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Laser vector measurement technique for the determination and compensation of volumetric position errors. Part II: Experimental verification

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A Giddings and Lewis, model RAM 630 horizontal machine center was used to verify the laser vector measurement technique. The repeatability of the machine and the repeatability of the vector measurements were verified over a six month period. A compensation file was generated based on the laser vector measurement technique and the body diagonal measurements were used to check the volumetric accuracy of the machine. The results indicated that a gain of a factor of 3-4 in accuracy was achieved with the volumetric compensation than without compensation. The time required to compensate for the machine using the laser vector measurement technique is significantly less than that using conventional measurement procedures. © 2000 *American Institute of Physics.* [S0034-6748(00)04110-1]

I. INTRODUCTION

The basic concept and theory of the laser vector measurement technique for the determination of the volumetric positioning errors of a computer numerically controlled (CNC) machine tool, a coordinate measuring machine (CMM), or a precision instrument are described in Part I of this article.' To experimentally verify the theory, extensive measurements and testing over a period of six months have been performed at Giddings and Lewis (G & L) Machine Tools on a RAM 630 machining center.'` A laser Doppler displacement meter (LDDMTM) model MCV-500 linear calibration systems with a diagonal steering mirror and a 3 in. X4 in. flat-mirror target as used.

The repeatability of the machine and the repeatability of the laser vector measurement technique have been checked. Comparisons with conventional measurement results 4 and the effect of volumetric compensation have been studied. The results are described in the following.

II. MEASUREMENT SETUP

A. Machine description

The Giddings and Lewis RAM 630 machining center is a horizontal milling machine. The machine is considered machine type XFYZ, where the axis slides are stacked as pallet (x) to floor (F) to headstock (Y) to ram (Z). The machine configuration is shown below.

Error measurements and compensation are done for the three linear axes; the rotary table axis is not included. The error measurement and compensation envelope consists of X = 500 mm, Y = 500 mm, and Z= 500 mm. The headstock hydraulic pad compensation feature used to correct ram pitch error is normally the only compensation active during implementation of volumetric measurements. No other compensations are used. The machine accuracy was measured by laser interferometers and the angular errors are less than a few arcsec.

B. Setup description

For the testing here, the respective coordinates are X: from -240 to 260 mm, Y: from 253 to 753 mm, Z: from 160 to 660 mm. The laser head was mounted on the machine bed using a steering mirror to point the laser beam in the diagonal direction. The flat mirror was mounted in the spindle and the mirror surface was perpendicular to the laser beam, shown in Fig. 1. The machine was programmed to move the spindle starting from one corner to the opposite corner. The laser beam is aligned to parallel to the spindle diagonal motion. Typical alignment tolerance was less than 0.5 mrad or 0.5 mm over a distance of 1 m.

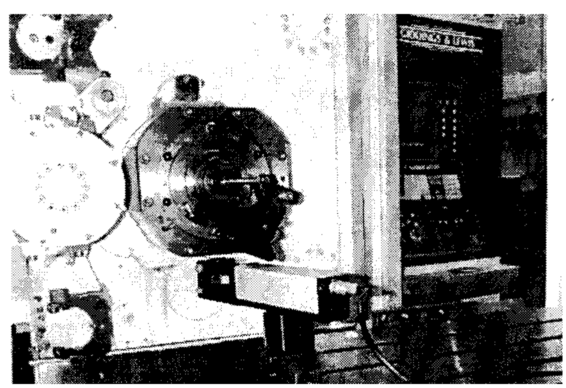

FIG. 1. Photo of the Giddings and Lewis RAM 630 machining center with the laser head mounted on the pallet and the flat-mirror target in the spindle.

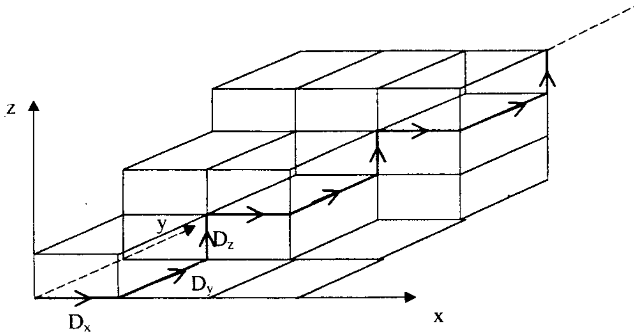

FIG. 2. Schematic illustrating the sequential diagonal path.

