A noncontact laser technique for circular contouring accuracy measurement

Charles Wang[a] and Bob Griffin
Optodyne, Incorporated, 1180 Mahalo Place, Compton, California 90220
(Received 22 May 2000; accepted for publication 20 November 2000)

The worldwide competition in manufacturing frequently requires the high-speed machine tools to deliver contouring accuracy in the order of a few micrometers, while moving at relatively high feed rates. Traditional test equipment is rather limited in its capability to measure contours of small radius at high speed. Described here is a new noncontact laser measurement technique for the test of circular contouring accuracy. This technique is based on a single-aperture laser Doppler displacement meter with a flat mirror as the target. It is of a noncontact type with the ability to vary the circular path radius continuously at data rates of up to 1000 Hz. Using this instrument, the actual radius, feed rate, velocity, and acceleration profiles can also be determined. The basic theory of operation, the hardware setup, the data collection, the data processing, and the error budget are discussed. © 2001 *American Institute of Physics.* [DOI: 10.1063/1.1340556]

For high speed machining operations or die and mold manufacturing, machine tool contouring accuracy is very important. To achieve high quality and productivity, it is important to know what is the maximum feed rate while meeting the required accuracy.[1] The standard verification of machine contouring performance is the use of circular tests.[2-4] The circular test provides a rapid and efficient way of measuring a machine tool's contouring accuracy. The circular tests show how the two axes work together to move the machine in a circular path. As the machine is traversing with multiple axes along a circular trajectory, each axis goes through sinusoidal acceleration, velocity and position changes.[2] The measured circular path data will show any deviation the machine makes from a perfect circle.

For most dies and molds, the radii of curvature are less than 50 mm and the feed rates are a few hundreds millimeters per second, and it is more desirable to perform the contouring tests at smaller radius and at high feed rate[1], Most telescoping ball bar systems normally work with radii of 50-600 mm, hence they are unable to perform circular tests with smaller radii as required in some applications. Also, the errors that the telescoping ball bars detect usually are a combination of problems with the machine's geometry and the controller or servo systems. These errors are then larger than those produced by the control loops only.

The noncontact laser measurement technique described here is based on a single-aperture laser Doppler displacement meter using a flat mirror as target.[5] 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.

As shown in Fig. 1, two laser systems, one pointing in the x direction and the other pointing in the y direction, are mounted on the bed and two flat mirrors, one perpendicular to the x-direction laser beam and the other perpendicular to the y-direction laser beam, are mounted on the spindle. As the machine spindle moves along a circular path, the flat mirrors remain perpendicular to the laser beams and the displacement along the laser beam direction is measured even with a large lateral movement. The measured displacement in the x direction is a sine curve and the measured displacement in the y direction is a cosine curve as shown in Fig. 2. A computer is used to collect the data on x and y displacement simultaneously.

The measured displacement data in the x direction and y direction are $X(N)$ and $Y(N)$, respectively, where $N = 0,1,2,3,\ldots,N_{\max}$ is the point number. The deviation from a perfect circle in the radial direction is *dR(N), which* can be expressed as in the following,

$$dR(N)=SQRT\{[X(N)-X_0]^2+[Y(N)-Y_0]^2\}-R_0 \tag{1}$$

where Xo, Yo, and Ro are constants. The angle θ of the circular path can be expressed as

$$\theta = 360*N/(\text{number of points in one period}) \text{ degree.} \tag{2}$$

A typical radial deviation calculated by least square fitting and plotted by the POLARCHECK[6] program is shown in Fig. 3. Here the backlash, axis pikes, and nonroundness are clearly shown.

There are many measurement errors such as synchronization, mirror flatness, alignment, nonperpendicular, and angular motions.

Synchronization error: The displacement data $X(N)$ and $Y(N)$ are collected simultaneously by a latching clock signal. The maximum delay between these two displacement data is 50 ns. At a feed rate of 1000 mm/s, this corresponds to an error of 50 nm.

Mirror flatness: The flat mirror used is a quarter wave flatness mirror. Hence over 150 mm travel, the maximum deviation is 1 μm. For more accurate measurement, the mirror flatness can be mapped and compensated.

