

# **A laser Non-contact Measurement of Static Positioning and Dynamic Contouring Accuracy of a CNC Machine tool**

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## **Abstract**

For accurate and fast machining, both the static volumetric positioning accuracy, including the 3 displacement errors, 6 straightness errors, and 3 squareness errors, and the dynamic contouring accuracy, including the errors due to the servo mismatch, servo lag, loop gain, acceleration and deceleration, are very important. Conventional measurement techniques, such as laser interferometers and telescoping ballbars, are complex, inefficient and time consuming.

Reported here are a new laser vector measurement technique for the measurement of the volumetric positioning accuracy and a laser/ballbar technique for the measurement of dynamic contouring accuracy. Measurements have been performed on a JOBS-LINKS 5-axis linear motor machine with the laser vector technique. The volumetric positioning accuracy has been improved by 300% with the volumetric compensation. The basic theory, the hardware, the data collection and processing, and the measurement results are described.

## **I. Introduction**

In order to improve the positioning accuracy of a machine tool it is important to measure the volumetric errors, including the linear displacement errors, the geometrical errors of straightness and squareness of all the 3 axes and the sag and deformation errors. The check of dynamic behavior completes the information on the machine status.

With the new generation of CNC machines, it is possible to obtain better performance machines even at better prices using the software compensations providing that the errors are repeatable and measurable. In this paper a new laser vector method for the measurement of the volumetric positioning errors of a machine tool or coordinate measuring machine (CMM) is described.

The laser vector method measures the vector errors, which are the linear displacement errors, the vertical straightness errors, the horizontal straightness errors, and squareness errors, instead of only the linear displacement errors measured by the conventional laser interferometer. It is also possible to measure the angular errors and the errors due to the sag or non-rigid body. The measured errors were used for the machine compensation to improve the accuracy. The basic concepts, the theory, the measurement errors, and the experimental verification are described.

The performance or the accuracy of a CNC machine tool is determined by 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.

The laser vector measurement techniques or in other words the method of *laser sequential diagonal measurement techniques* [2,3] can measure all those volumetric errors by using a Laser Doppler Displacement Meter (LDDM) which is a new generation of laser interferometer with a single beam and single aperture, and able to use a flat mirror as target.

## **II. Body Diagonal Displacement Measurement**

The body diagonal displacement measurement method is recommended for a fast examination of the positioning and geometrical performances of the machine in all its components. Practically it is the measurement of the volumetric positioning accuracy by a laser interferometer. A retroreflector is mounted on the spindle and illuminated by the laser beam, which is aligned along the machine diagonal, for example from the lower left corner ( $X=0$   $Y=0$   $Z=0$ ) to the upper right corner ( $X_{max}$ ,  $Y_{max}$ ,  $Z_{max}$ ). 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, and usually also by the machine geometry. 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 then 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. It is possible to determine the positioning errors for each one of the three axes.

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, then along the Y axis and then 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 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 either a standard corner cube or a flat mirror as target. It is noted that with a flat mirror as target, the movement parallel to the mirror does not displace the laser beam and does 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 a JOBS 5-axis machine**

The measurement was performed on a JOBS-LINKS COMPACT 5AX linear motor machine in the Piacenza facility. The machine working volume is 2 m by 3 m by 1 m (80" x 120" x 40"), and

the controller is Siemens 840D. Without any compensation, the volumetric errors were measured by the Vector method or sequential diagonal measurement. All the errors were measured and automatically generated the 24 error tables that allowed the global machine compensation. The verification of the compensation was performed with the body diagonal displacement measurement. The dynamic performance, and dynamic step verification were also performed.

## 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 align the laser beam parallel to the diagonal within 0.25 m rad or 1 mm at 4 m distance. 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 from one corner by X, Y, and Z sequences to the opposite corner. All the compensation in the CNC controller was turned off.

### 2. The laser measurement system

The positioning errors were measured by a single aperture laser Doppler displacement meter (LDDM). The Air temperature and pressure were measured to compensate the speed of light and the machine temperature were measured to compensate the machine thermal expansion.

