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홀-플레이트(Hole-Plate)를 이용한 3차원좌표측정기의 공간오차 측정

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3-Dimensional Error Calibration of CMMs Using a Hole-Plate Artefact

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ABSTRACT

3차원좌표측정기(Coordinate Measuring Machine)의 공간오차(Volumetric error)의 측정을 위하여 홀-플레이트(Hole-Plate)를 이용하는 방법이 연구되었다. 티타늄 또는 세라믹으로 제작되는 홀-플레이트의 설계 예를 보였다. 홀-플레이트의 측정홀 숫자와 진원도(Roundness)의 영향이 연구되었으며, 또한 홀-플레이트의 설치시 발생하는 오차도 검토되었다. 3차원좌표측정기의 공간오차성분 모두를 별도로 측정하는 방법이 제안되었다. 홀-플레이트를 이용 2차원 및 3차원 공간의 길이오차를 직접적으로 측정하는 방법도 소개되었다.

Key Words : Hole plate(홀-플레이트), Parametric error(오차성분), Volumetric error (공간오차),
Coordinate Measuring Machine (3차원좌표측정기)

NOMENCLATURES

ey(i,a) : Error vector at the Hole 'i' along the Y-axis using the Hole plate 'a'.

E_R : Roundness error.

E(i,j) : 2-Dimensional error vector at the Hole 'ij'.

HT(i) : Roll error compensation factor in the Hole 'i'.

Ex(Y),Ez(Y),Ey(Y) : Pitch,Yaw and Roll error in the Y-axis.

HxD,HyD,HzD : Distance between two hole lines.

N : Number of holes.

SE : Straightness error band

Sxy,Syz,Sxz : XY,YZ,XZ Squareness error.

Xc,Yc : Eccentricity in X,Y Coordinates.

XD,YD,ZD : Distances between the two Hole plates in the X,Y and Z directions.

Xi,Yi,Zi : Coordinates of the Hole 'i'.

ϕ : Divided angle in a hole, Hole plate vertical tilting angle.

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1. INTRODUCTION

To measure the error of machine tools, plate type test bodies, artefact, ball/hole plates(1,2) or cone plate(3) have been developed. All the plate artefacts used to measure error of Coordinate Measuring Machines (CMMs) require knowing the calibration canter distances of the ball/hole/cone. Using the ball/cone plate, 3-dimensional measurement is possible for the hole plate method which uses only 2-dimensional measurements in a plane.

The minimum number of touch points for determining a ball canter is four compared with three points needed for a hole plate. In the case of a cone plate, only one touch point is required to determine the cone centre. However, there will be some uncertainties of contact with the cone. The cone plate will be useful for checking manually operated CMMs. In the ball outside type (with ball stem), bending of the plate results in changes of the ball canter distance, which is not serious in a hole/cone plate or a ball inside type (ball centers placed on the same plane with the plate), as shown in Figure 1. The bending could be due to thermal expansion or other external forces such as plate weight and clamping. In spite of some advantages in using the ball plate, ball height calibration is difficult, which is not required in the case of hole plates. Also, the exposed ball surfaces are susceptible to damage during transit. As for hole plate, hole manufacturing, squareness with respect to the plate face and hole roundness, will influence the measuring accuracy. For a ball plate, standard high precision balls are readily available from specialist ball manufacturers.

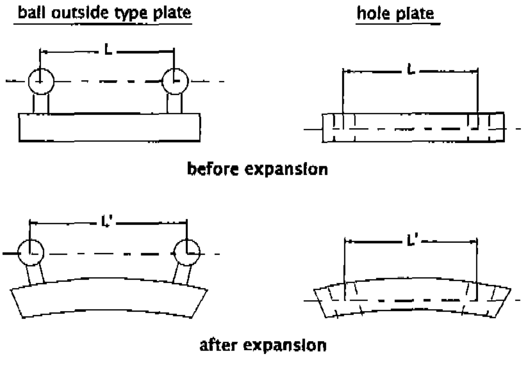


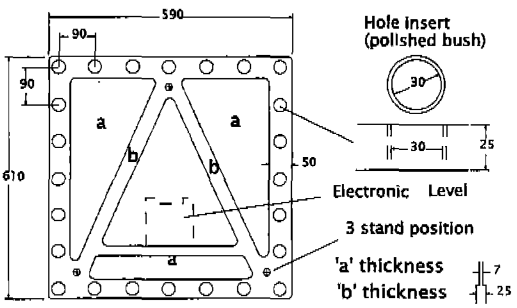
Fig.1 Influence of bending in the plate centre.

