Performance Evaluation of Rotary Table Using an Angular Indexing System with Self-Calibration Technique

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Abstract— The angular error of indexing table on machine tool is measured using new developed measuring device. The measuring techniques, which have been reviewed in this paper, are currently available in manufacturing engineering to calibrate the angle measurement. The new developed measuring device using 6 points kinematic concept and employing ball and vee grooves is used to calibrate angle errors of rotary tables using a laser interferometer. Compact new automatic indexing table was achieved by driving the cam mechanism. The design for an automatic indexing table is considered to be satisfactory for company to calibrate rotary table. This automatic system gives the time saving during measurement process. The equipment required for economical manufacture is relatively simple and could be undertaken by most machine shop

Keyword-Indexing system, rotary table, Self-calibration, Interferometer, Kinematic Design

I. INTRODUCTION

Many types of indexing tables appear in industry. One of the most widely used general groups in angle measurement is based on comparing the angular conditions of a part or a feature to an angle of known size. The inspection then consists of checking the compliance, or in determining the magnitude of discrepancy between the master and the object.

To calibrate these indexing tables, a polygon and autocollimator, or the serrated type indexing table which is usually 0.1 arcsecond accuracy, are usually used and the calibration accuracy of the polygon and autocollimator is about 1 arcsecond. The calibration method using a laser interferometer was developed.[2] This performed very well in a laboratory situation, it was not considered robust enough to reproduce as a commercial design. A new mechanism should be considered for the indexing table.[7] Thus a 6 point contact kinematic design concept of ball and vee groove was used, because the ball and vee groove system can attain 0.1 µm repeatability [3] and has good rigidity. The aim of this research is performance evaluation of rotary table using new automatic indexing table system employed kinematic concept design.

II. TECHNIQUES FOR THE CALIBRATION OF ROTARY INDEXING TABLES

A. *Calibration of indexing table by polygon and autocollimator*

For the calibration of an indexing table, the most generally used method is based on the use of a polygon and autocollimator. Calibration of the rotary table is readily performed by means of a precision polygon mounted on a table and read by a single fixed autocollimator.

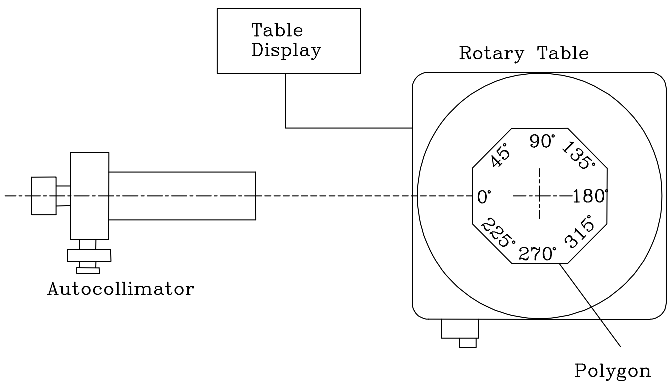


Fig. 1. Calibration of rotary table by autocollimator and polygon

The fixed autocollimator is null on the center of the polygon first face. Next the rotary table is rotated through the prescribed angle, corresponding to the increments (number of faces) of the polygon. Angular deviation shown by the autocollimator is recorded when returning to its original setting face. A correction factor (angle error of each polygon face from nominal) furnished by the manufacturer is applied to the reading to find the actual error of the rotary table. But it is limitations of polygon for calibration rotary table.

It is impossible to make a comprehensive calibration of the rotary table with one polygon because the angular sectors are limited to a maximum of about 72 in number. Even a 72 - sided polygon would not detect periodic error of a mechanical rotary table. Also, all of the lines of the circular scale in an optical rotary table are not inspected for error. The secondary graticule or optical vernier used for fine arcminute and arcsecond increments are not inspected. Overall certainty of rotary table calibration faced on the polygon as an angle standard is not much better than one or two arcsecond, after applying the correcting factor [1]

B. Rotary table calibration with serrated tooth type indexing table

Fig. 2 shows a 1440 index table mounted on a rotary table for calibration. A single reflecting mirror, autocollimator and much the same as that employed for self-calibration of the 1440 index table are used. The arrangement is already supplied by the rotary table manufacturers.

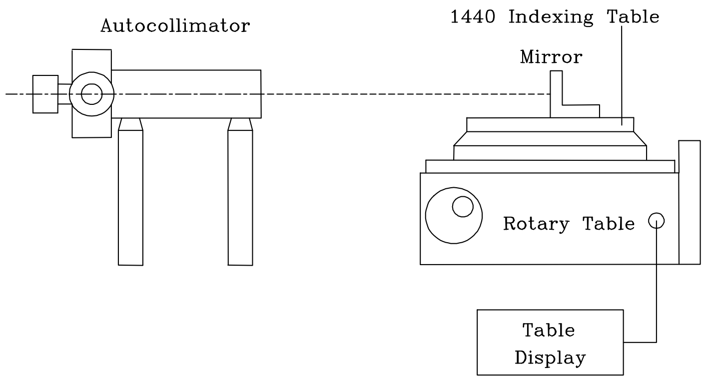


Fig. 2. Calibration of 1440 indexing tables

Errors of the rotary table are read directly on the autocollimator, nor use of calibration factors. Errors of the 1440 index table in this application may be considered negligible. The advantages compared to the other method can be summarized as follows. The polygon can only be relied on to 1 or 2 arcsecond, compared to the 0.1 arcsecond accuracy of the 1440 index table. Only one mirror is used. The importance of the single mirror cannot be over emphasized, a large flat mirror may be perfected for maximum reflectivity. Effort need only be expended to assure that it is absolutely flat without having to consider simultaneously its angular position. The same spot in the mirror is always used, instead of shifting mirror to mirror. The mirror actually becomes of secondary importance [2].

