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An advanced 6-degree-of-freedom laser system for quick CNC machine and CMM error mapping and compensation

K. Lau, Q. Ma, X. Chu, Y. Liu, S. Olson
Automated Precision Inc., Gaithersburg, MD 20879, USA

Abstract

It is well understood that if one wants to measure all geometric error components (i.e. linear, straightness, pitch, yaw, roll and squareness) of a 3 axes CNC machine tool using a conventional laser interferometer system [1,2], it may take somewhere between 2 to 3 days to complete. To measure each error component, the laser is required to setup and align with the appropriate optics, and each measurement has to be done independently. The entire process requires some 20+ measurement runs and some of the runs may have to be repeated since the environmental conditions may have changed since the first run. This process is so tedious and time-consuming that very often, component measurements are limited to linear only. Other parameters like straightness, squareness, and angles, although known to be equally important, are generally ignored.

Since the successful introduction of the 5-Degree-of-Freedom (5-D) laser measuring system in 1996, and the 6-D laser[1] [3] in 1998, the generally perception of geometric error measurements and performance evaluation of machine tools has altered significantly. The new 6-D laser offers tremendous time saving by allowing an operator to setup and measure all 6-D errors (i.e. linear, straightness in Y and Z, plus pitch, yaw and roll angles) of a rectilinear axis simultaneously. Squareness measurement is readily achieved with the use of a penta-prism while measuring the perpendicular axis. In addition, alignment of the laser is made easy with the compact, on-machine mounting design and the build-in fine adjustments.

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[1] Patent Pending

Compared to a conventional laser system, the time saving can be as much as 75%, or about a half day for a complete geometric error measurement of a typical machine. Although the precision of the 6-D laser is generally comparable with the conventional systems, the measurements do gain robustness simply because of the much reduced measurement time. As such, there is a growing interest in the machine tool and CMM communities to use the 6-D laser to do quick machine error mapping and compensation.

2 Principle Of Operations And Applications

Figure 1 shows the configuration of the API's 6-D laser system for both the regular 6DLS and the precision 6DLSP models. Figure 2 shows the configuration of a high precision 6DLSH model. Each system consists of a laser head, an interferometer module, a sensor head and a laser controller. The high precision model utilizes a polarization maintaining fiber collimator as the interferometer module. It offers high degree of flexibility, compactness and heat isolation. The interferometer of the regular or the precision unit can also be removed for heat isolation.

