Laser Metrology and Machine Performance III

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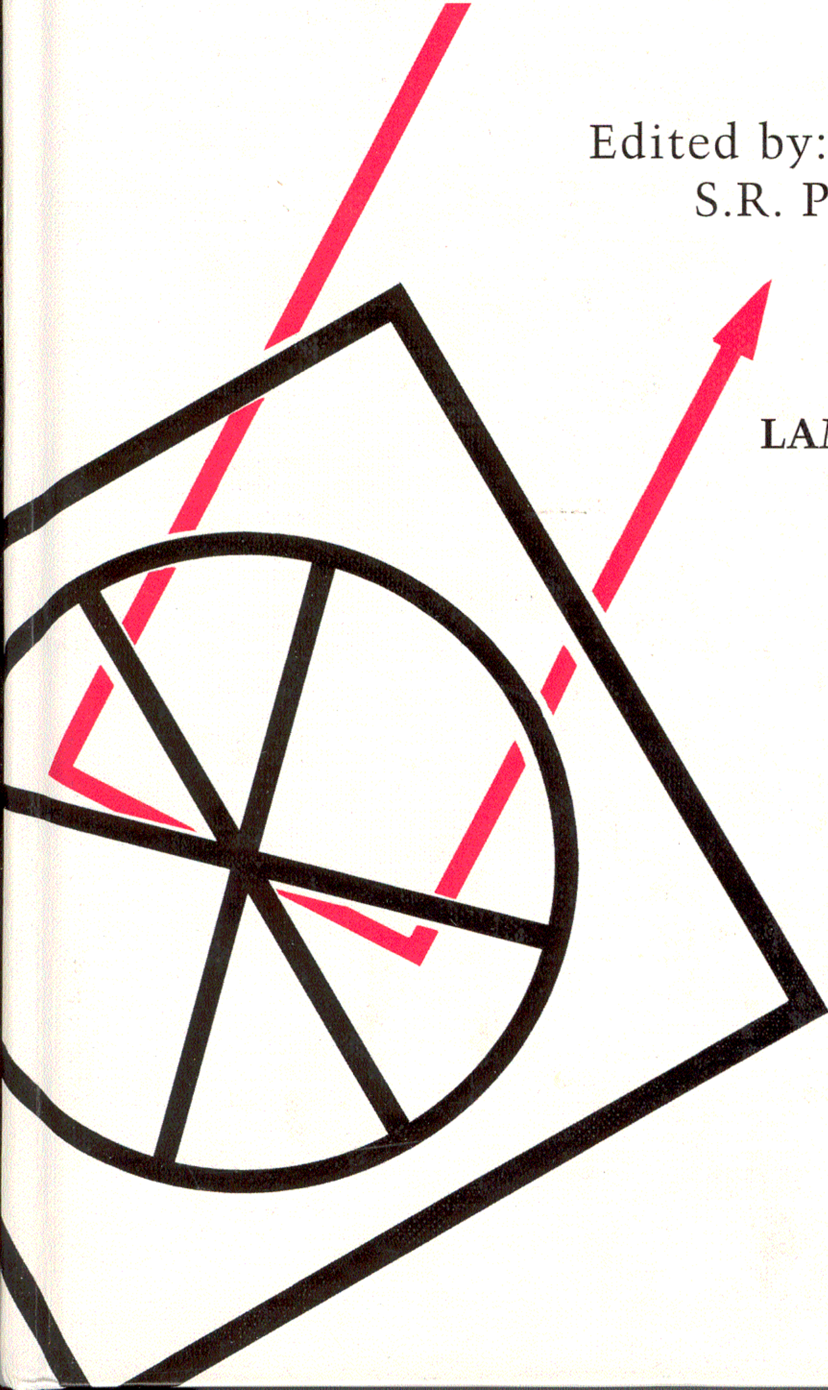

LAMDAMAP 97

Computational
Mechanics
Publications

Laser Doppler displacement meter (LDDM) allows new diagonal measurement for large aspect ratio machine tool easily and accurately

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Abstract

The diagonal measurement method has been recommended by many standards such as B5, for a quick check on the volumetric performance of machine tools.

However, for *large aspect machine tools*, it is insensitive to the axes with short travels. A *new diagonal measurement method*, a *sequential three axes movement* and data collection method, has been developed to provide information on the two short axes in a single diagonal measurement.

