CALIBRATION OF PRECISION ROTARY TABLE USING LASER INTERFEROMETER SYSTEM

Michal Šindelář

Doctoral Degree Programme (4), FEEC BUT

E-mail: sindelar@feec.vutbr.cz

Supervised by: Petr Beneš

E-mail: benesp@feec.vutbr.cz

Abstract: Calibration of a rotary axis can be useful to determine angular deviations throughout the measuring range. Specified accuracy presented in the specification list represents the worst case, therefore information about magnitudes of deviations of individual measuring points are unknown. The resulting error map of the device under test allows correction of the indicated value. As a result, the measurement accuracy of the device can be increased. Calibration of a precision rotary table was performed using a Keysight 5530 laser interferometer system. The presented paper briefly describes the fundamentals of this portable calibrating system. Also, the results and accuracies are discussed.

Keywords: Calibration, rotary table, laser interferometer

1 INTRODUCTION

Precision rotary and index tables are devices with accurate angular positioning capabilities. Rotary tables are widely used as measuring devices in many applications, such as machining, welding, manufacturing of ball bearings cages, calibration, or R&D purposes in laboratory environments.

In terms of precision rotary positioning, parameters as absolute deviation, repeatability, and angular resolution are crucial. Usually, manufacturers of rotary tables specify these parameters in a datasheet, but there are two important facts to consider. Firstly, a given absolute deviation of a rotary table represents maximal positioning error throughout a measurement range. Hence, the specified absolute deviation is not assigned to the particular angle and affects all measuring points in the same way. Secondly, a manufacturer guarantees absolute deviation in the determined running conditions. Since the performance of a rotary table may vary due to different running conditions (aging, unbalanced load, bearing condition, different temperature, etc.), it can be useful to provide in situ calibration directly on its application axis [1].

In general, calibration is a process, where the device under test is compared to the more accurate reference standard. Thus, the calibration of a rotary table is based on a comparison of angular values indicated by a rotary table and angular standard. Comparison for i-th measuring point is obtained by the difference between i-th measured value and i-th reference value. As a result, these angular deviations provide an error map that contains information about the magnitude of absolute measurement error related to nominal angular positions. Consequently, known angular deviations allow compensation of indicated values. Hence, measurement accuracy can be significantly increased.

2 CALIBRATION APPROACHES

The calibration process can be carried out in several ways. We can divide calibration techniques into two groups. Firstly, methods referred to as cross-calibration. These techniques are carried out in the way mentioned above, i.e., comparison of the device under test against a reference standard. For example, an autocollimator against precision optical polygon is widely used in metrology laboratories, such as Czech metrology institute [2], or National Institute of Standard and Technology. This method with optical polygon offers very high accuracy, however, the angular step is limited by the number of polygon faces. Another option is to employ a laser interferometer system with retroreflective optics [3], [4].

Secondly, methods referred to as self-calibration are based on the device capability to determine its deviations. Thus, the external angular standard is not necessary and calibration of the device under test is accomplished by the device itself [1]. To achieve this self-calibration functionality, a feature of a circle closure is applied. The total sum of plane angular intervals around any point inside any closed curve is exactly 2π rad. Hence, self-calibration devices require special design which increases the cost of the device. Also, at least one full rotation run from 0° to 360° is essential for the self-calibration process. As a result, a self-calibration approach is not applicable for rotary axes with reduced operating range. On the other hand, self-calibration techniques have many advantages, such as calibration directly on the application axis under real running conditions, no external standard, zero-cost and time-saving calibration, etc. More information about self-calibrate rotary tables can be found in [5], [6].

3 EXPERIMENTAL SETUP

The device under test is a rotary table SDL 1401 manufactured by RMS. This rotary table allows free turning and provides several operating modes including absolute positioning mode with a resolution of 0.18 arcsec, repeatability of ±1 arcsec, and absolute accuracy of ±4 arcsec [7]. The motion controller of a direct drive motor can be controlled by using a touch panel or remotely. One of the main goals of this paper is to verify absolute angular positioning error. Another goal is to obtain an error map to increase angular positioning accuracy by correcting indicated values.

