A Laser Vector Technique for the Measurement of Static Positioning Errors & Compensation

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Abstract

The competition in global manufacturing today requires higher accuracy and better quality machine tools. Just calibrate and compensate the 3 displacement errors (or pitch errors) are not enough. To determine the volumetric positioning accuracy, all 3 displacement errors, 6 straightness errors and 3 squareness errors have to be measured and compensated.

Recently, Optodyne has developed a new laser vector measurement technique for the determination of volumetric positioning errors including 3 displacement errors, 6 straightness errors and 3 squareness errors, in a few hours instead of a few days. Using this laser vector measurement technique the volumetric positioning errors of an AWEA vertical machining center, model FV-1000 with Fanuc 18M controller has been measured. To check the effectiveness of various compensation schemes, the volumetric positioning accuracies were measured without any compensation, with pitch error compensation, with pitch error and straightness error compensation, and with volumetric compensation. The measured volumetric errors were 110 μm without compensation, 95 μm with pitch error compensation, 16 μm with pitch error and straightness error compensation, and 12.5 μm with volumetric compensation. The basic theory of operation, the hardware, the data collection and processing, and some test results will be discussed.

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I. Introduction

The performance or the accuracy of a CNC machine tool is determined by the volumetric positioning accuracy, which includes the linear displacement error, the straightness error, the angular error and the elastic error. A complete measurement of those errors is very complex and time consuming, for those reasons the measurement of the body diagonal displacement errors is recommended by many international standards such as ISO 230-6 and ASME B5.54 [1] for a fast check of the volumetric performance. This is because the body diagonal displacement measurement is sensitive to all of the error components. However, if the errors exceed the specification, there is not enough information for the identification of the error sources and for their compensation.

Recently, a new laser vector technique [2,3] is developed by Optodyne for the measurement of the volumetric errors, including 3 displacement errors, 6 straightness errors, and 3 squareness errors by using a laser Doppler Displacement Meter (LDDM). Using this laser vector measurement technique the volumetric positioning errors of an AWEA vertical machining center model FV-1000 with Fanuc 18M controller has been measured.

II. Body Diagonal Displacement Measurement

The body diagonal displacement measurement method is recommended for a fast check of the positioning and geometrical accuracy of a machine. Briefly, similar to a laser linear displacement measurement, instead of pointing the laser beam in the axis direction, pointing the laser beam in the body diagonal direction as shown in Fig.1a. Mount a retroreflector on the spindle and move the spindle in the body diagonal direction, for example from the lower left corner (X=0 Y=0 Z=0) to the upper right corner (Xmax, Ymax, Zmax). Starting from the zero position and at each increment of the three axes, which are moved together to reach the new position along the diagonal, the displacement error is measured. The accuracy of each position along the diagonal depends on the positioning accuracy of the three axes, including the straightness errors, angular errors and squareness errors. Hence the body diagonal displacement measurement is a good method for the machine verification, but there is not enough information for the identification of the error sources.

III. Vector or Sequential Diagonal Measurement

The new vector measurement method or *Sequential Diagonal Measurement Method* differs from the traditional method because each axis is moved separately and the positioning error is collected after each single movement of the X axis, of the Y axis and than of the Z axis. For this reason, 3 times more data is collected and also the positioning error due to each single axis movement can be separated. The collected data can be processed as the projection of the displacement of each single axis along the diagonal.

In the conventional body diagonal displacement measurement, the target trajectory is a straight line and it is possible to use the corner cube as target that can tolerate a small lateral displacement. In the vector method, the movement is alternatively along the X axis, than along the Y axis and than along the Z axis, and repeated until the opposite corner of the diagonal is reached. As shown in Fig. 1(b), the trajectory of the target is not a straight line and the lateral movement is quite large. Hence it is not possible to use a conventional interferometer that cannot tolerate such large lateral movement. A laser interferometer with single aperture is used with a flat mirror as target. It is noted that with a flat mirror as target, the movement parallel to the mirror do not displace the laser beam and do not change the distance from the source so the measurement is not influenced. Hence, it measures the movement along the beam direction and tolerates a large lateral movement of the target.

IV. Measurement on an AWEA machine

The measurement was performed on an AWEA vertical machining center model FV-1000 in Hsinchu, Taiwan, Republic of China. The FV-1000 is designed for high-speed mold making. It has thick steel structure with reinforcement ribs to give the machine unsurpassed rigidity and prevent any bending or twist that may affect machining accuracy. The column and bridge are a single one-piece casting that allows for maximum cutting performance and vibration absorption. The column is bolted to the top of the machine bed to ensure the best accuracy alignment and squareness and to allow for maximum rigidity. The machine working volume is 1050 mm by 600 mm by 540 mm and the controller is Fanuc 18M. Without any compensation, the volumetric errors were measured by the laser vector method or sequential diagonal measurement. All the errors were measured and automatically generated the pitch errors and straightness error tables that allowed the global machine compensation. To check the effectiveness of various compensation schemes, the volumetric positioning accuracies were measured without any compensation, with pitch error compensation, with pitch error and straightness error compensation, and with volumetric compensation.