### 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 results are shown in tables or graphic forms in Figs. 3, 4 and 5. The body diagonal displacement errors of the machine without and with volumetric compensation are shown in Fig.6 and 7 respectively. The total error without compensation was 90  $\mu\text{m}$  and with compensation was 30  $\mu\text{m}$ .

### 4. The generation of error compensation tables

At the end of the error analysis, the Windows LDDM software automatically generated the 24 bi-directional error tables, the SAG compensation tables. These compensation tables were loaded into the Siemens 840D CNC controller by a floppy disk.

The 24 compensation tables with 41 points each for a total of 984 points are:

3 tables for linear pitch error for X, Y and Z and 3 for the reverse travel;  
6 tables, (2 each axis) for the straightness of X, Y, and Z axes and 6 for the reverse travel;  
3 tables for the gantry (AX10) axis compensation ( AX10 moves together and parallel to AX1) and 3 for the reverse travel.

The following is an example of the compensation file

```
%_N_NC_CEC_INI

CHANDATA(1)
$AN_CEC[0,0]=0.0000
$AN_CEC[0,1]=+0.0001
$AN_CEC[0,2]=+0.0000
.....

$AN_CEC[0,37]=-0.0019
$AN_CEC[0,38]=-0.0016
$AN_CEC[0,39]=-0.0025
$AN_CEC[0,40]=-0.0037
```

```

$AN_CEC_INPUT_AXIS[0]=(AX1)
$AN_CEC_OUTPUT_AXIS[0]=(AX1)
$AN_CEC_STEP[0]=+50.0000
$AN_CEC_MIN[0]=-2100.0000
$AN_CEC_MAX[0]=-100.0000
$AN_CEC_DIRECTION[0]=1
$AN_CEC_MULT_BY_TABLE[0]=0
$AN_CEC_IS_MODULO[0]=0
$AN_CEC[1,0]=+0.0008
$AN_CEC[1,1]=+0.0006
$AN_CEC[1,2]=+0.0007
$AN_CEC[1,3]=+0.0007
$AN_CEC[1,4]=+0.0029

.....

.....

$AN_CEC[23,33]=-0.0021
$AN_CEC[23,34]=-0.0041
$AN_CEC[23,35]=-0.0053
$AN_CEC[23,36]=-0.0056
$AN_CEC[23,37]=-0.0060
$AN_CEC[23,38]=-0.0061
$AN_CEC[23,39]=-0.0084
$AN_CEC[23,40]=-0.0085
$AN_CEC_INPUT_AXIS[23]=(AX3)
$AN_CEC_OUTPUT_AXIS[23]=(AX10)
$AN_CEC_STEP[23]=+25.0000
$AN_CEC_MIN[23]=-1125.0000
$AN_CEC_MAX[23]=-125.0000
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$AN_CEC_MULT_BY_TABLE[23]=0
$AN_CEC_IS_MODULO[23]=0
M17

```

**5. Measurement errors in the laser sequential diagonal measurement**

The accuracy of the laser system is very high, better than 1ppm, the typical error sources are: alignment errors or cosine error, errors due to the temperatures and pressure measurement. The error in the sequential diagonal measurements that are typical of the vector method: Flat mirror alignment error, this depends on the misalignment errors and the step size. The error can be quite large, but it is constant and is removed by the software. Angular error, the reflector may not be in the center of rotation of the machine and may generate a large error that is measured together with the linear and straightness error. It is possible to determine the rotational angles by changing the measurement sequence without to change the laser alignment. The rotational errors cannot be used for the compensation in most of the CNC controllers.

