table can be registered.

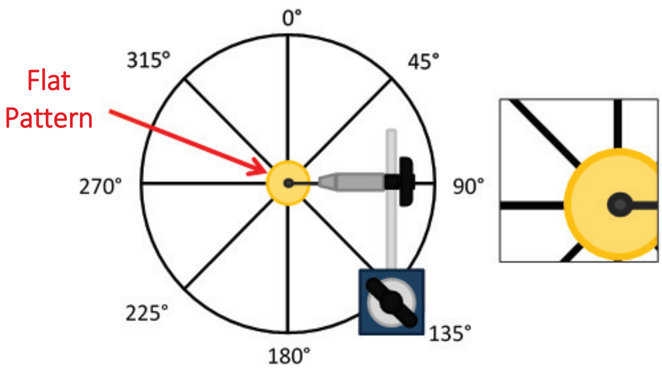

Fig. 5. Axial Movement Error measuring setup with LDS.

3.2 Measuring procedure

The rotary axis of the index table has been tested by making a unidirectional approach in the clockwise direction for a total measurement travel of 810 degrees, obtaining the coordinates of 8 measuring points per revolution every 45 degrees.

Once the maximum travel is reached, the rotary table is tested in the opposite direction until reaching the starting point, obtaining the coordinates of the same measuring points. Fig. 6.

This rotary procedure and the data acquisition is always made in both directions, with a repetition of three times for every axial measuring position.

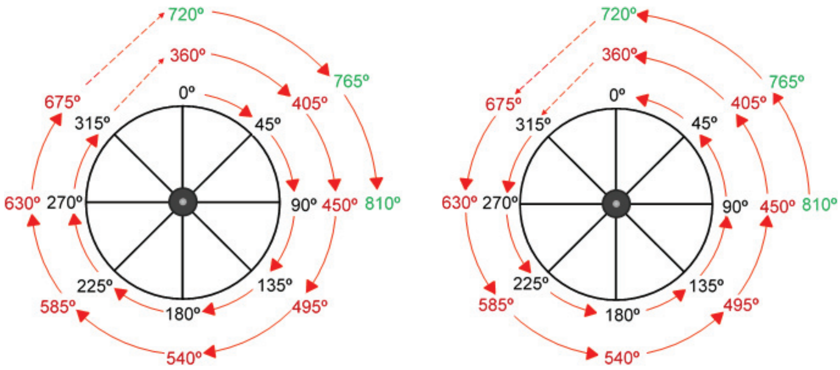

Fig. 6. Total measurement travel and measuring points of the rotary axis in both directions.

4. Results

The obtained results of the calculation of the Radial Movement Error, the Pendulum Movement Error and the Axial Movement Error are presented according to current standard ISO 230-7 which specifies that errors must be presented as a single value. For a close comparison between measuring instruments graphics are shown, taking into account the correlativity of the methods used in each test and reflecting the synchronous error of the Total Radial or Pendulum Error.

4.1 Radial Movement error comparison

The Radial movement errors are calculated from the measures made in the axial position 2 of both tests. The errors obtained from Test 1 show similar results for the total error and for each axis. The Total Radial Movement Error calculated with LDS has an absolute range of -21 to 5 micrometres, while the measured error range with LT is of -22 to 6 micrometres, which means a difference of only 2 micrometres. In both cases, the maximum error is reached in the 270 degrees point. The trend and behaviour is the similar in all measurement points.

The calculated errors for axes X and Y show a similar behaviour, where the magnitude of the calculated errors with LDS is of 28 to 18 micrometres respectively, though for the LT is of 28 micrometres for the X axis and 20 micrometres for the Y axis.

The next table shows the synchronous error values for the calculated errors. The values of the asynchronous error are of 1,7 micrometres for $r(\theta)$, 1,2 micrometres for $EXC(\theta)$ and 1,5 for $EYC(\theta)$.

Table 1. Synchronous error value comparison of the test 1 Radial Movement Error.

Error	Synchronous error Value	
	LDS (mm)	LT (mm)
$r(\theta)$ Test 1	0,0261	0,0282
$EXC(\theta)$ Test 1	0,0281	0,0285
$EYC(\theta)$ Test 1	0,0178	0,0208

The results of the calculation of the errors measured on Test 2 reflect a similar behaviour between both measurement instruments, with certain differences in wideness regarding the maximum and minimum error as can be seen in Fig. 7. The synchronous error value for the Total Radial Movement Error measured with LDS is of about

60 microns, and of 63 microns with SCP. On the other hand, the Radial Movement Errors for the X and Y axes calculated with LDS and SCP also have a similar trend, although their error ranges are smaller, being of about 35 micrometres for the X axis and of 53 micrometres for the Y axis. The asynchronous error values of the Radial Movement Errors on Test 2 are in a range of 2,7 to 3,7 micrometres. The synchronous values of the Radial Error are shown in Table 2.

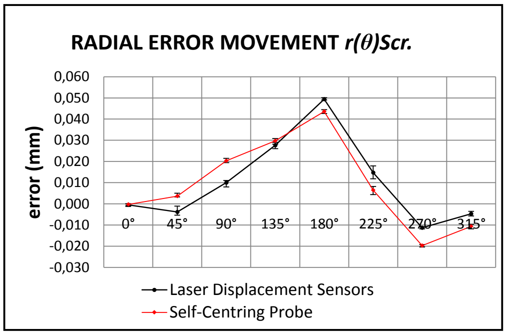

Fig. 7. Synchronous r(θ) error measured in Test 2.