C. Calibration of indexing table by laser interferometer and ball type automatic indexing table

1) The kinematic structure of the automatic indexing table

As this system is used for calibration, the most important thing is that automatic indexing table should give good repeatability. To accomplish repeatability the automatic indexing table employs the ball and pin using a kinematic design principle. This kinematic design principle was described. [7]. The balls are in contact with the circumference of the body and outer ring holding the balls fixed on the circumference of the body. The pins are fixed in the top disc. The top disc can be moved 6 degrees each step by a camshaft and motor. Also the pins are kinematically located at every target position.

2) Calibration method with automatic indexing table

This system incorporates an automatic indexing table and laser interferometer with angular optics. As mentioned above with this system the table only needs to be repeatable. The range of angular optics is normally restricted to ±10° but by using the indexing table to repeatedly reset of the angular optics to a nominal zero position, it becomes feasible to undertake a 360° full scale test. The automatic indexing table is driven by a camshaft and motor assembly. This allows indexing by one single step of 5° during angular measurement. The angular optics is mounted on the automatic indexing table which is clamped to the table under calibration.[7].

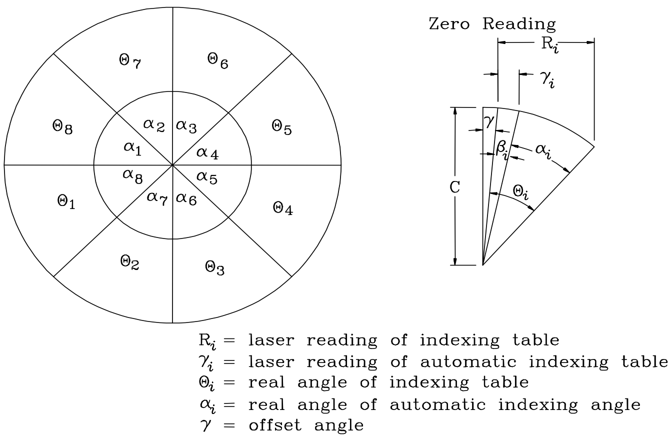


Fig. 3. Mathematic modelling for angle analysis [7]

This reading is accomplished by stepping the table under test forward one step and then indexing backward through the same nominal angular increments. This measuring technique contains two sets of laser readings which are needed to calibrate errors for both tables.

From above figure

$$CSin(\gamma + \theta_i) = CSin\,\gamma + R_i$$

$$CSin(\gamma + \beta_i) = CSin\,\gamma + \gamma_i$$

$$\theta_i = \beta_i + \alpha_i$$

From above equations, $\gamma, \beta_i, \theta_i, \alpha_i$ are calculated. It is so called a self - calibration technique that requires no pre - calibration of the indexing table [6]

III.DESIGN OF THE NEW AUTOMATIC INDEXING TABLE

A. Concept of kinematic design

Kinematic design is one of the foremost design concepts in precision engineering. Most objects in space have three degrees of translators and three degrees of rotational freedom [6]. Two different philosophies for mechanical design exist - kinematic and elastic. While being quite different in approach they can be combined in a design. In the kinematic design philosophy, the aim is to locate all parts relative to each other, while allowing a degree of freedom as needed, by connecting points together without significant elastic deformation.

A simple theorem that allows calculation of the number of points of contact was enunciated by Strong 1938. He defined:-

“Kinematic design is correct when a body in contact with another has at least 6-n points of contact where n is the number of degrees of freedom existing. If the system has more than 6-n points of contact it has mechanical redundancy” [4]

B. Feature of the new automatic indexing table

As mentioned in previous section, the automatic indexing table which was developed by Lin [2] employs pins and balls. The balls are in contact with the circumference of the body and the outer rings hold the balls fixed on the circumference of the body. The ball is moved by applying high speed rotation of camshaft. Consequently the automatic indexing table cannot give good repeatability. This device applies only vertical calibration (axes of rotary table is vertical) due to insufficient spring force. Thus this project considers a new type of indexing table to improve previous automatic indexing table

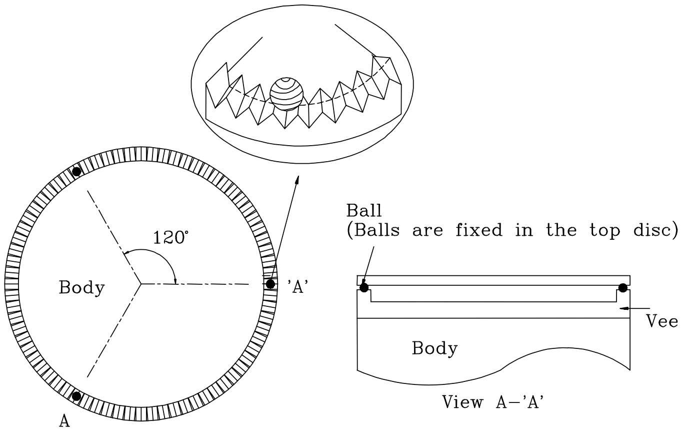


Fig. 4. Kinematic location of balls in radial vee

1) Detailed consideration of new automatic indexing table

The basic principle of this new automatic indexing table employs a vee and balls kinematic location system. The chosen incremental indexing angle is 5 degree because 5 degree incremental angle is considered to be the smallest increment used for the practical calibration of 360° indexing tables. The detailed specification of this new table is as follows: An incremental angle indexing device which is small and light weight thus does not influence the machine on which it is being used. The table should be capable of operating in any attitude. (i.e. vertical, horizontal and up-side down). Accuracy of step angle of about ±1 arcsecond but it is not essential using the calibration technique employed. Repeatability of indexing is ±0.2 arcsecond.