**VI. Laser circular contouring and dynamic step measurement**

A noncontact laser technique for circular contouring accuracy measurement were performed. The same single aperture laser head was used with a long flat-mirror target as shown in Fig. 8. The major features are the measurement is noncontact; the circular path radius can be varied continuously from less than 1 mm to 150 mm; the feed rate is up to 4 m/s; the data rate is up to 1000 Hz; and the actual radius, feed rate, velocity, and acceleration profiles can also be determined. For more detailed description of the theory and the setup see Ref [4]. A typical measured circular contour with diagnosis output is shown in Fig. 9. The circular contour was

measured in the XY-plan and the diameter was 50 mm. The feed rate was 5000 mm/min (200 in/min) and the data rate was 250 Hz. The measured non-roundness was 24  $\mu\text{m}$ .

To measure the dynamic performance with high acceleration and sharp turns, a rapid step back and forth movement is measured with a data rate of 1000 Hz. The measured travel of 1000 mm (40") is shown in Fig. 10, the maximum velocity +/- 845 mm/sec is shown in Fig. 11, and the maximum acceleration +/- 4348 mm/sec/sec is shown in Fig. 12.

## VII. Summary and conclusion

In summary, we have demonstrated that with the laser vector measurement and the volumetric compensation, the volumetric positioning accuracy of a JOBS 5-axis machine with a working volume of 6 cubic meters can be improved by more than 300%.

Furthermore, the laser vector measurement only took 4/8 hours instead of 24/40 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. The laser circular contouring measurement can be used to measure the dynamic performance and to tune the servo controller.

## 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, 1992, p69.
- [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, October 2000.
- [3] G. Liotto and C. Wang , " Laser Doppler Displacement Meter (LDDM) allow new diagonal measurement for large aspect ratio machine tool easily and accurately", Proceedings of LAMDAMAP International Conference of Laser Metrology and Machine Performance, Huddersfield, West Yorkshire England, 15-17 July, 1997.
- [4] C. Wang and B. Griffin, "A noncontact laser technique for circular contouring accuracy measurement", Review of Scientific Instruments, Vol. 72, No. 2, February 2001.

## Figure caption

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.
2. A photo of 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 90  $\mu\text{m}$  (0.0022").

7. Four body diagonal displacement errors measured with volumetric compensation. The total error is reduced to 30  $\mu\text{m}$  (0.0007), a 300% improvement.
8. A photo of the circular contouring measurement setup with the laser on the table and the long flat mirror on the spindle.
9. A polar plot of the circular contouring accuracy with all the errors tabulated.
10. Plot of the displacement of a rapid step forward and back movement.
11. Plot of the velocity of the same movement.
12. Plot of the acceleration of the same movement.