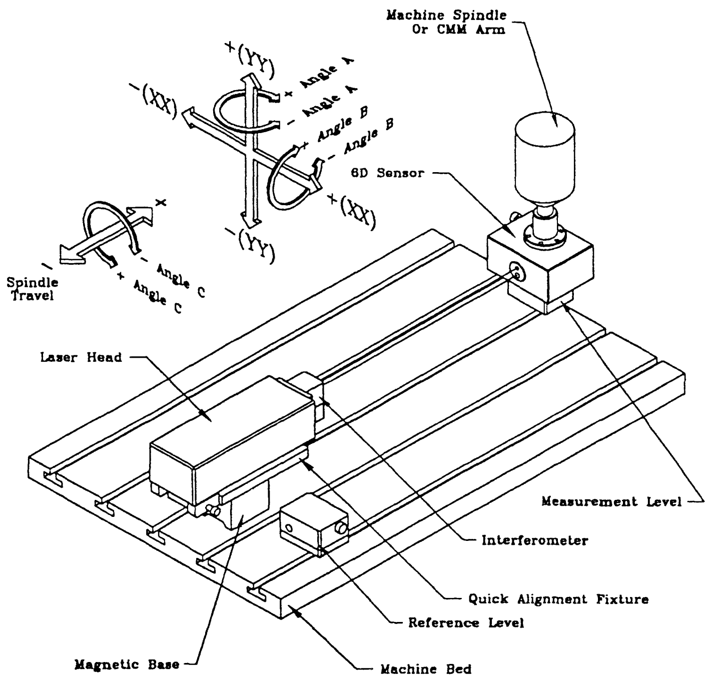

Figure 1. An API 6-D Laser System

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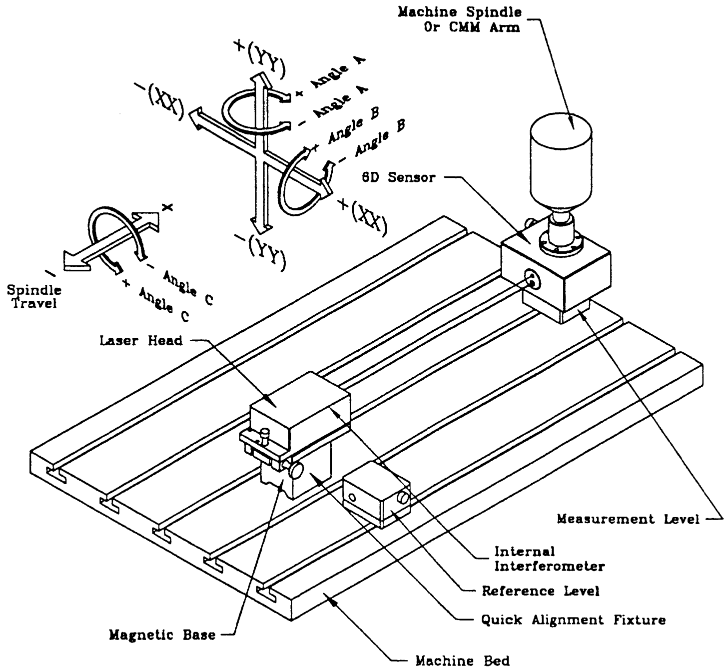

Figure 2. A High Precision Laser Interferometer Setup (Laser head not shown)

2.1 Principle of operations

The laser head (or interferometer module) emits a highly stabilized and collimated laser beam to be aligned with the machine axis. Inside the sensor head, the laser beam is split into three paths (figure 3), one for the vertical and horizontal straightness measurements, one for the pitch and yaw angle measurements, and one for linear distance measurement. Both the straightness and angle measurements are achieved with precision optics and a lateral effect photo-detector.

A pair of precision electronic levels is used to provide roll measurements between the laser head and the sensor. With one of the levels mounted on the sensor and the other on the laser head, the pair provides pure roll measurements of the sensor by eliminating inadvertent roll of the machine or its foundation. Such can be caused by the change of weight distribution of the machine as the axis travels.

Although the laser and sensor designs are optimized to yield the highest precision as possible, it is important to realize that, like all laser systems, the environmental effects can play a major role in governing the final performance of the measurement results. For practical considerations, a 0.5 ppm linear

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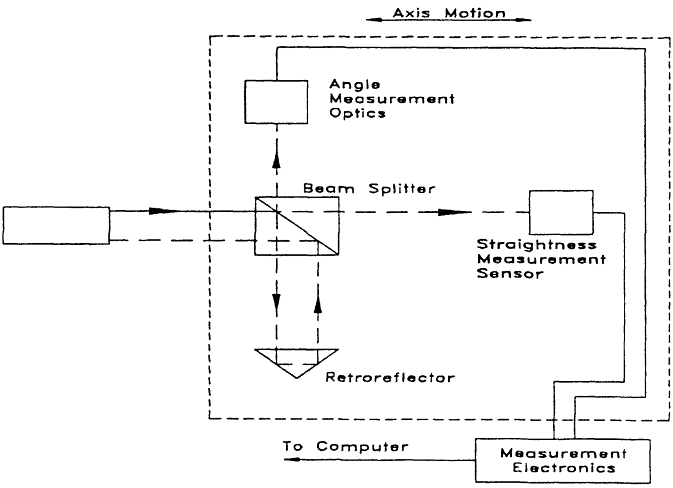

Figure 3. A 5-D Sensor Head

accuracy is probably the best one can expect to obtain in a typical uncontrolled shop floor environment. Our test also indicated that with the high precision interferometer module, the beam pointing stability can fluctuate by as much as 30 μm (p-p) at 31 meters distance. The test was conducted in a typical manufacturing environment over a period of 4 hours. The same test for the precision unit sees a 55 μm (p-p) fluctuation at 31 meters.