2) Mechanism of new automatic indexing table

An incremental indexing angle of 5 degrees was selected as being the smallest practical angle which could be manufactured using non-specialist equipment. Generally, commercially available indexing tables (except worm and wormwheel type and optical grating type indexing tables) contain two step operations for indexing (i.e. lift up and rotate)[8], but this new type of indexing table employs one step operation, lifting up and rotating simultaneously by using a camshaft and motor. Fig. 5 shows the mechanism of the new automatic indexing table.

To hold the top disc on the body and lock the top disc on the vee, the new automatic indexing table employs a compression spring between the body and pindisc which is connected to the shaft by screws. To prevent movement of the spring during operating, a circular groove holds one end of the spring, and the clearance between the spring and the bore of the pindisc is minimized to provide spring location. Also a needle bearing is fitted between the spring and pin disc to prevent torsion and minimize friction.[7]

The vee and ball type of new automatic indexing table is designed to minimize the working space and to achieve that, the motor and camshaft are mounted in parallel. Spur gears are employed to translate motor motion into the camshaft and to increase rotation force (i.e. torque).

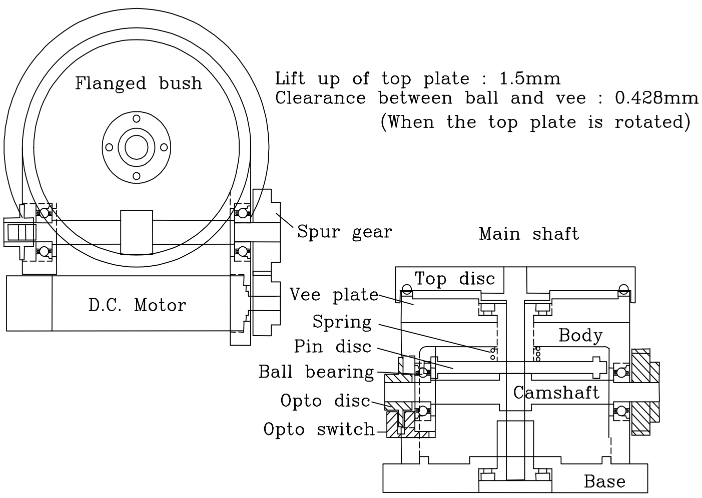


Fig. 5. Mechanism of new automatics indexing

IV. PRACTICAL EVALUATION OF THE NEW AUTOMATIC INDEXING TABLE

A. Repeatability test of the new automatic indexing table

As the system is used for calibration, one of the most important things is that a new automatic indexing table should give good repeatability. Also repeatability defined as follows [5],

"The quality which characterizes the ability of a measuring instrument to give identical indications, or response, for repeated application of the same value of the measured quantity under same condition of use."

The accurate measuring device and technique is developed for this purpose. The repeatability of the new automatic indexing table was measured as shown below. The laser optics is mounted on the new automatic indexing table which was clamped on the rotary table. The computer is programmed to control the rotation and direction of a new automatic indexing table, (i.e. clockwise and anticlockwise), and takes the laser display reading. The value is read at each target when the indexing table is rotated clockwise and then back to same position. The reading is taken 3 times in the clockwise direction and 3 times in the anticlockwise direction with a 5 degree incremental angle during a 360 degree rotation. The bi-directional standard deviation (σ) at each position of the table was evaluated. The 2σ(95% confidence) is shown in the figure. The repeatability result of the new automatic indexing table in the horizontal and vertical directions is shown in fig. 7. The repeatability of the new automatic indexing table is 0.21 arcsecond at vertical application and 0.22 arcsecond at horizontal application. It shows good repeatability at any direction application.