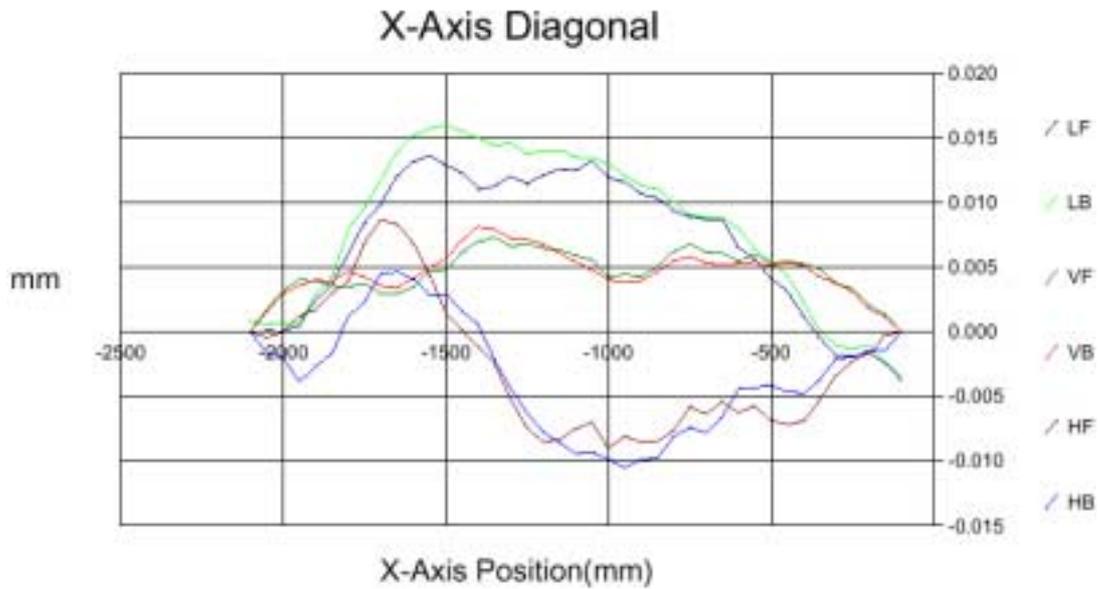


Fig. 3 X-axis errors, the upper curves are the bi-directional displacement error, the curves in the middle are the straightness error in y-direction and the lower curves are the straightness error in the z-direction.

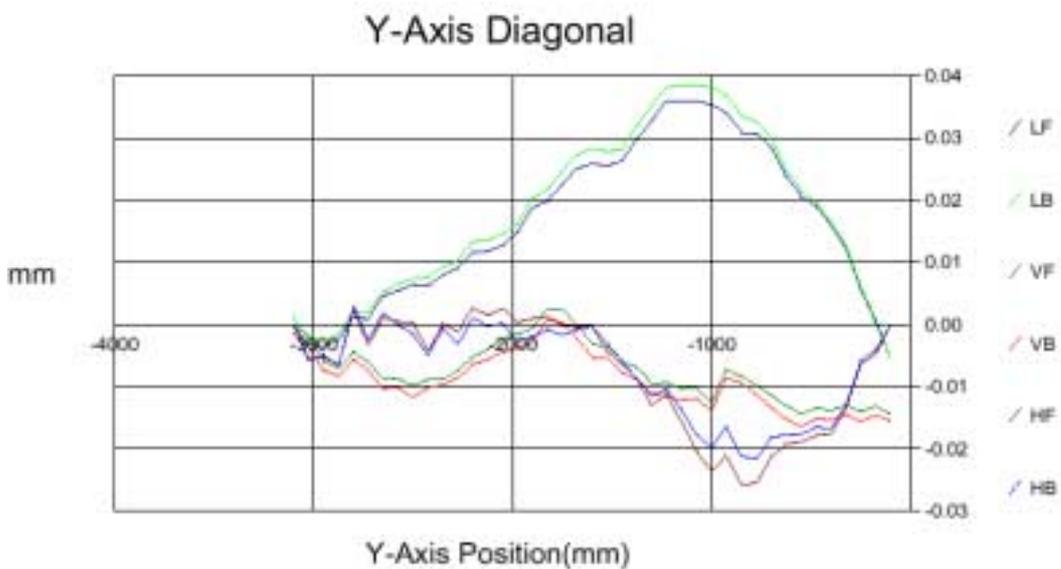


Fig. 4 Y-axis errors, the upper curve is the bi-directional displacement error, and the lower curves are the straightness error in x-direction and z-direction respectively.