V. Laser vector method, measurements and compensation

1. The setup and alignment

The machine has been measured along the 4 body diagonals by means of the laser vector method. The laser was mounted on the machine table and using the steering mirror to aligned the laser beam parallel to the diagonal. The flat mirror was mounted on the spindle with the surface perpendicular to the laser beam, as shown in the Fig. 2. The machine was programmed to move the spindle starting from one corner to the opppsite corner. All the compensation in the CNC controller was turned off. As showing in the Fig.1a, eight types of commanded path direction is used to measure volumetric errors and verify the experimental results. In which,

PPP : direction from a to g (solid line)
NNN: direction from g to a (reverse of solid line)
PNP : direction from b to h (dotted line)
NPN: direction from g to a (reverse of dotted line)
PPN : direction from c to e (dashed line)
NNP: direction from e to c (reverse of dashed line)
PNN : direction from d to f (dash-dotted line)
NPP: direction from f to d (reverse of dash-dotted line)

2. The laser measurement system

The laser calibration system is a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500. It is a newest generation laser interferometer based on Doppler effect with single aperture. The system is completed with an alignment mirror to easily steer the laser beam in the diagonal direction.

The target on the moving part of the machine was a 75×100mm flat mirror. The Air temperature and pressure were measured to compensate the changes in speed of light and the machine temperature was measured to compensate the machine thermal expansion. The automatic data acquisition, the error analysis and automatic generation of the compensation tables, were performed by the Optodyne LDDM Windows software version 2.50.

3. Data collection and analysis of the volumetric errors

The measurement data were automatically collected by the Windows LDDM software at every machine stop or at each single axis of movement. The error data has been analyzed by the LDDM software, by clicking on *4-diagonal* on the analysis section and loading the four collected diagonal data files. The errors for each axes were automatically calculated. The body diagonal displacement error, which is a measurement of the volumetric positioning errors, was automatically generated. Several sets of data were collected, such as without compensation, with pitch error compensation, with pitch error and straightness error compensation, and with volumetrically compensated parts program.

The results are shown in tables or graphic forms in Figs. 3, 4 and 5, where "F" denotes measurement in forward direction; "R" denotes measurement in reverse direction; "NC" denotes without compensation; "PC" denotes with pitch error compensation; "VC" denotes with pitch error and straightness error compensation; "SC" denotes with volumetrically compensated parts program; and "Dij" denotes errors on j axis when i axis is moving, i,j=X,Y,Z. Fig.3 is the x-axis errors, the upper curves are the bi-directional displacement error, the middle curves are the straightness error in the y-direction and the lower curves are the straightness error in the z-direction. Similarly, Fig.4 and 5 are the y- and z-axis errors respectively. The body diagonal displacement errors of the machine without compensation are shown in Fig. 6, where the diagonal directions are indicated by the positive or negative increments of the diagonal.

4. The generation of error compensation tables

At the end of the error analysis, the Windows LDDM software automatically generated the Fanuc 18M straightness compensation file. After calculating the errors on X-axis, Y-axis and Z-axis. Click on save icon to generate compensation files and a screen will popup for the selection of the format. Click on “FANUC 16/18” for FANUC 16/18M format and select the units, increment, reference point, travel direction and the compensation unit as follows:

Dxx:
Units: mm,
Increment: 35,
Reference point: 0,
Comp unit: 0.001,
Travel direction: positive,
Dyy:
Units: mm,
Increment: 20,
Reference point: 600,
Comp unit: 0.001,
Travel direction: positive,
Dzz:
Units: mm,
Increment: 18,
Reference point: 540,
Comp unit: 0.001,
Travel direction: positive,

Keep the default values of start address, compensation algorithm, compensation digits, change sign. The compensation file is for the Fanuc 16/18M with 4-point option. The file extension is *.FN8. The following is an example of the compensation file:

```
N3620A1P0A2P130A3P230            N10000P0
N3621A1P0A2P100A3P200            N10001P-1
N3622A1P31A2P131A3P231           N10002P0
N3623A1P1A2P1A3P1                N10003P-1
N3624A1P35000A2P20000A3P18000    N10004P-1
N5711P2                          N10005P-1
N5712P3                          …………..
N5713P3                          N10026P-1
N5721P1                          N10027P1
N5722P1                          N10028P-1
N5723P2                          N10029P1
%                                N10030P3
%                                N10101P0
```

N5731P100	N10102P0
N5732P110	………….
N5733P120	N10125P0
N5734P130	N10126P1
N5741P200	N10127P0
N5742P210	N10128P0
N5743P220	N10129P-2
N5744P230	N10130P-1
N5751P200	N10131P0
N5752P210	N10201P1
N5753P220	N10202P-1
N5754P230	N10203P0
N5761P0	N10204P0
N5762P-14	N10205P-1
N5763P-32	…………...
N5764P-46	N10224P0
N5771P0	N10225P0
N5772P2	N10226P0
N5773P2	N10227P0
N5774P3	N10228P1
N5781P0	N10229P1
N5782P9	N10230P-6
N5783P24	N10231P0
N5784P34	%

Finally, the compensation files were loaded into the Fanuc 18M controller.

