AN APPLICATION OF NEURAL NETWORK IN CALIBRATION OF COORDINATE MEASURING MACHINES

Thai Thi Thu Ha, Nguyen Van Quoc Khanh

University of Technology, VNU-HCM

(Manuscript Received on October 21th, 2010, Manuscript Revised January 21st, 2011)

ABSTRACT: *Two most important requirements of Coordinate Measuring Machines (CMM) are the accuracy and the traceability. However, after a long period of use, errors caused by dynamic forces, thermal expansion, loads, etc can decrease the accuracy as well as the traceability. Therefore, CMM is calibrated to minimize these errors as small as possible. First at all, a geometric error model of CMM is proved mathematically. A method of determining 21 parametric errors by using a Hole Plate then is presented. In addition, a back-propagation algorithm is introduced to approximate parametric errors of all points in the CMM working volume. Finally, the proposed calibration method is demonstrated experimentally.*

Key words*: calibration, coordinate measuring machines, CMM, neural network, parametric errors.*

1. INTRODUCTION

Coordinate Measuring Machines were invented more than two decades ago, has made differences, and changed profoundly in the metrology technology. Because CMM can measure coordinates of points on object surfaces, reconstruct 3D model of objects and compare with original 3D model, they has become a standard to guarantee the quality of manufacturing products. However, after a long period of use, CMM will contain errors. Sources of errors are loads (deformation), dynamic forces (ex inertial force, vibration), thermal expansion coefficient differences of machine part materials (distortion)...[1]. Therefore, CMM is calibrated to minimize errors as small as possible. On the other hand, when CMM is assembled, geometric errors of its components increase its systematic error. Instead of reducing geometric errors of machine parts, calibration of CMM is considered.

To determine coordinate errors of points in the working volume of CMM, two geometric error models of CMM are proposed [2]. The first one is a volumetric model which only considers position errors of grid-points in the working volume. The position errors are determined by 3-D Artifact [3], or laser tracker [4], or another CMM. The advantages of these models are to neglect the kinematics of CMM, to measure straightforwardly, and not to require a laborious calibration set-up. The disadvantages are that the calibration uncertainty depends on the uncertainty of the artifacts, and these models do not give insight into significant error sources [5, 6]. On the contrary, the parametric model considers 21 parametric errors of axes. Coordinate errors are calculated on these parametric errors. There are many methods of determining parametric errors, for example 1-D Ball Array [7], laser interferometers [8].

In the present paper, a new method for calibration of coordinate measuring machines is proposed, and proved mathematically as well experimentally. One of the most primary advantages of this method is to apply Neural Network to interpolate errors of all points in the working volume. Firstly, a parametric error model is demonstrated mathematically in a different way. Secondly, a Hole Plate is used to determine 21 parametric errors of considered points in each axis. A back-propagation algorithm is introduced to approximate parametric errors of other points in each axis. Coordinate errors of CMM at the Metrology Lab are calculated by “CMM Calibration” software, and compensated by the proposed method. As the results, the accuracy and the traceability of this CMM increase significantly.

2. A GEOMETRIC ERROR MODEL OF COORDINATE MEASURING MACHINE

To calibrate CMM based on the parametric model, 21 parametric errors need to be determined [8]. Each axis has three translational errors and three rotational errors. Three squareness errors between x and y-slide, y and z-slide, z and x-slide are also considered. Parametric errors are denoted in table 1, and have directions in fig 1.

Consider 4 coordinate systems (O,X,Y,Z), (O_1,X_1,Y_1,Z_1), (O_2,X_2,Y_2,Z_2), and (O_3,X_3,Y_3,Z_3) respectively attached to table system, bridge system, carriage system and ram system (fig 2).

