STRAIGHTNESS MEASUREMENT BY LASER DOPPLER DISPLACEMENT METER TECHNIQUE

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ABSTRACT

In high accuracy Coordinate Measuring Machines (CMM) or precision machine tools, it is important to measure the straightness, pitch and yaw angles of the linear travel of the spindle or bed. Conventional techniques are either inaccurate or very difficult and time consuming.

Described here is a technique to determine the straightness by measuring the slopes at each point along the travel using a dual-beam Laser Doppler Displacement Meter (LDDM™). The straightness is obtained by integrating the local slopes at each measuring point over the total travel. The theoretical basis of the technique, the accuracy of the measurement, and a comparison with other techniques will be discussed.

Since both displacement and angle can be measured simultaneously, the straightness can be measured in one continuous stroke without stopping. The technique can be used in CMM calibration for three-dimensional mapping or replacing linear encoders for linear positioning and angular corrections.

INTRODUCTION

Achieving micrometer tolerances on a mechanical system with moving parts, such as a Coordinate Measuring Machine (CMM), Computer Numerical Controlled (CNC) machine tool, etc becomes more and more important. A constant concern is how to measure and maintain the structure integrity of a complex machine. Positioning accuracy along each axis of motion can be measured by a laser interferometer or a Laser Doppler Displacement Meter (LDDM™). The measured position errors can be used to correct for linear encoder errors. However, to measure the straightness of the spindle or the guideways of each axis, the existing techniques are either difficult to use and time consuming, or do not have enough resolution. Discussed here is a dual-beam LDDM which measures both linear displacement and the angle simultaneously. It can be used to measure the straightness in one continuous stroke without stopping (on the fly).

LASER DOPPLER DISPLACEMENT METER

As described in Ref. 2, the LDDM is based on the principles of laser radar, the Doppler effect and optical heterodyne. Basically, a laser beam illuminates a target or retroreflector. The laser beam that is reflected by the retroreflector is frequency shifted by the motion of the retroreflector and the phase of the retroreflector. That is:

$$x = \frac{c}{2f}(N + \frac{phi}{p}) \qquad (1)$$

Where x is the position of the retroreflector, c is the speed of light, f is the laser frequency, N is the number of 2π and phi is the phase angle. For a typical output, N is expressed as quadrature square waves and phi is expressed as analog signal. The maximum speed for the phase detection is 8mHz which corresponds to 96 ips (2.5 mps) and the maximum resolution using an 8-bit ADC is 0.05 microinch (1.2nm). A block diagram of the LDDM is shown in Fig. 1.

A dual-beam laser head functions like putting two LDDMs into one head. As shown in Fig. 2, two laser beams are emitted from the laser head. A dual-retroreflector, two retroreflectors mounted together with a separation of d, is used to reflect both laser beams back to the laser head. There are two outputs from the processor module, one is the linear displacement of top retroreflector and the other is the difference of displacement between the top and the bottom retroreflector. The difference in displacement divided by the separation d, of the two retroreflectors is the pitch angle. Using an RS-232 interface and a computer, both the linear position and pitch (or yaw, depending on orientation) angle of the dual-retroreflector can be recorded simultaneously in one continuous stroke without stopping. The major features of this technique are automatic data collection, easy setup and operation, with high resolution and accuracy.

STRAIGHTNESS MEASUREMENT

A straightness measurement is a measurement of perpendicular motion along a travel path as shown in Fig. 3. The ideal travel path is a straight line; any deviation from the straight line in the horizontal plane is called horizontal straightness and in the vertical plane is called vertical straightness.

As shown in Fig. 3, let the actual travel path with perpendicular motion in the vertical plane be Z (x), and define the reference as a straight line passing through the initial point and the end point. That is Z(0) = Z(L) = 0. The local slope is:

$$\frac{\mathrm{dz}}{\mathrm{dx}} = \tan J \qquad (2)$$

Assuming the radius of curvature R is much larger than the measurement increment Δx. Tan θ is approximately equal toθ. Hence:

$$z(x) = \int_0^x \frac{dz}{dx}dx = \int_0^x J(x)dx \qquad (3)$$

The total number of point N is equal to L/Δx. Let Xn = nΔX
then,

$$z(x_n) = \sum_{i=0}^{n} J(x_{i-1})\Delta x + const \qquad (4)$$

Since Z(0) = Z(L) = O, Eqn (4) becomes

$$z(x_n) = \sum_{i=0}^{n} q(x_{i-1})\Delta x - \frac{n}{N}\sum_{i=0}^{N} J(x_{i-1})\Delta x \qquad (5)$$

where Z(Xn) is the straightness in the vertical plane, θ(Xn) is the measured pitch angle, Δx is the increment of the measurement, and N is the total number of points.

Similarly for the horizontal plane,

$$y(x_n) = \sum_{i=0}^{n} f(x_{i-1})\Delta x - \frac{n}{N}\sum_{i=0}^{N} f(x_{i-1})\Delta x \qquad (6)$$

where Y(Xn) is the straightness in the horizontal plane, φ(Xn) is the measured Yaw angle, Δx is the increment of the measurement, and N is the total number of points.