C. Description of the sequential step diagonal path

The machine spindle is programmed to move in a diagonal path within the working volume, starting from one corner at the base plan and moving to the opposite corner at the top plan. There are eight body diagonals. We define the eight body diagonals by the positive or negative axis movement. For example, ppp means from the starting corner (smallest machine coordinates) to the opposite corner (largest machine coordinates); all three axes move with positive increments. The *npn* means from the starting corner (largest x-axis coordinate, smallest machine y-axis coordinate, and largest z-axis coordinate) to the opposite corner (smallest x-axis coordinate, largest machine y-axis coordinate, and smallest z-axis coordinate), the y-axis moves with positive increments and the x axis and z axis move with negative increments. The eight body diagonals are *ppp, npp, pnp, ppn, nnn, pnn, npn,* and *nnp.* The last four body diagonals are the same corners as the first four diagonals except the directions are reversed. Hence, there are only four body diagonal directions with
forward movement and reverse movement (bidirectional).

More specifically, first define the starting point (Xs, Ys, and Zs) and the end point *(Xe, Ye, Ze)* for the first diagonal ppp. The working volume is defined by *(Xe-Xs)*(Ye - Ys) * (Ze - Zs) . The* number of increments per axis is *n* and the total number of increments is *3n.* The measurement increments X, Y, and Z, which are limited by the size of the flat mirror, and the number of steps per axis *n,* are determined by the following relations:

X=(Xe-Xs)ln, *Y=(Ye-Ys)ln,*

and

Z=(Ze-Zs)ln.

The machine spindle is programmed to move in an XYZ sequence as shown in Fig. 2, that is, starting from (Xs, Ys, and Zs). More X in the x direction at a feed rate F (usually between 20% and 80% of the maximum feed rate). Stop for a dwell time of T seconds (usually 1-5 s, depending on the machine structure), then move Y in the y direction at the same feed rate and stop for the same dwell time, then move Z in the z direction at the same feed rate and dwell time. Continue the sequence until the opposite corner is reached. For bidirectional data, reverse sequence to ZYX back on the diagonal path. For this diagonal, since all three increments are positive, we call this ppp, and the reverse *nnn.* For the

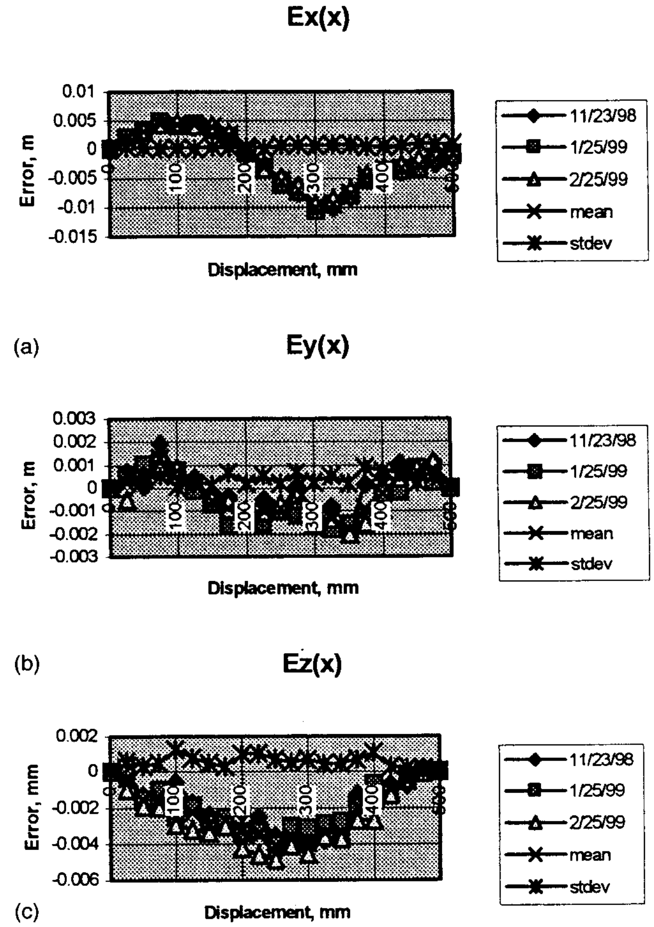

FIG. 3. (a) Volumetric error components $Ex(x)$ measured on 11/23/98, 1/25/99, and 2/25/99 plotted together and with the mean and standard deviation values. Similar plots for (b) $Ey(x)$ and (c) $Ez(x)$.

second diagonal, *npp* or the reverse *pnn,* change the starting point to *Xe, Ys,* and Zs and the increments to -X, Y, and Z. Similarly, for the third diagonal *npn* the starting point *is Xe, Ys, Ze* with increments of -X, Y, and -Z. For the fourth diagonal *ppn* the starting point *is Xs, Ys, Ze* with increments of X, Y, and - Z.

