Study of Vee Plate Manufacturing Method for Indexing Table

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Abstract—The indexing tables have recently become an increasing necessity for improving the precision and accuracy of angle measurement. The indexing table employs a vee and 3 balls kinematic location system. A 6 point contact kinematic design concept of ball and vee groove was used, because the ball and vee groove system can attain good repeatability and has good rigidity. The vee plays an important role as the indexing angle and locking mechanism. Also eccentricity is an important factor as alignment between the rotation centre of the rotary table and the edge of the grinding wheel during the manufacturing process. So the concentricity between the centre of the vee plate and the centre of the rotary table is required to be as close as possible to make an accurate vee plate. The grinding technique developed for the vee plate enables the vee grooves to be machined with minimum eccentricity. To achieve manufacturing accuracy of the vee plate the grinding machine spindle had to operate for 2 hours prior to grinding in order to minimise thermal deformation

Keyword-Indexing table, Thermal expansion, Vee plate, Kinematic Design, Eccentricity

I. INTRODUCTION

The indexing tables have recently become an increasing necessity for improving the precision and accuracy of angle measurement, and circle dividing in various fields of science and technology. Most indexing tables use a worm wheel mechanism or a grating disc. The manufacturing process together with the requirements for precision is very difficult. Consequently these indexing tables are expensive and usually used for manufacturing purpose of rotating [1].

The indexing table using a ball and pin was developed [2]. This performed very well in a laboratory environment, but it was not considered robust enough to reproduce as a commercial design. The problem with this indexing table is the balls which are located on the circumference of the body could move when the top plate was located, or any force was applied to the top plate. Consequently a new mechanism should be considered for the indexing table. 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.

II. MECHANISM OF INDEXING TABLE

The indexing table employs a vee and 3 balls kinematic location system. Each ball is contact with both side of vee surface so each ball has 2 contact points on the vee. Therefore three balls have 6 kinematics contact points. The 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. Generally, commercially available indexing tables contain two step operations for indexing (i.e. lift up and rotate), but this indexing table employs one step operation, lifting up and rotating simultaneously by using a camshaft and motor. Fig. 1 shows the mechanism of the indexing table.

To hold the top disc on the body and lock the top disc on the vee, the indexing table employs a compression spring between the body and pindisc which is connected to the shaft by screws. A needle bearing is fitted between the spring and pin disc to prevent torsion and minimize friction. The vee and ball type of indexing table is designed to minimize the working space and gives good repeatability because the vee and ball contact with 6 points kinematic concept.(ie each ball contact with vee surface with 2 contact points). Spur gears are employed to translate motor motion into the camshaft and to increase rotation force (i.e. torque).

The indexing table employed a pindisc to transform the rotation motion into lift-up and rotation motion of the top disc. The pindisc which is assembled with main shaft and top disc, had 36 equally spaced pins giving a 10 degree incremental angle around the circular disc. Pins are designed to guide, lift-up and rotate during camshaft rotation. The pindisc follows the groove of the camshaft during camshaft rotation [1].