5. Measurement results

The measured maximum diagonal displacement error without compensation is 110 μm. Similarly, the body diagonal displacement errors of the machine with pitch error compensation are shown in Fig. 7. Here the maximum displacement error is 95 μm, an improvement of 15%. The body diagonal displacement errors of the machine with pitch error and straightness error compensation are shown in Fig. 8. Here the maximum displacement error is 16 μm an improvement of 700%. The body diagonal displacement errors of the machine with volumetric compensation are shown in Fig. 9, where the maximum displacement error is 12.5 μm, an improvement of 900%.

VI. Summary and conclusion

In summary, we have demonstrated that with the laser vector measurement and the volumetric compensation, the volumetric positioning accuracy of an AWEA vertical machining center can be improved by more than 700%. It is noted with pitch error compensation only, the improvement in positioning accuracy is only 15%. Hence, only compensate the pitch errors are not enough. It is more important to compensate both the pitch errors and straightness errors.

Furthermore, the laser vector measurement only took 2 to 4 hours instead of 20 to 40 hours by a conventional laser interferometer. The laser setup is very simple and the data collection is automatic. The data processing and compensation file generation are all automatic without manual compilation to minimize errors. Hence, a machine operator may be trained to perform the laser calibration and compensation without the need of an experienced quality engineer.

References

[1] "Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers" An American National Standard, ASME B5.54-1992 by the American Society of Mechanical Engineers, p69, 1992.

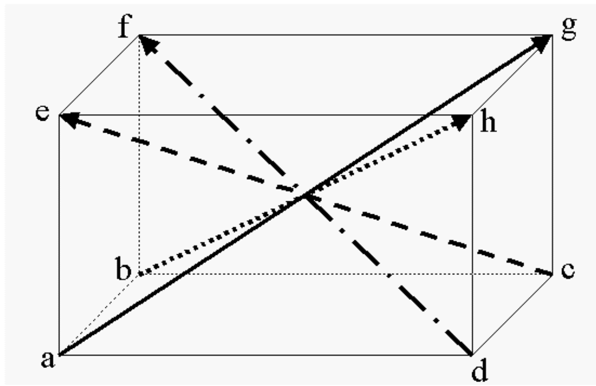
[2] C. Wang, " Laser Vector measurement Technique for the determination and compensation of volumetric positioning errors. Part I: Basic theory", Review of Scientific Instruments, Vol. 71, No 10, pp 3933-3937, October 2000.

[3] J. Jenecko, B. Griffin and C. Wang, "Laser Vector Measurement Technique for the determination and compensation of volumetric positioning errors. Part II: Experimental verification", Review of Scientific Instruments, Vol. 71, No. 10, pp.3938-3941, October 2000.

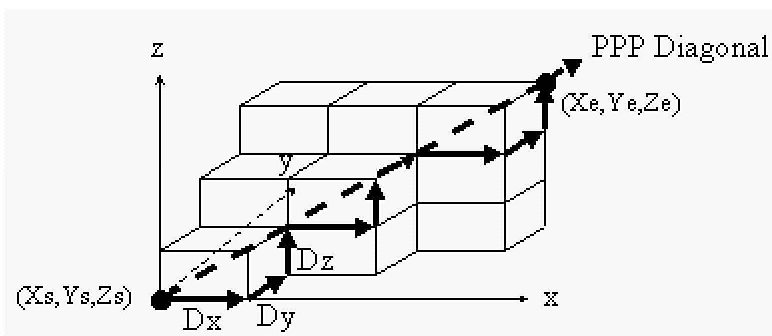
Figure caption

1. Schematics of the sequential diagonal measurement. (a) Body diagonal. (b) The working volume is divided into elementary blocks and the measurement is done for three sides of the blocks along the diagonal path.
2. A photo of the AWEA vertical machining center and the sequential diagonal measurement setup with the laser on the table and the flat mirror on the spindle.
3. X-axis errors, the upper curves are the bi-directional displacement error, the curves in the middle are the straightness error in y-direction and the lower curves are the straightness error in the z-direction.
4. Y-axis errors, the upper curve is the bi-directional displacement error, and the lower curves are the straightness error in x-direction and z-direction respectively.
5. Z-axis errors, the upper curve is the bi-directional displacement error, and the lower curves are the straightness error in the x-direction and y-direction respectively.
6. Four body diagonal displacement errors without compensation. The total error is 110 μm.
7. Four body diagonal displacement errors measured with pitch error compensation. The total error is 95 μm. A small improvement.
8. Four body diagonal displacement errors measured with pitch error and straightness error compensation. The total error is 16 μm. An improvement of 700%.

9. Four body diagonal displacement errors measured with volumetric compensation. The total error is 12.5 μm. An improvement of 900%.