The table below shows the specifications of the regular, precision and high precision models:

Accuracy	Regular	Precision	High Precision
Linear (ppm)	1.0	0.2	0.2
Pitch & Yaw (arc-second) Max. range (arc-second)	± (1.0 ± 0.1/m) or 1% display whichever greater +/- 800	± (0.5± 0.05/m) or 1% display whichever greater +/- 400	± (0.2 ± 0.02/m) +/- 50
Roll (arc-second)	+/- 1.0	+/- 0.5	+/- 0.5
Straightness (μm) Max. range (μm)	± (1.0 ± 0.2/m) or 1% display whichever greater +/- 500	± (0.5± 0.1/m) or 1% display whichever greater +/- 300	± (0.2 ± 0.05/m) +/- 100
Squareness (arc-second)	+/- 1	+/- 0.5	+/- 0.5
Temperature (°C)	0.2	0.1	0.1
Humidity (%)	5	3	3
Pressure (mmHg)	1	0.3	0.3

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2.2 Flatness measurement application

In additional to the linear, straightness, angular and squareness measuring functions, the 6-D laser system is also well suited for table flatness measurement, rotary axis calibration and axis parallelism measurement. Figure 4 illustrates the using of a 5-/6-D system for flatness calibration of a table. Unlike a conventional laser system, the 5-/6-D system relies on the straightness sensor to measuring the flatness, not the angle sensor. The advantage of it is the ability of getting a one-to-one correspondence measurement of the surface flatness, which is far superior to the angle measurement.

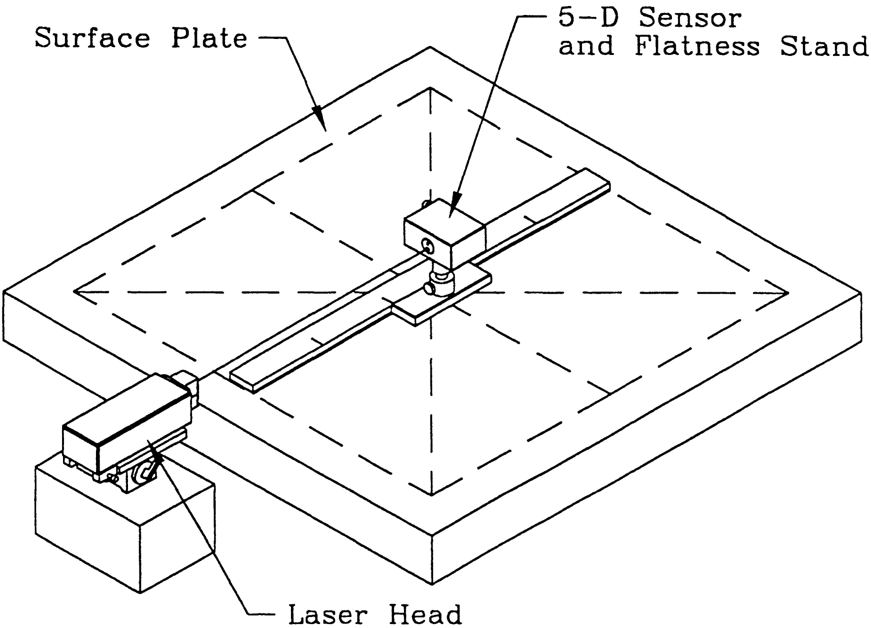

Figure 4. Flatness Measurement using a 5/6-D Laser

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2.3 Rotary measurement application

Figure 5a illustrates a 5-/6-D laser setup with a precision 12-face or 36-face polygon for rotary table calibration. For much finer interval of calibration, one may choose to use a motorized unit (figure 5b). As the table rotates, the motorized unit, which is controlled by the laser controller, counter-rotates the mirror at top by the same nominal amount. A precision rotary encoder mounted on the axis of the unit measures the amount of counter-rotation. This amount is then combined with the angle output of the sensor to yield the true rotation of the table. The accuracy of this measurement is +/- 1 arc-second.