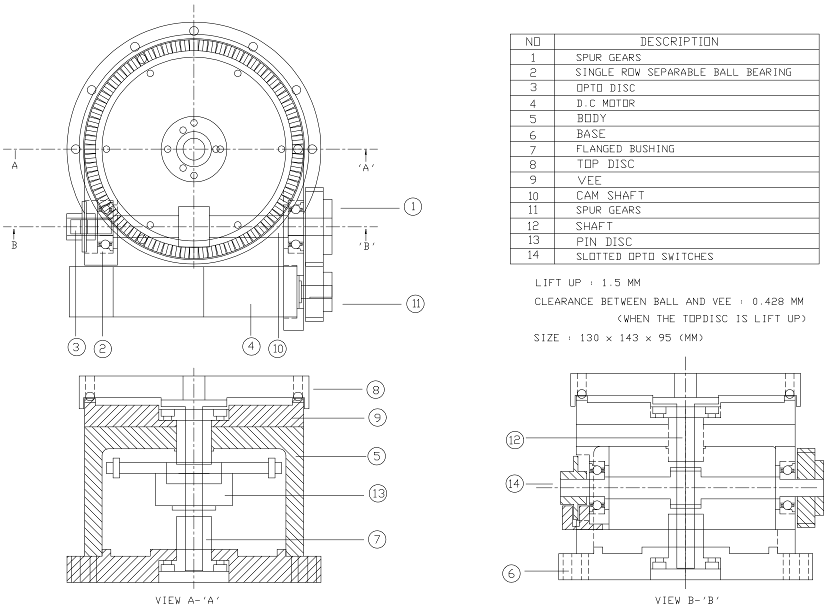

Fig. 1, Mechanism of indexing table

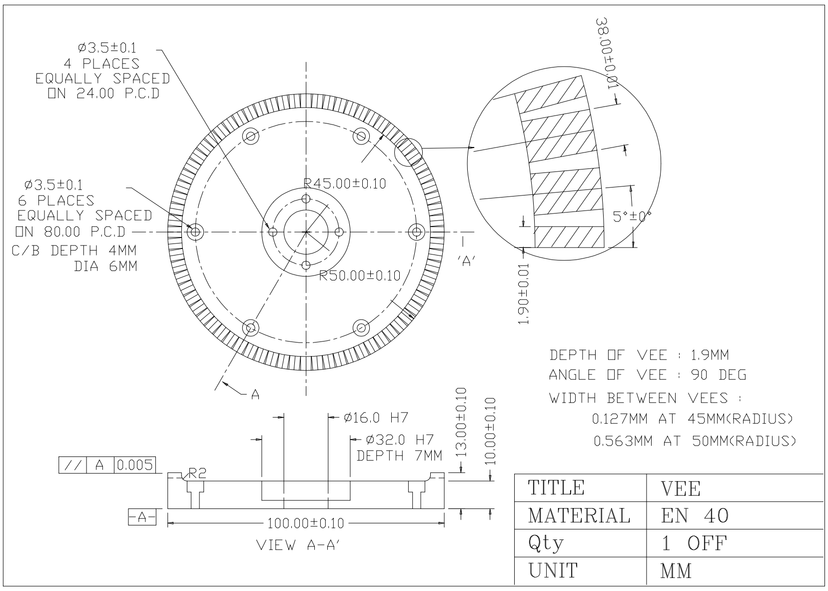

Fig. 2 Drawing of vee plate

III. MANUFACTURING VEE PLATE FOR INDEXING TALE

The vee plays an important role as the indexing angle and locking mechanism. This is one of the most important parts of the indexing table because the interval between vees determines the incremental angle. If the incremental angle is erratic, the accuracy of indexing is lost. Generally the accuracy of the indexing position is dependant on the vee angle, and consequently an O.M.T. table was used for making a 5 degree incremental angle.

A. Alignment between centre of vee and centre of O.M.T table

As seen on the drawing of the vee plate in fig. 2, the vee plate is free of the teeth in during turning. Also the centre hole of the vee plate which forms the cage of the linear bearing, is reamed with ransition tolerance because this hole will be used for concentricity alignment between vee plate and O.M.T. rotary table, and fitting of the linear bearing.

The vee plate is clamped in the O.M.T. table which is fixed on the bed of a milling machine. The eccentricity is less than 0.0001 inch. A dial indicator was used for alignment between the centre of the vee plate and the centre of the O.M.T. rotary table using the concentricity alignment method.

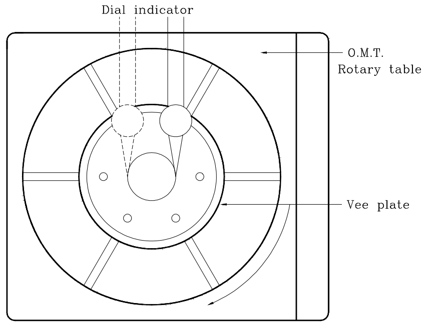

Fig. 3 Concentricity alignment method

The concentricity alignment method is shown above in fig. 3. The finger of the dial indicator is located against the hole in vee plate. Readings are taken at 0° and than the O.M.T. rotary table is rotated to 180° a position and further readings are taken. So the concentricity error is equal to half the difference between two diametrically opposite readings. The vee plate is moved half the concentricity error. This alignment continues iteratively until the reading is almost zero.

B. Setting the O.M.T. table on the milling machine

To make a vee angle of 90 degrees, the spindle head of the milling machine was rotated 45 degrees in other to use a general milling cutter. The setting of the knee type of milling machine is shown in fig. 4.

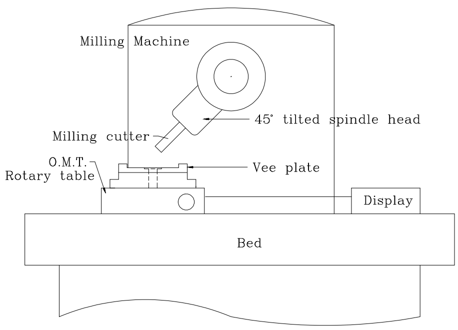

Fig. 4 Setting of the knee type of milling machine

The edge of the milling cutter should be through the centre of the vee plate. The problem is how to align the centre of the vee plate. The top surface of the vee plate was marked out. The centre line was scribed on the centre of the vee plate, and the edge of the milling cutter aligned as close as possible on the centre of the vee plate by eye and magnifier. The alignment method between the edge of cutter and centre of vee plate is shown fig. 5(a).

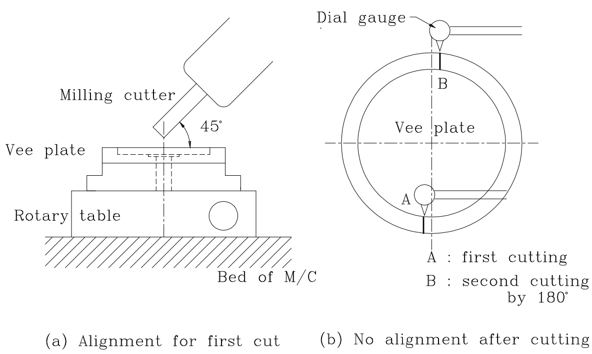

Fig. 5 Alignment method

The vee plate was cut to a depth of 0.7 mm to one side and rotated 180 degrees by the O.M.T. the rotary table, and then cut again. Although aligned by eye and magnifier, the centre of rotation is not exact so a situation is arisen fig. 5(b). The difference between the two cuts (i.e. A and B) is measured with a dial indicator by moving the bed of the milling machine. If A and B are not aligned, the display of the dial indicator is moved. It means that the centre of rotation of the vee plate is the half distance between A and B.