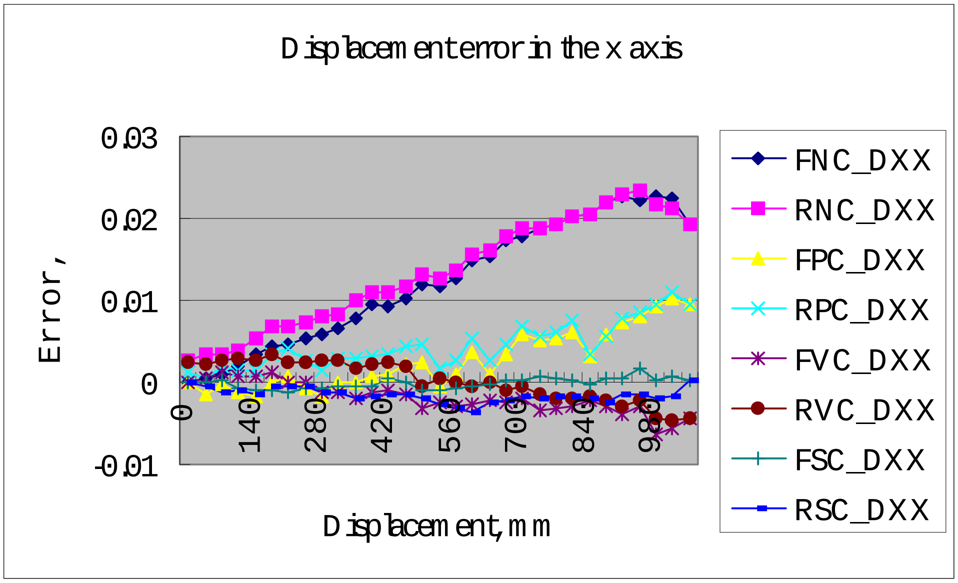
(a)



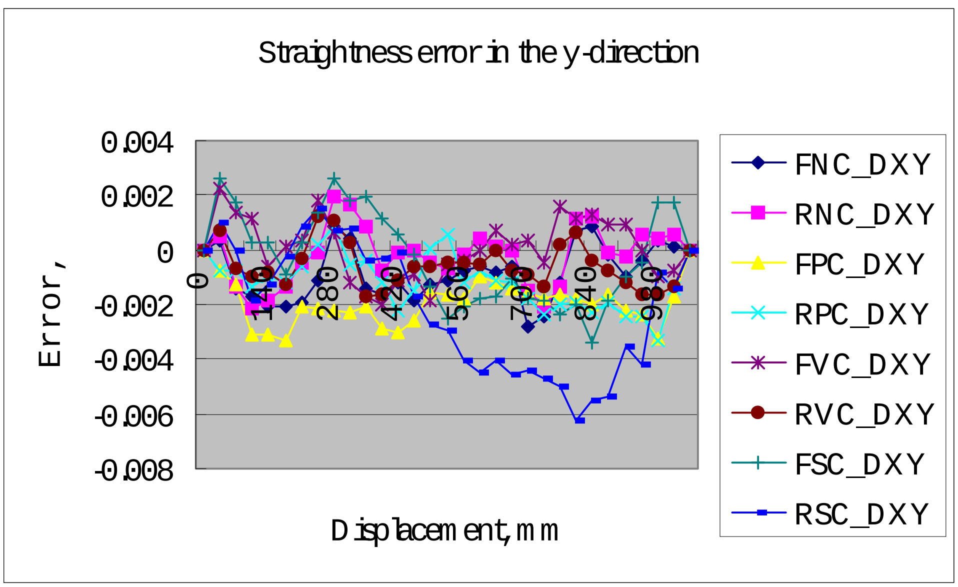
(b)

1. Schematics of the sequential diagonal measurement. (a) Body diagonal. (b) The working volume is divided into elementary blocks and the measurement is done for three sides of the blocks along the diagonal path.

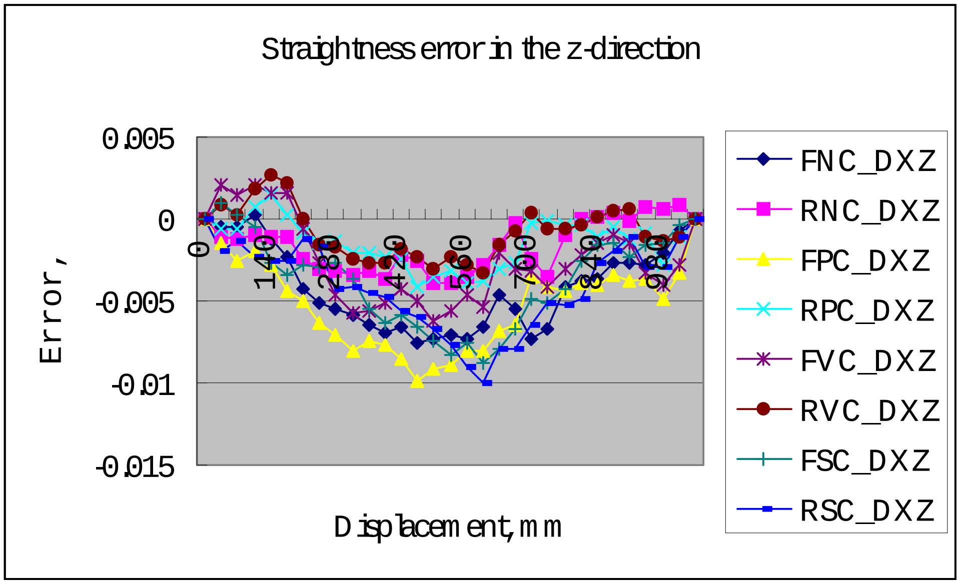
2. A photo of the AWEA vertical machining center and the sequential diagonal measurement setup with the laser on the table and the flat mirror on the spindle.