In this study, a hole plate method is undertaken as a transfer standard for measuring the volumetric error of CMMs. Examples of the hole plate design are shown using titanium and ceramic materials. Also, we discuss the measuring hole including number of holes in a plate and roundness of the hole. The hole pate set-up errors are also discussed. Using the hole plate measurement data, we developed a method to analyze machine parametric errors. Two dimensional (2-D) length error measurements using the hole plate artefact is shown. Also, a method for measuring 3-D length error by combining a series of 2-D data using a hole plate is proposed.

2. DESIGN OF THE HOLE PLATE

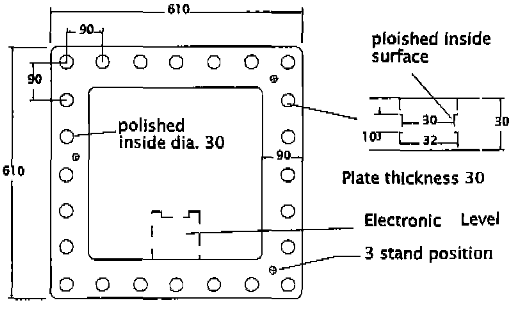
The British Standard [BS-7172] recommends at least five different points to determine a circle, although three points determine a circle mathematically. In this case, the measurement hole diameters should be large enough for the CMM probe to touch at five different points. However, such large hole diameters result in a large hole plate. To remove the thermal distortion of the hole plate, the best ones are designed without any hole insert and use a different material. Usually, it is not easy to obtain high precision manufacturing of hole roundness in the hole plate. There are some commercial inserts in which the hole roundness is adequate, such as the polished bearing bush. It is more practical to use such a hole insert instead of direct manufacturing in the plate.

Figure 2 show examples of a hole plate design using titanium and ceramic materials in order to reduce the thermal influence. Both types are set horizontally with 3 supports and designed to be used with an electronic level, to cover roll error measurement, inside the plate. The inside material of Type A is removed to reduce its weight, and is designed to be used with a hole insert. The hole inside of the ceramic hole plate, Type B, is polished to increase the roundness. The thickness of the two plates are 30 mm, and are able to be set vertically without other support. The weight of the hole plates was limited for easy transport by one man.



(a) Type A, Material : Titanum, Weight : 12.5 Kg

Unit : mm



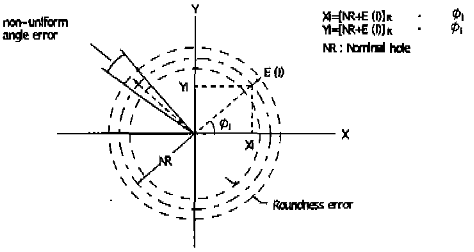
(b) Type B, Material : Ceramic, Weight : 12 Kg

Fig.2 Examples of the hole plate designs using titanium and ceramic materials.

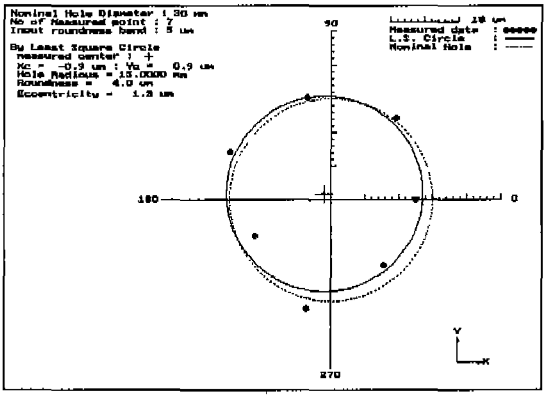
2.1 Hole roundness effect

The inside of the manufactured hole will include roundness errors, which are not uniformly distributed or periodical. However, hole roundness may not seriously influence the Least Squares circle centre. We studied hole roundness effect on the eccentricity of the Least Squares circle, using a synthetic roundness error.