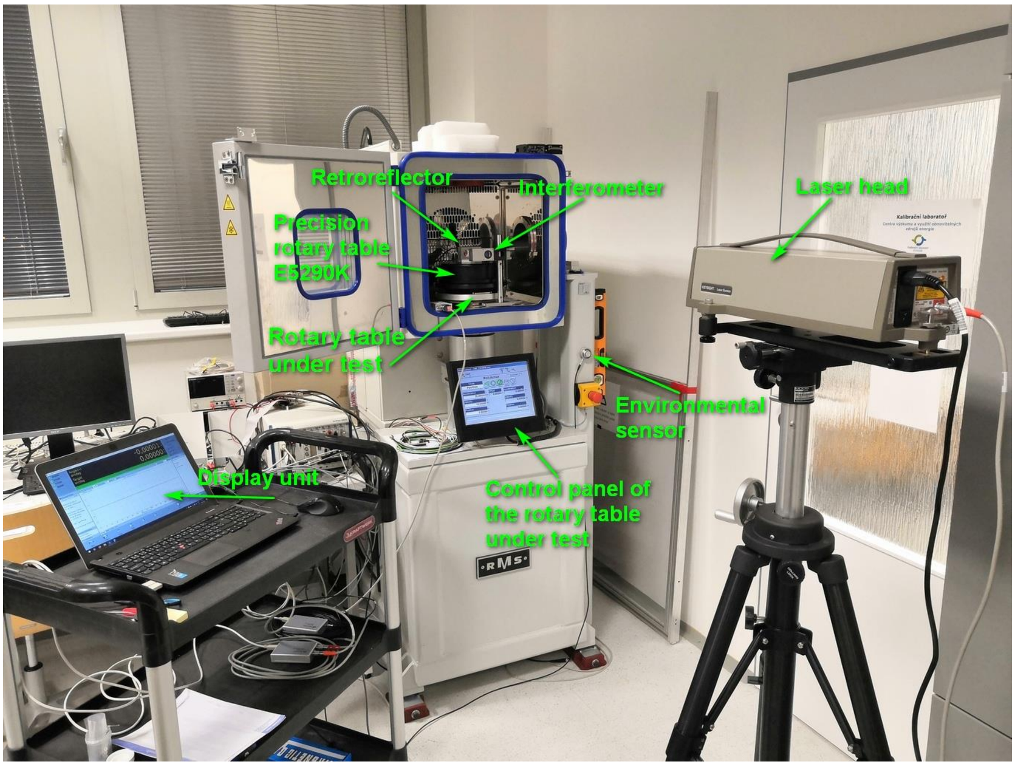

Figure 1: Calibration of a rotary table

The angular standard is represented by Keysight 5530 laser interferometer system cooperating with rotary axis measurement kit E5290K by Cullam Technologies. A rotary axis measurement kit consists of a precision rotary table, which is mounted on a device to be calibrated. The laser system with the rotary axis measurement kit offers total absolute accuracy of 1.0 arcsec, repeatability of 0.8 arcsec, and resolution of 0.02 arcsec [8]. The laser system maintains its accuracy even if it is mounted on the to be calibrated rotary axis. Typically, the dominant contributor to the total error budget is caused by imperfect installation due to misalignment of the to be calibrated rotary axis and the rotary axis of the reference rotary table. Eccentrics movement is interpreted as corresponding angular displacement. Hence, the indicated value of angular displacement also contains invalid angular displacement acquired by eccentricity movement. The magnitude of eccentricity error negatively affects total accuracy. In general, the more accurate measuring system, the higher requirements for its installation. For the measuring system with an accuracy of 1 arcsec, the eccentricity has to lie within several microns and the centering of the rotary axis becomes challenging. To avoid this, compensation of the eccentricity error is crucial. For this reason, the 5530 laser calibration system employs an angular interferometer, which is sensing the position of the retroreflector mounted on the precision (i.e. reference) rotary table. Change in relative position is measured and used for angular position compensation.

In addition, the accuracy of the laser measurements is affected by environmental conditions, such as air temperature, air pressure, and relative humidity. To accomplish compensation of these error producing conditions, the Keysight 5530 laser system employs a remote environmental sensor. The environmental data are processed in the metrology software E1733A, where a compensation factor is computed and applied for the measurement.