At the beginning of a motion, $O \equiv O_1 \equiv O_2 \equiv O_3$. The bridge moves a nominal distance Y, and the actual position of O_1 is then expressed as follow:

$$\overrightarrow{OO_1} = \begin{pmatrix} ytx \\ Y - yty \\ ytz \end{pmatrix} \qquad (1)$$

The rotational matrix of bridge system to table system is:

$$R_1 = Rot(x, yrx).Rot(z, yrz).Rot(y, yry) \qquad (2)$$

Table. 1. 21 parametric errors

Parametric errors	Notation	Description
Positioning errors	xtx	the translation error of X-axis in X direction
	yty	the translation error of Y-axis in Y direction
	ztz	the translation error of Z-axis in Z direction
Straightness error	xty, xtz	the translation errors of X-axis in Y, Z directions
	ytx, ytz	the translation errors of Y-axis in X, Z directions
	ztx, zty	the translation errors of Z-axis in X, Y directions
Pitch and yaw error	xry,xrz	the rotational errors of X-axis around Y, Z axes
	yrx,yrz	the rotational error of Y-axis around X, Z axes
	zrx,zry	the rotational error of Z-axis around X, Y axes

Roll error	xrx	the rotational error of X-axis around X axis
	yry	the rotational error of Y-axis around Yaxis
	zrz	the rotational error of Z-axis around Z axis
Squareness error	xwy	the squareness errors between X and Y-axes
	ywz	the squareness errors betweenYand Z-axes
	zwx	the squareness errors between Z and X-axes

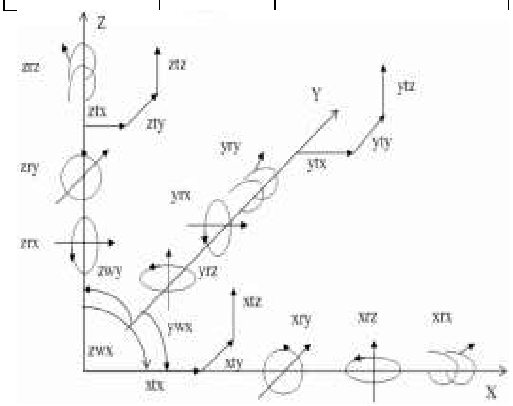


Fig1. Directions of parametric errors

$$R_1 = \begin{pmatrix} 1 & -yrz & yry \\ yrz + yrx.yry & 1 & yrz.yry - yrx \\ yrx.yrz - yry & yrx & yrx.yrz.yry + 1 \end{pmatrix} \quad (3)$$

Or $R_1 = \begin{pmatrix} 1 & -yrz & yry \\ yrz & 1 & -yrx \\ -yry & yrx & 1 \end{pmatrix}$ (4)

since $yrx, yry, yrz \ll 1$

Where

$$Rot(x, yrx) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -yrx \\ 0 & yrx & 1 \end{pmatrix} \quad (5)$$

$$Rot(y, yry) = \begin{pmatrix} 1 & 0 & yry \\ 0 & 1 & 0 \\ -yry & 0 & 1 \end{pmatrix} \quad (6)$$

$$Rot(z, yrz) = \begin{pmatrix} 1 & -yrz & 0 \\ yrz & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (7)$$

Similarly, when the carriage moves a nominal distance X, and the ram then moves a nominal distance Z, we have:

$$\overrightarrow{O_1O_2} = \begin{pmatrix} X - xtx \\ -X.xwy + xty \\ xtz \end{pmatrix} \quad (8)$$

$$\overrightarrow{O_2O_3} = \begin{pmatrix} -Z.zwx + ztx \\ -Z.zwy + zty \\ Z - ztz \end{pmatrix} \quad (9)$$

$$R_2 = \begin{pmatrix} 1 & -xrx & xry \\ xrz & 1 & -xrx \\ -xry & xrx & 1 \end{pmatrix} \quad (10)$$

$$R_3 = \begin{pmatrix} 1 & -zrz & zry \\ zrz & 1 & -zrx \\ -zry & zrx & 1 \end{pmatrix} \quad (11)$$