The bed of the milling machine is moved to half the distance of between A and B as explained by using a dial indicator. Then A and B are cut again and measured iteratively until the distance between A and B is within 12.7µm. Because milling machines have backlash, it is difficult to align less than 12.7 µm. After alignment of less than 12.7µm, the cutting process was continued around 360 degree by 5 degree increments, rotating the O.M.T. table until the depth of the vee is 1.9mm.

C. Thermal expansion of knee type of milling machine with 45° tilted spindle head

After finishing the cutting process of the vee plate, the resulting component is shown in fig. 6. The depth change of the vee at 5° incremental angles was measured using a Heidenhein transducer which has a resolution of 0.5 µm with a 4mm ball nose. The angle measured was the same as the cutting process angle. As shown in fig. 7, the depth of the vee is enlarged, so the displacement change of the milling cutter is measured by using a transducer.

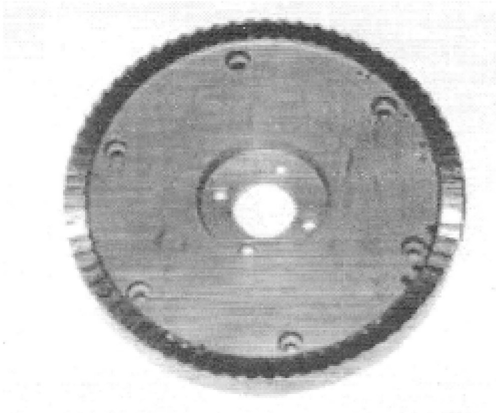

Fig. 6 Vee plate

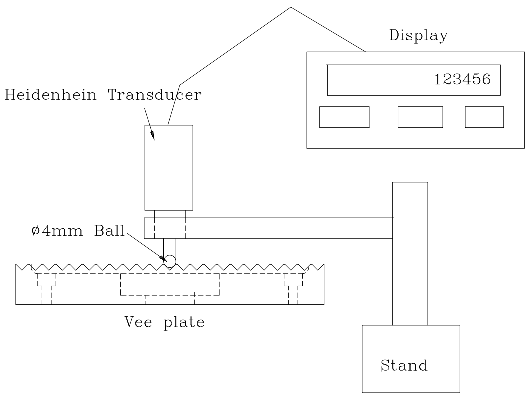

Fig. 7 Method for measuring of depth change of vee

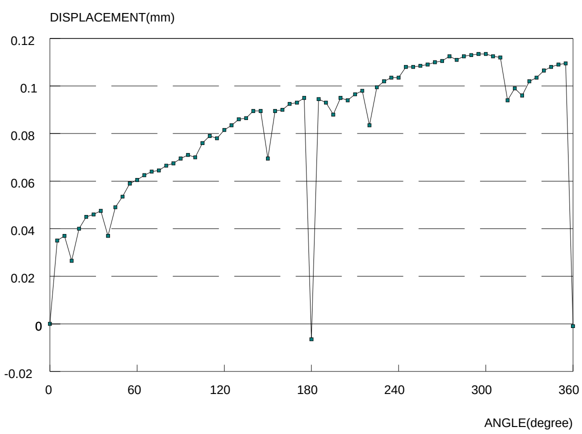

Fig. 8 The depth change of the 1st vee plate

A steel cylinder was fixed on the spindle head instead of the actual milling cutter due to non-uniform surface of the milling cutter. The equipment set up is shown in fig. 7. The transducers were set-up to operate in the radial and axial directions of the rotating cylinder. Because these transducers required mechanical contact with the cylinder during measurement, they had to be set with a known clearance from the cylinder and the spindle stopped in order to carry out a displacement reading. The transducer operates in two directions, radial and axial, also the displacement change of the rotating cylinder can not be measured during rotation by the transducer so that indirect measurement is used.

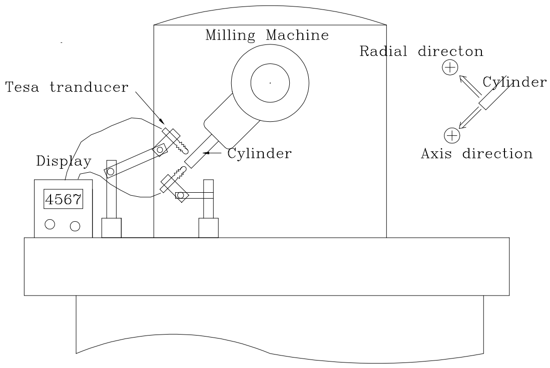

Fig. 9 Setting of equipment on the knee type milling machine with tilted spindle

The gap between the transducer and cylinder was set to 1mm. The display set to zero when a 1mm slip gauge was inserted between transducer and cylinder. The milling machine was run at the same revolution as the real vee plate cutting process, about 457 rpm. The displacement change was measured every 10 minutes interval during 2.5 hours, and the machine stopped every 10 minutes to measure the displacement change of the cylinder. The reading was taken after inserting the 1mm slip between gaps at same point on the cylinder every 10 minutes. After measuring the displacement change of the cylinder, the results were plotted in fig. 10.