The synthetic roundness error was assumed to be (roundness band)/2 with respect to the nominal radius. Both uniformly or non-uniformly spaced angle measuring points were considered, as shown in Figure 3(a). Figure 3(b) shows an example of Least Squares circle determined by synthetic error, with 7 points in uniform angle division.



(a) Synthetic roundness assumption as E_R = (roundness band)/2, with non-uniform spaced points



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Nominal Hole Diameter : 30 mm
No of Measured point : 7
Input roundness band : 5 um

By Least Square Circle
 measured center : +
 Xc = -0.9 um : Yc =  0.9 um
 Hole Radious = 15.0000 mm
 Roundness =   4.0 um
 Eccentricity =   1.3 um
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10 um
Measured data  :
L.S. Circle    :
Nominal Hole   :
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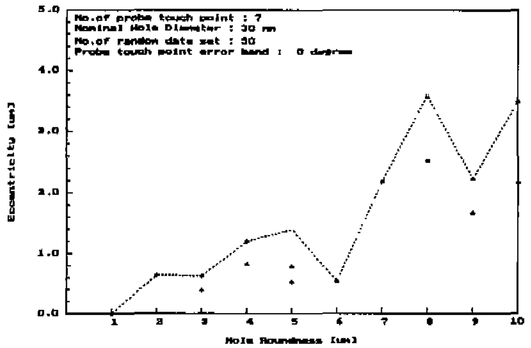
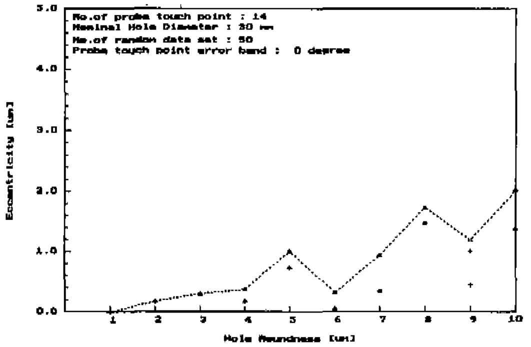
(b) An example of the Least Squares circle using the synthetic hole roundness

Fig.3 Synthetic hole roundness and an example of the calculated Least Squares circle using 7 data points.



(a) With 7 data points



(b) With 14 data points

Fig.4 Hole roundness effect on the calculated eccentricity of the Least Squares circle centre, with assumed uniformly spaced measuring points.

The eccentricity was defined as the distance from the nominal centre to the Least Squares circle centre as follows :

$$Eccentricity = \sqrt{X_C^2 + Y_C^2}$$

where Xc and Yc are eccentric X,Y-coordinates of the Least Squares circle.

Figure 4 shows the influence of different roundness on the eccentricity of the Least Squares centre, using 50 times the random synthetic roundness data. In this calculation, it was assumed that the CMM probe touches in 7 or 14 uniformly spaced points around the hole inside. From the Figure 4(a), it is seen that the eccentricity of the hole is less then 1 (m from a perfect hole centre up to a 3 (m hole roundness error. It is assumed that the manufacturing of the hole with 3 (m roundness is not so difficult. The eccentricity from using 14 measuring points is smaller than when using 7 points. The calculation results of the non-uniform measuring points different spaced angle points around the hole were very similar with the uniformly spaced data.

2.2 The effect of number of holes on its squareness calculation

The number of holes in a plate should be limited due to manufacturing and calibration difficulties. Nevertheless, more holes give more error data for the CMM. In this section, the number of holes effect on the squareness error calculation from the synthetic straightness error is considered. The straightness error was simulated in the orthogonal axis with fixed squareness at each hole as shown in Figure 5.

Figure 6(a) shows the difference in squareness input the output which is calculated from the synthetic straightness error band of 5 (m for the 50 times random simulation. The Least Squares line was used to obtain the best fit line from the straightness error of the hole centre. As hole distance increases, the squareness calculation error will be less as shown in Figure 6(b).