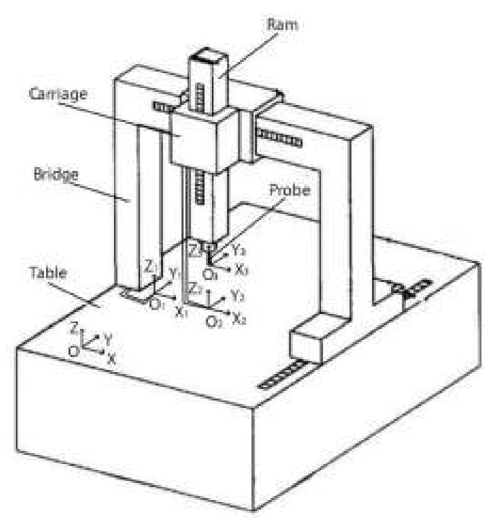


Fig. 2. Four coordinate systems

Let $\left(X_P, Y_P, Z_P\right)$, and $\left(X^{/}, Y^{/}, Z^{/}\right)$ be respectively the coordinates of an arbitrary point P in the ram system and the table system. Coordinates of the point P in the coordinate system of the table can be determined as the following equations:

$$\overrightarrow{OP} = \overrightarrow{OO_1} + R_1.\overrightarrow{O_1P}_{/R1} \quad (12)$$

$$\overrightarrow{O_1P}_{/R1} = \overrightarrow{O_1O_2} + R_2.\overrightarrow{O_2P}_{/R2} \quad (13)$$

And $\overrightarrow{O_2P}_{/R2} = \overrightarrow{O_2O_3} + R_3.\overrightarrow{O_3P}_{/R3}$ (14)

Therefore, we have:

$$\overrightarrow{OP} = \overrightarrow{OO_1} + R_1.(R_2.(R_3.\overrightarrow{O_3P}_{/R3} + \overrightarrow{O_2O_3}) + \overrightarrow{O_1O_2})$$

(15)

Calculating Eq. (15) in Maple and neglecting terms of higher order than 1st degree, we have:

$$X^{/} = X + X_P + xry.(Z + Z_P) - xtz - xrz.Y_P - yrz.Y_P + yry.(Z + Z_P) + ytx - zrz.Y_P - zwx.Z + ztx$$

16)

$$Y^{/} = Y + Y_P - yty + xrz.X_P + yrz.(X + X_P) + zrz.X_P - zrx.Z_P - zwy.Z + zty - xrx.(Z + Z_P) - xwy.X + xty - yrx.(Z + Z_P)$$

(17)

$$Z^{/} = Z + Z_P + ytz - yry.(X + X_P) + yrx.Y_P - xry.X_P + xrx.Y_P - zry.X_P + zrx.Y_P - ztz + xtz$$

(18)

Thus, coordinate errors of the point P are determined as follows:

$$E_x = xry.(Z + Z_P) - xtz - xrz.Y_P - yrz.Y_P + yry.(Z + Z_P) + ytx - zrz.Y_P - zwx.Z + ztx$$

(19)

$$E_y = -yty + xrz.X_P + yrz.(X + X_P) + zrz.X_P - zrx.Z_P - zwy.Z + zty - xrx.(Z + Z_P) - xwy.X + xty - yrx.(Z + Z_P)$$

(20)

$$E_z = ytz - yry.(X + X_P) + yrx.Y_P - xry.X_P + xrx.Y_P - zry.X_P + zrx.Y_P - ztz + xtz$$

(21)

Although the given error model has a proof different from previous scientists, it has the same final result with Zhang's model.

Therefore, basing on the duality principle, the proposed error model is reasonable.

In summary, applying the proposed error model, coordinate errors of an arbitrary point in the working volume of CMM can be determined if 21 parametric errors are known.

