3D Volumetric Positioning Measurement and Compensation of CNC Machines Using Laser Vector Technique

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Abstract

The worldwide competition and quality standards such as ISO 9000 and QS 9000, demanded tighter tolerance and regular maintenance of all machine tools. Twenty years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. Now, most of the above errors have been reduced by linear encoder and compensation. The largest machine tool positioning errors become squareness errors and straightness errors. Hence, to achieve higher 3D volumetric positioning accuracy, all 3 displacement errors, 6 straightness errors and 3 squareness errors have to be measured and compensated. Using a conventional laser interferometer to measure these errors is rather difficult and costly. It usually takes days of machine down time and experienced operator to perform these measurements.

Optodyne has developed a new laser vector measurement technique for the measurement of these errors in a few hours instead of a few days. The measured errors can be used to generate 3D volumetric compensation files to compensate the volumetric positioning errors and achieve higher volumetric positioning accuracy. To determine the angular errors, 3 displacement measurements along the same axis but at different Abbe offsets can be used. Hence all 18 errors can be determined.

Reported here are the basic theory and operation, the hardware, the data collection and analysis, and the test results. Using the laser vector technique the volumetric positioning errors of 4 Deckel Maho Gildemeister 3-axis milling machines with Heidenhain controller have been measured. For each axis, the linear displacement errors were also measured at 3 different locations. Data were collected with 5 bidirectional runs over 4 machines. The averaged linear displacement errors at the center of working volume, the pitch and yaw angular errors, and their statistical deviations can all be calculated. The agreement between all different measurements was within the statistical deviation.

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I. Introduction

The competition in global manufacturing today requires better quality, higher productivity and lean manufacturing. Manufacturing process control has long been recognized as an important and necessary milestone on the road to reduce cost, improve throughput and superior quality product. Calibrate and compensate the positioning errors can be used to improve quality without excessive capital investment. It yields time, quality and productivity improvement. However, the major objection for this approach is that only calibrate and compensate the pitch error is not enough. But calibrate and compensate the volumetric positioning errors by using a conventional laser interferometer are very time consuming and costly.

However, using the new revolutionary laser vector measurement technique developed by Optodyne (US Patent 6,519,043, 2/11/2003), the 3 D volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors, can all be measured in a few hours instead of a few days by a conventional laser interferometer. Hence the 3 D volumetric calibration and compensation become practical, and enable higher accuracy and tighter tolerance to be achieved. The setup and alignment of the laser vector measurement are easy and usually a machine operator can be trained to perform the measurement.

A complete measurement, including pitch and yaw angular errors, linear displacement errors, straightness errors, and squareness errors of 4 Deckel Maho Gildemeister 3-axis milling machine model DMU 80T was performed by using the latest LDDM technology and the laser vector measurement technique. The result of the measurement, the effect of volumetric compensation, and the quick check by body diagonal displacement, will be reported.

II. Basic 3D volumetric positioning errors

For a 3-axis machine, there are 6 errors per axis or a total of 18 errors plus 3 squareness errors. These 21 rigid body errors [1] can be expressed as the following.

Linear displacement errors: Dx(x), Dy(y), and Dz(z)
Vertical straightness errors: Dy(x), Dx(y), and Dx(z)
Horizontal straightness errors: Dz(x), Dz(y), and Dy(z)
Roll angular errors: Ax(x), Ay(y), and Az(z)
Pitch angular errors: Ay(x),Ax(y), and Ax(z)
Yaw angular errors: Az(x), Az(y), and Ay(z)
Squareness errors: Øxy, Øyz, Øzx,
where, D is the linear error, subscript is the error direction and the position coordinate is inside the parenthesis, A is the angular error, subscript is the axis of rotation and the position coordinate is inside the parenthesis. Basically, a 5-axis machine is a 3-axis machine plus A, B, or C rotary axes. The angular error of the rotary axes can be calibrated separately.

III. Linear displacement, pitch and yaw angular error measurement

For linear displacement error measurement, the measured error D along x, y, and z-axis at each increment can be expressed as [2]:

$$DX = Dx(x) + m * Ay(x) + p * Az(x), \qquad (1)$$
$$DY = Dy(y) + q * Ax(y) + s * Az(y), \qquad (2)$$
$$DZ = Dz(z) + t * Ax(z) + u * Ay(z), \qquad (3)$$

where Abbe offsets m and p are distances from the measurement line to the reference line in y and z directions respectively, q and s are distances from the measurement line to the reference line in x and z directions respectively, t and u are distances from the measurement line to the reference line in x and y directions respectively.

It is noted that the linear displacement errors are different when measured at different locations due to the pitch or yaw angular errors. However, if the machine is repeatable, the measured linear displacement errors can be used to calculate the pitch and yaw angular errors. For example, make 3 linear displacement measurements, one along the top edge, one along the bottom edge, and one along the side edge of the working volume. The differences in the two measurements along the vertical edges (top and bottom) divided by the Abbe offset is the pitch angular error, and the differences in the two measurements along the horizontal edges (left and right) divided by the Abbe offset is the yaw angular error.

Theoretically, based on Eq. 1, three linear measurements along X-axis at 3 different locations with known Abbe offsets m1,p1; m2, p2; and m3, p3, can be expressed as,

$$DX1 = Dx(x) + m1 * Ay(x) + p1 * Az(x), \tag{4}$$
$$DX2 = Dx(x) + m2 * Ay(x) + p2 * Az(x), \tag{5}$$
$$DX3 = Dx(x) + m3 * Ay(x) + p3 * Az(x), \tag{6}$$

There are 3 sets of data DX1, DX2 and DX3 and 3 unknowns Dx(x), Ay(x) and Az(x). The solutions are,

$$Ay(x) = [(m3-m1)*(DX2-DX1)-(m2-m1)*(DX3-DX1)] / [(m3-m1)*$$
$$(p2-p1) - (m2-m1)*(p3-p1)]. \tag{7}$$
$$Az(x) = [(p3-p1)*(DX2-DX1)-(p2-p1)*(DX3-DX1)] / [(m3-m1)*$$
$$(p2-p1) - (m2-m1)*(p3-p1)]. \tag{8}$$
$$Dx(x) = DX1*(m2*p3-m3*p2) + DX2*(m3*p1 - m1*p3) + DX3*$$
$$(m1*p2 - m2*p1) / [(m3-m1)*(p2-p1)-(m2-m1)*(p3-p1)]. \tag{9}$$

Similarly for the Y- and Z-axis errors, Ax(y), Az(y), Dy(y), Ax(z), Ay(z), and Dz(z) can all be determined.

IV Body diagonal displacement error measurement
The performance or the accuracy of a CNC machine tool is determined by the 3 D volumetric positioning errors, which includes the linear displacement error, the straightness error, the angular error and the thermal induced 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 standards such as ASME B5.54 [3] and ISO 230-6 [4] for a fast check of the volumetric performance. This is because the body diagonal displacement measurement is sensitive to all of the error components [2].

Briefly, similar to a laser linear displacement measurement, instead of pointing the laser beam in the axis direction, point the laser beam in the body diagonal direction. Mount a retroreflector on the spindle and move the spindle in the body diagonal direction from the lower corner (X=0 Y=0 Z=0) to the opposite upper 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. As shown in Ref [2], 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.

The formulae for the 4 body diagonal displacement errors derived in [2] include all the geometric errors, namely, 3 displacement errors, 6 straightness errors, 3 squareness errors, and some angular errors. The errors in the above formulae may be positive or negative. Hence, they may be canceling each other and reduced the total error. However, the errors are statistical in nature, the probability that all of the errors will be cancelled in all of the positions and in all of the 4 body diagonals are theoretically possible but very unlikely. Recently, based on a few special examples, it was claimed that some possible limitations on the body diagonal displacement measurement may exist [5]. As shown in Ref. [2], these few examples were theoretically possible but no practical significance. It is concluded that if the 4 body diagonal displacement errors are large, the machine positioning errors are large. However, if the 4 body diagonal displacement errors are small, the linear displacement errors may still be large for certain non-isotropic machines. More discussion on this is in Section IX.

Furthermore, the ASME B5.54 body diagonal displacement tests have been used by Boeing Aircraft and many others for many years with very good results and success in determine the volumetric positioning accuracy. Hence, it is a good check on the volumetric positioning accuracy. However, if the machine is not accurate, there is not enough information on where the errors are and how to compensate them.