Cosine error: If the flat mirror is not perpendicular to the laser beam, there is cosine error. This error is equal to the

a)Electronic mail: optodyne@aol.com

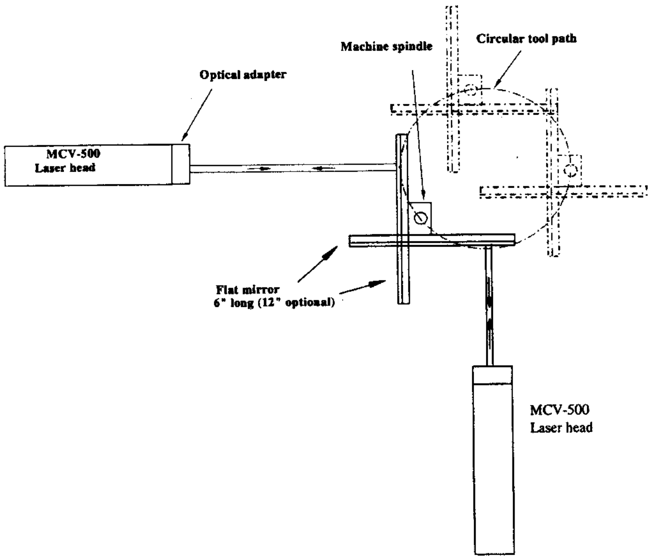

FIG. 1. Schematic of a laser circular test with synchronized data collection using two laser systems.

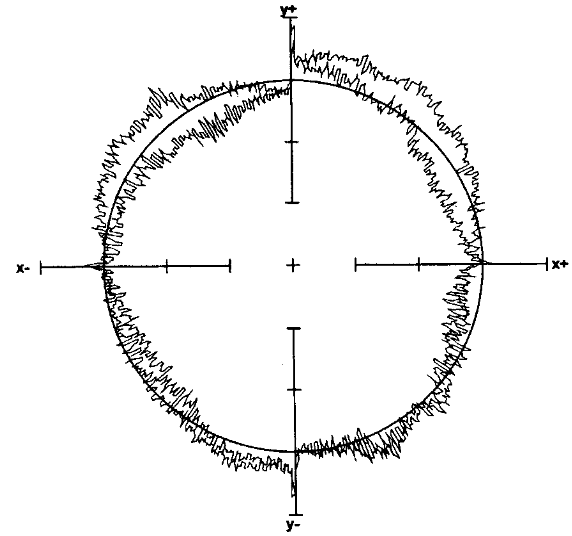

FIG. 3. A typical plot showing the radial deviations calculated by synchronized data processing.

square of the misalignment angle divided by 2. For a misalignment angle of 1 mrad or 1 mm over 1 m, the error is 0.5 E-6 times the distance of travel. For a total travel of 150 mm, the cosine error is 75 nm.

Alignment error: If the x-direction beam or y-direction beam is nearly parallel to within a few degrees to the respective axis of motion, the measured radial deviations are essentially the same except the locations of the backlash and axis spikes are shifted a few degree from the x axis or the y axis.

Nonsquareness error: If the x-direction beam and the y-direction beam are not perpendicular to each other, the measured circular path will be elongated along the 45° and 225° directions. This will be interpreted as a squareness error of the machine. Assuming the angle between x axis and y axis is 90+ε degrees, where ε is small, a perfect circle, $R(\theta)=R_0$, will become $R(\theta)=R_0$ (1-sinε sin2θ). Hence, the difference in radius is +/- R_0sinε. For ε =0.01°, and Ro = 25 mm, the difference in radius is Rosinε = 4μm. The alternative is to move the two laser beam directions by 45°. That is, pointing one laser beam in