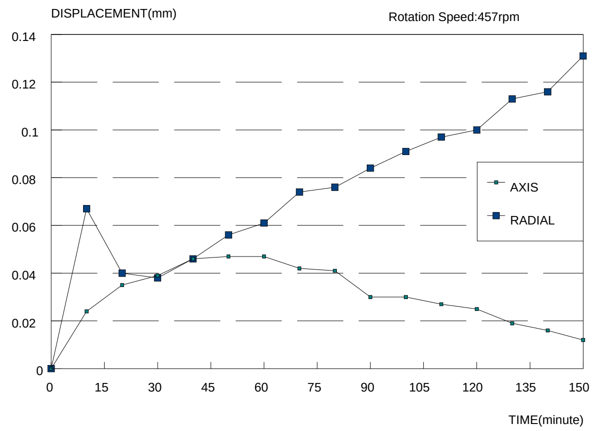

Fig. 10 Thermal expansion of knee type of milling machine with 45° tilted spindle head

As seen from fig. 10, the radial direction increases with time and does not stabilize even after 2.5 hours. The axial direction is more stable than radial direction and stabilizes after about 1 hour. This means that the cylinder spindle is getting higher. For the measurement period of two and half hours, the cylinder spindle is not stable. As can be seen in fig. 8, the vee depth is getting higher due to the displacement change of the cylinder spindle. i.e. the tendency between fig. 8 and fig. 10 is similar.

Therefore the displacement change of the cylinder induces the error in the vee depth change. The thermal expansion of this milling machine is due to internal heat sources such as spindle bearings, gear box and spindle instability. Heat dissipation from these heat sources are into the structure resulted in thermal gradients which cause structure deformation. These structure deformations mean that as the machine spindle is run, relative movement between the spindle axis and the workpiece (vee plate) occurs. This movement can not be detected by the measuring system along the machine tool axis, so a different method can be considered to make the vee plate.

D. Thermal expansion of knee type horizontal milling machine

It was observed that the tilted spindle head on the milling machine is not stable, and consequently a knee type horizontal milling machine without a spindle head was used to make the vee plate. The thermal expansion of the knee type horizontal milling machine was measured to make sure the machine was thermally stable before cutting a further vee plate.

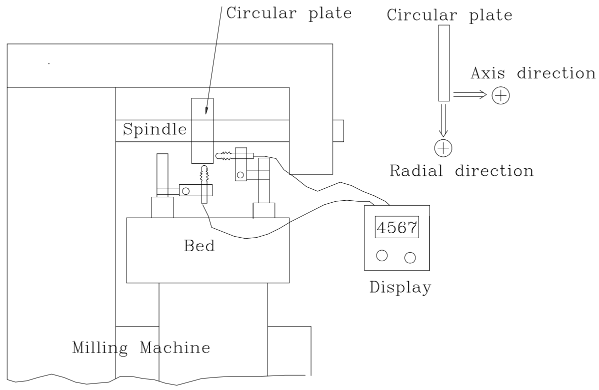

Fig. 11 Setting of equipment on the knee type horizontal milling machine for measuring the thermal expansion

The axis and radial direction was measured using a similar procedure. The revolution of the milling machine was set to 124 rpm, representing the cutting speed for the vee plate. Measurements were taken at 10 minutes interval over 3 hours and the results are shown in fig. 12.

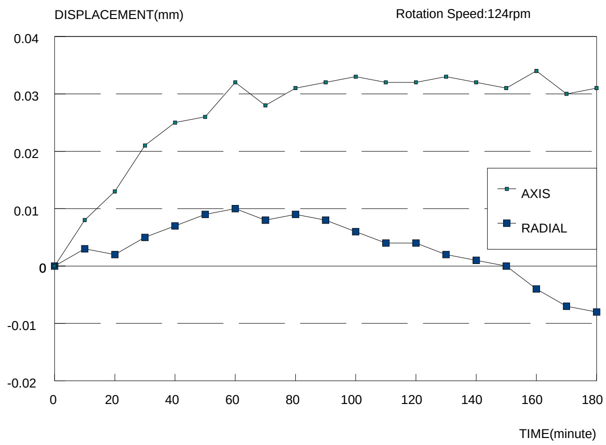

Fig. 12 Thermal expansion of the knee type horizontal milling machine

As seen in fig. 12, the change of thermal expansion is overall less than 50µm, noticeably the axis direction is stable after 1 hour of running. It means that the angle change of the vee plate could be stable. Also the displacement change of the radial direction is about 20µm, so the knee type horizontal milling machine without spindle head is significantly more stable than milling with the tilted spindle head. It was therefore decided that the knee type horizontal milling machine without the spindle head should be used to make the vee plate. Also a 90° angle formed milling cutter is used. The machine was set as shown in fig.13.

The alignment method between the milling cutter and the centre of the vee plate is the same as in section B. The cutting method is also the same as in the section C. After cutting the vee plate, the depth change of the vee was measured with the Heidenhein transducer. Fig. 14 shows the result.