V.   Vector or Sequential step diagonal measurement

The sequential step diagonal measurement or laser vector measurement technique was developed by Optodyne for the calibration of 3 D volumetric positioning accuracy of a machine tool [6,7]. Similar to the ASME B5.54 standard body diagonal displacement measurement, the laser beam is pointing in the body diagonal direction. However, instead of move x, y, and z-axis together along the body diagonal direction, stop and collect data as shown in Fig. 1, now move x only, stop and collect data, then move y only, stop and collect data, then move z only, stop and collect data, and so on until the opposite corner is reached. Hence, 3 times more data can be collected. For 4 body diagonal measurement, a total of 12 sets of data can be collected and the volumetric positioning errors determined. The measurement time is short, the equipment is compact, the setup and alignment is simple and therefore the cost is low.

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, the trajectory of the target is not parallel to the laser beam direction 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. The vector technique has been successfully used to measure the 3 D volumetric positioning accuracy of many CNC machines (including the progressive linear motor drives)[8, 9].

VI. 3 D volumetric positioning error compensation

For the existing machine tools, as long as they are repeatable, the volumetric positioning accuracy can be improved up to the positioning repeatability of the machine. Many CNC machines with advanced controllers have the capability to perform the 3 D volumetric compensation, such as Fanuc with straightness compensation capability, Heidenhain with nonlinear compensation capability and Siemens with sag compensation capability. For some CNC machines without the volumetric compensation capability, the 3 D volumetric compensation can be achieved by compensate the parts program using the formulae below.

$$Dx(x,y,z) = Dx(x) + Dx(y) + Dx(z) \qquad\qquad (10)$$
$$Dy(x,y,z) = Dy(x) + Dy(y) + Dy(z) + Øxy*x/X \qquad\qquad (11)$$
$$Dz(x,y,z) = Dz(x) + Dz(y) + Dz(z) + Øyz*y/Y + Øzx*x/X. \qquad\qquad (12)$$

Where the $Dx(x,y,z)$, $Dy(x,y,z)$ and $Dz(x,y,z)$ are correction values in the x, y, and z direction at the position (x,y,z). Many software can be used to convert an existing parts program to a new parts program with corrected positions[10].

VII. Measurement on 4 DMU machines

The measurements were performed on 4 Deckel Maho Gildemeister Universal milling machine model DMU 80T with Heidenhain iTNC 530 controller. The working volume is 780 mm x 585 mm x 450 mm.

The laser calibration system used was a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500. The target on the moving part of the machine was a 75×100 mm 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.

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 opposite corner. 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. The errors for each axis were automatically calculated.

It is noted that, 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.

VIII.　　　　Measurement results

All the measurements were performed bidirectional and repeated 5 times. Based on the ASME B5.57 standard or the ISO 230-2 standard, the accuracy A, the repeatability R, the systematic deviation E, and reversal value B were calculated and tabulated in the tables. Typical results are shown in Table 1 the x-axis linear displacement errors, Table 2 the x-axis vertical straightness errors, and Table 3 the x-axis horizontal straightness errors. For linear displacement errors, the accuracy A = 0.0193 mm, the repeatability R = 0.0023 mm, and the systematic deviation E = 0.0183 mm. For vertical straightness errors, the accuracy A = 0.0037 mm, the repeatability R = 0.0024 mm, and the systematic deviation E = 0.0019 mm. For horizontal straightness errors, the accuracy A = 0.0071 mm, the repeatability R = 0.0048 mm, and the systematic deviation E = 0.0026 mm. These results show that the repeatability of the machines is very good and the straightness errors are not negligible as compared to the linear displacement errors. Hence, only compensating the 3-axis displacement errors is not enough. The straightness and squareness errors should also be compensated to achieve higher volumetric positioning accuracy.

The pitch and yaw angular errors of each axis were determined by measuring linear displacement errors at 3 different locations. A typical plot of pitch angular errors of X-axis and Z-axis are shown in Fig. 3a and 3b respectively. The maximum X-axis pitch angular errors were + 1 arcsec to -7 arcsec, the maximum Z-axis pitch angular errors were +1.4 arcsec to - 1.4 arcsec. The measured maximum squareness error was YZ-plan -11.35 arcsec. The 3D volumetric positioning errors, namely, displacement errors, vertical and horizontal straightness errors and squareness errors of each axis were measured by the vector or sequential step diagonal technique. Based on these measured errors, 3D volumetric compensation files were generated for the volumetric compensation.

The measured 4 body diagonal displacement errors without and with volumetric compensation are plotted in Fig. 4a and 4b respectively. The maximum body diagonal displacement errors were reduced from 0.027 mm to 0.007 mm by 3D volumetric compensation, a factor of 3.8 in improvement.

IX.　Machines with non-isotropic thermal growth

For most machines, the thermal growth of all axes is the same. Hence for machining parts of same type of material, the thermal growth of the machine and the parts are canceling out to achieve higher accuracy parts even with large temperature variations. However, there are machines using different glass scales or ball screws with encoders for different axes, hence the thermal growth on all axes may not be the same or non-isotropic. As point out in [5], for a non-isotropic machine, some axes may be increasing in length and some may be decreasing in length. The 4 body diagonal displacement errors may be small even the axis displacement errors are large.

Theoretically, for a rectangular cubic with length X, Y, and Z of each edge, the body diagonal distance, R can be expressed as $R*R = X*X + Y*Y + Z*Z$. The displacement error in R, can be expressed as $DR = DX*X/R + DY*Y/R + DZ*Z/R$, where DR, DX, DY, and DZ

are the displacement errors in the R, X, Y, and Z direction, respectively. Here all 4 body diagonal displacement errors are the same and equal to DR. For a non-isotropic machine, DX, DY, and DZ are not isotropic, they may be positive or negative. Hence, it is possible to have large |DX|, |DY|, or |DZ| while |DR| is small. Furthermore, since all 4 body diagonal displacement errors are the same, there is not enough information to determine the linear displacement error of the 3 axes. For this special case, it is necessary to measure the displacement errors on two of the axes to determine the linear errors of all 3 axes.

To experimentally demonstrate this, we have performed measurement on a Bridgeport type vertical machining centre, VMC500XP with Heidenhain TNC410 controller. First, the 3D volumetric positioning errors were measured by the vector method over the volume of X= 491.52 mm, Y= 327.68 mm, and Z=458.75 mm. The measured squareness errors were XY-plan: 7.47 arcsec, YZ-plan: 11.95 arcsec and ZX-plan: 9.62 arcsec. The measured displacement errors, vertical straightness and horizontal straightness errors of X-axis, Y-axis and Z-axis are shown in Fig. 5a, 5b, and 5c respectively. The results indicated that there are large squareness errors, especially in the YZ plane, and linear errors of the axes are bellow 0.020 mm. The angular errors were measured by two linear measurements with different Abbe off-sets on the same axis. The results are, X-axis pitch error of 30µm/m (probably the sagging of the table due to its weight), Y-axis yaw error of 20µm/m (makes about 8µm/300mm of the total axis stroke), and Z-axis yaw error of 9µm/500mm of the axis stroke. Thus we can say there were no extensive angular errors present in the machine movements.

Then added a large linear error into the Z-axis by a compensation table (0.2mm/492mm), and performed the vector measurement over the same volume again. The measured squareness errors were essentially the same, XY-plan: 7.89 arcsec, YZ-plan: 11.90 arcsec and ZX-plan: 9.67 arcsec. The measured displacement error, vertical straightness and horizontal straightness errors of X-axis, Y-axis and Z-axis are shown in Fig. 6a, 6b, and 6c respectively. Here the linear displacement errors are 0.068 mm in x-axis, 0.045mm in y-axis and 0.064mm in z-axis. For this special case, it is obvious that the vector method distributed the deliberately introduced large linear error into all the machine tool axes, which consequently caused a degradation of the X and Y-axis and slightly improved Z-axis positioning accuracy. This is because the Fig. 6 was derived by assuming the machine is isotropic and the measured diagonal errors were distributed to all 3 axes. Hence, for the special case here, linear displacement data of 2 axes is needed to determine the linear errors of all 3 axes.