(a)

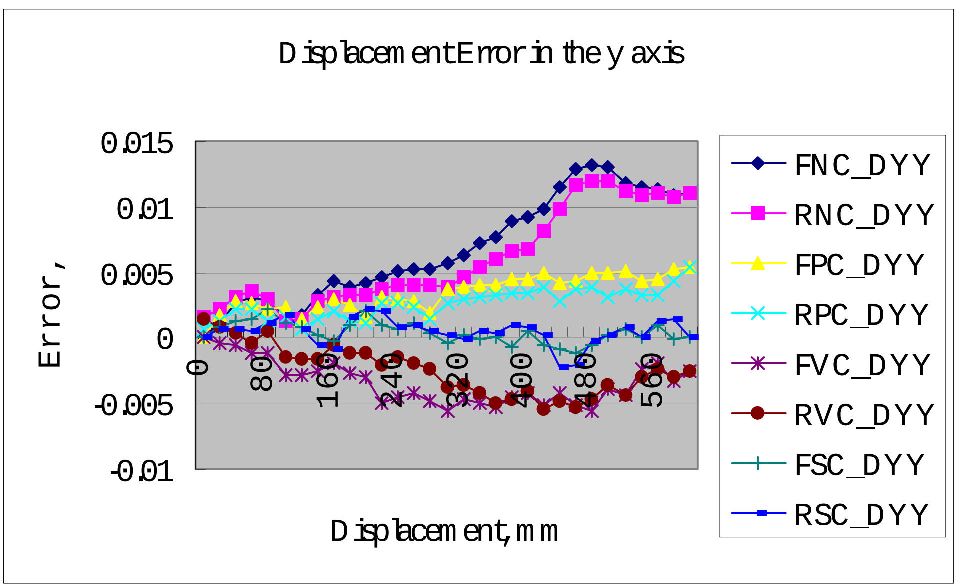


(b)

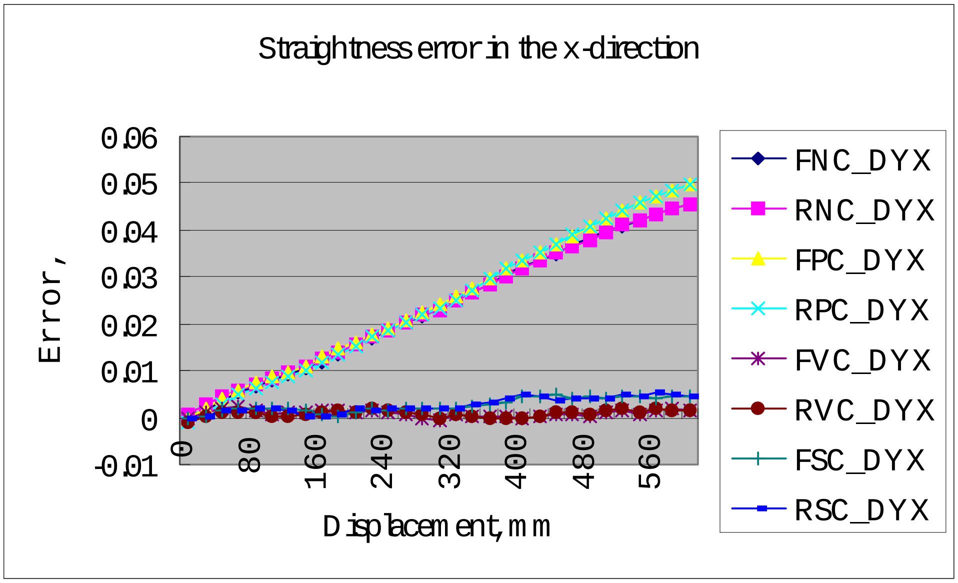


(c)