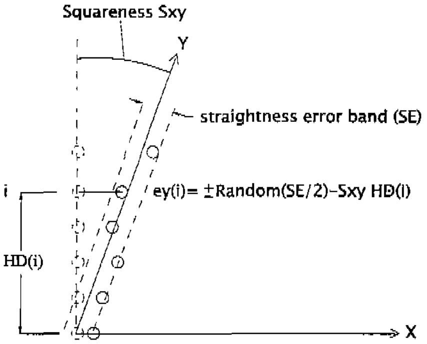
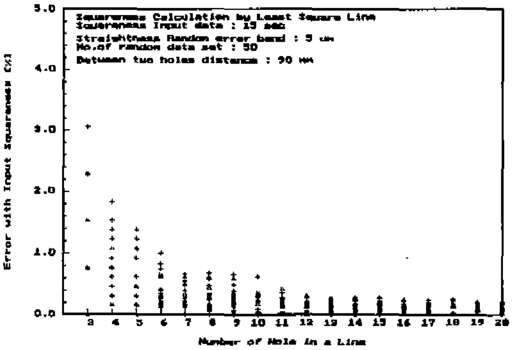
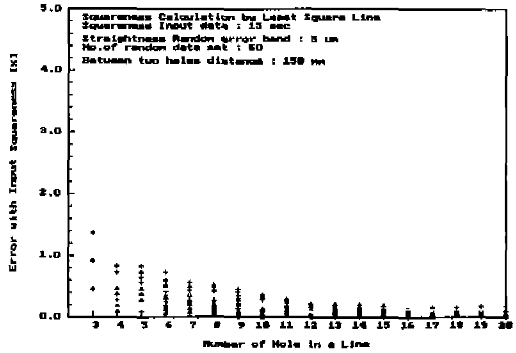


Fig.5 Synthetic straightness and squareness error input.



(a) Hole distance 90mm



(b) Hole distance 150 mm

Fig. 6 Squareness calculation error with different hole distances (synthetic straightness error band 5 (㎛).

3. HOLE PLATE SET-UP ERRORS

The hole may include some roundness and squareness error with respect to the plate face. However, if the measuring height is the same as the calibration, those errors could be minimized. There are four types of hole plate set up errors as shown in Figure 7. The horizontal set-up error is due to the different length of horizontal stands or bad flatness of the table. Also, the example 'C' of vertical set-up errors is due to the vertical stand or bad flatness of the table. The set-up errors will influence the hole distances by the inclined angle of the plate. Though the compensation of set-up errors is possible, it is inevitable that the CMM probe touch points will be changed with respect to the nominal measuring height, due to the set-up errors.

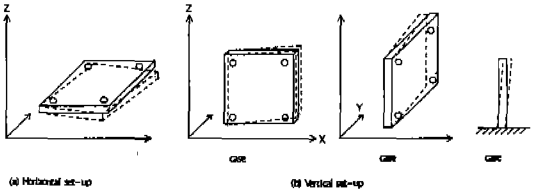
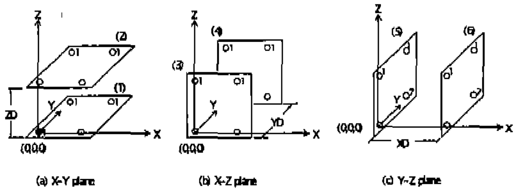


Fig. 7 Hole plate set-up errors. To minimize the effects of set-up errors, the calibration is required in different horizontal set-up positions.