The error of this technique is proportional to the inverse of N. With automatic data collection, the number of points N, can be very large. The resolution of the angular measurement is 1 microradian or 0.2 arc seconds, hence the resolution of the straightness measurement could be less than 1 microinch. It is noted that this technique cannot be used to measure squareness. A quad-detector and an optical square are needed to do such measurements. It is also noted that this technique and additional optics can be used to measure parallelism of two guideways. (Ref. 5)

APPLICATIONS

To achieve higher accuracy in CMMs or machine tools, a laser interferometer or LDDM can be used to measure the linear positioning at regular intervals along each axis. The measured data can be stored in computer memory to correct the position error. Hence achieve higher accuracy, this is caller computer aided accuracy or "Mapping". Based on the same concept, its possible to do a three-dimensional mapping by measuring the linear position error, Δx, the vertical straightness, Δz, and the horizontal straightness, Δy, along X-axis and at various heights and locations. All these data can be stored in the computer memory and can be used to correct the position error. As long as the machine is repeatable, higher accuracy can be achieved.

The task of three-dimensional mapping, using conventional techniques is very difficult and time consuming. However, using the dual-beam LDDM with its automatic data collection capabilities; all the error mapping data can be collected in a few strokes.

Another application is to replace the linear encoders by the dual-beam LDDMs, which measures both the linear displacement and the pitch or yaw angle. Pitch or yaw angle information can be used to correct the Abbe error caused by the non-straightness of the guideways. Because the LDDM is very accurate less error mapping would be required. Other applications are the calibration or precision machines and x/y-stages.

In conclusion, straightness of a spindle or machine bed can easily be measured by a dual-beam LDDM. It is compact, easy to setup and simple to operate. The automatic data collection may also save machine downtime and reduce human error.

REFERENCES

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4. C.P. Wang, "Using the Laser Doppler Displacement Meter for Precision Positioning and Motion Control" Motion Control, June 1991.

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Figure Captions

1. LDDM system block diagram
2. A dual-beam laser head mounted on a spindle
3. Definition of the straightness

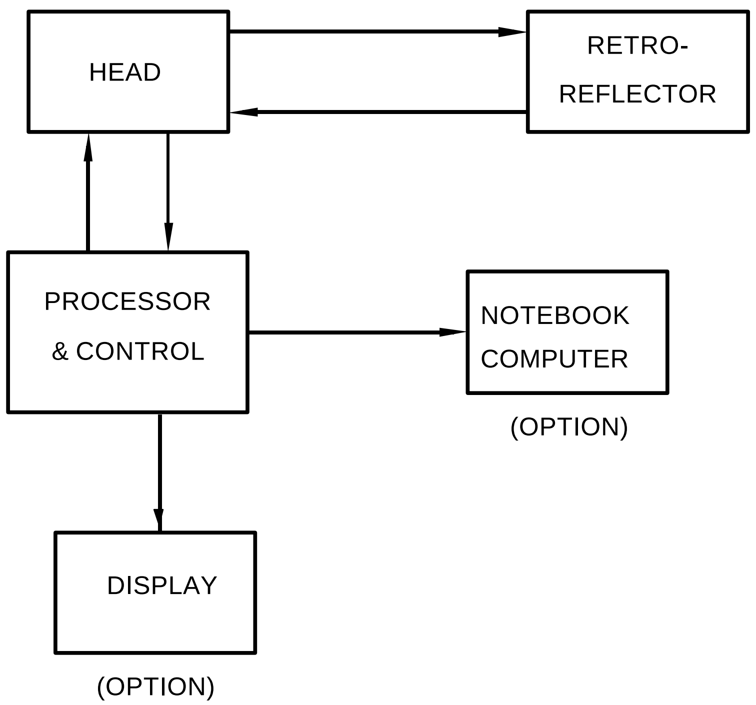

FIG. 1, LDDM SYSTEM BLOCK DIAGRAM

FIG 2, A DUAL-BEAM LASER HEAD ON A SPINDLE

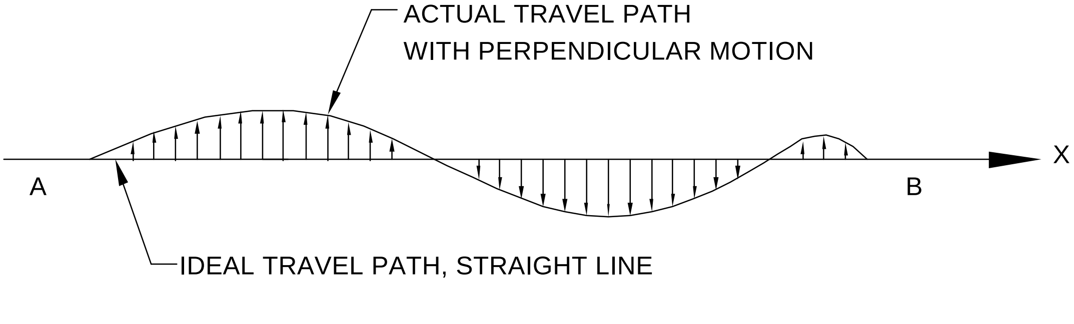

FIG 3, DEFINITION OF THE STRAIGHTNESS