The Laser Doppler Displacement Meter (LDDM), that makes this method practical, performs like a Laser interferometer but with a single aperture for the exit Laser beam and the return Laser beam. The *single aperture Laser* makes it possible to implement the double-path optical arrangement that allows an increase in the capability to tolerate lateral movement.

1. Introduction

The new regulation for quality management require more strictly control of the quality and the record of performances, while the world competition is asking for reduction in timing.

As was recommended in B5 standard, the volumetric accuracy of a machine may be rapidly estimated by measuring the displacement accuracy of the machine along body diagonals.

However, for large aspect ratio machines, the diagonal displacement measurement test is insensitive to the axes with short travels.

Described here is a *new diagonal displacement measurement method*. It is based on a *sequential three axes movement and data collection method* that allow diagonal measuring preserving short axes accuracy. The basic theory, error analysis, equipment and set up are described.

2 Basic Theory

For a body diagonal measurement from O to $R(x,y,z,)$ shown in Fig. 1

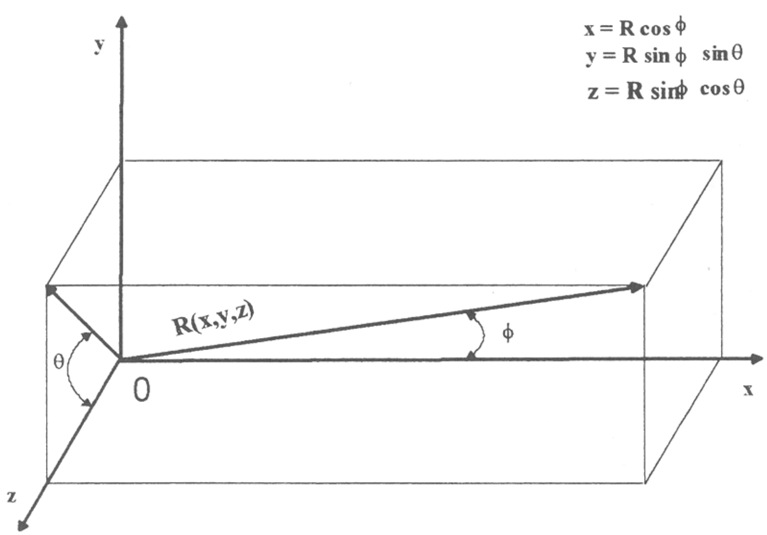

Fig. 1 Scheme of Body diagonal measurement geometry

R^2 can be expressed as $x^2+y^2+z^2$. X can be expressed as $R\cos\phi$, Y can be expressed as $R\sin\phi\sin\theta$ and Z $R\sin\phi\cos\theta$.

For the motion along each axis, there is one linear error and two straigtness errors. These errors divided by displacement in x- direction can be expressed as

$$\frac{\in_{xx}}{x}, \quad \frac{\in_{yx}}{x} \text{ and } \frac{\in_{zx}}{x}$$

where: $\in_{xx}$ is the linear error in x-direction due to x-axis movement
$\in_{yx}$ is the straightness error in y-direction due to x-axis movement
$\in_{zx}$ is the straightness error in z-direction due to x-axis movement

Similarly, for y-axis movement, these are

$$\frac{\in_{yy}}{y}, \quad \frac{\in_{xy}}{y} \text{ and } \frac{\in_{zy}}{y}$$

the z-axis movement, these are

$$\frac{\in_{zz}}{z}, \quad \frac{\in_{xz}}{z} \text{ and } \frac{\in_{yz}}{z}$$

Let θ_{yz} to be the non -squareness in the yz-plane,
θ_{yx} to be the non- squareness in the yx-plane
θ_{zx} to be the non-squareness in the zx-plane,

the measured diagonal displacement error due to non-squareness can be expressed as

$$\frac{\Delta R^2}{R^2} = 2\frac{yz}{R^2}\theta_{yz} + 2\frac{yx}{R^2}\theta_{yx} + 2\frac{zx}{R^2}\theta_{zx} \tag{1}$$

In general, the measured linear error in the diagonal (R-direction) displacement is the sum of all errors in X-displacement, Y-displacement, Z-displacement and non-squareness.