Table 2. Synchronous error value comparison of the Test 2 Radial Movement Error.

Error	Synchronous error Value	
	LDS (mm)	SCP (mm)
r(θ) **Test 2**	0,0607	0,0636
EXC(θ) **Test 2**	0,0350	0,0320
EYC(θ) **Test 2**	0,0485	0,0531

4.2 Pendulum Movement Error comparison

The Pendulum Movement Errors resulting of the measurement with LDS and LT shows an amplitude of 114 and 94 arc seconds respectively for the Total part of the error. Relative to the calculated errors for each axis, this shows an error range of -44 to 42 arc seconds with LDS for the X axis and of 78 to 10 arc seconds for the Y axis, while the calculated errors with the measurements made with LT are in a range of ±32 arc seconds for the X axis an of -78 to 19 arc seconds for the Y axis. In Table 3 can be seen the values of the synchronous error of the Pendulum Movement Error in Test 1. The maximum difference between the two measuring methods is of 20 arc seconds or 0,006 degrees.

Table 3. Synchronous error value comparison of the Test 1 Pendulum Movement Error.

Error	Synchronous error Value	
	SDL (arcsec)	LT (arcsec)
p(θ) **Test 1**	114,73	94,75
EAC(θ) **Test 1**	86,02	64,98
EBC(θ) **Test 1**	88,50	98,22

Fig. 8 shows how the trend of the synchronous error of the Total Pendulum Movement Error calculated with LDS and LT are very similar, being contained in a range of -40 to 85 arc seconds approximately. The Pendulum Movement Errors of the axis X and Y present the same trend.

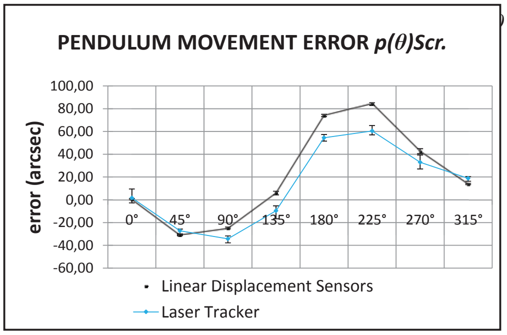

Fig. 8. Synchronous p(θ) error measured in Test 1.

The synchronous error value of the Pendulum Movement Errors obtained with the measures of LDS and LT in Test 2 can be seen in Table 4. The Total Pendulum Movement Error measured with LDS has been calculated to be in a range of -67 to 74 arc seconds, and the error calculated with LT measures in a range of -67 to 69 arc seconds. Calculated Pendulum Movement Errors for the X axis measured with LDS and LT are in a range of -74 to 8 arc seconds and -68 to 10 arc seconds respectively, while the Pendulum Movement Errors for the Y axis are in a range of -24 to 57 arc seconds and -41 to 51 arc seconds with LDS and LT respectively. Trends of calculated errors are similar in all cases.

Table 4. Synchronous error value comparison of the Test 2 Pendulum Movement Error.

Error	Synchronous error Value	
	LDS (arcsec)	SCP (arcsec)
p(θ) Test 2	142,09	135,76
EAC(θ) Test 2	82,12	78,25
EBC(θ) Test 2	81,52	93,15

4.3 Axial Movement Error comparison

Conversely to what happened with Radial and Pendulum Movement Errors on both tests, where the results not allowed a comparison due to the influence of positioning of the measurement element onto the centre of the table, the Axial Movement Error was measured in a way that made possible the comparison of the results obtained with each measuring instrument. The values of the Asynchronous Axial Movement Error are of 0,9, 1,3 and 1,4 micrometres for LDS, LT and SCP measures respectively. Fig. 9 shows the comparison of the synchronous Axial Error calculated with each measurement instrument. All trends are similar and the error value is of about 12 micrometres.

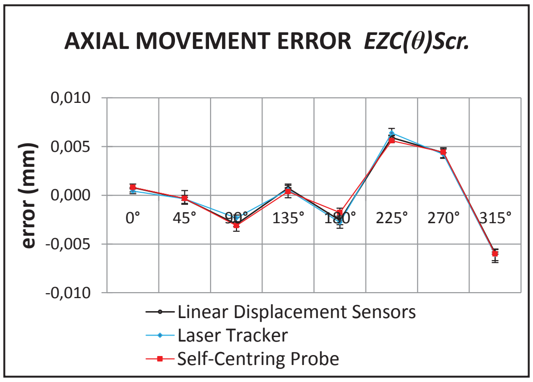

Fig. 9. Synchronous EZC (θ) error. Measurement instrument comparative.

5. Conclusions

The verification of a rotary indexing table was made by conducting various tests for the identification of the Position Independent Geometrical Errors.

We have calculated the Radial, Pendulum and Axial Movement errors in a direct way. The results obtained in each test, and comparisons thereof, give sufficient evidence of the possibility to use instruments such as a Laser Tracker or a Self-Centring Probe to achieve the geometric verification of a rotary axis.

One of the main difficulties this method encounters is the placement of the rectified steel bar in the centre of the plate, since it is extremely difficult to ensure a good mounting repeatability.

This change in mounting influences the results, therefor it has not been possible to make a comparison between the values of Radial and Tilting errors calculated with measurements of both tests. However the comparative of Axial Movement Error calculated with the three measuring instruments provide results that validate the hypothesis that it is possible to obtain such good results with a Laser Tracker and a Self-Centring Probe as with Linear Displacement Sensors, as indicated by the standard.

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