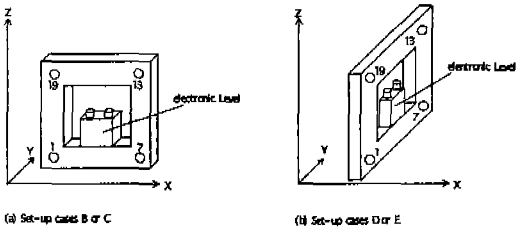
4. VOLUMETRIC ERRORS VERIFICATION

4.1 Hole plate data measurement

The hole plate data will be measured by a CMM



(a) Hole plate set-up cases in 3 planes on CMM table



(b) Measurement of hole plate vertical set-up angle

Fig. 8 Hole plate (24 Holes, 7 x 7) set-up cases and measurement of the hole plate set-up angle for roll error calculation.

at six different set up cases as shown in Figure 8(a). In the case 3,4 or 5,6, the distance of two set-up positions (XD or YD) will be chosen by two times the CMM probe length. The hole plate vertical set-up angles with respect to the CMM table are measured in set-up case 3,4,5, or 6, for roll error calculation as shown in Figure 8(b). Measured holes data include set-up errors which are due to the inclined angle with respect to the calibration axis in vertical set-up cases. Therefore, to compare with the calibration coordinate, the coordinate transform will be also required.

4.2 Parametric error analysis

It is possible to verify the 21 parametric error components using the hole plate data measured in the six set-up case as shown in Figure 8. Figure 9,10,11 show the method of angular error measurement, yaw, pitch and roll in Y-axis (Ez(Y), Ex(Y) and Ey(Y)) using two hole lines data. In the case of roll error measurement, the hole plate vertical tilting angles ((5 and (6 in set-up cases 5 and 6) are included due to the CMM table flatness in the Z-direction error of the two set-up cases. Therefore, the influence of tilting angle at Yi on the Z-direction error for the calculation of Y-roll error, HT(i) should be compensated. The hole plate tilting angle also effects the X-direction error for Z-roll measurement to the same degree, HT(i).

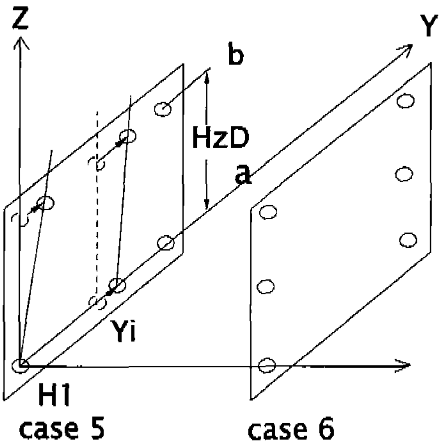
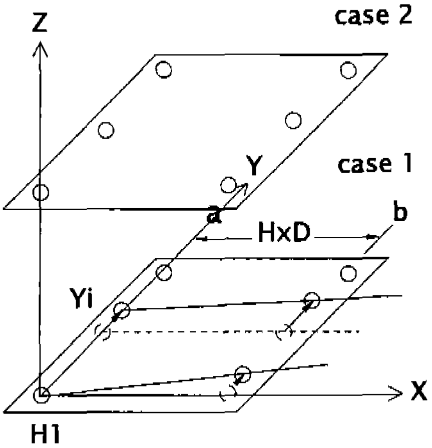
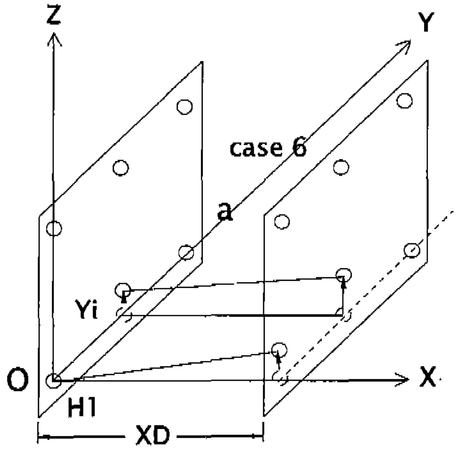


Fig. 9 Y-pitch error measurement and calculation using hole data $e_y(i,a)$, $e_y(i,b)$: Y-direction hole errors at Hole 'i' in hole line 'a' and 'b'.



$$Ez(Yi) = \frac{[e_y(i,b) - e_y(i,a)] - [e_y(1,b) - e_y(1,a)]}{HxD}$$

Fig.10 Y-yaw error measurement and calculation using hole data $e_y(i,a)$, $e_y(i,b)$; Y-direction hole errors at Hole 'i' in hole line 'a' and 'b'.



$$Ey(Yi) = \frac{[e_z(i,b) - HT(i) - e_z(i,a)] - [e_z(1,b) - ez(1,a)]}{XD}$$

$$\textit{where} \quad HT(i) = Yi \cdot Tan(\phi_6 - \phi_5)$$

Fig.11 Y-roll error measurement and calculation using hole data $e_z(i,a)$, $e_z(i,b)$; Z-direction hole errors at Hole 'i' in hole line 'a' and 'b'.