That is

$$\frac{\Delta R}{R} = \frac{x^2}{R^2}\frac{\in_{xx}}{x} + \frac{y^2}{R^2}\frac{\in_{yx}}{x} + \frac{z^2}{R^2}\frac{\in_{zx}}{x}$$

$$+\frac{y^2}{R^2}\frac{\in_{yy}}{y} + \frac{x^2}{R^2}\frac{\in_{xy}}{y} + \frac{z^2}{R^2}\frac{\in_{zy}}{y} \qquad (2)$$

$$+\frac{z^2}{R^2}\frac{\in_{zz}}{z} + \frac{x^2}{R^2}\frac{\in_{xz}}{z} + \frac{y^2}{R^2}\frac{\in_{yz}}{z}$$

$$+\frac{xy}{R^2}\theta_{xy} + \frac{xz}{R^2}\theta_{xz} + \frac{yz}{R^2}\theta_{yz}$$

For most of machine tools, the straightness errors are much smaller than the linear error.

That is

$$\in_{xx}, \in_{yy}, \in_{zz} >> \in_{yx}, \in_{zx}, \in_{xy}$$

$$\in_{zy}, \in_{xz}, \in_{yz}$$

Hence Eq. (2) can be approximated by

$$\frac{\Delta R}{R} = \frac{x^2}{R^2}\frac{\in_{xx}}{x} + \frac{y^2}{R^2}\frac{\in_{yy}}{y} + \frac{z^2}{R^2}\frac{\in_{zz}}{z} \qquad (3)$$

$$+\frac{xy}{R^2}\theta_{xy} + \frac{xz}{R^2}\theta_{xz} + \frac{yz}{R^2}\theta_{yz}$$

Note that the non-squareness, θ_{xy}, θ_{xz} and θ_{yz} are constant. Hence the non-squareness can be determinated by the end point of the four body diagonal measurements.

for small aspect ratio machines, that is

$$\frac{x^2}{R^2} \simeq \frac{y^2}{R^2} \simeq \frac{z^2}{R^2}$$

Eq. (3) shows that the diagonal measurement is equally sensitive to the three axes movement. However, for large aspect ratio machines, that is

$$\frac{x^2}{R^2} >> \frac{y^2}{R^2} \simeq \frac{z^2}{R^2}$$

then Eq. (3) becomes

$$\frac{\Delta R}{R} = \frac{x^2}{R^2}\frac{\epsilon_{xx}}{x} + \frac{xy}{R^2}\theta_{xy} + \frac{xz}{R^2}\theta_{xz} \qquad (4)$$

Hence, it is sensitive to errors due to all axes movement.

3. Sequential Movement and Data Collection Method

Conventional body diagonal measurement moving all three axes simultaneously along a body diagonal and collect data at each preset increment. For a large aspect ratio machine, *the new body diagonal measurement moving the x, y, and z in sequence and collect data after each axes is moved.* Hence the error due to the movement of each axis can be separated. The collected data can be plotted as deviations measured in the body diagonal direction due to x-axis movement, y-axis movement and z-axis movement.
Assume for a large aspect ratio machine,

$$\frac{x^2}{R^2} >> \frac{y^2}{R^2} \simeq \frac{z^2}{R^2}$$

We have

$$\left(\frac{\Delta R}{R}\right)_x = \frac{x^2}{R^2}\frac{\epsilon_{xx}}{x}$$

$$\left(\frac{\Delta R}{R}\right)_y = \frac{y^2}{R^2}\frac{\epsilon_{yy}}{y} + \frac{x^2}{R^2}\frac{\epsilon_{xy}}{y} + \frac{xy}{R^2}\theta_{xy} \qquad (5)$$

$$\left(\frac{\Delta R}{R}\right)_z = \frac{z^2}{R^2}\frac{\in_{zz}}{z} + \frac{x^2}{R^2}\frac{\in_{xz}}{z} + \frac{xz}{R^2}\theta_{xz}$$

Here θ_{xy} and θ_{xz} are constants. With 4 body diagonal measurements we have 12 equations with 12 unknowns. Hence all the linear errors and non squareness could be determinate to within the repeatability of the machine.

4. Measurement Equipment and Set Up

For conventional body diagonal measurement, the displacement is a straight line along the body diagonal, hence a Laser interferometer can be used to do the measurement.
However, for the sequential body diagonal measurement described here, the displacements is along the x-axis, then along the y-axis and along z-axis.
The trajectory of the retroreflector is not a straight line. The maximum deviation from the body diagonal is $\Delta x \sin\phi$, where Δx is the increment in the x-axis.