3.DETERMINATION OF PARAMETRIC ERRORS

To determine 21 parametric errors of points in the working volume of CMM, Hole Plate is placed in 5 different positions described in fig 3. At each position, the coordinates of hole centers in the hole plate are measured by CMM. In addition, we also take into account set-up errors as described in fig 4, and manufacturing straightness errors of Hole Plate.

Positioning errors, pitch yaw errors, and roll errors can be calculated by using measurement results of hole centers and set-up errors. In general, the reversal method is utilized to measure straightness errors. However, artifacts which can apply this method are usually small, for example 1-D artifacts. On the contrary, Hole Plate occupies large space when placed in 5 different positions. Therefore, straightness errors are determined by measuring both straightness errors of Hole

Plate and coordinates of hole centers. Finally, using the diagonal method, values of other parametric errors calculated before and the parametric error model of CMM, squareness errors are also determined.

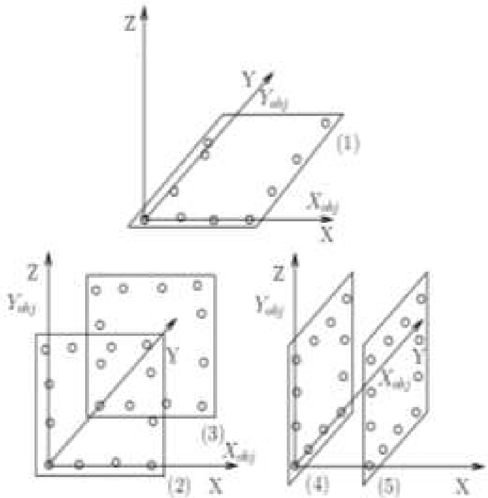


Fig. 3. Setup positions

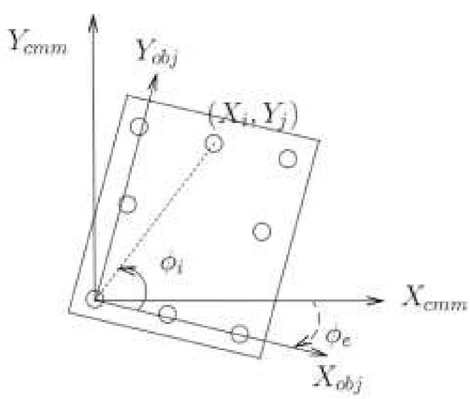


Fig. 4. Set-up error

4. AN APPROXIMATION OF ERROR FUNCTIONS USING NEURAL NETWORK

In the previous section, 21 parameter errors of some points in the working volume are determined. By applying equation (19), (20), and (21), coordinate errors are also determined. However, to calibrate CMM, coordinate errors of all points in CMM working volume must be calculated. Therefore, the back-propagation algorithm in Neural Network is considered to approximate the functions of parametric errors, for example $xwy(x, y, z)$ function.

Consider Neural Network as described in fig 5. The activation functions are:

$$f_o(x) = x$$

$$f_h(x) = \frac{e^{c.x} - e^{-c.x}}{e^{c.x} + e^{-c.x}} \quad (22)$$

where, $c = const$

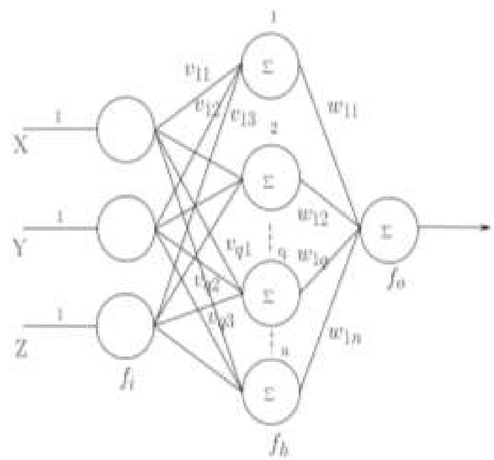


Fig. 5. The proposed Neural Network

The net output is a parametric error of a point and the net inputs are respectively its coordinates. The training data includes $\square(k), g(k)$ where,

$\square(k) = [x(k), y(k), z(k)]^T$, g(k) is a parametric error, $k = \overline{1, K}$

The back-propagation algorithm of approximating xrx functions is shown in fig 6.