Added the linear displacement data of X-axis and Y-axis (The software allows the user to enter up to 3 linear displacement data files); the results are shown in Fig. 7. Here the displacement errors in X-axis and Y-axis were not changed and in Z-axis was 0.2 mm as it should be. It is concluded that for a non-isotropic machine, additional linear displacement data on 2 axes is needed.

Please note that with an artificially added linear error of 0.2 mm in the z-axis, the measured squareness and straightness results were essentially the same. It is a good indication that the measured squareness and straightness errors are not affected by the large errors of the linear axes. Furthermore, the key advantage of the vector method is the ability to measure the squareness and straightness errors easily in a short time, while complex optics and expensive equipment are needed for a conventional laser interferometer to measure these errors.

X.   Summary and conclusion

The linear displacement errors were measured at 3 different locations for 3 axes. With the new software, the pitch and yaw angular errors of all 3 axes can be calculated. The **vector** technique or sequential step diagonal technique has been used to measure the 3 D volumetric positioning errors.   The measured 3 D volumetric positioning errors have been used to generate the compensated parts program. The 4 body diagonal displacement errors were reduced considerably with the volumetric compensation.

In conclusion, as manufacturers continue to expand six sigma quality programs to improve products and reduce costs, their vendors are being required to improve the quality of their work.   To comply with quality programs, shops should be required to calibrate and compensate machine tools volumetrically instead of just linearly.   With 3 D volumetric calibration and compensation, better quality and higher precision parts can be cut.

Acknowledgement

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          c) With 0.2 mm error added in Z-axis and with linear displacement data of X- and Y -axis, the measured Z-axis displacement error, vertical straightness error and horizontal straightness error.

Table 1, Linear displacement errors of x-axis based on the ASME B5.57 standard

Position Measurement (Linear), ISO-230-2 (1997) (mm)   Date :06.19.03
File=C:\Lddm232\DMU80T-1\dmu80tAR2.sdx   By   :Bobes Bobr
Machine :DMU80T   SIN :I-1-4447L
Start Position: (0,0,0)   End Position: (780,585,450)
Total Travel = 1073.8365797mm   Points = 11   No Runs= 5
Air Temp: 23.58   Pressure: 743.04   Humidity: 50.00
Material Temp: 23.05   MTE = .999963

Forward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000001	0.000003	0.000003	-0.000002
1	78.000000	-0.001069	0.000358	-0.000712	-0.001427
2	156.000000	-0.002600	0.000520	-0.002080	-0.003120
3	234.000000	-0.004656	0.000631	-0.004026	-0.005287
4	312.000000	-0.006010	0.000742	-0.005268	-0.006753
5	390.000000	-0.008053	0.000900	-0.007154	-0.008953
6	468.000000	-0.010400	0.001142	-0.009258	-0.011542
7	546.000000	-0.011935	0.000969	-0.010966	-0.012904
8	624.000000	-0.014325	0.000802	-0.013524	-0.015127
9	702.000000	-0.017335	0.000954	-0.016381	-0.018289
10	780.000000	-0.018313	0.001031	-0.017283	-0.019344
Average		-0.008609	0.000732		

Backward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000001	0.000003	0.000003	-0.000002
1	78.000000	-0.001540	0.000310	-0.001231	-0.001850
2	156.000000	-0.002885	0.000483	-0.002402	-0.003368
3	234.000000	-0.004817	0.000741	-0.004076	-0.005558
4	312.000000	-0.006330	0.000779	-0.005550	-0.007109
5	390.000000	-0.008290	0.000818	-0.007472	-0.009107
6	468.000000	-0.010553	0.000803	-0.009750	-0.011356
7	546.000000	-0.011938	0.000994	-0.010944	-0.012932
8	624.000000	-0.014219	0.000920	-0.013298	-0.015139
9	702.000000	-0.016917	0.000970	-0.015947	-0.017888
10	780.000000	-0.018313	0.001031	-0.017283	-0.019344
Average `		-0.008709	0.000714		

Reversal value, B=   0.000471(at point=1)
Mean reversal value, <B>=   0.000100
Range mean bidirectional positional deviation, M= 0.018314
Systematic deviation of positioning, E=
          0.018314 (0.000001, -0.018313) (Forward),
          0.018314 (0.000001, -0.018313) (Backward),
          0.018314 (0.000001, -0.018313) (Bi-directional)
Repeatability of positioning, R=
          0.002284 (at point=6) (Forward),
          0.002062 (at point=10) (Backward),
          0.002342 (at point=9) (Bi-directional).
Accuracy, A=
          0.019348 (0.000003, -0.019344) (Forward),
          0.019348 (0.000003, -0.019344) (Backward),
          0.019348 (0.000003, -0.019344)   (Bi-directional).

Table 2, Vertical straightness errors of X-axis based on the ASME B5.57 standard

Position Measurement (Vertical), ISO-230-2 (1997) (mm)   *Date:06.19.03*
File=C:\Lddm232\DMU80T-1\dmu80tAR2.SdX   *By*   *:Bobes Bobr*
Machine :DMU80T   *SIN :I-1-4447L*
Start Position: (0,0,0)   *End Position: (780,585,450)*
Total Travel = 1073.8365797mm   *Points = 11*   *No Runs= 5*
Air Temp: 23.58   *Pressure: 743.04*   *Humidity: 50.00*
Material Temp: 23.05   *MTE = .999963*
Forward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.000088	0.000763	0.000850	-0.000675
2	156.000000	-0.000496	0.000809	0.000313	-0.001305
3	234.000000	-0.001812	0.001009	-0.000803	-0.002822
4	312.000000	-0.000990	0.000756	-0.000234	-0.001746
5	390.000000	-0.000966	0.000833	-0.000133	-0.001799
6	468.000000	-0.001098	0.001121	0.000023	-0.002220
7	546.000000	-0.001484	0.000810	-0.000673	-0.002294
8	624.000000	-0.001136	0.000494	-0.000642	-0.001630
9	702.000000	-0.001101	0.000876	-0.000226	-0.001977
10	780.000000	0.000000	0.000000	0.000000	0.000000
Average		-0.000818	0.000679		

Backward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.000073	0.000355	0.000428	-0.000282
2	156.000000	-0.000519	0.000338	-0.000181	-0.000857
3	234.000000	-0.001716	0.000501	-0.001214	-0.002217
4	312.000000	-0.001139	0.000471	-0.000668	-0.001610
5	390.000000	-0.000940	0.000500	-0.000440	-0.001441
6	468.000000	-0.000807	0.000948	0.000142	-0.001755
7	546.000000	-0.001113	0.000962	-0.000151	-0.002076
8	624.000000	-0.000995	0.000381	-0.000615	-0.001376
9	702.000000	-0.000711	0.000319	-0.000392	-0.001030
10	780.000000	0.000000	0.000000	0.000000	0.000000
Average		-0.000715	0.000434		

Reversal value, B= 0.000149 (at point=4)
Mean reversal value, <B>= -0.000103
Range mean bidirectional positional deviation, M= 0.001844
Systematic deviation of positioning, E=
    0.001900 (0.000088, -0.001812)   *(Forward),*
    0.001788 (0.000073, -0.001716)   *(Backward),*
    0.001900 (0.000088, -0.001812)   *(Bi-directional).*
Repeatability of positioning, R=
    0.002243 (at point=6) (Forward),
    0.001925 (at point=7) (Backward),
    0.002361 (at point=6) (Bi-directional).
Accuracy, A=
    0.003672 (0.000850, -0.002822) (Forward),
    0.002645 (0.000428, -0.002217) (Backward),
    0.003672 (0.000850, -0.002822) (Bi-directional).