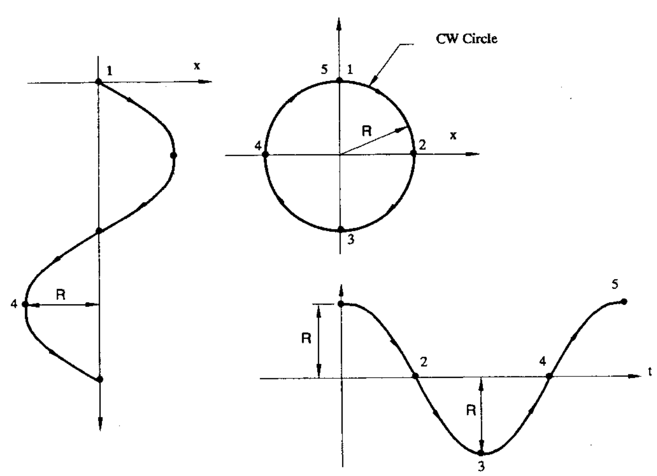

FIG. 2. Schematic showing the spindle circular path, the corresponding x-direction displacement, and the y-direction displacement.

the x+45° direction and the other laser beam in the y +45° direction. The difference in the maximum displacements between these two measurements is proportional to the squareness error of the machine.

Errors due to the angular motion of the machine: The separation of the two flat mirrors is small, hence the error due to the angular motion is small. However, the error due to the angular motion in the flat-mirror direction, because of the large Abbe offset, may be large. Assuming a maximum angular motion of 10 arcsec, the maximum displacement error at the end of the 150 mm long flat mirror is 3.6 μm. For more accurate measurement, before starting the circular motion, move the flat mirror perpendicular to the laser beam direction from one end to the other and record the position and the displacement errors. Fit this displacement error with a polynomial. The first order, linear error is due to the mirror alignment. The second and higher order, quadratic or high errors are due to the straightness and angular motion of the spindle. Using this measured background error as a compensation table, the angular motion of the spindle can be partially compensated.

In summary, the root mean square sum of the above errors is less than 6 μm. This error may be minimized by measuring the background errors and compensating. It is important to note that, for smaller radius circular contours, all the geometrical errors become smaller and most of the measured errors are due to the servo control and motion dynamics. Hence, it is more desirable to run smaller radius circular contours to separate the servo errors from the geometrical errors.

If the machine is repeatable, it is possible to collect the x-direction displacement X(N) and the y-direction displacement Y(M) separately. Hence, a single MCV-500 laser calibration system with an optical adapter and a flat mirror as target can be used. A personal computer (PC) interface card and a notebook PC with Windows^{TM} software can be used to collect the data in x- and y-directions separately. A typical

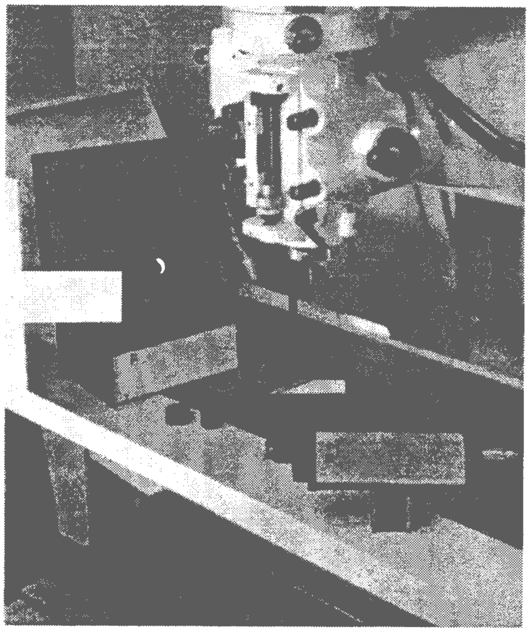

FIG. 4. A laser system for circular contouring measurement on a CNC machine tool.