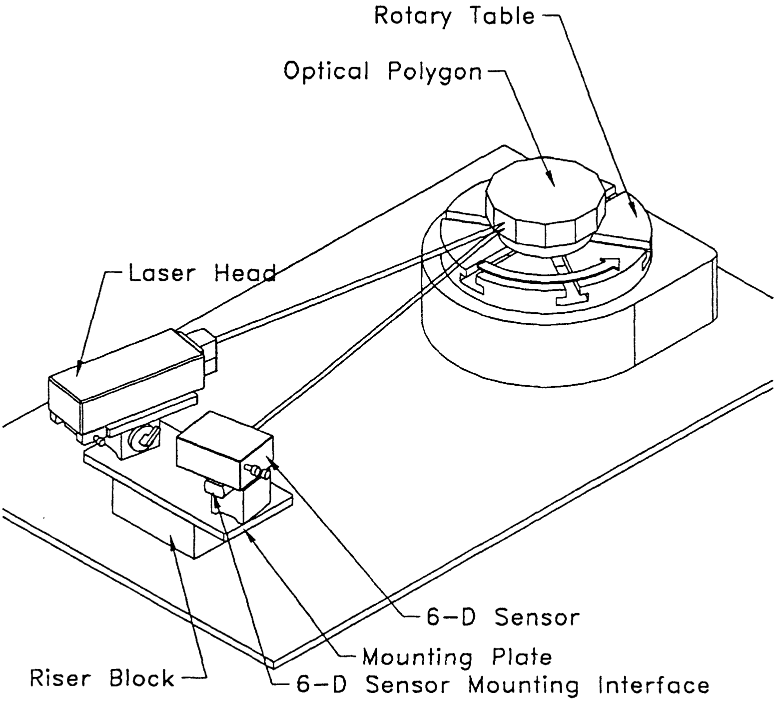

Figure 5a. Rotary Table Measurement with a Polygon

2.4 Parallelism measurement application

Traditionally precision parallelism measurement is a non-trivial process. The 5-D or 6-D laser system solves this problem with the use of a precision penta-prism and an electronic level, both can be provided as optional accessories. Figure 6 illustrates the setup of a 5-D system for the axis parallelism measurement of a pair of precision guideways. The system begins with the establishment of the alignment of the first guideway as reference. Then the laser

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beam is transferred to the second guideway by moving the penta-prism and the electronic level to the second guideway. Again, the beam is aligned in the same manner as the first and the straightness measurement is taken. By combining the straightness measurements of the two guideways, the parallelism is found. Such a measurement has an accuracy of +/- 1 arc-second.