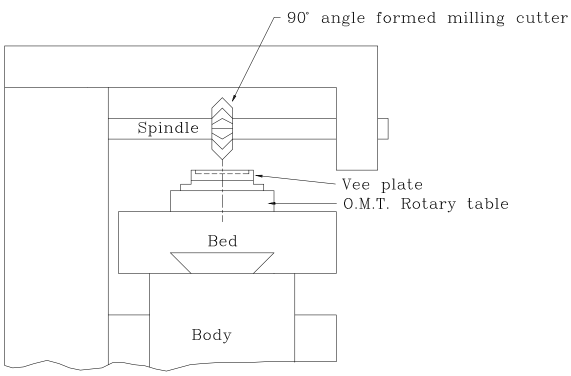

Fig. 13 Setting the knee type horizontal milling without a spindle head to make vee plate

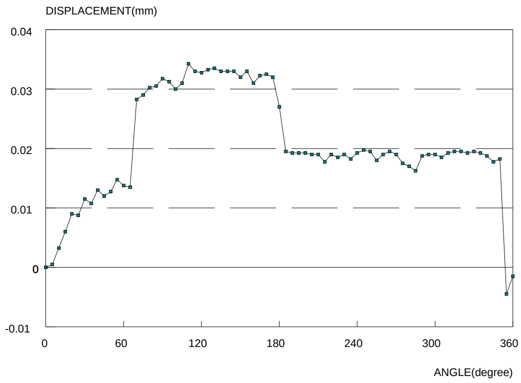

Fig. 14 The depth change of the 2nd vee plate

The sudden change at 180° degrees and 360° degrees is due to the first cut. It means that the step existed on the vee plate at 180° degree. The sudden change at 65 degree is due to the machine being uncompleted problem with O.M.T. table display.

E. Angle error of vee plate after cutting on the milling machine

The vee plate was mounted on the O.M.T. table with less than 5μm eccentricity. A special bar arrangement with two fixed balls (4mm and 18mm diameter) mounted at each end. One end of the bar with a 4mm ball was located on the vee, the other end with the 18mm ball is fixed on a kinematic holding device as shown in fig. 15. A transducer was located against the bar. The set up of the equipment is shown in the fig. 15.

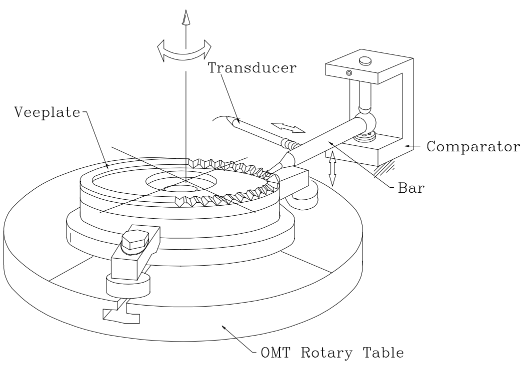

Fig. 15 Measurement of the angle error of the vee plate

The cumulative angle error of the vee plate was measured as following

- Set the equipment like fig. 15 and Reset the equipment i.e. O.M.T. rotary table and transducer
- Move the kinematically location ball bar to the next vee i.e. 5 degree incremental angle and Rotate the rotary table until the transducer display indicated zero
- Take the display reading from the O.M.T. rotary table and this display reading was the cumulative angle error, assuming no angle error of O.M.T. rotary table.

These results are shown in fig. 16 and fig. 17.

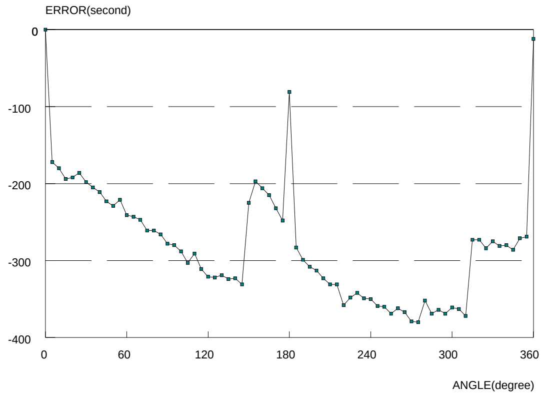

Fig. 16 The cumulative angle error of the 1st vee plate

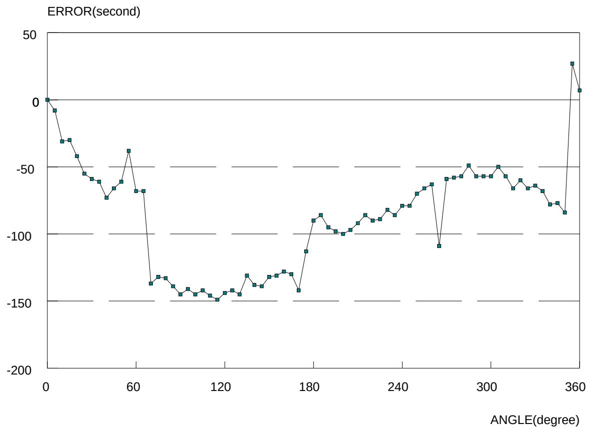

Fig. 17 The cumulative angle error of the 2nd vee plate

The two peaks at 180° and 360° are due to the wrong first cut, and the angle error is generally due to the thermal effects in the milling machine spindle. Comparing two figures 16 and 17, the cumulative angle error of fig. 16 is reduced because the thermal expansion of the knee type horizontal milling machine is less than that of the knee type horizontal milling machine with a tilted spindle head. The cumulative angle error of the vee plate was too big to allow its utilisation in the indexing table. A surface grinding machine was therefore used to finish machine the vee plate because the thermal expansion of the grinding machine should be less than that of the milling machine.

IV. VEE PLATE MANUFACTURE BY THE SURFACE GRINDING MACHINE

A. Thermal distortion of the surface grinding machine

The accuracy of the depth of the vees which are ground on the surface grinding machine varies gradually with the running time of the machine. The error in the depth of the vee is induced by thermal displacement of the spindle head of the surface grinding machine.