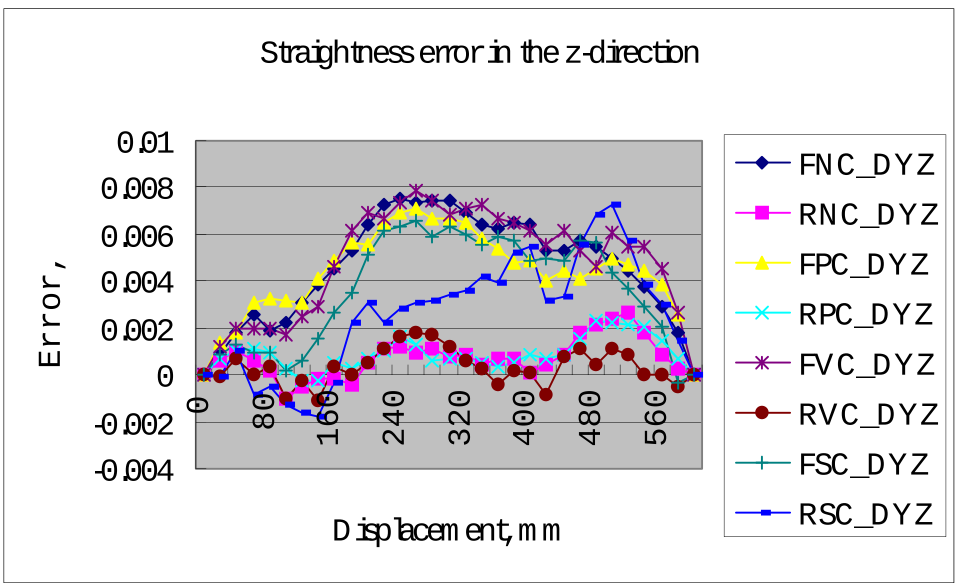
3. X-axis errors, the upper curves are the bi-directional displacement error, the curves in the middle are the straightness error in y-direction and the lower curves are the straightness error in the z-direction.



(a)

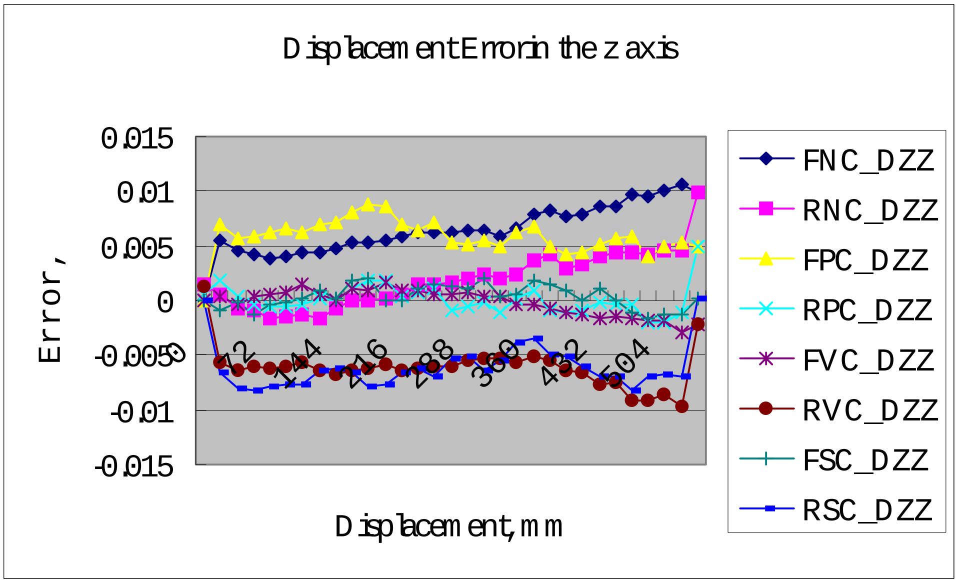


(b)

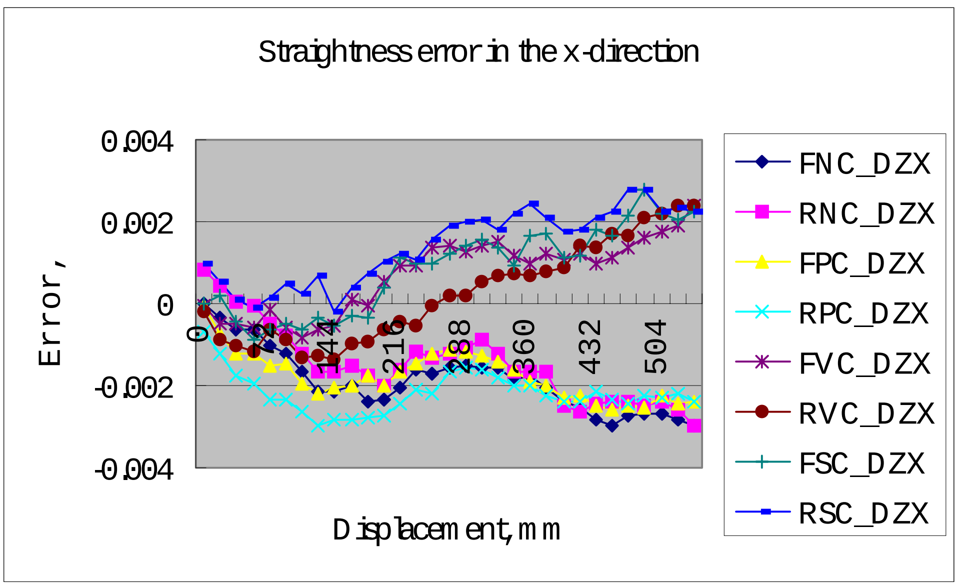


(c)