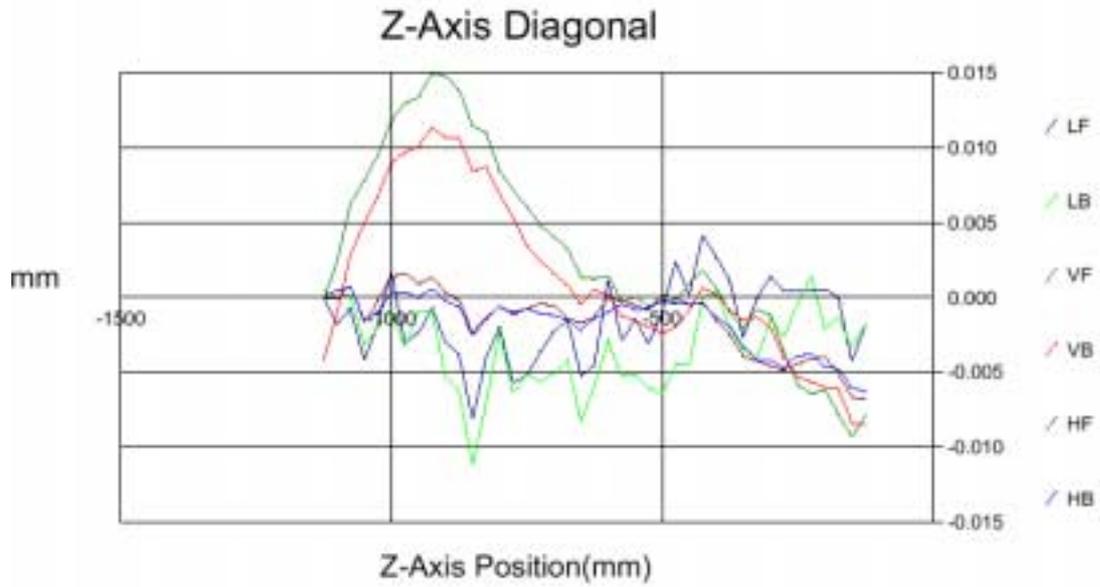


Fig. 5 Z-axis errors, the upper curve is the bi-directional displacement error, and the lower curves are the straightness error in the x-direction and y-direction respectively.

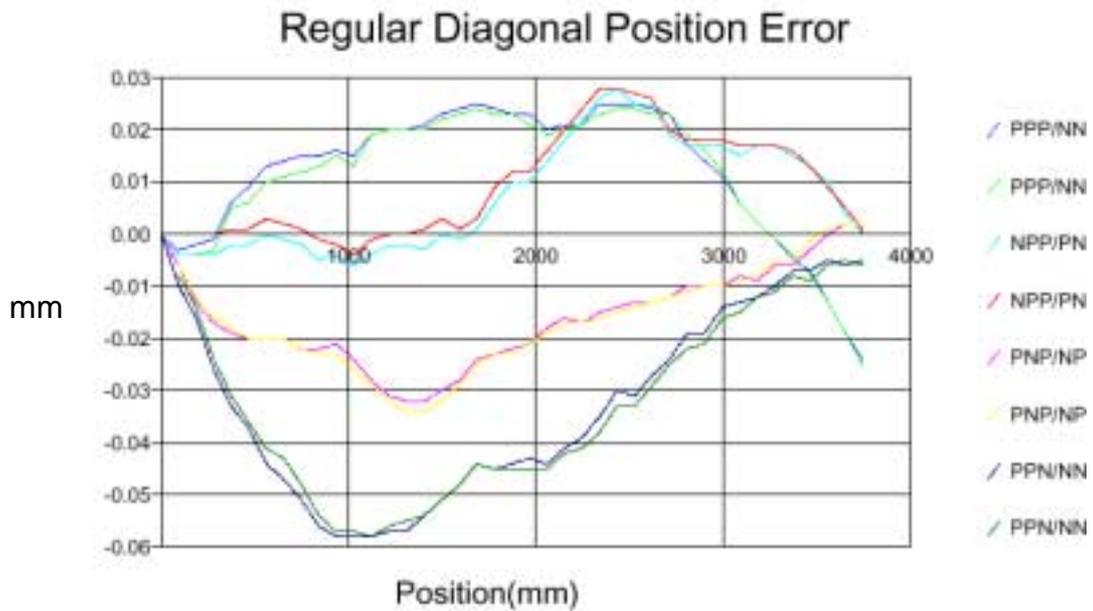


Fig. 6 Four body diagonal displacement errors without compensation. The total error is  $90 \mu\text{m}$  ( $0.0022''$ ).