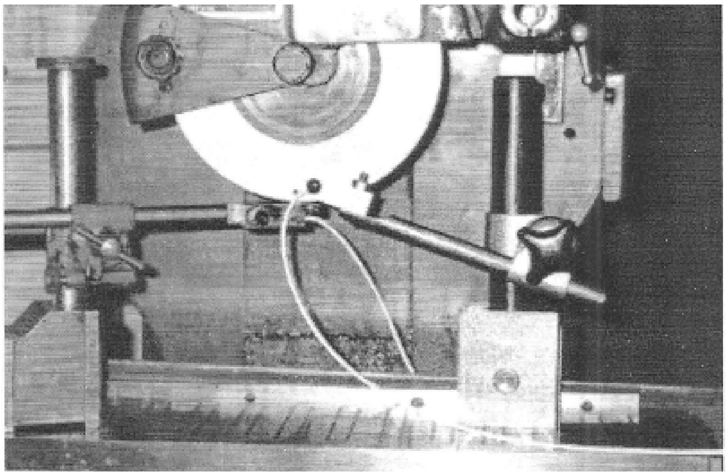

Fig. 18 The Measurement method of thermal distortion

Thermal distortion has a vital effect on grinding machine accuracy because they are generally used in the final machining process. The thermal distortion of grinding machine used to produce the vee plate was therefore assessed. To undertake these measurements, an aluminium disc was fixed on the spindle instead of the actual grinding wheel .The equipment set up is shown in fig. 18. Proximity Displacement Gauge which is non contact, capacitive gauging instrument designed for precision distance in the machine, was used to measure the relative displacement between the wheel and workpiece. The non-contact probes were set up in the radial and axial direction of the rotating aluminium disc. The relative distance between the probe and aluminium disc are measured in the two directions (radial and axial direction) under the no-load running condition. During the experiment, the spindle was continuously rotated at the normal spindle speed of 2800 rpm. When the grinding machine spindle was started, non contact probes were reset to zero. The distance between the non-contact probes which are fixed on the bed of grinding machine, and the displacement change of the grinding wheel spindle was measured every 5 minutes over a period of 5 hours.

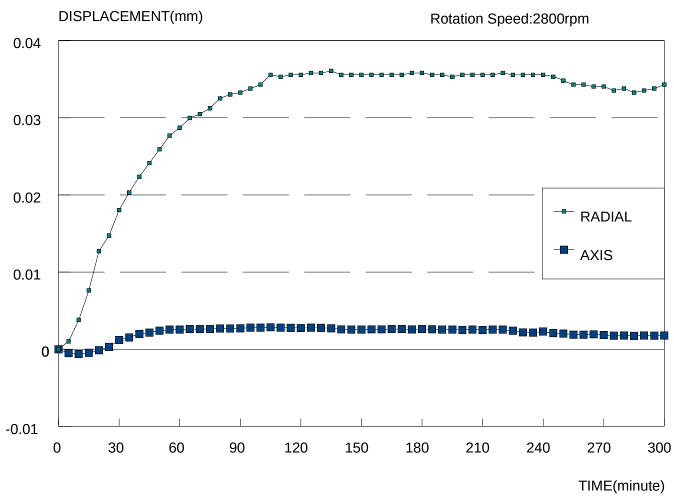

Fig. 19 The thermal expansion of the grinding machine

Fig. 19 shows the variation of the displacement caused by the thermal expansion of the surface grinding head. It can be seen from this figure that the rate of variation is gradual up to 2 hours of running after start up. After 2 hours of running, the rate of this variation is small and stable. Also the vertical direction of displacement is smaller than horizontal direction displacement. If the surface grinding machine is operated for 2 hours without load, the error in the depth of the vee could be reduced when the vee was manufactured.

B. Vee manufactured

Although the O.M.T. rotary table was used to generate a 5 degree angle on the knee-type milling machine, it could not be used on the surface grinding machine because of its weight and size. To overcome this problem a the Milichex rotary table which has a 1 degree incremental angle using a Hirth coupling mechanism was used, to generate a 5 degree angle.

Before using the Milichex rotary table, it was calibrated. Because the rotary table influences the angle of error of the vee plate, it was calibrated and results of which are shown in fig. 20, and was considered to be good enough to allow manufacture of the vee plate.

The grinding wheel was dressed to a 90 degree form and aligned with respect to the Milichex table and vee plate using a method similar to that used for milling process. The grinding process is commenced after the surface grinding machine has running for 2 hours. The results are shown in fig. 4-21 and fig. 4-22.