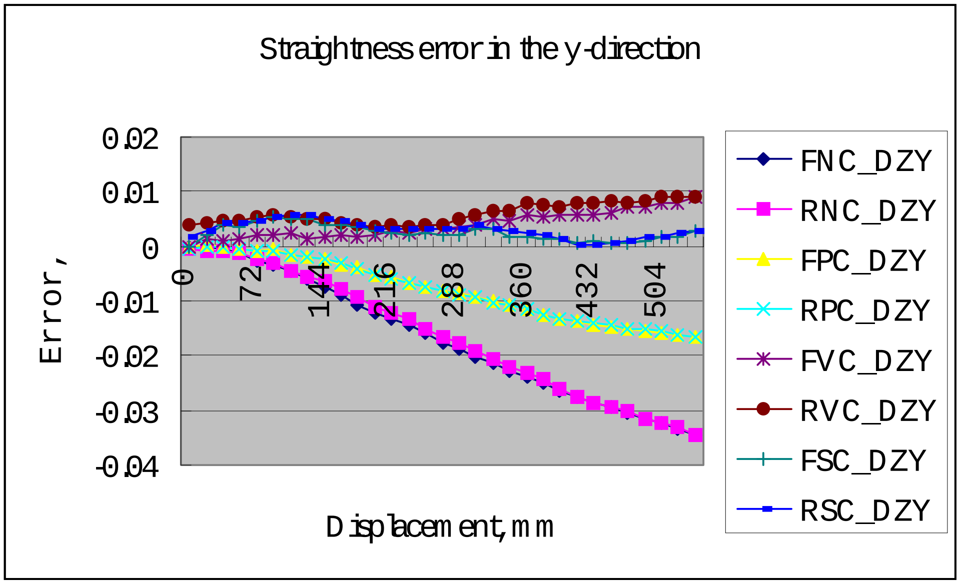
4. Y-axis errors, the upper curve is the bi-directional displacement error, and the lower curves are the straightness error in x-direction and z-direction respectively.


Displacement Error in the z axis
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Error,
0
72
144
216
288
360
432
504
Displacement, mm
FNC_DZZ
RNC_DZZ
FPC_DZZ
RPC_DZZ
FVC_DZZ
RVC_DZZ
FSC_DZZ
RSC_DZZ

(a)

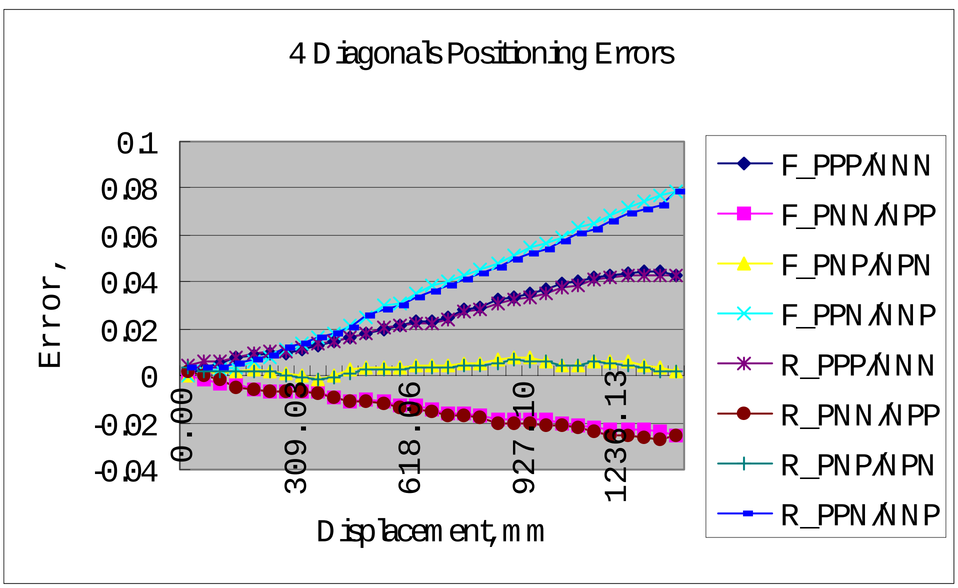

Straightness error in the x-direction
0.004
0.002
0
-0.002
-0.004
Error,
0
72
144
216
288
360
432
504
Displacement, mm
FNC_DZX
RNC_DZX
FPC_DZX
RPC_DZX
FVC_DZX
RVC_DZX
FSC_DZX
RSC_DZX

(b)