The output of the output node is

$$a = f_0\left(\sum_{q=1}^{n} w_{1q}.f_h(v_{q1}.x + v_{q2}.y + v_{q3}.z)\right) \quad (23)$$

The sum of the squares of the errors for the output unit is

$$E(w,v) = \frac{1}{2}\left(g - f_0\left(\sum_{q=1}^{n} w_{1q}.f_h(v_{q1}.x + v_{q2}.y + v_{q3}.z)\right)\right)^2 \quad (24)$$

Output-layer weights are updated:

$$w_{1q}(k+1) = w_{1q}(k) + \eta.\delta_{o1}.b_q(k) \quad (25)$$

where,

$$\delta_{o1} = -\left(-g(k) + a(k)\right) f_o^{'}(net) \quad (26)$$

Similarly, hidden layer weights are updated:

$$v_{qj}(k+1) = v_{qj}(k) + \eta.\delta_{hq}.x_j(k) \quad (27)$$

where, $j = \overline{1,3}$

$$\delta_{hq}(k) = \delta_{o1}(k).w_{1q}(k).f_h^{'}\left(net_q(k)\right)$$
(28)

If $N > N_{\max}$ or $RMS < RMS_{\max}$, the training will be discontinued. Where, N is training cycle, RMS is the root mean square defined as follows:

$$RMS = \sqrt{\frac{\sum_{k=1}^{K}\left(g(k) - a(k)\right)^2}{K}} \quad (29)$$

In fact, most of CMM have the accuracy less than $4\mu m$. Therefore, it is acceptable to stop training Neural Network if $RMS \le 1\mu m$

5. SOFTWARE COMPENSATION

After applying NN to interpolate parametric errors of all points in the CMM working volume, coordinate errors of an arbitrary point can be determined by using Eq (19), (20), (21). Therefore, the actual coordinate of this point is compensated for the coordinate measured by CMM by adding the coordinate error of this point. The process is named after software compensation.

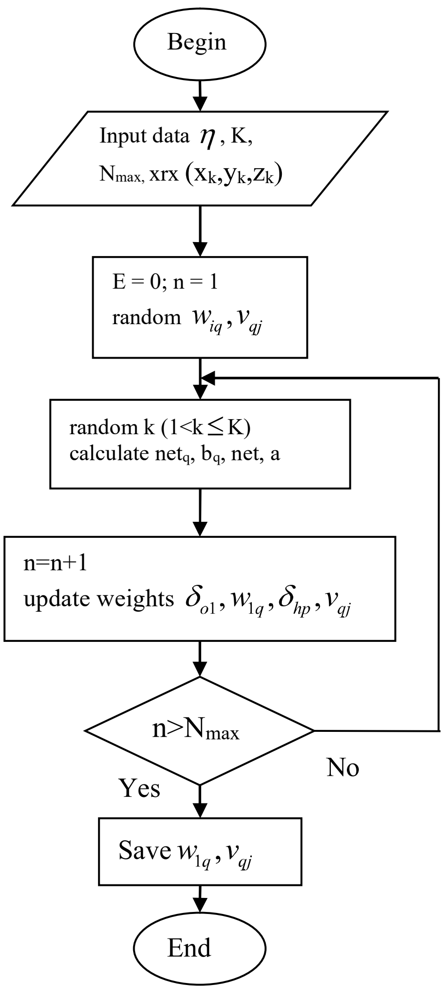


Fig 6. The flow chart of the back-propagation algorithm approximating xrx function