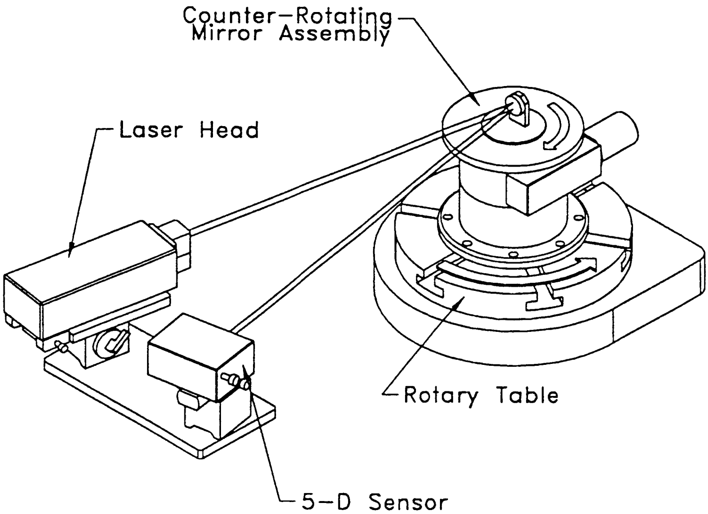

Figure 5b. Motorized Rotary Table Measurement

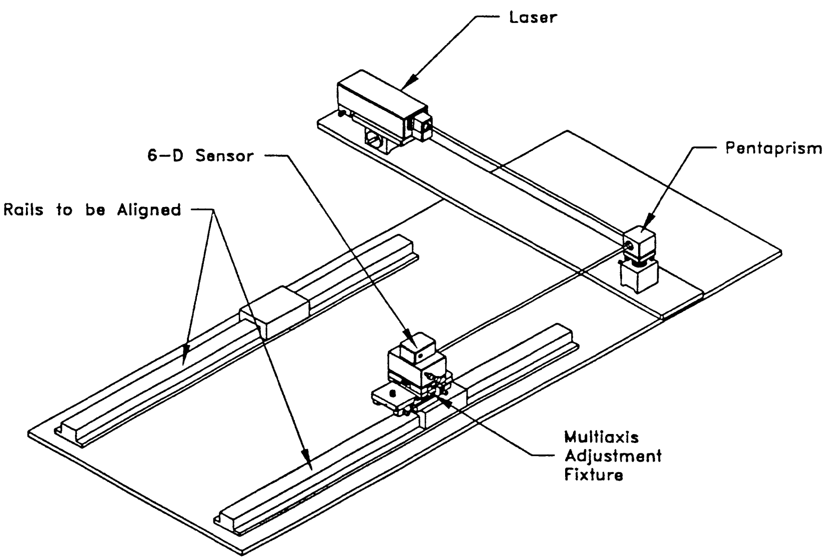

Figure 6. Parallelism Measurement

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3. Procedures and Algorithms For Quick Machine Error Mapping

Machine volumetric error mapping involves the establishment of the positioning errors of the cutting tool tip and the workpiece in the 3-dimensional space of the machine. The vectorial errors can be represented by a combination of all the individual error components of the machine.

With the assumption of a rigid body, there are a total of 21 error components for a 3-axis Cartesian coordinate machine. These are the 6-D (linear, δY, δZ, pitch, yaw and roll) error components for each of the axis, plus the 3 squareness errors, one for each coordinate plane. Table 3-1 lists the denotation of the error components and the measuring procedures.

The general formula of the error model is as the following:

$$P_R := P - \Delta \qquad (1)$$

$$\Delta := A_L(P) + A_A(P) \cdot P + A_T(P) \cdot T$$

where:

- P_R: corrected machine position vector;
- P: original machine position vector;
- Δ: errors at position P.
- T: tool offset vector;
- $A_L(P)$: linear geometry factor matrix;
- $A_A(P)$: angle geometry factor matrix;
- $A_T(P)$: tool geometry factor matrix.

$$P_R := \begin{bmatrix} X_R \\ Y_R \\ Z_R \end{bmatrix}$$ corrected positions

$$P := \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$ 3-axis readings

$$T := \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix}$$ tools offset

$$A_L(P) := \begin{bmatrix} O_{LX} \\ O_{LY} \\ O_{LZ} \end{bmatrix}$$ linear geometry factor

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$$A_A(P) := \begin{bmatrix} O_{A1X} & O_{A2X} & O_{A3X} \\ O_{A1Y} & O_{A2Y} & O_{A3Y} \\ O_{A1Z} & O_{A2Z} & O_{A3Z} \end{bmatrix} \quad \text{angle geometry factor}$$

$$A_T(P) := \begin{bmatrix} O_{T1X} & O_{T2X} & O_{T3X} \\ O_{T1Y} & O_{T2Y} & O_{T3Y} \\ O_{T1Z} & O_{T2Z} & O_{T3Z} \end{bmatrix} \quad \text{tool geometry factor}$$

The elements of the matrices $A_L(P)$, $A_A(P)$, and $A_T(P)$ are functions of the 21 geometric error components of the machine. The 5-/6-D laser measuring results will be fitted into a polynomial equation for each error term. The coefficients of the polynomial equations and the equation of the volumetric error model are transferred to the machine controller. During the machining operation, the controller retrieves the parameters and calculates the volumetric error compensation in real-time.