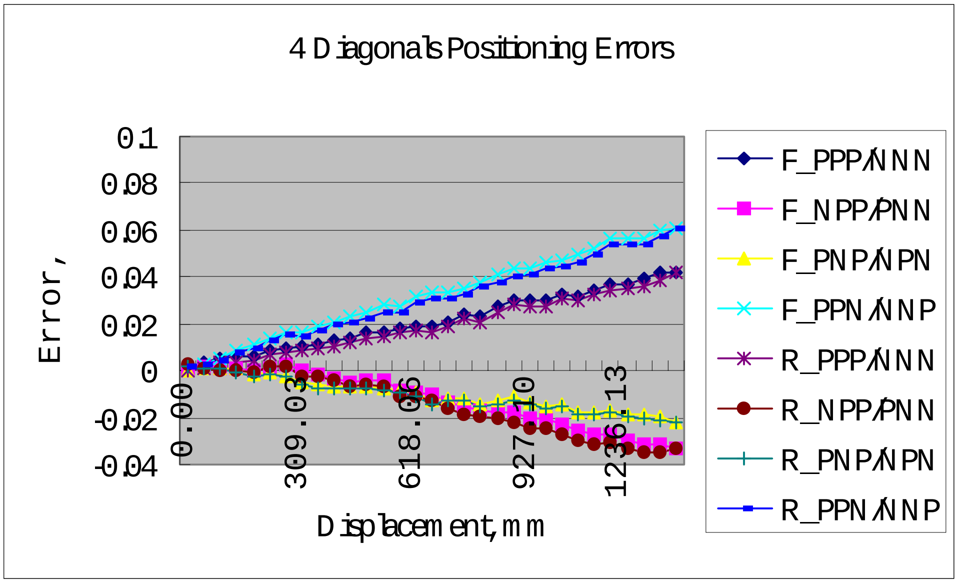


(c)

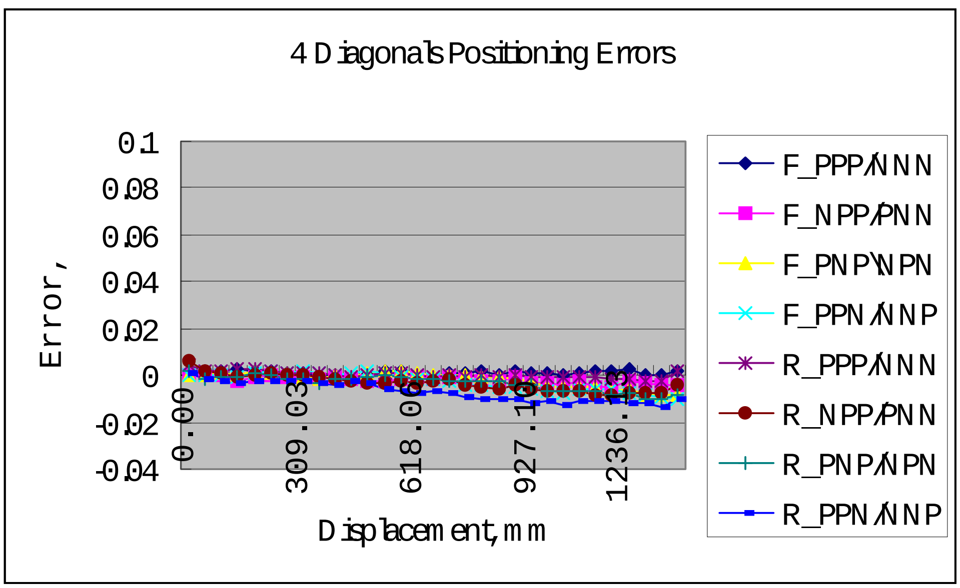
5. Z-axis errors, the upper curve is the bi-directional displacement error, and the lower curves are the straightness error in the x-direction and y-direction respectively.



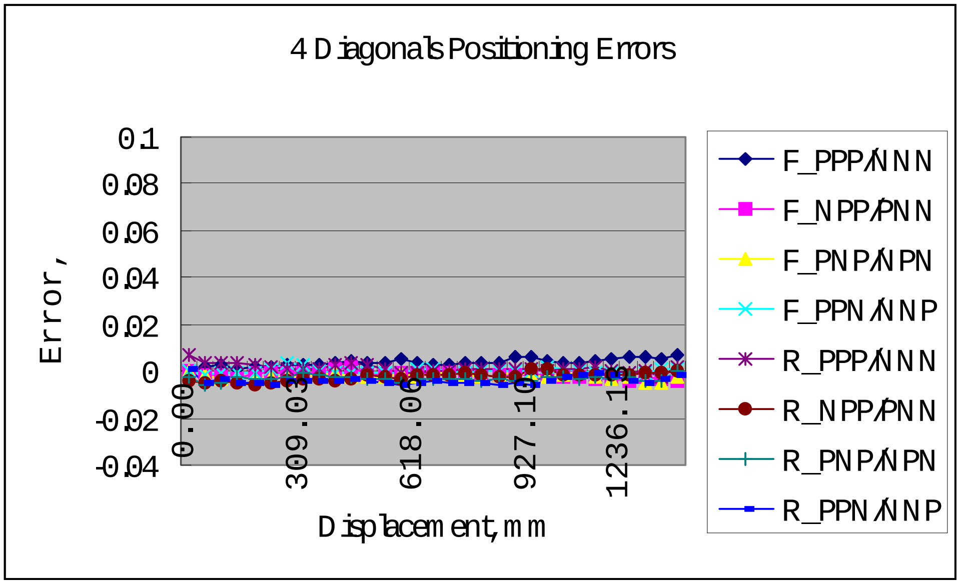
6. Four body diagonal displacement errors without compensation. The total error is 110 µm.



7. Four body diagonal displacement errors measured with pitch error compensation. The total error is 95 µm. A small improvement.



8. Four body diagonal displacement errors measured with pitch error and straightness error compensation. The total error is 16 µm. An improvement of 700%.



9. Four body diagonal displacement errors measured with volumetric compensation. The total error is 12.5 μm. An improvement of 900%.