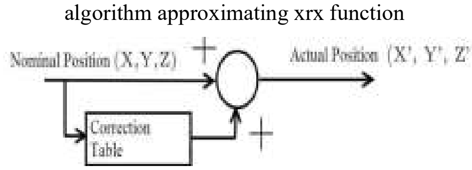


Fig 7. Software compensation

6.EXPERIMENTAL RESULTS

Applying the above calibration method, “CMM Calibration” software is written in Java to calculate all errors of CMM (fig 8). The inputs of the software are coordinates of hole centers when Hole Plate is placed in 5 different positions, set-up errors, and straightness errors of Hole Plate. “CMM Calibration” can calculate and approximate 21 parametric errors as well as coordinate errors of all points in the working volume of CMM. The output data of CMM Calibration is used as input data of other software, CMM Metrology, to compensate coordinate errors.

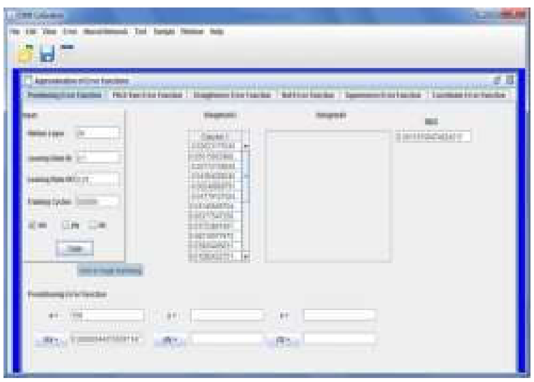
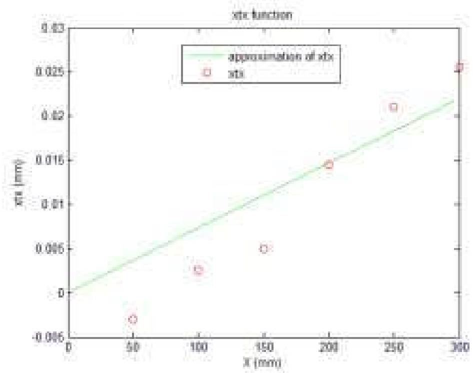


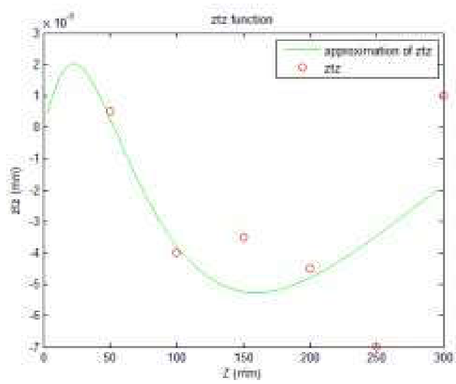
Fig. 8. The “CMM Calibration” software

The Hole Plate and CMM, both of which are designed and manufactured by our Metrology Lab, are shown in fig 9.