The optical path of the Keysight 5530 laser calibration system is comprised of a laser head 5519B, an angular interferometer, and retroreflective optics. An experimental setup is illustrated in Figure 1. A retroreflector is mounted on the top of the precision calibration rotary table E5290K. An angular interferometer is placed in front of the retroreflector. The laser head is aligned so its beam goes through an angular interferometer and enters the port of the retroreflector and is perpendicular to the port surface.

4 RESULTS

Calibration of the rotary table was carried out at steps of 30° from 0° to 360°. Each angular interval was measured five times in each approach direction (forward and backward). Therefore, ten calibration values per measuring step were acquired, and the mean values of the deviations were calculated as shown in Figure 2. This graph also includes the maximum and minimum envelope obtained by repeated measurements.

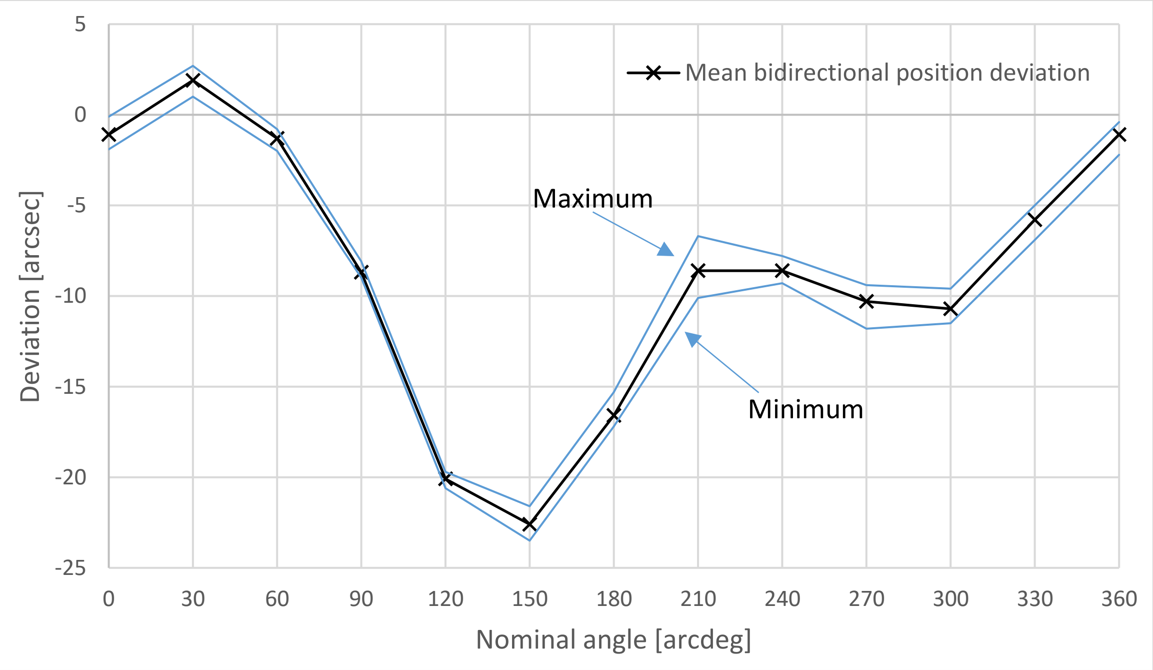

Figure 2: Result of the calibration

It can be seen, that the greatest angular deviation reaches 23,5 arcsec and it is related to the nominal angle of 150°. Figure 3 shows the standard deviation of each measured angular position. The maximal value of 1.3 arcsec corresponds to the repeatability of the rotary table. Note that the standard deviation of each nominal position is taken from five measurements by forward and backward approach direction. Thus, the estimated bidirectional standard deviation involves the hysteresis effect. Hysteresis presented in the specification is ±1 arcsec. Considering the specified repeatability and hysteresis, both of ±1 arcsec, the estimated standard deviation complies with the specification.