Table 3, Horizontal straightness errors of X-axis based on the ASME B5.57 standard

Position Measurement (Horizontal), ISO-230-2 (1997) (mm)   Date:06.19.03
File=C:\Lddm232\DMU80T-1\dmu80tAR2.sdX   By   :Bobes Bobr
Machine :DMU80T   SIN :I-1-4447L
 Start Position:(0,0,0)   End Position: (780,585,450)
 Total Travel = 1073.8365797mm   Points = 11   No Runs= 5
 Air Temp: 23.58   Pressure: 743.04   Humidity: 50.00
 Material Temp: 23.05   MTE = .999963
Forward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.000277	0.001166	0.001443	-0.000890
2	156.000000	-0.000523	0.001222	0.000699	-0.001745
3	234.000000	-0.000449	0.001325	0.000876	-0.001775
4	312.000000	0.001696	0.002507	0.004203	-0.000811
5	390.000000	0.001739	0.002213	0.003951	-0.000474
6	468.000000	0.000485	0.002854	0.003339	-0.002368
7	546.000000	-0.000066	0.002780	0.002713	-0.002846
8	624.000000	0.000968	0.002352	0.003320	-0.001384
9	702.000000	0.000844	0.002006	0.002851	-0.001162
10	780.000000	0.000000	0.000000	0.000000	0.000000
Average		0.000452	0.001675		

Backward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	-0.000597	0.000442	-0.000155	-0.001039
2	156.000000	-0.001042	0.000909	-0.000134	-0.001951
3	234.000000	-0.000489	0.001693	0.001204	-0.002183
4	312.000000	0.001289	0.001147	0.002437	0.000142
5	390.000000	0.000992	0.001157	0.002149	-0.000165
6	468.000000	0.000175	0.001594	0.001769	-0.001419
7	546.000000	0.000182	0.001409	0.001591	-0.001227
8	624.000000	0.000606	0.000457	0.001063	0.000149
9	702.000000	0.000559	0.000289	0.000848	0.000270
10	780.000000	0.000000	0.000000	0.000000	0.000000
Average		0.000152	0.000827		

 Reversal value,   B=   0.000874 (at point=1)
 Mean reversal value, <B>=   0.000300
 Range mean bidirectional positional deviation, M= 0.002275
 Systematic deviation of positioning, E=
                    0.002261 (0.001739, -0.000523) (Forward),
                    0.002331 (0.001289, -0.001042) (Backward),
                    0.002781 (0.001739, -0.001042) (Bi-directional)
 Repeatability of positioning, R=
                 0.005708 (at point=6) (Forward),
                 0.003387 (at point=3) (Backward),
                 0.004758 (at point=6) (Bi-directional).
 Accuracy, A=
                 0.007049 (0.004203, -0.002846) (Forward),
                 0.004619 (0.002437, -0.002183) (Backward),
                 0.007049 (0.004203, -0.002846)   (Bi-directional).

PPP Diagonal

(X_e, Y_e, Z_e)

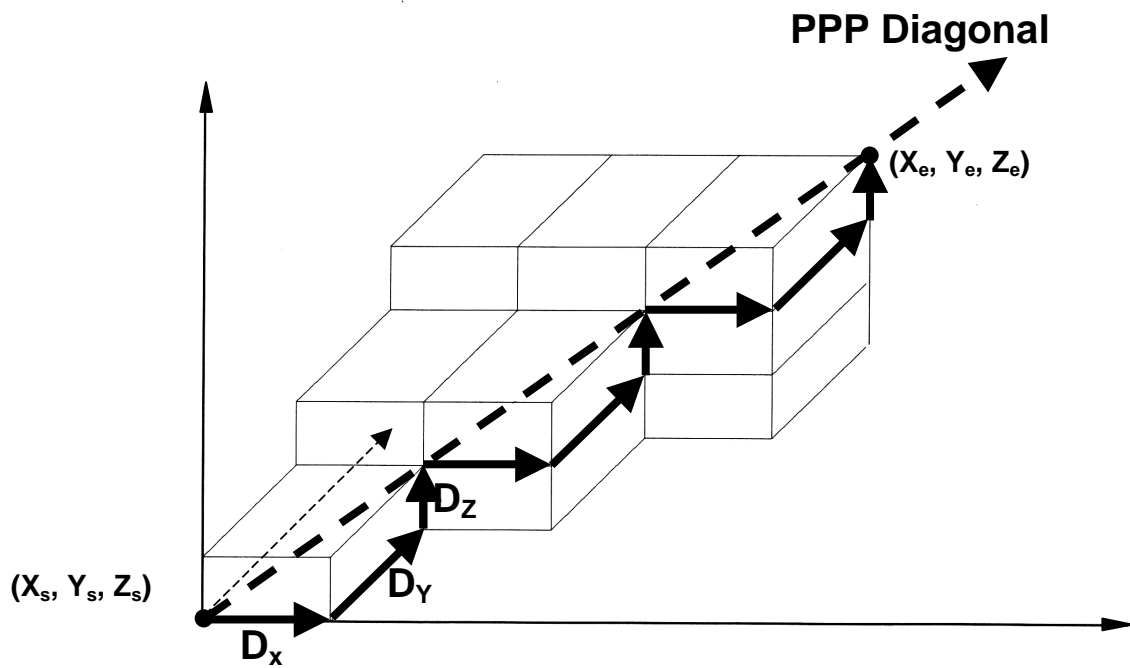D_Z

D_Y

(X_s, Y_s, Z_s)

D_X

Fig. 1, Schematics of the sequential diagonal measurement. The working
volume is divided into elementary blocks and the measurement is done
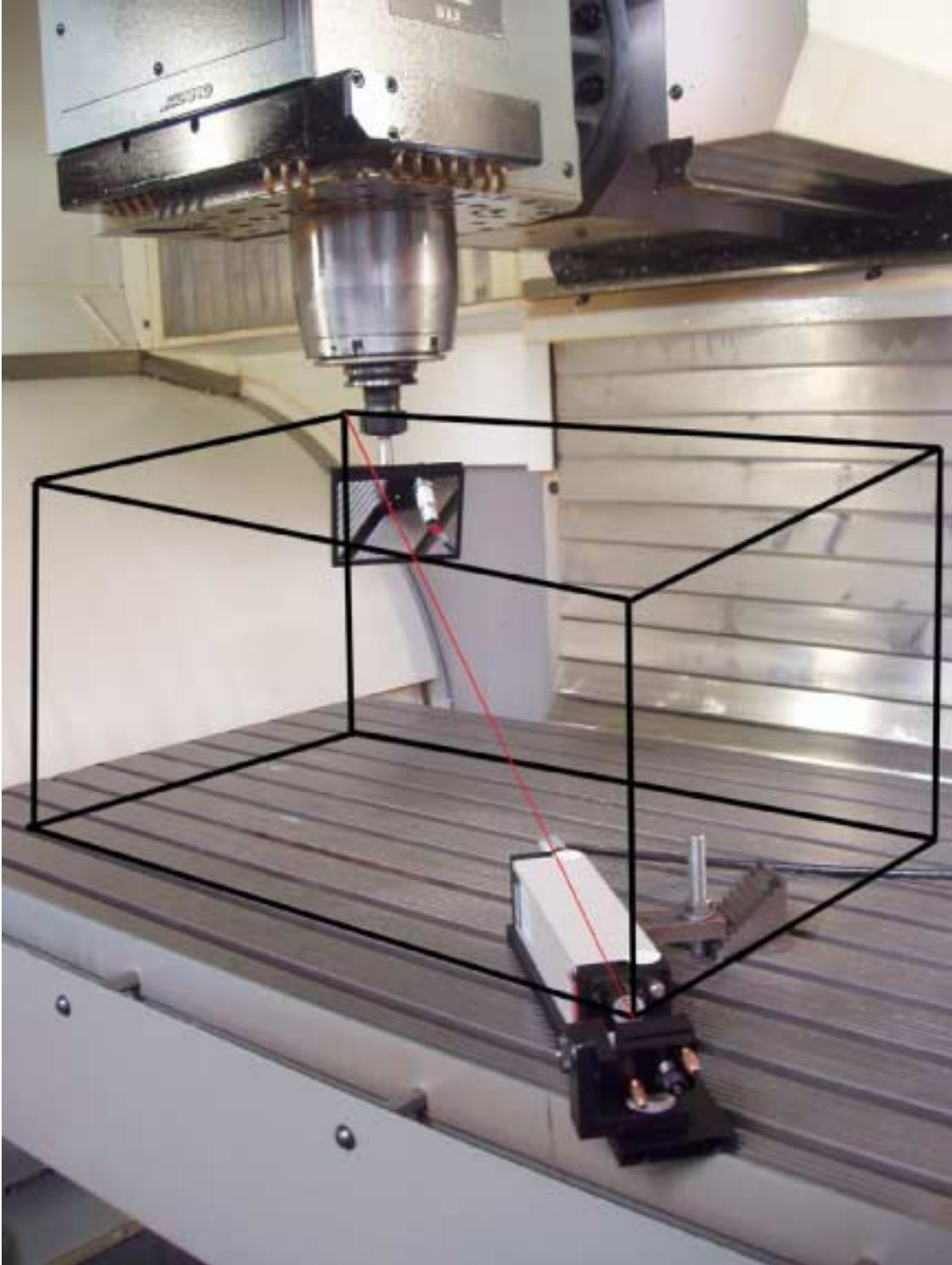for three sides of the blocks along the diagonal path.