The procedures for the quick error mapping of a 3-axes vertical spindle machine are:

1. Measure the 6-D error components of the first horizontal axis, i.e. X-axis.
2. Measure the second horizontal axis (i.e. Y-axis) with the use of a penta-prism without removing the laser. In that way, the squareness of the XY plane is also obtained.
3. Measure the vertical, Z-axis, by rotating the penta-prism upward. This also helps to establish the squareness information of the XZ plane.
4. Align the laser in the Y-direction, repeat (2) and (3) to establish the squareness information of the YZ plane.
5. Enter the data into the volumetric error model and establish the coefficients of the model.
6. Establish a compensation algorithm in the machine controller using the error coefficients.
7. Verify the performance of the model by re-measuring the axes while the controller is implementing the compensation algorithm.
8. Verify the squareness compensation with a mechanical square.
9. Verify the full-body volumetric compensation by running the four body diagonal measurements.

No	Description	Symbol	Procedures
1	X linear error (scale)	$\delta_x(X)$	6-D Laser
2	Y Straightness of X axis	$\delta_y(X)$	
3	Z straightness of X axis	$\delta_z(X)$	
4	pitch of X axis	$\varepsilon_y(X)$	
5	yaw of X axis	$\varepsilon_z(X)$	
6	roll of X axis	$\varepsilon_x(X)$	
7	Y linear error (scale)	$\delta_y(Y)$	6-D Laser
8	X Straightness of Y axis	$\delta_x(Y)$	
9	Z straightness of Y axis	$\delta_z(Y)$	
10	pitch of Y axis	$\varepsilon_x(Y)$	
11	yaw of Y axis	$\varepsilon_z(Y)$	
12	roll of Y axis	$\varepsilon_y(Y)$	
13	Z linear error (scale)	$\delta_z(Z)$	6-D Laser
14	X Straightness of Z axis	$\delta_x(Z)$	
15	Y straightness of Z axis	$\delta_y(Z)$	
16	pitch of Z axis	$\varepsilon_x(Z)$	
17	yaw of Z axis	$\varepsilon_y(Z)$	
18	roll of Z axis	$\varepsilon_z(Z)$	Straight edge
19	Squareness in the XY plane	α_{XY}	Penta-prism
20	Squareness in the YZ plane	α_{YZ}	Penta-prism
21	Squareness in the ZX plane	α_{ZX}	Penta-prism

Table 3-1. Geometric Error Components of a 3-Axis Machine

4.0 Examples Of Error Map And Compensation

A 3-axis CNC machine was error mapped using the 6D laser system. The elements of the matrices $A_L(P)$, $A_A(P)$, and $A_T(P)$ were determined based on the machine structure. Refer to the denotation of the error terms above:

$$A_L(P) := \begin{bmatrix} \delta x(Z) - \delta x(X) + \delta x(Y) \\ \delta y(Z) - \delta y(X) + \delta y(Y) \\ \delta z(Z) - \delta z(X) + \delta z(Y) \end{bmatrix}$$

is the linear geometry factor;

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$$A_A(P) := \begin{bmatrix} 0 & \varepsilon z(X) - \varepsilon z(Z) - \alpha xy & -\varepsilon y(X) - \alpha zx \\ \varepsilon z(X) & 0 & \varepsilon x(X) \\ -\varepsilon y(X) & \varepsilon x(Z) - \varepsilon x(X) - \alpha yz & 0 \end{bmatrix}$$

is the angle geometry factor; and

$$A_T(P) := \begin{bmatrix} 0 & -\varepsilon z(Z) - \varepsilon z(Y) + \varepsilon z(X) & \varepsilon y(Z) + \varepsilon y(Y) - \varepsilon y(X) \\ -\varepsilon z(X) + \varepsilon z(Y) + \varepsilon z(Z) & 0 & -\varepsilon x(Z) + \varepsilon x(X) + \varepsilon x(Y) \\ \varepsilon y(X) - \varepsilon y(Y) - \varepsilon y(Z) & \varepsilon x(X) + \varepsilon x(Y) + \varepsilon x(Z) & 0 \end{bmatrix}$$

is the tool geometry factor.