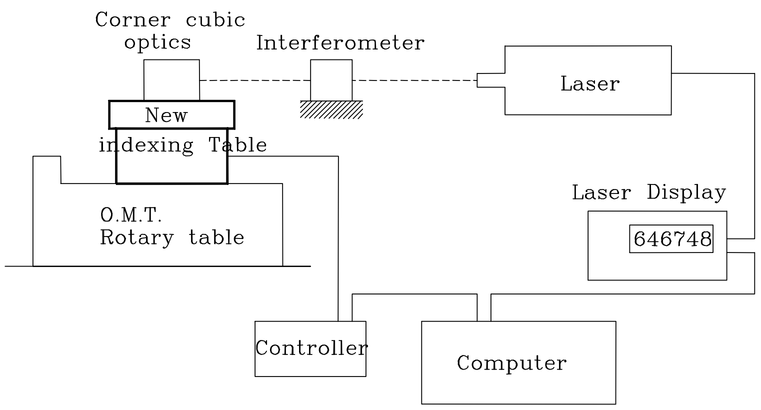
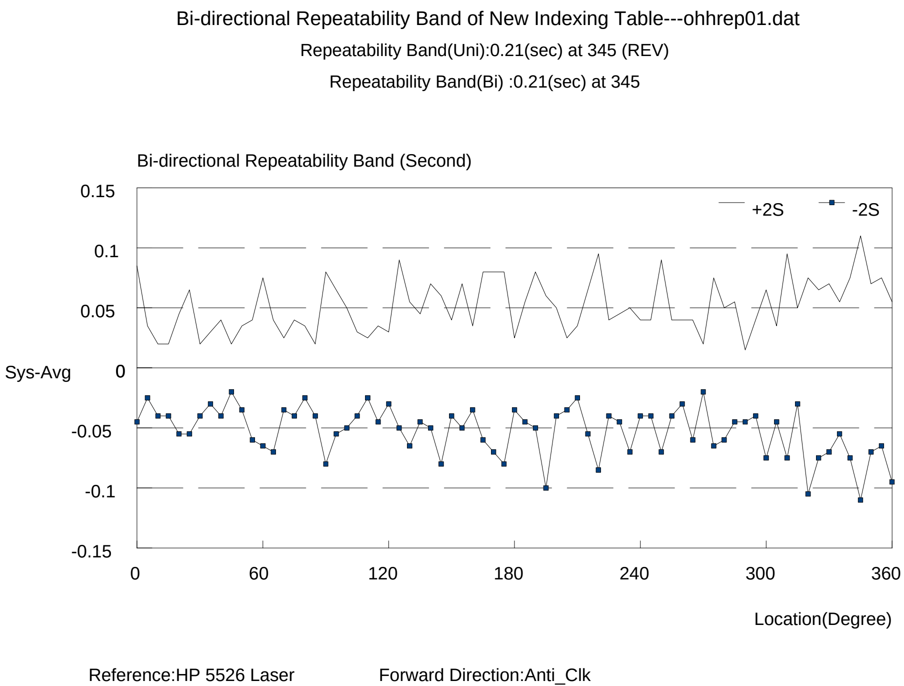
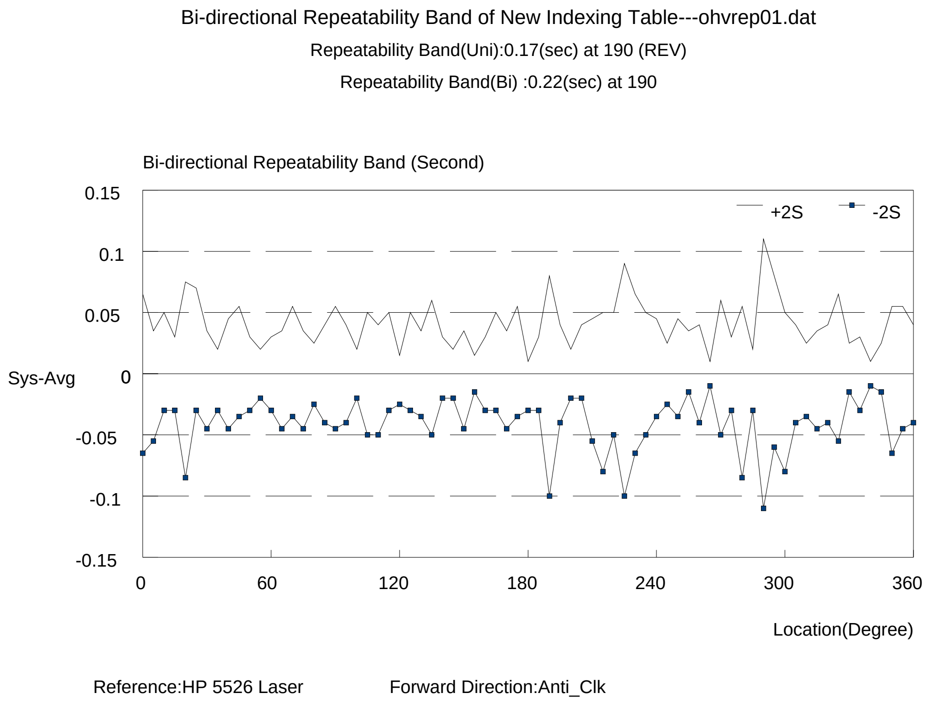


Fig. 6. Schematic of the equipment used to check the repeatability of the new automatic indexing table



(Vertical Application)

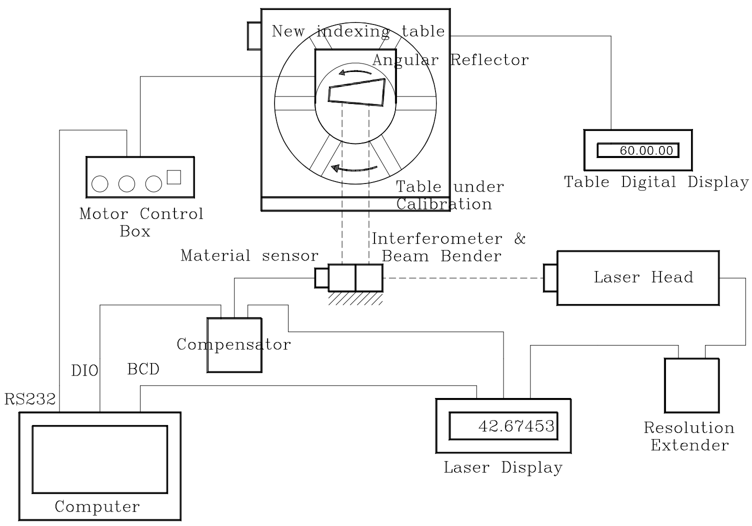


(Horizontal Application)