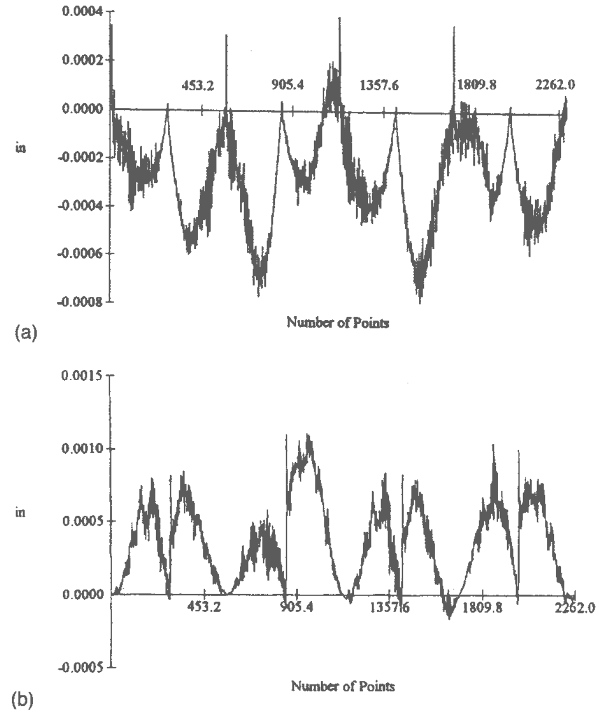

FIG. 5. Plots of nonsynchronized deviations $dX(N)$ and $dY(M)$ are shown in (a) and (b), respectively.

setup of the laser system on a computer numerical controlled (CNC) machine tool is shown in Fig. 4.

To analyze the data, first find the maximum and minimum of the displacement data, fit the *X(N)* with a sine curve and the *Y(M)* with a cosine curve then combine the *X(N)* and *Y(M)* to calculate the radial deviations. The deviation from a perfect sine curve is *dX(N),* which can be expressed as

$$dX(N)=[X(N)-Xo]-Ax*\sin(N*2\pi/Px+Qx), \quad (3)$$

where Xo is the mean value, Ax is the amplitude, Px is the period, and Qx is the phase shift. Similarly,

$$dY(M)=[Y(M)-Yo]-Ay*\text{cosine}(M*2\pi/Py+Qy), \quad (4)$$

where Yo is the mean value, Ay is the amplitude, Py is the period, and Qy is the phase shift. Using the least squares fit and combining these two files, the deviations in the radial direction can be obtained.

To verify the procedure, use the same data files but remove the synchronization between these two data files. First, use Eqs. (3) and (4) to calculate the deviations *dX(N)* and *dY(M).* The results are plotted in Figs. 5(a) and 5(b), respectively. Here the backlashes and axis spikes are clearly shown. Then by combining the *dX(N)* and *dY(M),* the radial deviations can be calculated. The result is the same asshown in Fig. 3. Hence, it is possible to process the nonsynchronizeddataand obtain the same result. Of course, the limitation is the repeatability of the machine motion.

For a circular contour, the axis motion is a sinusoidal function. Similarly, the velocity and acceleration are also sinusoidal. Hence, the feed rate and the acceleration/ deceleration can be calculated by differentiating the displacement data once and twice.

As compared to conventional telescoping ball bars, the noncontact laser technique makes a two-dimensional measurement, both the x coordinate and y coordinate are measured to generate the circular path. The telescoping ball bar is a one-dimensional measurement, only the radius changes along angular positions are measured. The angular positions are not measured but calculated by assuming the machine feed rate is a constant. Of course, the two-dimensional laser measurement will provide more information, such as feed rate and acceleration. These velocity and acceleration profiles are important to the determination of the motion dynamics and the servo performance of the machine.

The major features of this technique are the circular contour radius can be varied continuously down to less than 1 mm at high feed rate, the setup time is short, and the data rate is high. Hence, it is most suitable for circular tests of small radius and at high feed rate. Because of these capabilities, the laser technique should be very important for servo system, machine tool, and numerical control (NC) manufacture, to optimize motion control parameters and to verify the contouring accuracy.

[1] M. Omari, Proceedings of the Second International Advanced Technology for Die and Mold Manufacturing Conference, Columbus. OH, 16 October 1997.
[2] An American National Standard, ASME B5.54-1992 by the American Society of Mechanical Engineers (1992).
[3] Y. Kakino, Y. [ham and A. Shinohara, *An Accuracy Inspection of NC Machine Tools by Double Ball Bar Method* (Carl-Hanser, Munchen, Germany, 1993).
[4] Intemational Standard, ISO 230-4, Test code for machine tools (August 1996).
[5] C. Wang and B. Griffin, Am Mach. 143, 68 (1999).
[6] J.Holsa, *Method for Analyzing Planar Machine Tool Measurements,* Tampere University of Technology Publication 280 (Tampare University, Tampere, Finland, December 1999).