Fig. 2 A photo of the DMU 80T Universal milling machine and the sequential diagonal Measurement setup with the laser on the table and the flat mirror on the spindle.
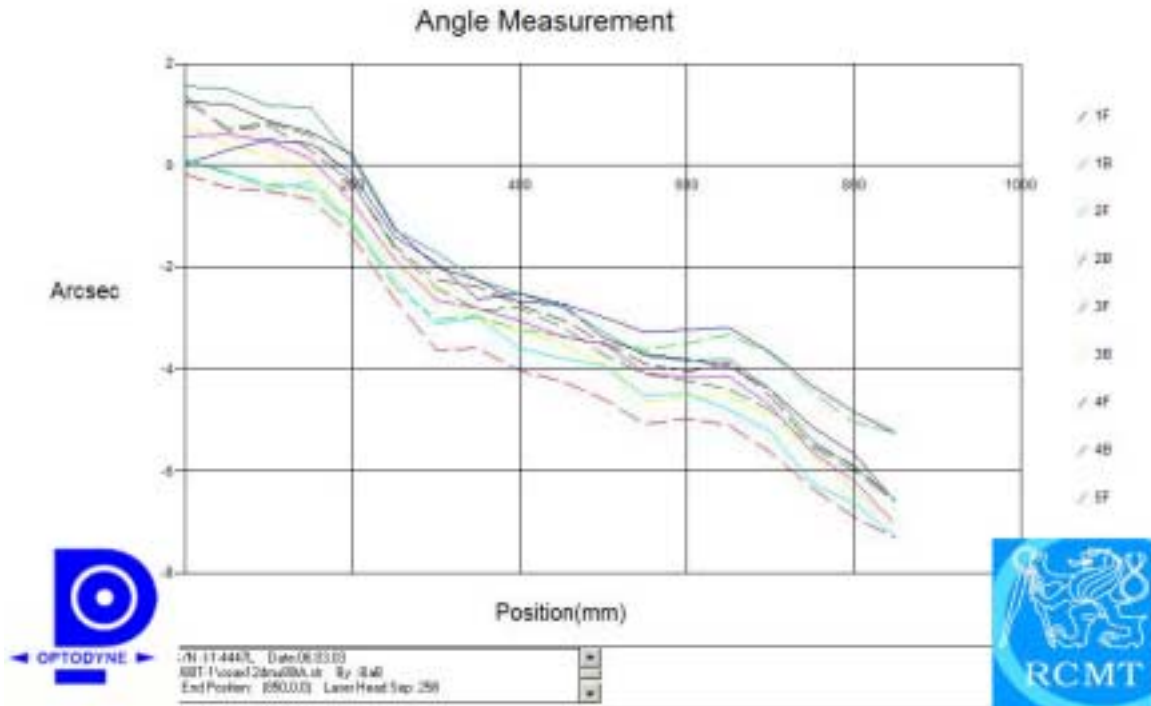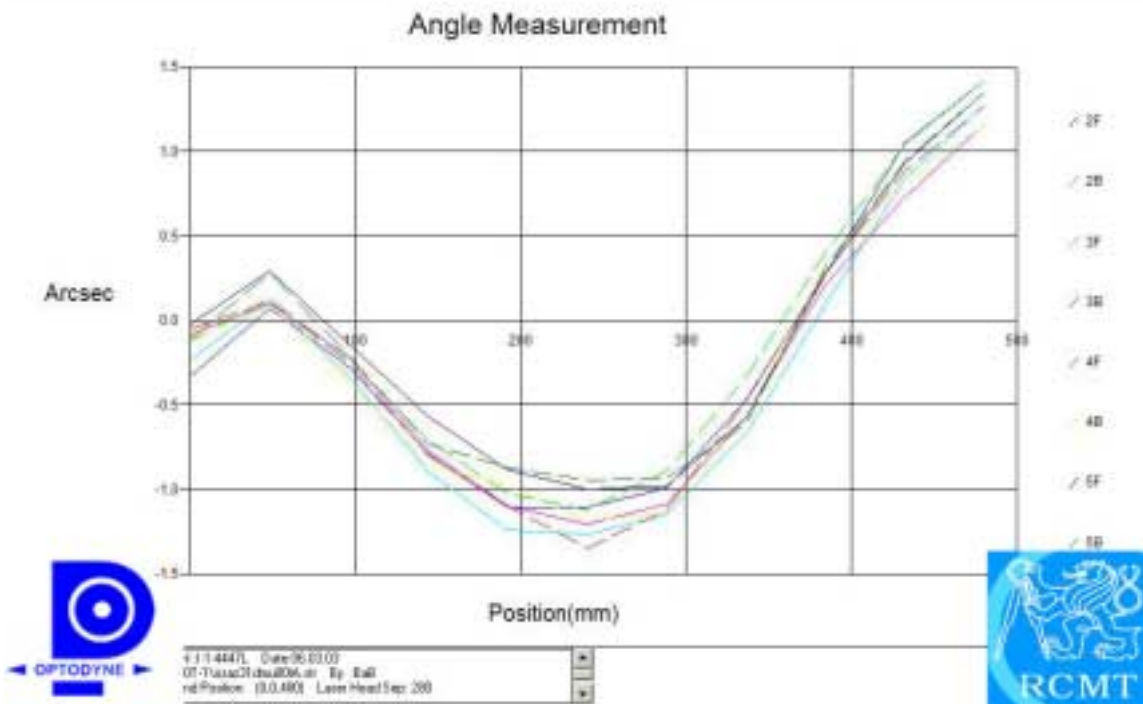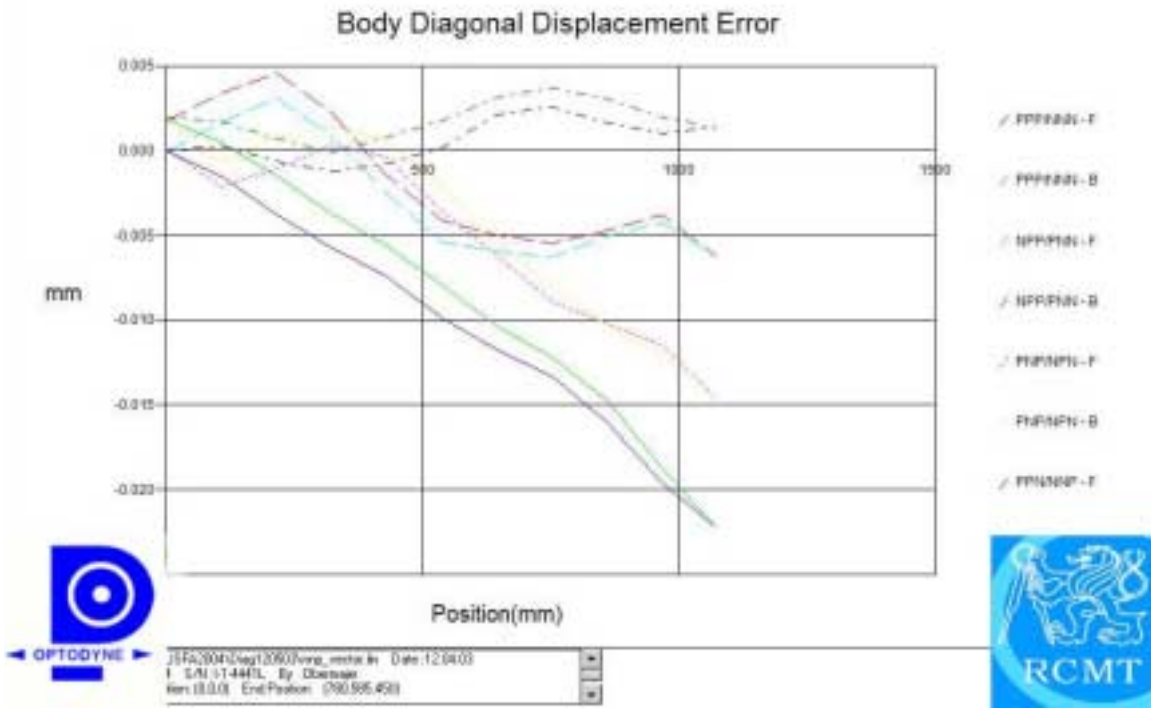
Fig. 3a X-axis pitch angular error