For most of the tests here the working volume is 500 mm X 500 mm *X* 500 mm. The increments are X = 25 mm, Y= 25 mm, and Z= 25 mm, and the number of steps *is n = 20.*

D. Data collection and processing

Using the Optodyne WindowsTM software, [3] the data collections are automatic. Once the data from each diagonal are collected, click on the four diagonal in the analysis portion of the program and enter all four files, and the volumetric errors for the x-axis motion, y-axis motion, and z-axis motion can be calculated and plotted. The results can be saved as output files to generate compensation files.

E. Machine compensation procedure

First measure the volumetric positioning errors of the machine without compensation. Use the analysis software to calculate the volumetric positioning errors and save the data in an output file. Use an appropriate program to convert the

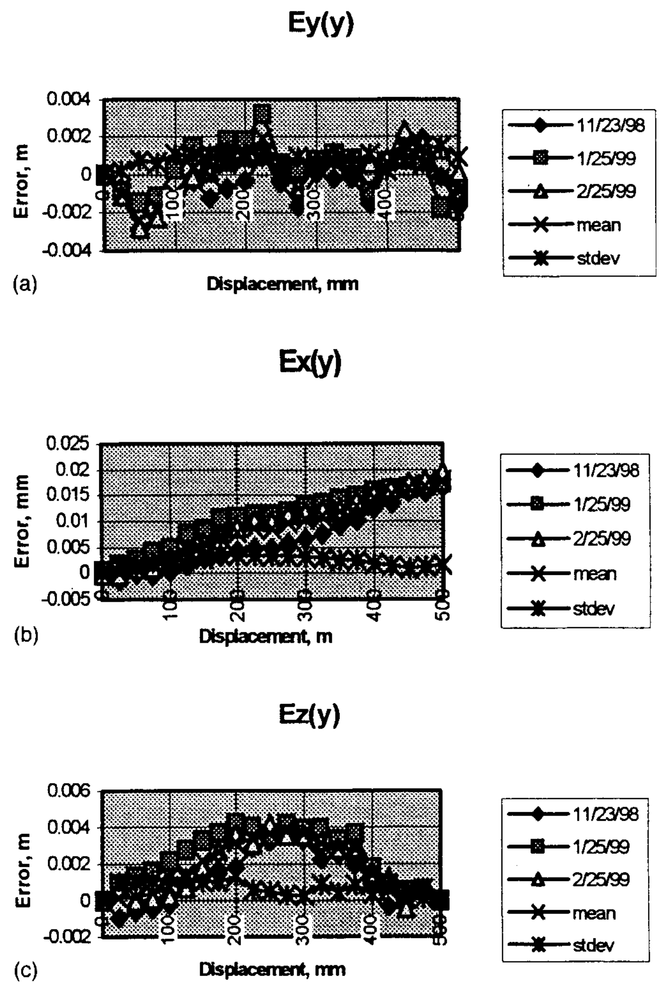

FIG. 4. (a) Volumetric error components $Ey(y)$ measured on 11/23/98, 1/25/99, and 2/25/99 plotted together and with the mean and standard deviation values. Similar plots for (b) $Ex(y)$ and (c) $Ez(y)$.