Fig. 7. Repeatability test result of new automatic indexing table

B. *Calibration of the rotary tables with vertical axis using the vee plate with the new automatic indexing table*

Practical calibration tests were undertaken on a rotary table manually operated table having digital readout with 1 arcsecond resolution. The driving unit used for the indexing table had been previously developed [2] together with software program. The drift compensation feature of the software was used in order to compensate for the thermal drift of the angular optics during a calibration. The set-up configuration of the equipment for this calibration is shown in fig. 6. Also fig. 8 shows the set-up in the horizontal application.



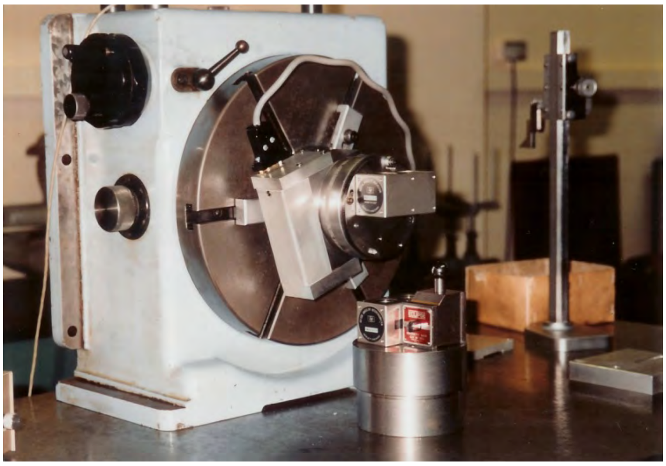


Fig. 8. Calibration of rotary table by laser interferometer in the horizontal application

Calibration tests were carried out with the rotary table operating in the both vertical and horizontal orientations. The process was repeated while calibrations were also undertaken in order to assess the reproducibility of the results

The calibration results of the rotary table using the new automatic indexing table, for vertical applications, are shown in fig 9 to 12. The cumulative angle error of new rotary indexing table shows 14.2 arcsecond, and the cumulative angle error of rotary table shows 7.8 arcsecond. The results for the rotary table measured on consecutive days, shown in fig. 10 and 12, indicate that the systematic error can be reproduced within the resolution of the table readout. The angular position error was the order of 7.8 arcsecond. The errors in the new automatic indexing table are shown in fig. 9 and 11. These are remarkably similar in both shape and magnitude and the calibration is not influenced by the resolution of the rotary table. It means that the new automatic indexing table has a good repeatability.