Fig. 3b Z-axis pitch angular error

Fig. 4a Four body diagonal displacement errors without compensation. The total error is 0.027mm.
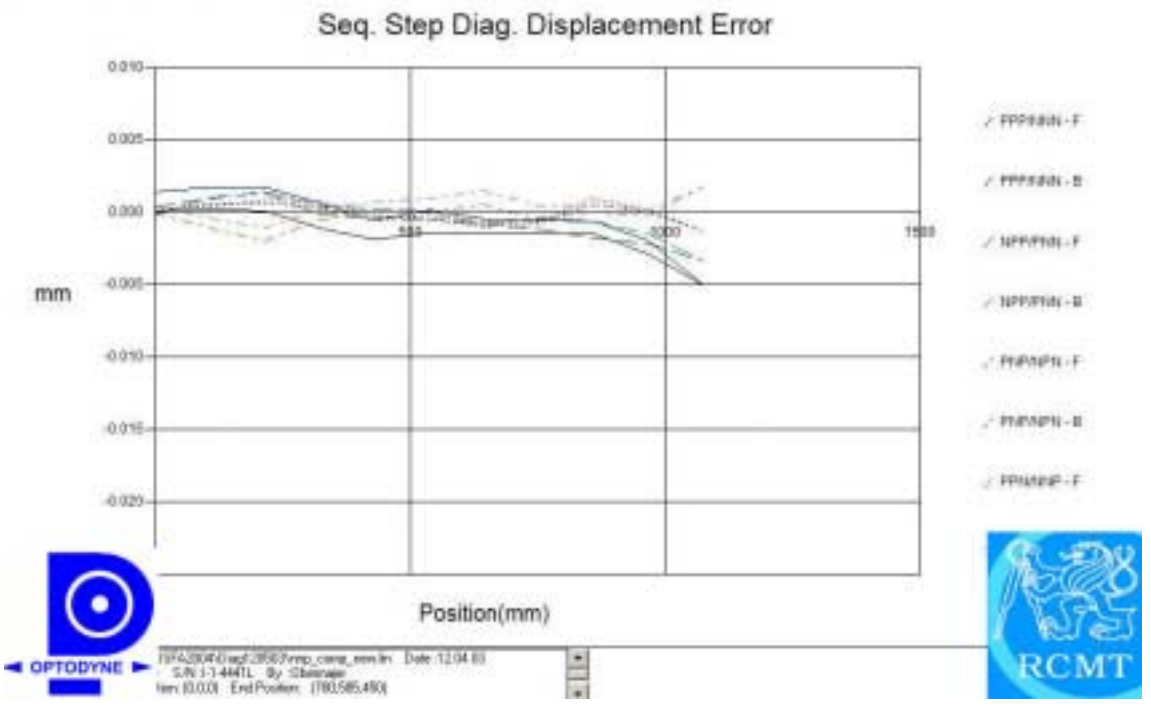
Fig. 4b Four body diagonal displacement errors measured with 3D volumetric error compensation. The total error is 0.007mm, an improvement of 380%.
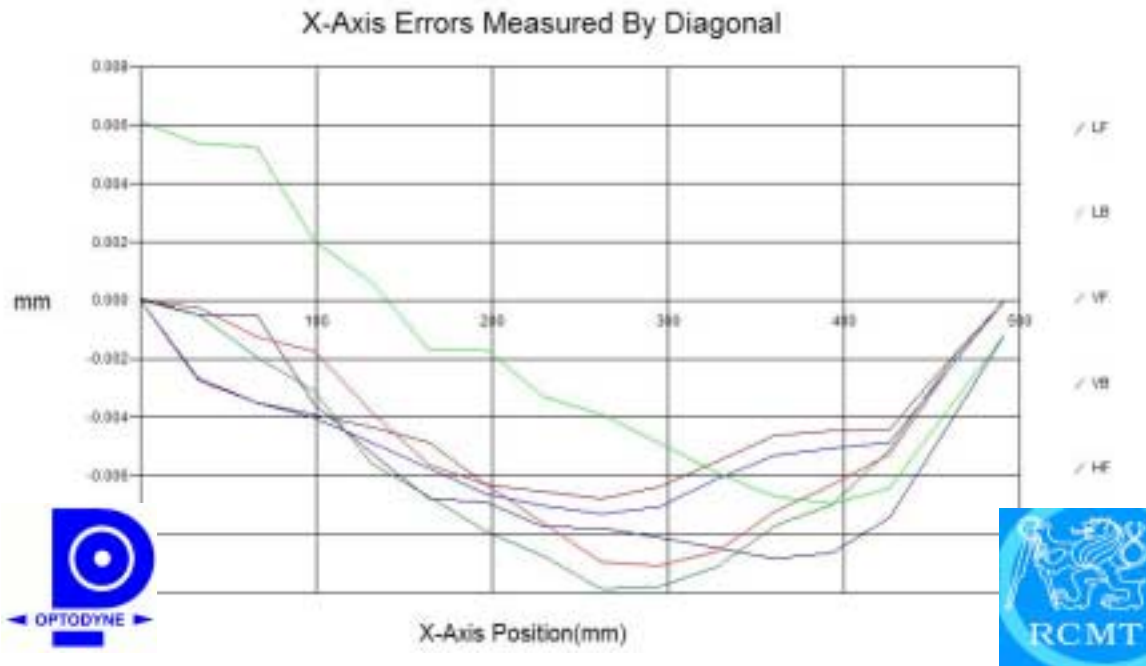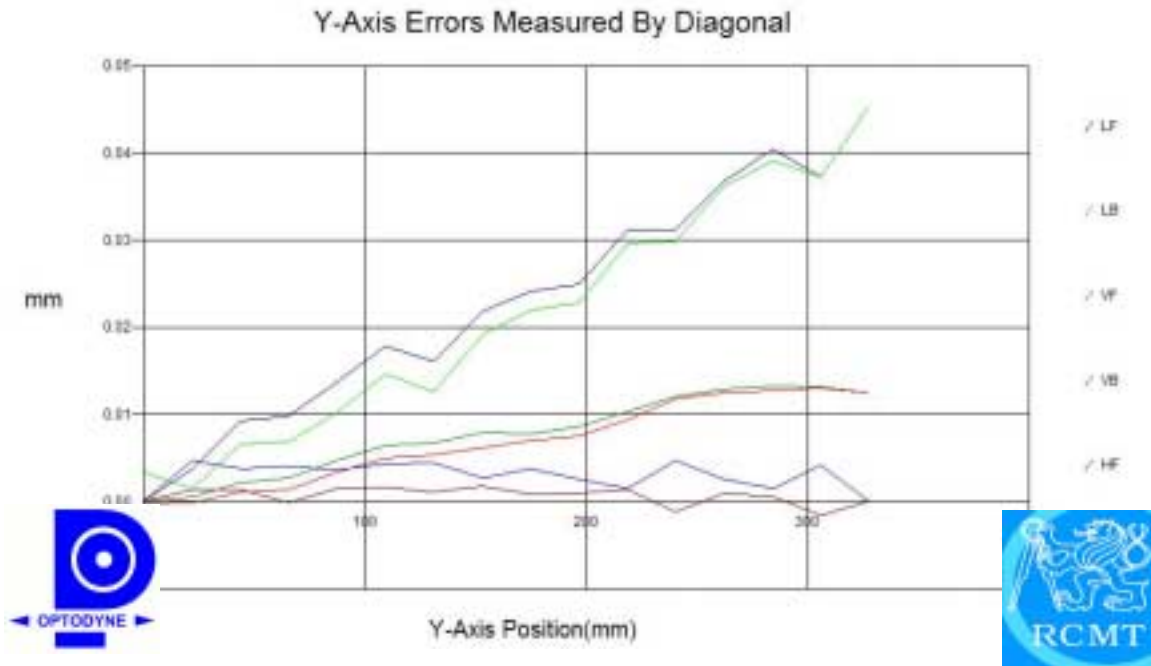
Fig. 5a Without compensation, the measured X-axis displacement error, vertical straightness error and horizontal straightness error.
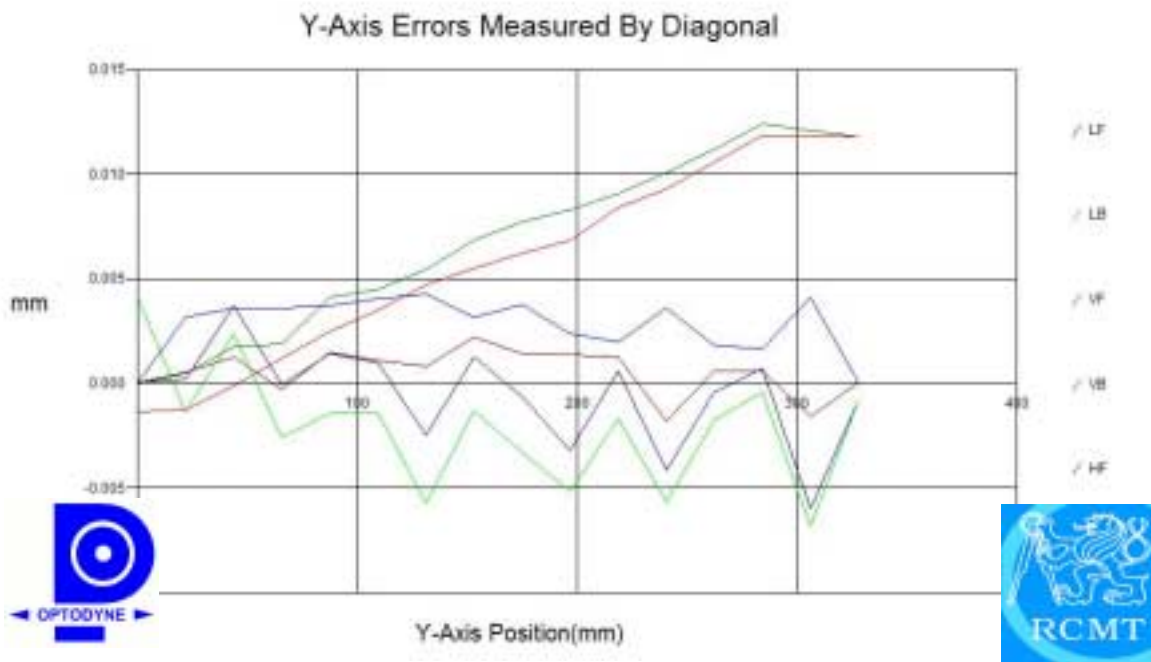
Fig. 5b Without compensation, the measured Y-axis displacement error, vertical straightness error and horizontal straightness error.