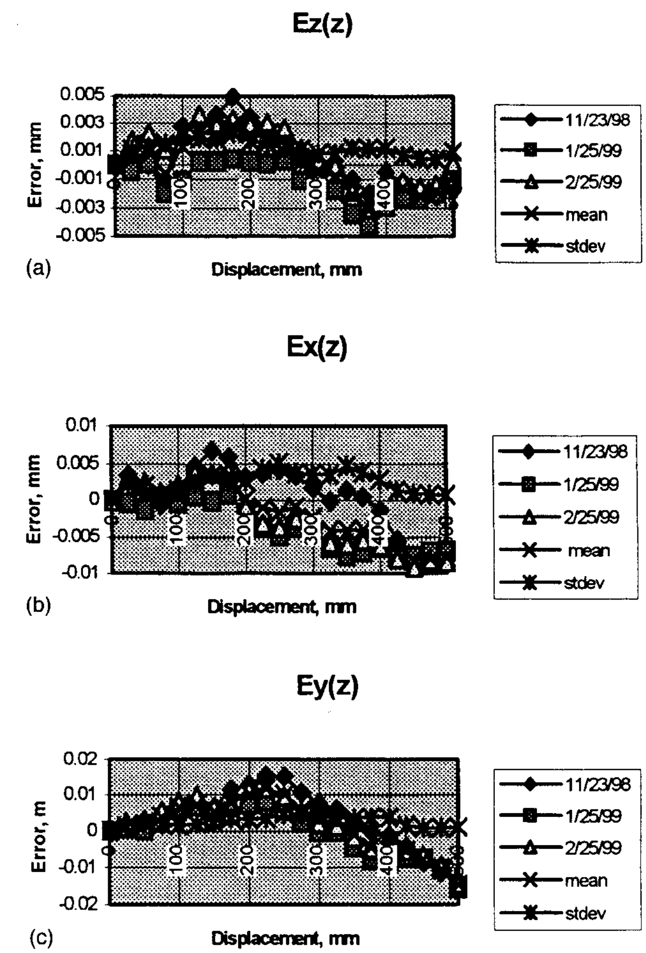

FIG. 5. (a) Volumetric error components $Ez(z)$ measured on 11/23/98, 1/25/99, and 2/25/99 plotted together and with the mean and standard deviation values. Similar plots for (b) $Ex(z)$ and (c) $Ey(z)$.

volumetric positioning error data to the required format for the machine compensation. Load the compensation files to the machine controller. Using the conventional diagonal measurement, 4 check the volumetric positioning accuracy with the machine compensation turned on.

III. ENVIRONMENT CONDITIONS

The machine is located in a machine assembly area where the room temperature does not vary more than ±2 °C. The machine was in a stable thermal condition in which the hydraulic and lubrication systems were on and the spindle not operated during the 8 h period prior to taking measurements. The machine was properly mounted on the floor where ground vibrations are small.

IV. MACHINE AND MEASUREMENT REPEATABILITY

Three sets of vector measurement were performed on 11/23/98, 1/25/99, and 2/25/99. The linear errors, including the displacement errors, vertical straightness errors, and horizontal straightness errors for x-axis movement, y-axis movement, and z-axis movement were measured. To check the repeatability, the results of the measurements on 11/23/98, 1/25/99, and 2/25/99 were plotted in the same graph together with the mean and the standard deviations. For x-axis motion, the linear error *Ex(x),* the vertical straightness error *Ey(x),* and the horizontal straightness error *Ez(x)* are plotted in Figs. 3(a)-3(c), respectively.

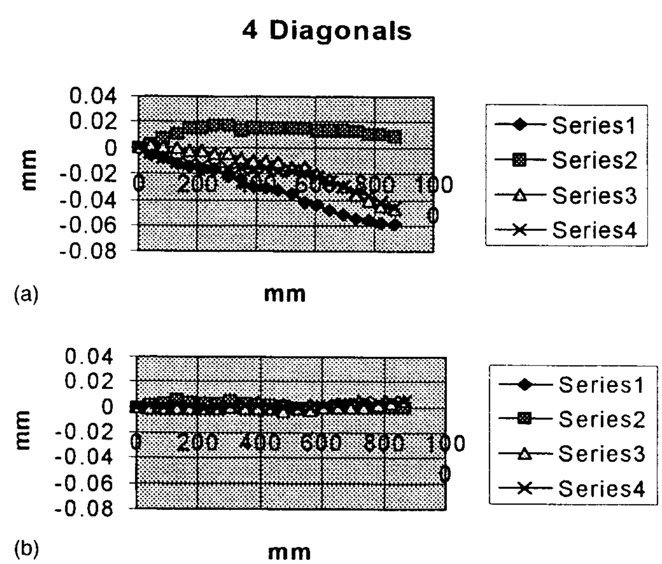

FIG. 6. Plots of conventional body diagonal measurement (a) without compensation and (b) with compensation.