Fig. 9. The Hole Plate

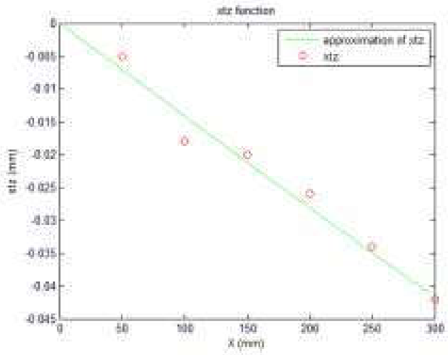


N= 50000 ; RMS = 0.0011 mm

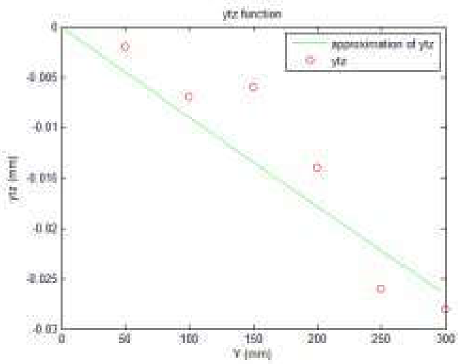


N= 50000 ; RMS = 0.0018 mm

Fig. 10. Positioning errors

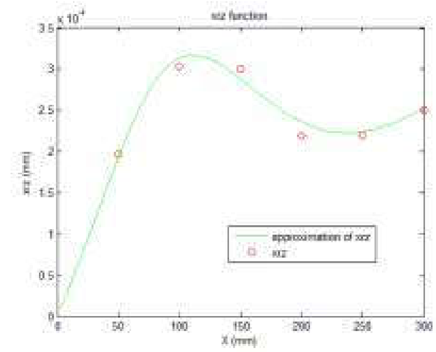


RMS = 0.0004 (mm)

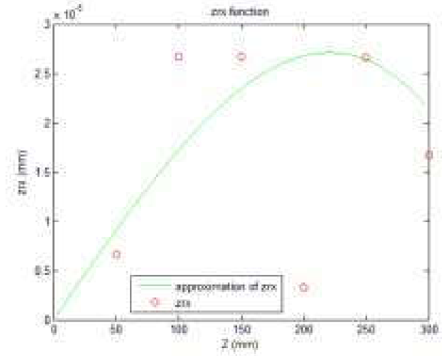


RMS = 0.0018 (mm)

Fig. 11. Straightness errors

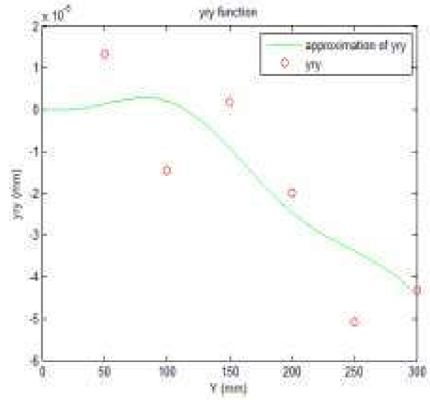


RMS = 9. 10^{-6} (mm)

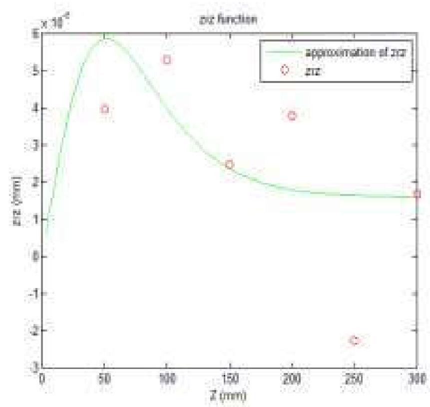


RMS = 9. 10^{-6} (mm)

Fig. 12. Pitch and yaw errors



RMS = 2. 10^{-5} (mm)

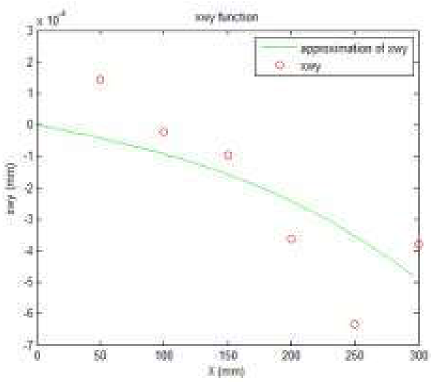


RMS = 1.8 10^{-5} (mm)

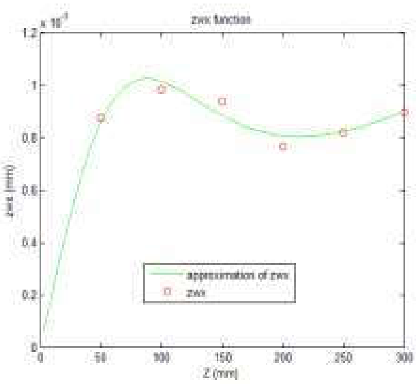
Fig.13. Roll errors

21 parametric errors of this CMM are determined by CMM Calibration, and shown in fig 10, 11, 12, 13, and 14.