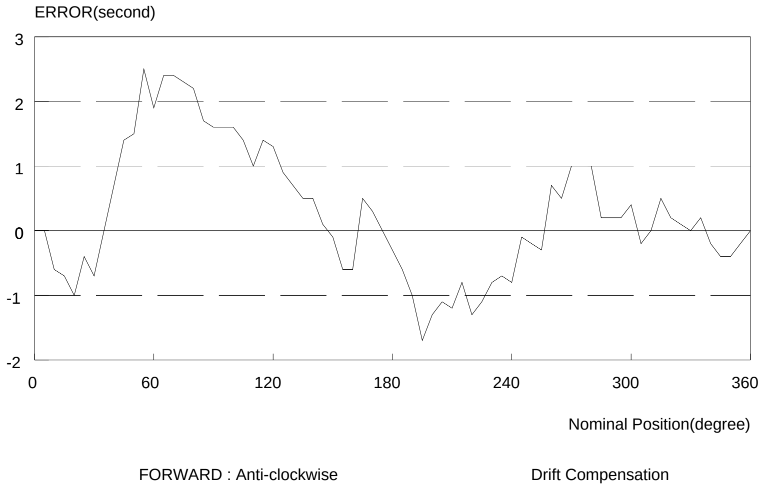

Fig. 20 The cumulative angle error of Milichex rotary table

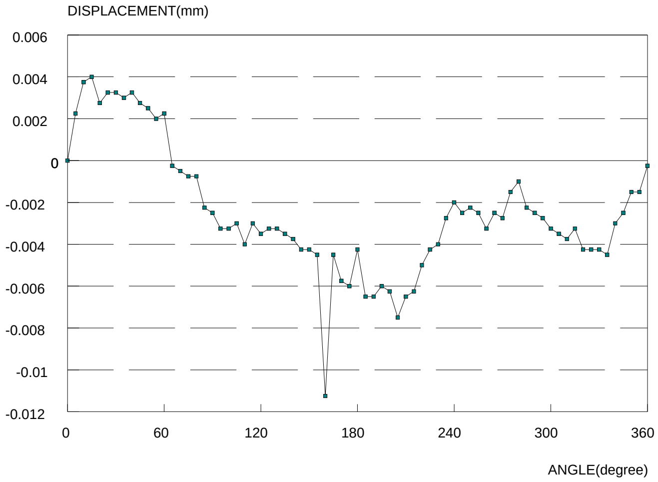

Fig. 21 The variation in height of the 1st vee plate after grinding

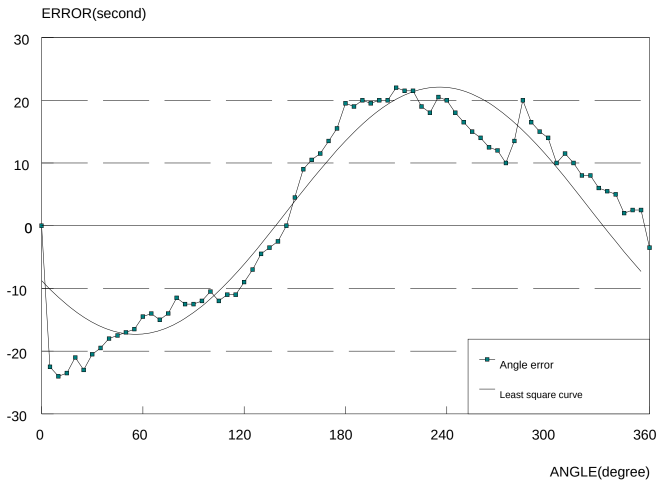

Fig. 22 The cumulative angle error of the 1st vee plate after grinding

The depth variation of the vee is dramatically reduced compared to the milling machine, and the peak at 160 degree is due to a manufacturing mistake. The cumulative angle error of the vee plate is also reduced.

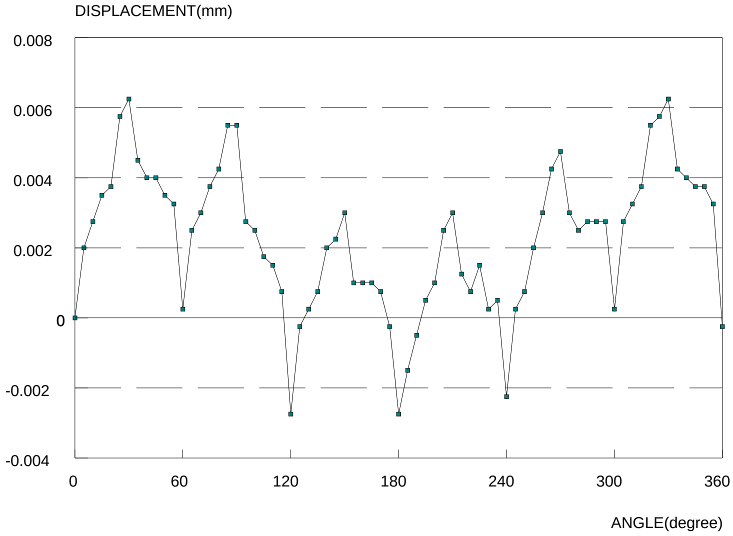

Fig. 23 The variation in height of the 2nd vee plate after grinding

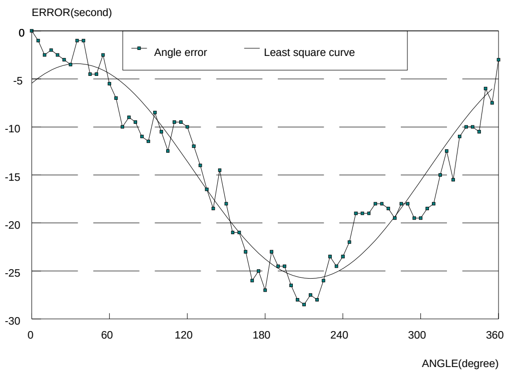

Fig. 24 The cumulative angle error of the 2nd vee plate after grinding

In the fig. 4-23, six peaks are shown due to the use of a different manufacturing method. The indexing table employs three balls in the top plate, these balls are located at 120 degree angle intervals on the vee plate. So the vee plate is cut at 0 degree, 120 degree and 240 degree. This is called a set, the nearest set is cut the next set (5 degree, 125 degree and 245 degree), so giving a total of six peaks in the error profile.