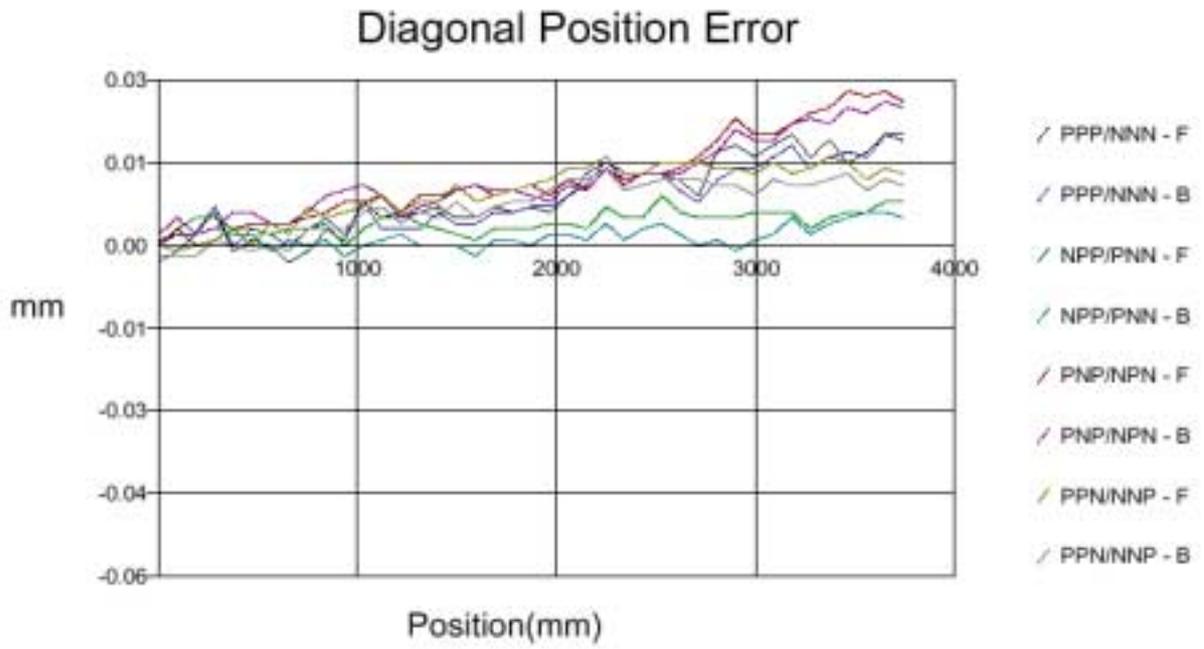


Fig. 7 Four body diagonal displacement errors measured with volumetric compensation. The total error is reduced to 30  $\mu\text{m}$  (0.0007), a 300% improvement.

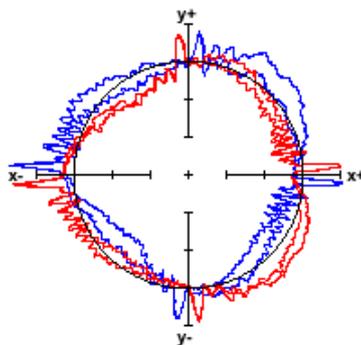


Fig. 8 A photo of the circular contouring measurement setup with the laser on the table and the long flat mirror on the spindle.

# PolarCheck

ISO 230-4  
Version: 2.3.0

Customer:		Plane:	xy
Machine:		Feedrate:	5011 mm/min
Measurement Session:		Ball Bar Length:	50.003 mm
Date:	10/18/01	Best Radius:	50.003 mm
Measured By:	Liotto	Sampling Rate:	125.2043
File Name:	JOBSXY2.RTB	Maximum Targets:	471
Origin of Measurement:	x:0 , y:0 , z:0	Calibration:	Calibrated
Circularity LSC:	25 $\mu\text{m}$	Circularity MZC:	24 $\mu\text{m}$
Scale Error (x-y):	-12 $\mu\text{m}/\text{m}$	Servo Mismatch (x-y):	0 %
Squareness Error:	8 $\mu\text{m}/\text{m}$	Random Vibration:	0 $\mu\text{m}$
		Directional Vibration:	9 $\mu\text{m}$ (163°)
Axis Spike x:	0 $\mu\text{m}$	Axis Spike y:	0 $\mu\text{m}$
Backlash Step x+:	-4 $\mu\text{m}$	Backlash Step y+:	0 $\mu\text{m}$
Backlash Step x-:	8 $\mu\text{m}$	Backlash Step y-:	2 $\mu\text{m}$
Cyclic Error x:	2 $\mu\text{m}$	Cyclic Error y:	1 $\mu\text{m}$
Pitch x:	38 mm	Pitch y:	
Lateral Play x:	0 $\mu\text{m}$	Lateral Play y:	1 $\mu\text{m}$
Scale Error x:	-10 $\mu\text{m}/\text{m}$	Scale Error y:	2 $\mu\text{m}/\text{m}$
Stick Slip x:	5 $\mu\text{m}$	Stick Slip y:	
Straightness x:	1 $\mu\text{m}$	Straightness y:	10 $\mu\text{m}$