The error model is as follow:

$$\begin{bmatrix} X_R \\ Y_R \\ Z_R \end{bmatrix} := \begin{bmatrix} \delta x(Z) - \alpha zx \cdot Z - X - \delta x(X) - \varepsilon y(X)\cdot Z + \delta x(Y) - \alpha xy\cdot Y - \varepsilon z(Z)\cdot Y + \varepsilon z(X)\cdot Y \\ \varepsilon z(X)\cdot X + \delta y(Z) - \delta y(X) + \varepsilon x(X)\cdot Z + Y + \delta y(Y) \\ -\varepsilon y(X)\cdot X + Z + \delta z(Z) - \delta z(X) - \varepsilon x(X)\cdot Y + \varepsilon x(Z)\cdot Y + \delta z(Y) - \alpha yz\cdot Y \end{bmatrix}$$

$$+ \begin{bmatrix} X_t - Y_t\cdot\varepsilon z(Z) - Y_t\cdot\varepsilon z(Y) + Y_t\cdot\varepsilon z(X) + Z_t\cdot\varepsilon y(Z) + Z_t\cdot\varepsilon y(Y) - Z_t\cdot\varepsilon y(X) \\ -X_t\cdot\varepsilon z(X) + X_t\cdot\varepsilon z(Y) + X_t\cdot\varepsilon z(Z) + Y_t - Z_t\cdot\varepsilon x(Z) + Z_t\cdot\varepsilon x(X) + Z_t\cdot\varepsilon x(Y) \\ X_t\cdot\varepsilon y(X) - X_t\cdot\varepsilon y(Y) - X_t\cdot\varepsilon y(Z) + Y_t\cdot\varepsilon x(X) + Y_t\cdot\varepsilon x(Y) + Y_t\cdot\varepsilon x(Z) + Z_t \end{bmatrix}$$

The 5/6D laser measuring results were fitted into a polynomial equation for each error term. The formula of the polynomial equation is:

$$\delta_x(X) = C1*(X-A) + C2*(X-A)^2 + C3*(X-A)^3$$

The curve fitting coefficients are listed in table 4-1. Figure 7 shows the comparison of a body diagonal measurement with and without the geometric error compensation. The position accuracy was improved from 0.0030" to 0.0005", a factor of 6 improvement.

No	Description	Symbol	A	sign	C1	C2	C3	C4
1	X linear error scale	$\delta_x(X)$	21.6456	+	0.32173	-0.00144	-5.7502E-04	0
2	Y Straightnes s of X axis	'$\delta_y(X)$	21.6456	-	0.05223	-0.00709	-1.799E-04	0
3	Z straightness of X axis	$\delta_z(X)$	21.6456	-	0	0	0	0
4	pitch of X axis	$\varepsilon_y(X)$	21.6456	+	-0.28132	0	0	0
5	yaw of X axis	$\varepsilon_z(X)$	21.6456	+	0.35924	-0.00283	-4.6539E-04	0
6	roll of X axis	$\varepsilon_x(X)$	21.6456	+	-0.09604	-0.01261	9.6143E-05	2.9E-05
7	Y linear error (scale)	$\delta_y(Y)$	26.3	-	0.41061	-0.00953	-6.6048E-04	0
8	X Straightnes s of Y axis	$\delta_x(Y)$	26.3	-	-0.18334	0.01627	7.3431E-04	0
9	Z straightness of Y axis	$\delta_z(Y)$	26.3	-	0.00122	-0.00238	0	0
10	pitch of Y axis	$\varepsilon_x(Y)$	26.3	-	0.21795	0	0	0
11	yaw of Y axis	$\varepsilon_z(Y)$	26.3	+	0.02988	-0.01924	-1.5118E-03	0
12	roll of Y axis	$\varepsilon_y(Y)$	26.3	not available				
13	Z linear error (scale)	$\delta_z(Z)$	15.7	-	-0.10147	0	0	0
14	X Straightnes s of Z axis	$\delta_x(Z)$	15.7	+	6.87317 E-5	-0.00754	0	0
15	Y straightness of Z axis	$\delta_y(Z)$	15.7	+	-0.38975	-0.03923	2.5431E-03	0
16	pitch of Z axis	$\varepsilon_x(Z)$	15.7	+	-0.09142	-0.00211	0	0
17	yaw of Z axis	$\varepsilon_y(Z)$	15.7	+	-0.10033	0.00387	0	0
18	roll of Z axis	$\varepsilon_z(Z)$	15.7	+	0.15120	-0.00523	0	0
19	squareness in XY planes	α_{XY}	32.7"					
20	squareness in YZ planes	α_{YZ}	-4.7"					
21	squareness in ZX planes	α_{ZX}	2.7"					