Fig. 5c Without compensation, the measured Z-axis displacement error, vertical straightness error and horizontal straightness error.
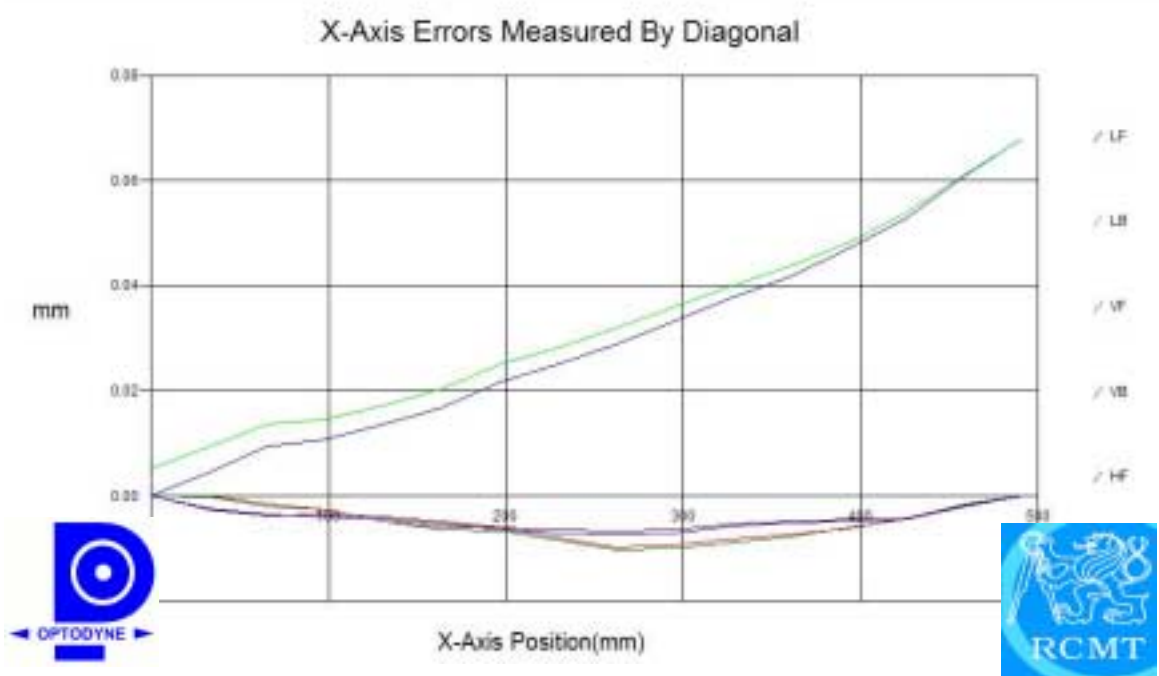
Fig. 6a With 0.2mm error added in Z-axis, the measured X-axis displacement error, vertical straightness error and horizontal straightness error.
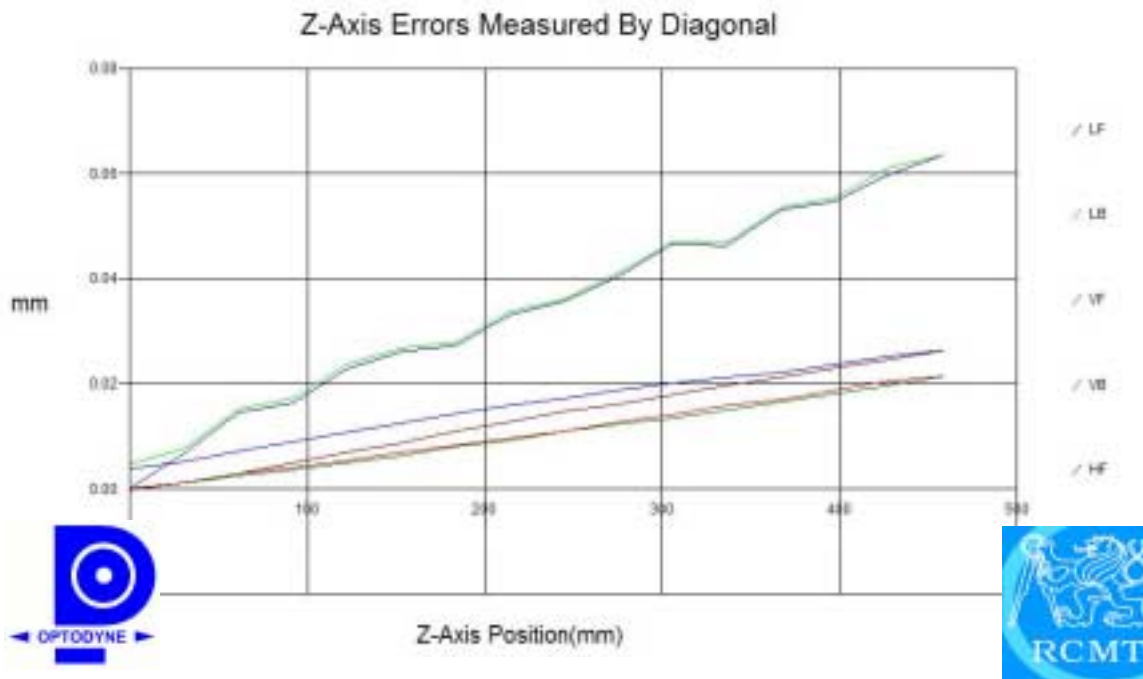
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Fig. 6b With 0.2mm error added in Z-axis, the measured
Y-axis displacement error, vertical straightness error and
horizontal straightness error.