Position error can be easily measured using the hole error data in the same direction with the hole line.

Straightness error also can be measured using the orthogonal error data from the hole line. The squareness error is calculated from the best fit lines of two straightness errors in the same plane. The X-Y squareness, Sxy can be measured from hole plate set-up case 1, Sxz from case 3 and Syz from case 5.

4.3 3-Dimensional length error

From the hole plate data, error vectors (ex,ey) in each hole of the six set-up cases, a 2-dimensional length error measurement is possible. Using data measured from any two holes in the orthogonal direction, 2-D length error E(i,j) between two holes 'i', 'j' can be calculated as shown in Figure 12.

Measuring the 3-D length error is also possible by using the 2-D hole distance data of the six set-up cases. Figure 13 shows the cubic measuring data points with 3-dimensional error vector, that were combined using the six hole plate set-up cases. At each data point, two set of 3 component error vectors can be collected, which come from the three hole plate set-up data. Using any two Holes error vectors (ex,ey,ez), 3-D length error calculation will be possible.

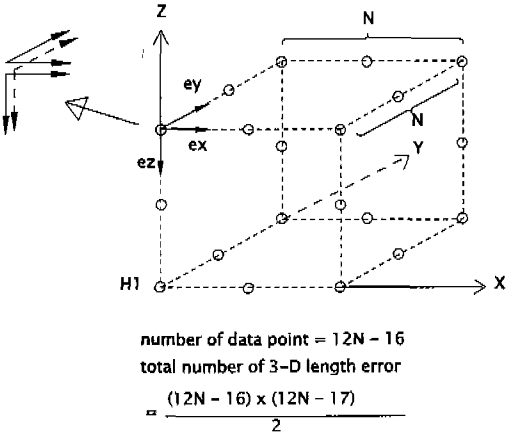


Fig.13 Cubic measuring points by the combination of the six hole plate set-up cases for 3-D length error measurement.

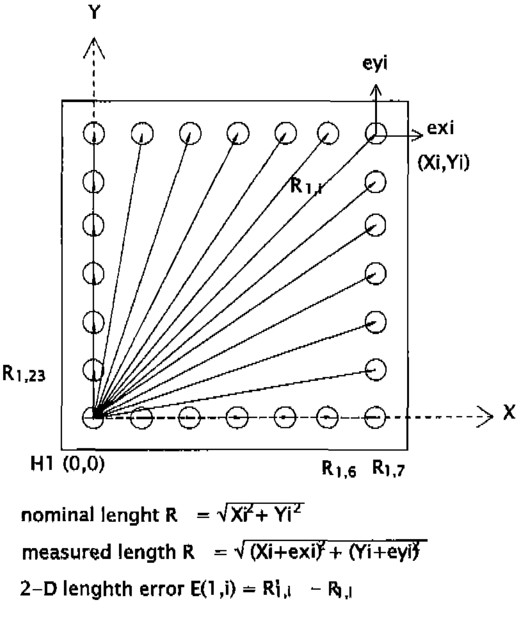


Fig.12 2-D length error, E(1,i) calculation with respect to Hole 1.

5. CONCLUSIONS

We have been shown the a possibility of a hole plate artefact method for determining the volumetric accuracy and 21 components of parametric errors of CMMs.

The hole plate calibration technique is also important for minimizing the influence of hole manufacturing errors (roundness, squareness, etc.). The same nominal measuring position of the hole should be kept as the calibration.

Analysis using the synthetic hole roundness data showed that the influence of hole roundness error was not very significant for the hole centre positioning.

When determining the number of data points for a line of the hole plate, the uncertainty of the squareness error calculation should be considered.

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