The resulting uncertainty of the calibrating method assumes zero eccentricity error due to laser compensation. Also, compensation for the environmental conditions and proper installation is assumed. Uncertainty of type A was estimated to 0.4 arcsec. Absolute accuracy of ±1.0 arcsec of the E5290K measurement kit represents an error contributor for the uncertainty of type B, which is estimated to 0.6 arcsec using rectangular distribution. The expanded uncertainty of the reference calibrating system (coverage factor of 2) is evaluated to 1.5 arcsec.

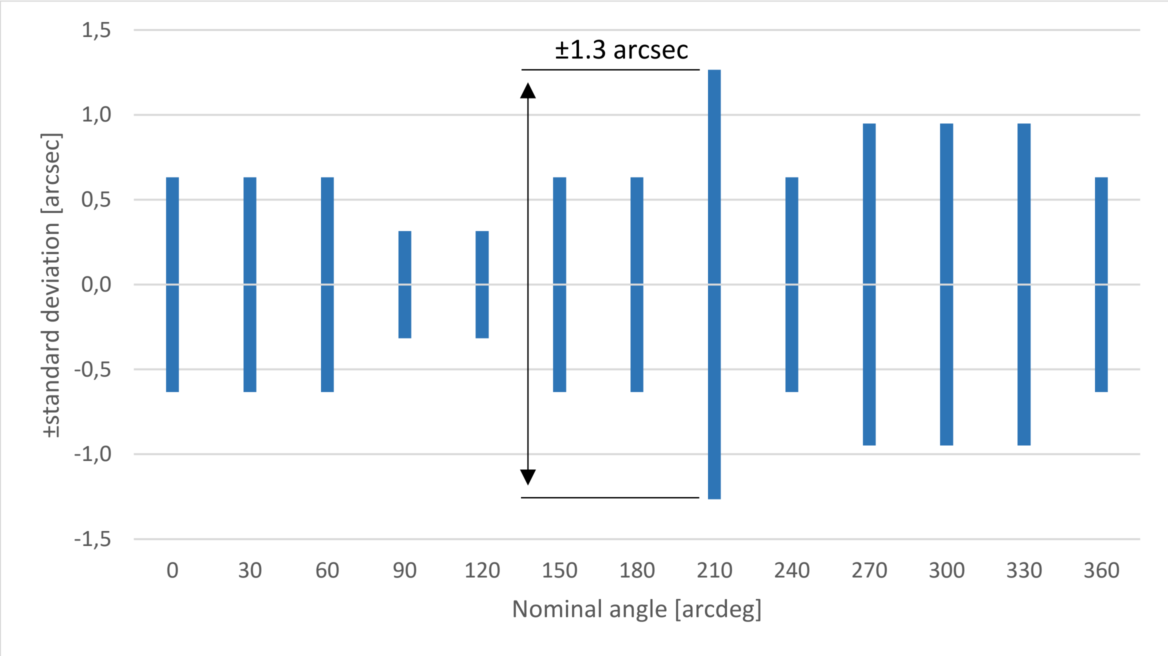

Figure 3: Standard deviation of positioning error

5 CONCLUSIONS

This article has only been able to touch on the most general features in the field of rotary axis calibration. Employing of commercial laser calibrating system Keysight 5530 is straightforward and provides high precision and resolution. The resulting angular deviations from the calibration reveal an angular positioning error map which can be applied to compensate positioning error of the SDL 1401 rotary table. It can be noted that the measured accuracy of the calibrated rotary table does not meet the specified accuracy. The worst case of the measured angular deviation reaches 23.5 arcsec.

The resulting position accuracy is not as good as we expected. On the other hand, the rotary table has been using for many years and the performance of the rotary table could be slightly reduced due to aging and wear. Thus, the parameters of the motion controller may need to be updated. Specification of the E5290K rotary axis measurement kit allows installation with 1 mm geometrical offset between measured and reference axis due to eccentricity compensation by the 5530 laser calibrator system. For this reason, error contributors for the type B uncertainty estimation were reduced to specified accuracy of ±1.0 arcsec and other contributors were neglected.

In future work, a detailed uncertainty analysis will be realized. Also, an experiment to verify the actual measure of eccentricity compensation of the calibrating system will be carried out. After this, the presented error map in this paper can be verified.

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