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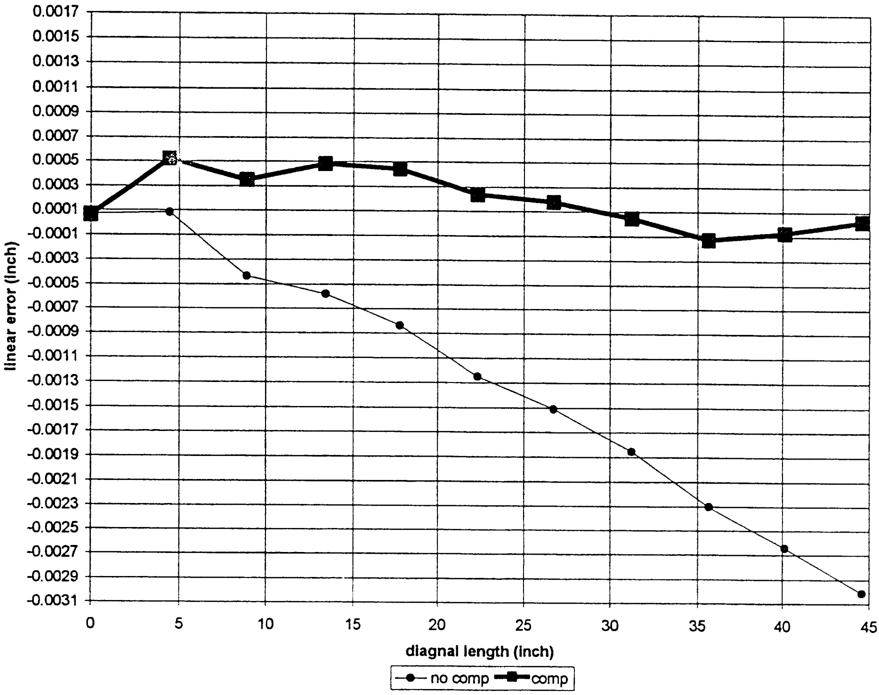

Figure 7: Comparison of Diagonal Measurement Results

5.0 Conclusion

From machine performance evaluation to machine quick error mapping, the new API 5-/6-D laser system offers tremendous cost and timesaving over the conventional laser interferometer system, and with comparable precision. The compactness and ease of use of the 5-/6-D system also lends itself for frequent in-house and field calibrations, predictive maintenance of CNC machine tools and routine CMM calibrations. More and more advanced applications of the 6-D system are being developed. Current applications include flatness measurement, rotary measurement and parallelism measurement. The new 5-/6-D laser system has generated a whole new thinking about machine tool and CMM metrology far beyond the boundary defined by the conventional laser interferometer system.

References

[1] Hewlett Packard Company Model 5517A Laser Interferometer Manual.

[2] Renishaw Inc. Model ML10 Laser Interferometer Manual.

[3] Automated Precision, Inc. Model 5D6DLS Laser Measuring System Manual.