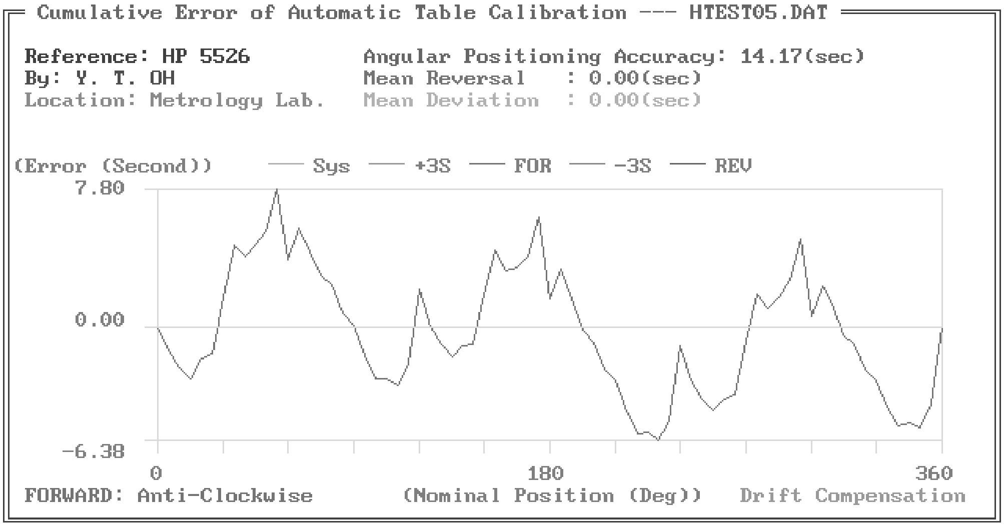


Fig. 9 Cumulative error of automatic table in the vertical application

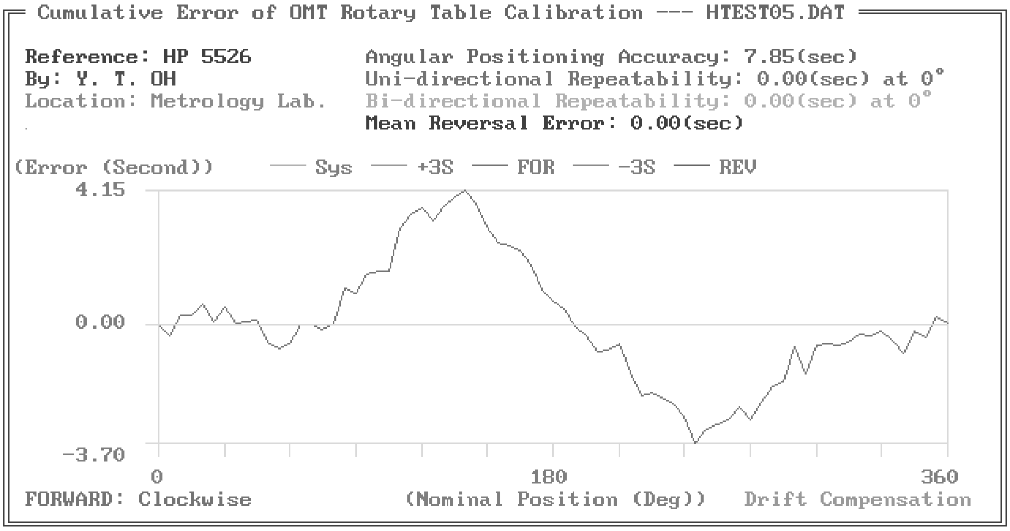


Fig. 10 Cumulative error of rotary table in the vertical application

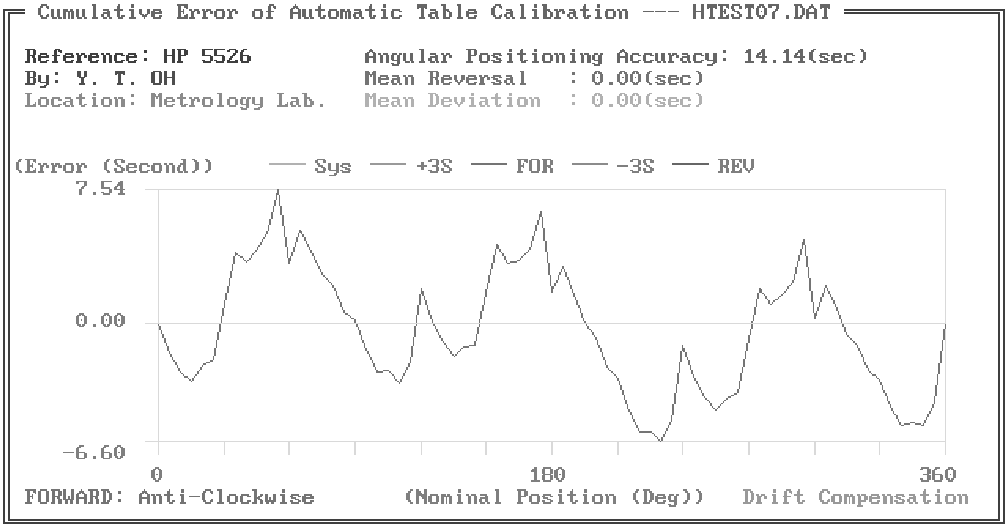


Fig. 11 Cumulative error of automatic table in the vertical application

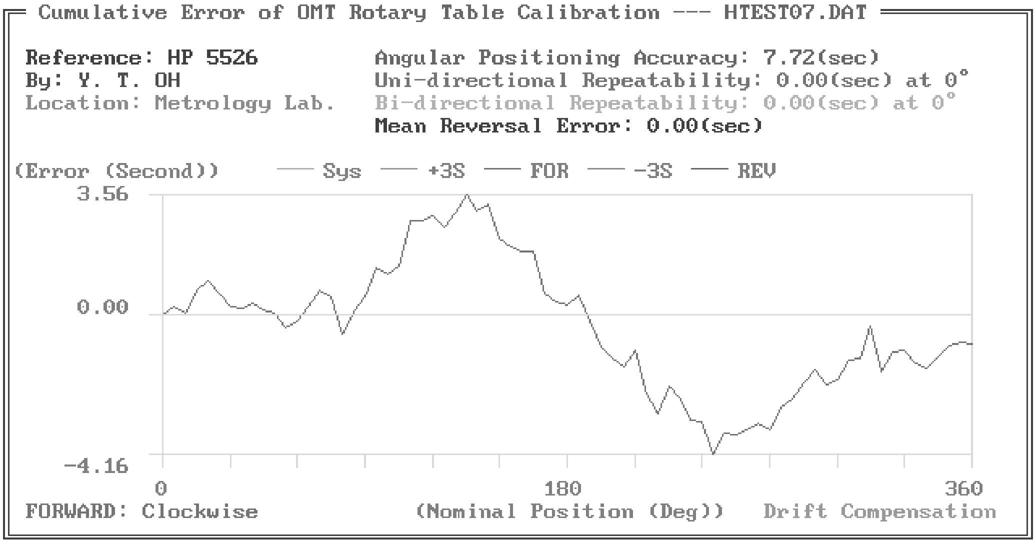


Fig. 12 Cumulative error of rotary table in the vertical application

C. Calibration of the rotary tables with horizontal axis using the indexing table

After completing the vertical axis calibration of rotary table, the rotary table was calibrated with the horizontal axis, i.e. rotation axis is horizontal. The experimental procedure is similar to that used for the vertical application. The calibration results from two sets of measurements are shown in fig. 13 to 16. Comparing fig. 13 and 15, the angle error of the new automatic indexing table from two sets of measurements is very similar and within 15 arcsecond. A comparison between the indexing table error characteristics when used in the vertical and horizontal orientation of the axis can be seen by comparing fig. 13 and 15 for horizontal axis orientation with fig. 9 and 11 for the vertical axis orientation. Although the results are similar in form, difference in this error form can be observed and the overall error band differs by about 0.5 arcsecond. These differences probably result from the elastic contact at the kinematic interface of the table and the resulting loading on the table.