To validate the above calibration method, we compare the length of a test specimen as shown in fig 15. The actual length of the specimen is 100 mm. “CMM Metrology” software is utilized to determine the distance between two surfaces of the specimen. Before CMM is calibrated, the distance is 100.037 (mm), or the length error is 0.037 (mm). After CMM is calibrated, the distance is 100.009 (mm). It means that the accuracy of CMM is improved profoundly after applying the above calibration method.



RMS= 1.7 10^{-4} (mm)



RMS= 3.6 10^{-4} (mm)

Fig 14. Squareness errors

Fig 15. Verification of the calibration method

7.CONCLUSION

A new method of calibrating Coordinate Measuring Machines by using Neural Network and Hole Plate is presented. 21 parametric errors as well as coordinate errors of all points in the working volume of CMM are determined quickly by using the “CMM Calibration” software. In addition, comparing results of measuring distances between two surfaces of the test specimen is demonstrated the advantages of the calibration method.

In the future, Hole Plate will be manufactured with the higher accuracy. Moreover, integrating “CMM Calibration” with “CMM Metrology” will be considered.

ỨNG DỤNG MẠNG THẦN KINH ĐỂ CALÍP MÁY ĐO TỌA ĐỘ CMM

Nguyễn Văn Quốc Khánh, Thái Thị Thu Hà
Trường Đại học Bách Khoa, ĐHQG-HCM

TÓM TẮT: *Hai yêu cầu quan trọng nhất của máy đo tọa độ CMM là độ chính xác và độ ổn định. Tuy nhiên, sau một khoảng thời gian sử dụng, các sai số sinh ra bởi lực tác dụng, sự giản nở vì nhiệt, tải trọng… làm giảm độ chính xác và độ ổn định. Vì vậy máy đo tọa độ CMM cần được calíp để giảm các sai số đó càng nhỏ có thể. Đầu tiên, mô hình sai số hình học của máy đo tọa độ được chứng minh toán học. Sau đó, một phương pháp xác định 21 thông số sai số bằng cách sử dụng Bàn Lỗ được giới thiệu. Giải thuật lan truyền ngược được trình bày để xấp xỉ các thông số sai số của mọi điểm trong không gian làm việc của máy đo tọa độ. Cuối cùng, phương pháp calíp đưa ra đã được kiểm nghiệm bằng thực nghiệm.*

Key words*: calibration, coordinate measuring machines, CMM, neural network, parametric errors.*

REFERENCES

[1]. Schwenke H, Knapp W, et al Geometric error measurement and compensation of machines-An update. *Annals of the CIRP 57*: 660-675, (2006).

[2]. Theo Ruijl. *Ultra Precision Coordinate Measuring Machine: Design, Calibration and Error Compensation*. PhD thesis,Technische Universiteit Eindhoven, (2001).

[3]. Q.C. Dang, S. Yoo, S.-W. Kim. Complete 3-D Self-calibration of Coordinate Measuring Machines. *Annals of the CIRP 50*, (2006).

[4]. Carl-Thomas Schneider. Laser tracer-a new type of self tracking laser interferometer. *IWAA2004*, (2004).

[5]. Spaan H.A.M. *Software Error Compensation of Machine Tools*. PhD thesis, Eindhoven University of Technology, (1993).

[6]. Soons J. A. *Accuracy analysis of Multi-Axis Machines*. PhD thesis, Eindhoven University of Technology, (1993).

[7]. Zhang G, Zang Y, A method for geometrical calibration using 1D Ball Array. *Annals of the CIRP 40*: 519-522

[8]. P. S. Huang and J. Ni. On-line error compensation of coordinate measuring machines. *J.Mach. Tools Manufact*, 35(5): 725 738, January (1994).