CW

CCW

Scale 10  $\mu\text{m}$

Fig. 9 A polar plot of the circular contouring accuracy with all the errors tabulated.

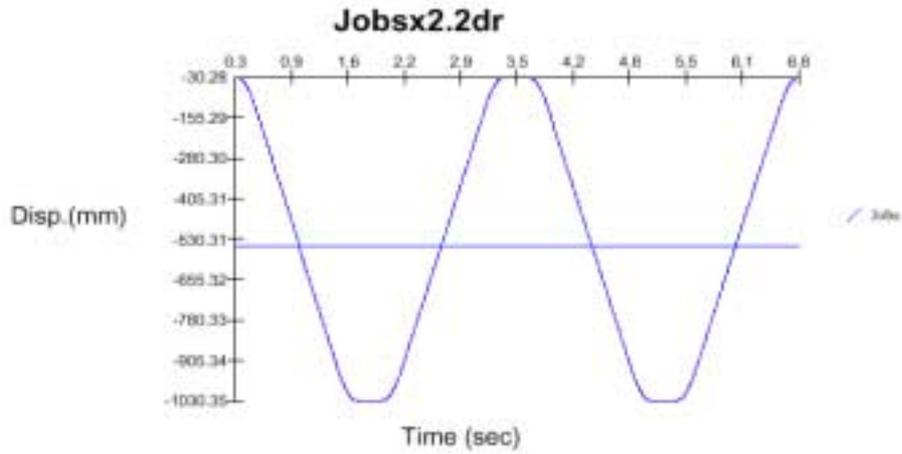


Fig. 10 Plot of the displacement of a rapid step forward and back movement.



Fig. 11 Plot of the velocity of the same movement.

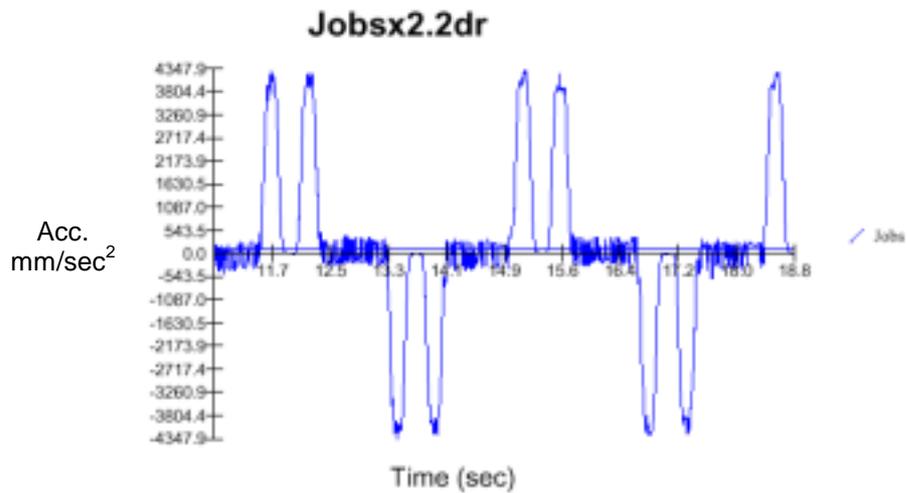


Fig. 12 Plot of the acceleration of the same movement.