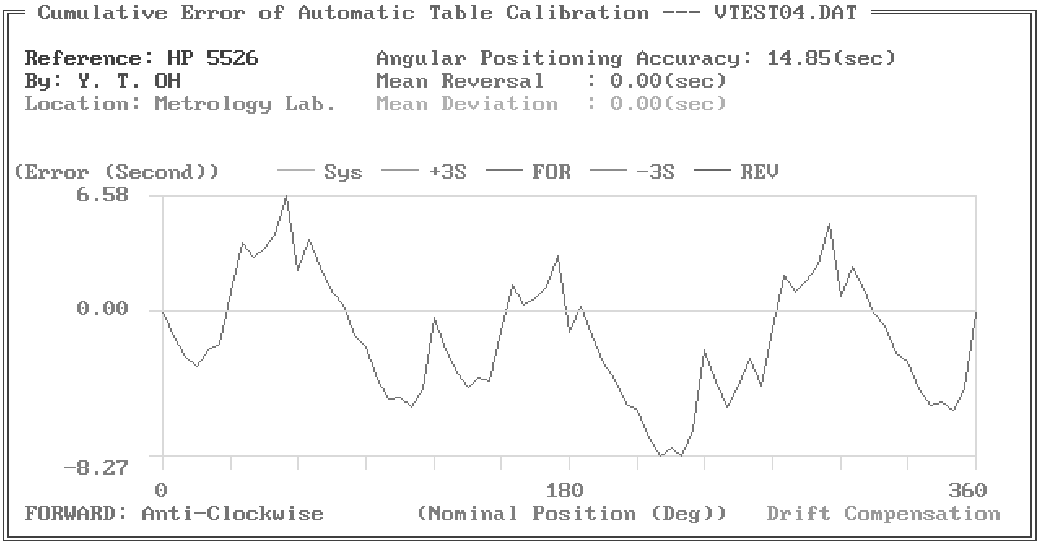


Fig. 13 Cumulative error of automatic table in the horizontal application

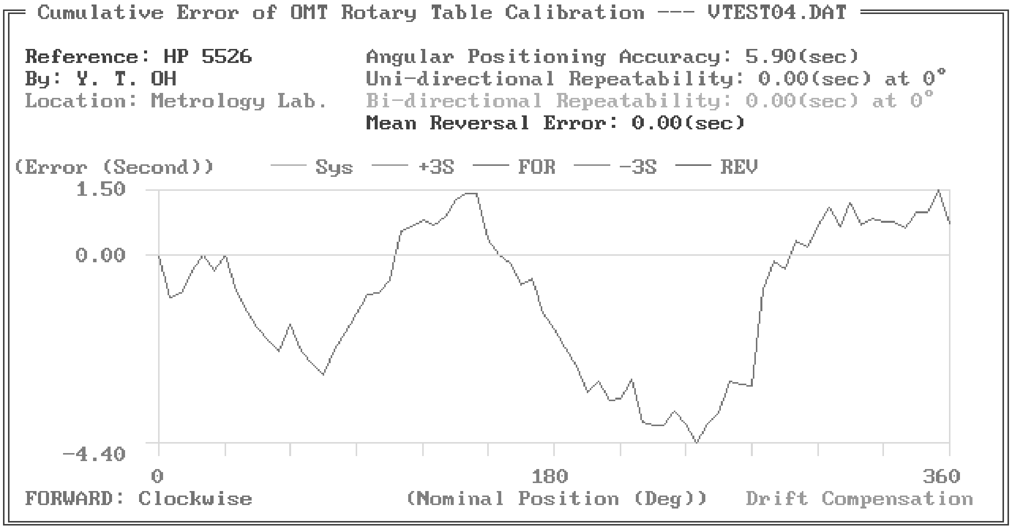


Fig. 14 Cumulative error of rotary table in the horizontal application

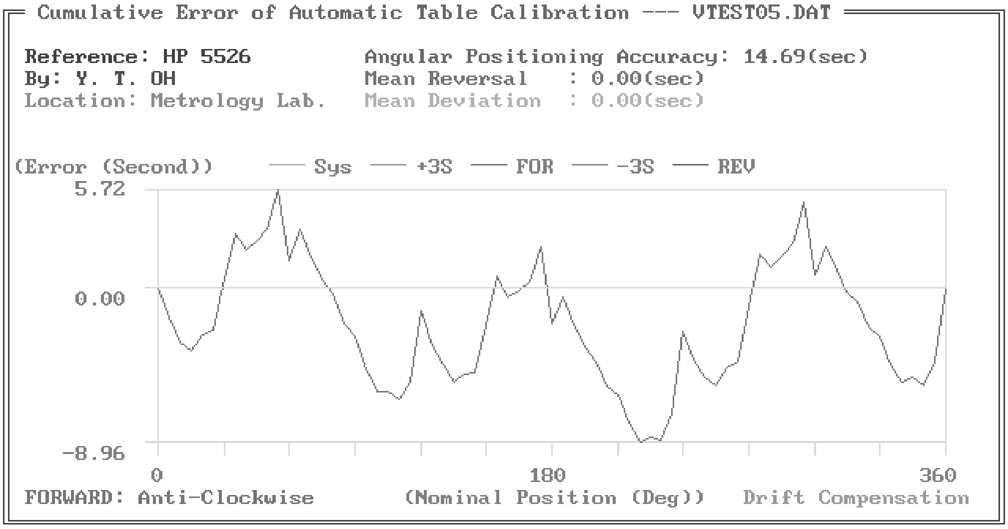


Fig. 15 Cumulative error of automatic table in the horizontal application

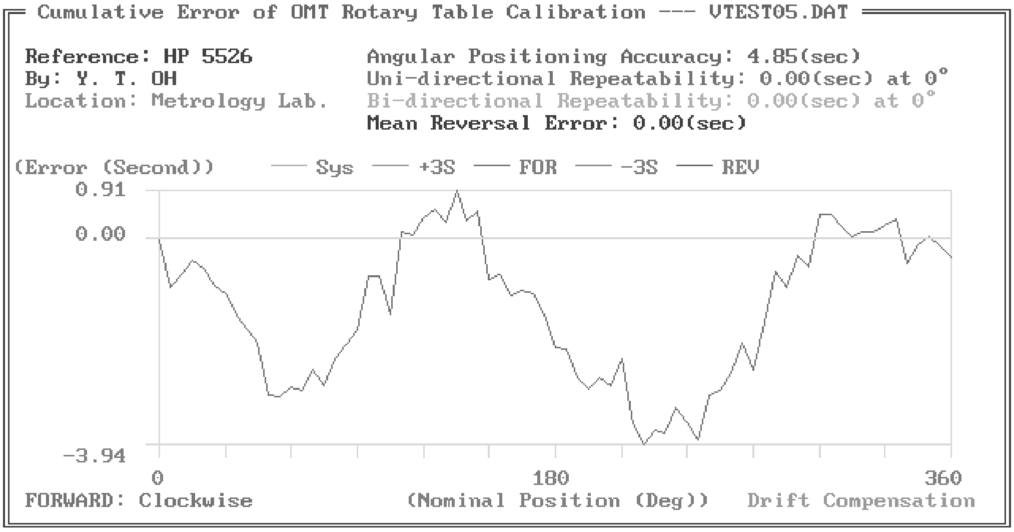


Fig. 16 Cumulative error of rotary table in the horizontal application

A comparison of the rotary table error when used in the horizontal and vertical orientation of the axis can be seen in fig. 14 and 10. Both the magnitude and shape of the error form can be seen. This difference is clearly the influence of loading between the two orientations of the rotary table which probably cause difference in the table eccentricity and have angular indexing error

V. CONCLUSION

Many techniques and methods for calibrating angular measurement exist in engineering industry. In general, the higher resolution systems have relatively small range with autocollimator, but the laser interferometer can have both a high resolution and range in order of ±10° with new automatic indexing table. This feature available with the laser interferometer has resulted in the development systems for measurement of angular error over 360° without having to rely upon precision reference tables.

Computer control of the calibration hardware and self-calibration features together with the analysis of the data means. The cost-effective systems are generally available using general purpose hardware such as a laser interferometer. The kinematic design of the new automatic indexing table using the vee plate and the ball location gives good repeatability for both vertical and horizontal application. It gives repeatability of 0.22 arcsecond.