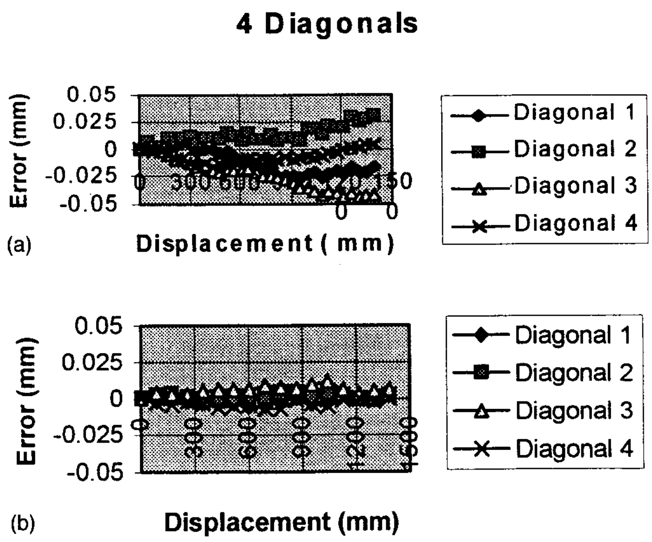

FIG. 7. Plots of conventional body diagonal measurements (a) without compensation and (b) with compensation (800 mm cube).

As shown in Fig. 3, the maximum positive error is about 0.005 mm, the minimum negative error is about -0.010 mm, and the repeatability is about 0.001 mm.

For the y-axis motion and z-axis motion also, the errors are plotted in Figs. 4 and 5, respectively. The maximum positive error is about 0.020 mm, the minimum negative error is about -0.015 mm, and the overall repeatability is less than 0.005 mm. Since the repeatability was measured over a three month period and in different environments using different setups and operators, we believe the repeatability of the vector measurement should be much better than 0.005 mm.

V. VOLUMETRIC POSITIONING ACCURACY

After the repeatability of the process was demonstrated, as discussed in Sec. IV, another RAM 630 machine was selected and the entire measurement and compensation process was completed in approximately 4 h.

The volumetric positioning errors of the machine were first measured by the vector method without compensation. Then the measured volumetric positioning errors, *Ex(x), Ey(x), Ez(x), Ey(y), Ex(y), Ez(y), Ez(z), Ex(z),* and *Ey(z),* were used to generate the compensation files. The compensation files were loaded into the controller of the machine. The volumetric accuracy of the machine was checked by the conventional body diagonal measurement. The body diagonal displacement errors measured without compensation are plotted in Fig. 6(a) and the same measurements with compensation are plotted in Fig. 6(b). The four diagonal displacement errors without compensation are 50 µm and the four diagonal displacement errors with compensation are 14 µm. Hence a significant improvement in diagonal accuracy is achieved.

VI. LARGE WORK ZONE

The measurements made on the RAM 630 machine previously discussed utilized a measurement cube of X = 500 mm, Y = 500 nun, and Z= 500 mm. To further demonstrate the utility of the vector method a larger machine was also tested. A horizontal spindle machine, type *FXZY,* using a measurement cube of X = 800 mm, Y = 800 mm, and Z = 800 mm was tested and the resulting conventional body diagonal displacement errors are shown in Fig. 7(a) without compensation and in Fig. 7(b) with volumetric compensation. The diagonal displacement errors without compensation are 53 µm and with compensation are 14 µm. Since the volumetric compensation worked for both type XFYZ and *FXZY* machine tools, this is a good indication that the basic theory and the assumptions used are essentially correct for most CNC machine tools and precision instruments.

VII. DISCUSSION

The experimental tests showed that (1) the overall repeatability due to both the machine tool and the measurement method over a three month period was 0.005 mm. (2) To compensate for the machine tool using the error components obtained by the vector measurement, the diagonal displacement errors are reduced from 50 to 14 µm, a factor of 4 improvement. (3) The fact that the volumetric compensation works is a good indication that the basic theory and the assumptions used are essentially correct for most CNC machine tools. Finally, (4) using a conventional laser interferometer to measure the volumetric errors and to verify the compensation performance usually 16-20 h is needed whereas using the vector method, it only takes 4 h.

[1]C. Wang, Rev. Sci. Instrum. 71, 3933 (2000).
[2]RAM 630 User's Guide, Giddings and Lewis, Fond du Lac, WI (1998).
[3]LDDM MCV-500 User's Guide. Optodyne, Compton. CA (1999).
4An American National Standard, ASME B5.54-1922. of the American Society of Mechanical Engineers (1992).