Fig. 6c With 0.2mm error added in Z-axis, the measured
Z-axis displacement error, vertical straightness error and
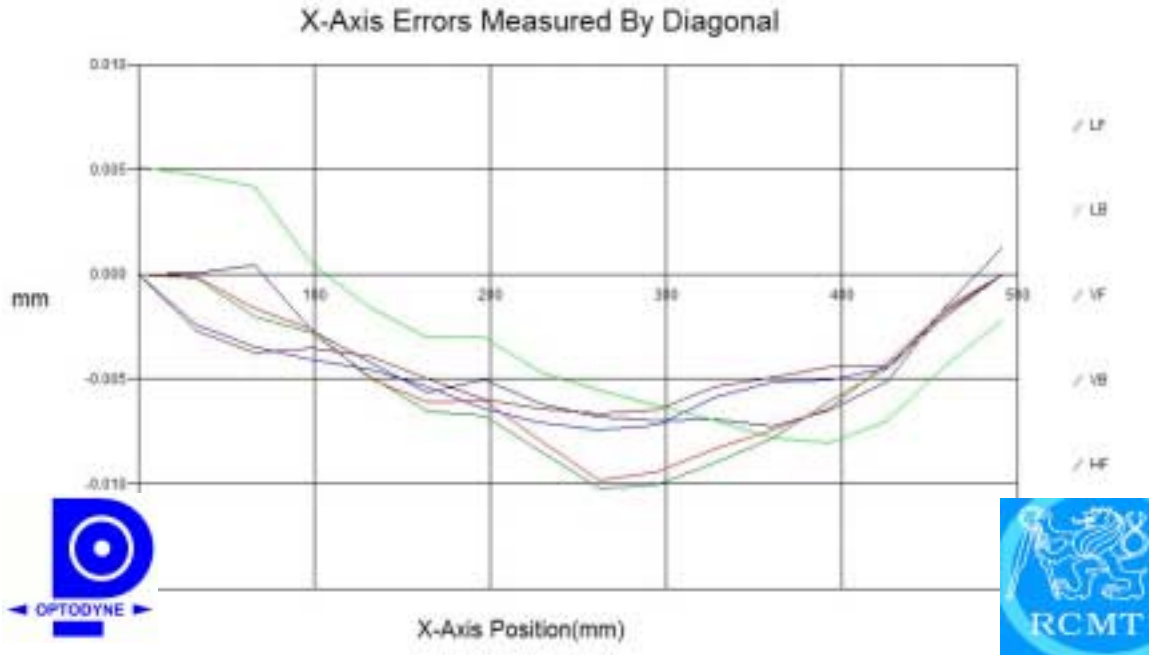horizontal straightness error.

Fig. 7a With 0.2mm error added in Z-axis and linear displacement data of X- and Y-axis, the measured X-axis displacement error, vertical straightness error and horizontal straightness error.
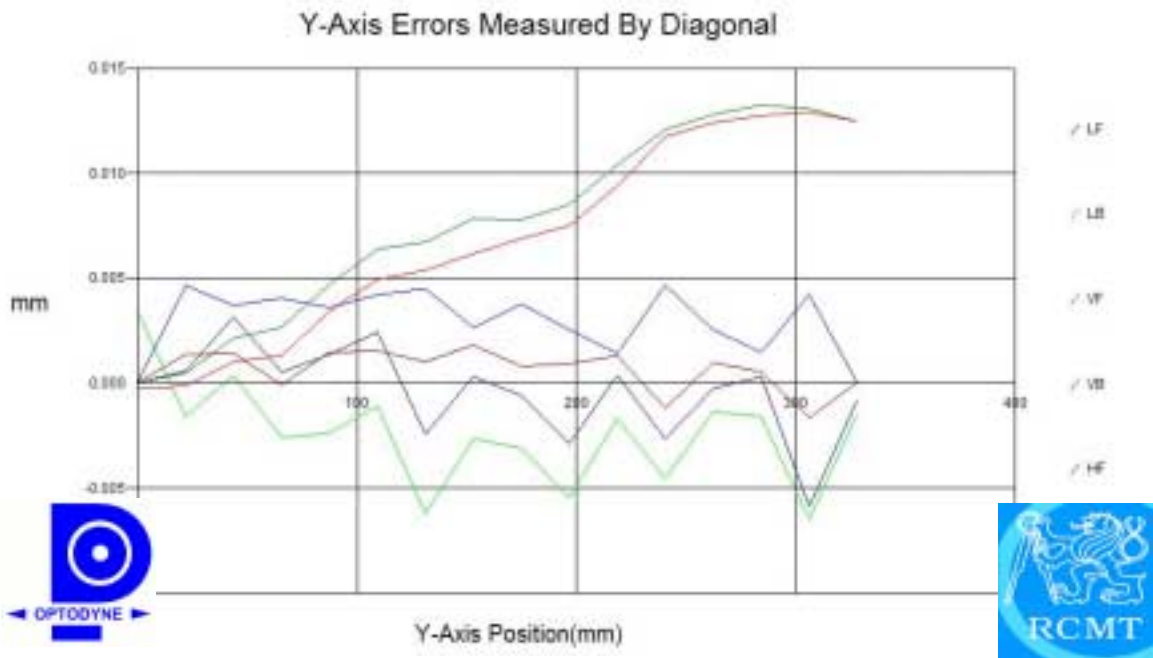

Fig. 7b With 0.2mm error added in Z-axis and linear displacement data of X- and Y-axis, the measured Y-axis displacement error, vertical straightness error and horizontal straightness error.
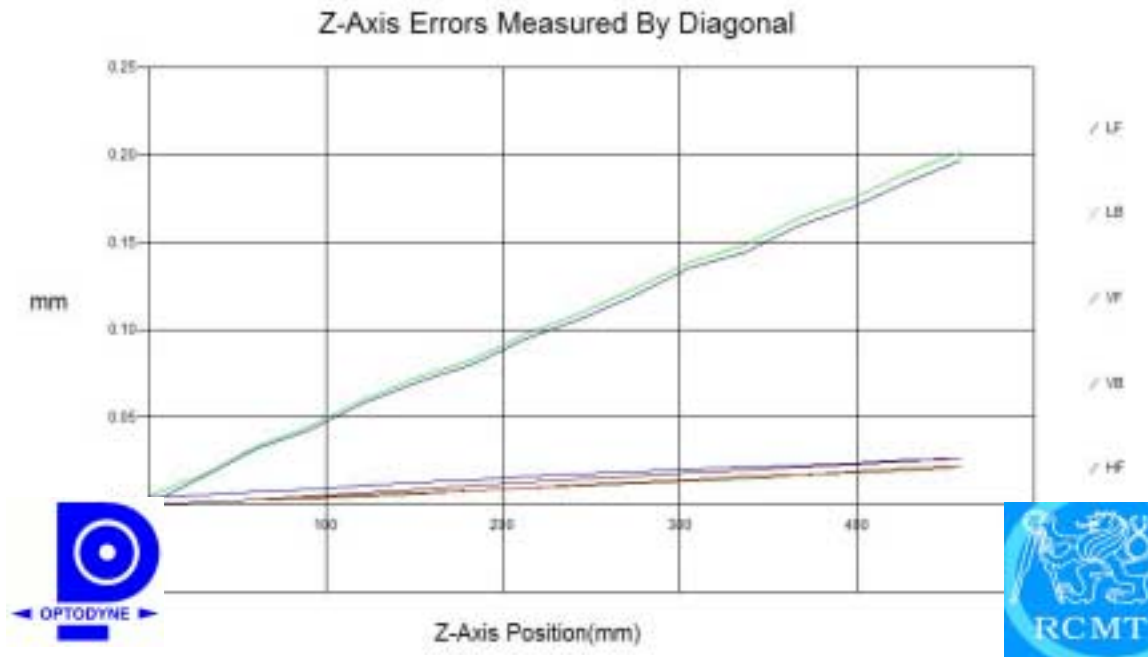
Fig. 7c With 0.2mm error added in Z-axis and linear displacement
data of X- and Y-axis, the measured Z-axis displacement error,
vertical straightness error and horizontal straightness error.