Compact new automatic indexing table was achieved by driving the cam mechanism. The proposed design for an automatic indexing table is considered to be satisfactory for company to calibrate rotary table. This automatic system gives the time saving during measurement process. The equipment required for economical manufacture is relatively simple and could be undertaken by most machine shop

REFERENCES

[1] J. C. Evans and C. D. Taylor, Measurement of angle in engineering, NPL Her Majesty's stationary office, London, 1986

[2] K. Y. Lin, Application of laser interferometer to automatic calibration of angular indexing on the machine tools, PhD. Thesis, Manufacturing Division, Dept. of Mechanical Engineering, UMIST, 1994

[3] A. Slocum and A. Donmez, Kinematic coupling for precision fixture-Part2- Experimental determination of repeatability and stiffness, Precision engineering vol. 10(3), 1998

[4] P. H. Sydenhan, N. H. Hancock and R. Thorn, Introduction to measurement science and engineering, John Wiley & sons, England, 1989

[5] T. W. Ng and T. S. Lim, Low-cost Precision rotary index calibration, Proc. SPIE, 5879, 58790C, The International Society for Optical Engineering, 2005

[6] M. K. Rashid and Z. A. Khalil, Tool orientation and motion error in microsurgical parallel manipulator, International Journal of Computer Application in Technology 20(4), 2004

[7] Y. T. Oh, Design of precision angular indexing system for calibration of rotary table, Journal of Mechanical Science and Technology 26(3) 1~9, 2012

[8] J. Karami and A. Roohi Design and implementation of electronic system and computer control of an indexing table and quality control unit, Journal of Intelligent and Robotics System 51(3) ,2008

[9] Z. Zhang and H. Hu, Three-point method for measuring the geometric error components of linear and rotary axes based on sequential multilateration, Journal of Mechanical Science and Technology 27 (9) 2801-2811,2013