For *example* for a machine travel of 30 m (1200") in X-axis,
3 m (120") in Y-axis,
and 1 m (40") in Z-axis,

the body diagonal distance is $\sqrt{x^2 + y^2 + z^2}$ = 30 166,206 mm (1206.65")

and

$$\phi = \cos^{-1}\left(\frac{x}{R}\right) = \quad 6.017 \text{ degree}$$

$$\theta = \tan^{-1}\left(\frac{y}{z}\right) = \quad 71.565 \text{ degree}$$ (71.57 for the example in inches)

Assume 100 data points, then each increment in the body diagonal is 301.663 mm(12.0665"), or 300 mm (12") in x-axis,
30 mm (1.2") in y-axis and
10 mm (0.4") in z-axis.

The maximum deviation from the body diagonal is

300 mm sin 6.017 = 31.447 mm (12" sin 6.017 = 1.258") .

A Laser Interferometer will be way out of alignment with such large lateral deviationtion.

A *single aperture* Laser Doppler Displacement Meter (LDDM™), with a large retroreflector a flat mirror and a *double- path* arrangement as shown in fig.2 , can be used for this measurement. It is noted that a lateral deviation larger than one half of the retroreflector diameter can be tolerate. Furthermore, the lateral deviation and rotation of the retroreflector will not change the optical path.

Hence only the displacement along the laser beam direction is measured. For the above example, the 31.447 mm (1.258") deviation can easily be covered by a 3" or 76.2 mm diameter retroreflector.

5. LDDM technology description

The LDDM is a precision displacement measure instrument based on principle of Dopplometry (see C.P. Wang, " Laser Doppler Displacement Measurement", laser and optronics, 6, p.69-71, Sept.. 1987).
Briefly, when a laser beam is reflected from a moving target, the Doppler frequency shift f_0 is

$$f_0 = f_L\left(2\frac{V}{C}\right) \tag{6}$$

where f_L is the laser frequency, C is the speed of light and V is the target velocity parallel to the laser beam.

Since frequency is the change of phase ϕ with respect to the time and velocity is the change of displacement X with respect to the time, after one integration respect to the time, Eq. 6 becomes

$$\frac{\phi}{2\pi} = 2\frac{f_L}{C}(X - X_0) \tag{7}$$

Where ϕ is the phase angle, X is the position and is the initial position. Hence displacement X can be determinate by measuring the phase angle ϕ . When phase change more than 2π, a counter is used to keep track of how many 2π 's. Because of the *single aperture* Laser head, it is possible to employ the *double-path* arrangement (as shown in fig.2) such that it can tolerate large lateral movement.

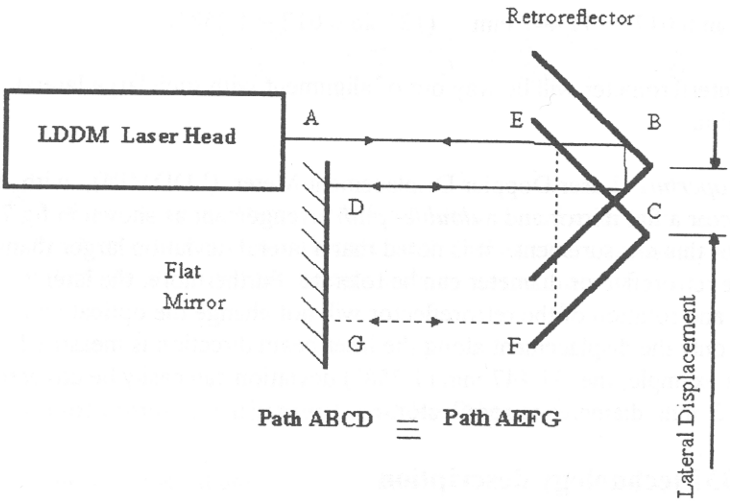

FIG. 2 LDDM with Double -path arrangement

6. Summary and conclusion

The *new body diagonal measurement with sequential 3 axis movement and data collection* will provide far more information with little additional effort. A typical set up and alignment is 15 to 20 minutes, data can be collected automatically at 5 to 10 sec per data point . For a large machine with 100 points per axis, 4 body diagonal measurements could be completed in less than 4 hours.