C. The angle error of the vee plate when the axis of rotation is eccentric

The rotary table has its own angle error, and centre-distance error (eccentricity). Assume that the actual angle generation of the rotary table is perfect, but that the axis of rotation wanders from A to B and back to A for each revolution. This problem is shown in fig. 25.

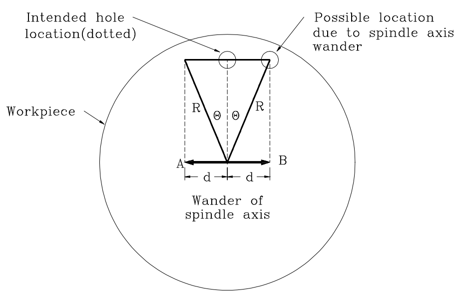

Fig. 25 Error due to eccentric mounting

From the fig. 25, the minimum and maximum errors are given by d/R radians and total range of the error is 2d/R radians

If the rotary table has an eccentric problem although the rotary table is perfect, the error results appear as a sine curve. As can be seen in fig. 24 curve is similar to a sine function. This means that this angle error includes centre-distance error, (eccentricity), due to a difference between the measuring centre and the manufacturing centre. The cumulative angle error of fig. 22 and 24 includes vee plate its own angle error and centre-distance error, so that the least square sine curve is calculated to find the eccentricity error of the vee plate with the cumulative angle error of fig. 22 and 22. Eccentricity error of the vee plate is subtracted from the cumulative angle error of fig. 21 and 23. Figure 22 and 24 shows the inherent vee plate angle error after subtracting the centre-distance error.

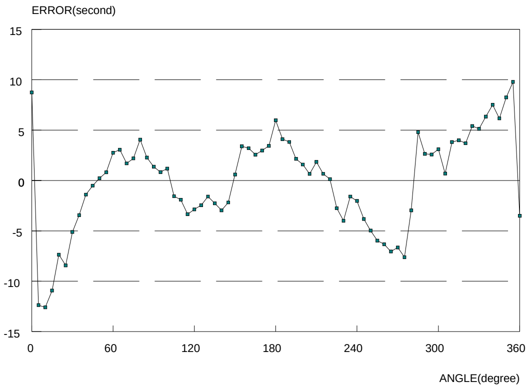

Fig. 26 Cumulative error after subtracting eccentricity (1st vee plate)

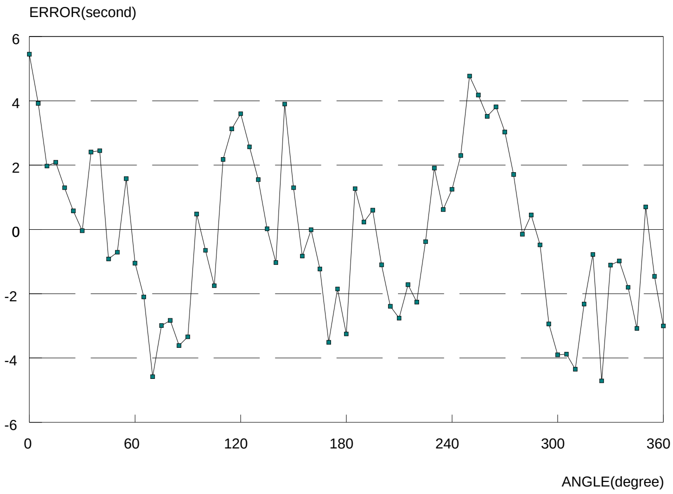

Fig. 27 Cumulative error after subtracting eccentricity (2nd vee plate)

The centre distance error (eccentricity) is an important factor as alignment between the rotation centre of the rotary table and the edge of the grinding wheel during the manufacturing process. So the concentricity between the centre of the vee plate and the centre of the rotary table is required to be as close as possible to make an accurate vee plate.

V. CONCLUSION

Many techniques and methods for calibrating angular measurement exist in engineering industry. The cost-effective systems are generally available using general purpose hardware. The kinematic design of the indexing table using the vee plate and the ball location gives good repeatability. Compact indexing table was achieved by driving the cam mechanism. The proposed design for an indexing table is considered to be satisfactory for company to calibrate rotary table. The grinding technique developed for the vee plate enables the vee grooves to be machined with minimum eccentricity. To achieve manufacturing accuracy of the vee plate the grinding machine spindle had to operate for 2 hours prior to grinding in order to minimise thermal deformation. The equipment required for economical manufacture is relatively simple and could be undertaken by most machine shop

REFERENCES

[1] Oh, Yeon Taek, Design of precision angular indexing system for calibration of rotary tables, Journal of mechanical Science and technology, 26/3, 2012, pp.1-9
[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] Oh, Yeon Taek, Performance evaluation of rotary table using an angular indexing system with self-calibration technique, International Journal of Engineering and Technology, Vol. 6, No. 6, (2015), pp. 2764-2772
[4] J. C. Evans and C. D. Tayler, Measurement of angle in engineering NPL Her Majesty's stationary office, London, 1986
[5] 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) (2013) 2801~2811