Non-contact Circular Tests Using a Laser/Ballbar

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I. Introduction
- Monitoring machine tool performances
- Why you need circular tests
- Perform circular tests using a telescopic ballbar
- Major features and difficulties

II. How the Laser/Ballbar works
- Laser Doppler Displacement Meter (LDDM) basic principle
- Single-aperture laser head and Flat-mirror target
- Circular test with a single laser system

III. Data collection and processing
- Data collection hardware and software
- Data processing and ASCII output file
- Polar plot of deviations
- Diagnostics and analysis program

III. Performance comparison
- 2-dimensional vs 1-dimensional measurement
- Measuring feed rate and acceleration
- Non-contact measurement
- A comparison table

IV. Summary and conclusion

I. Introduction

Competition in the worldwide manufacturing market requires improvement in productivity, quality, and also reduction of scrap and downtime. To achieve these, it is important to optimize and to monitor machine tool performance. For CNC machine tools, robots and multi-axes' servo system, both the static positioning accuracy and the dynamic motion control are important.

For many years, the machine tool position accuracy and the motion control system were tested by a variety of methods with different instruments, such as using a laser interferometer for position accuracy and a telescoping ballbar for circular tests. For example, each machine axis can be checked by a laser interferometer for position accuracy, but independent of one another. This is because the laser interferometers check only the end-points. They can not check the machine under true dynamic conditions or the actual tool path.

For dynamic tests a telescoping ballbar can be used. 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. The measured circular path data will show any deviation the machine makes from a perfect circle. The shapes are diagnosed and correlated to servo mismatch, backlash, reversal spikes, squareness error, cyclic error, stick slip, machine vibrations, etc.

The telescoping ballbar consists of two steel balls that are supported by two 3-point contact magnetic sockets that are clamped to the spindle nose and on the table of the machine, respectively. These balls are connected by a telescoping bar whose telescopic movement can be detected by a transducer similar to an LVDT (Linear Variable Differential Transformer). The ball clamped on the table socket is used as the center of rotation and the ball on the spindle socket performs a circular motion.

The control system moves the spindle around a circle that has the same radius as the ballbar's length. The change in the distance between the two ends of the device when the path deviates from a perfect circle, is measured by the transducer. Hence the deviations in circular interpolation or machine geometry are detected by the telescoping ballbar. The data collected can by plotted in a polar coordinate and compared with a perfect circle.

The telescoping ballbar systems normally work with radii of 50 mm to 600 mm, hence they can not follow circular tests with smaller radii, and the errors they detected usually trace back to problems with the machine's geometry rather than the controller. These machine errors are larger than those produced by the control loops and consequently tend hide them. Also, the transducer needs to be calibrated periodically, it is sensitive to temperature changes, and the cables limit its flexibility.

The Laser/Ballbar described here is a new technique based on a single-aperture Laser Doppler Displacement Meter (LDDM). The major features are: the measurement is non-contact; the circular path radii can be varied continuously from 1 mm to 150 mm (or larger with optional mirrors); the linear accuracy is traceable to N.I.S.T.; the feed rate is up to 4 m/sec; the date rate is up to 1000 data points per second with a file size up to 10,000 data points per run. The actual feed rate, velocity, and acceleration of the machine under test can also be determined and compared to the programmed feed rate.

II. How the Laser/Ballbar works

The Laser Doppler Displacement Meter (LDDM) is based on the principle of Dopplermetry. Briefly, when a stabilized laser beam is reflected from a target, the Doppler frequency shift is proportional to the velocity. Since the frequency shift is the change of the phase and the velocity is the change of the position, after an integration with respect to time, the Doppler phase shift is proportional to the position. Once the phase is measured the position can be determined.

The unique property of the LDDM is its flexibility and compact size. Hence, it is possible to fit two interferometers in one laser head; such as Optodyne's Dual-Beam laser. Or reduce the two apertures, an output beam aperture and a receiving beam aperture, to one aperture. That is, both the output laser beam and the receiving laser beam share the same aperture. Because of this single aperture optical arrangement, it is possible to use a flat-mirror as the target and tolerate large lateral displacement.

As shown in Fig. 1, the laser is pointing perpendicular to the flat-mirror, which is mounted in the spindle of a machine. As the machine spindle moves along a circular path, the flat-mirror remains perpendicular to the laser beam and the displacement along the laser beam direction is measured; even with a large lateral movement. By repeating the same measurement in the direction 90 degrees from the previous measurement, with the same spindle motion, the displacement along the laser beam direction is again measured. By combining the data from these two measurements the actual circular path can be generated. Fig. 2 illustrates how to combine the data on the two measurements, one is a sine curve and the other is a cosine curve, to generate the circular path. Here R is the radius of the circular path and the amplitude of the sine and cosine curves.

III. Data collection and processing

The hardware required for the Laser/Ballbar is: a MCV-500 (single-aperture laser calibration system), an optical adapter, a flat-mirror target with a mount, a PC interface card, a notebook PC and Windows™ software. The whole system fits into one small carrying case. A typical setup of the Laser/Ballbar on a CNC machine tool is shown in Fig. 3.

For a small radius or high feed rate circular test, high data rates are required. With a special PCMCIA interface card, data rates up to 1000 data points per second, can be achieved. The software for the data collection and data processing is Windows™ based. With a few clicks, the data can be collected automatically and processed to generate a polar plot of the circular path. A typical polar plot of the measured circular path is shown in Fig. 4. Here the radius is 4 inches, the feed rate is 40 in/min., and the sampling rate is 30 data points per second.

An ASCII output data file can also be generated for external data processing or diagnostics. For example, an output data file from Fig. 4 has been analyzed by “PolarCheck” software (developed by Qplus Oy, Finland). The simulated polar plot and the calculated parameters are shown in Fig. 5.

IV. Performance Comparison

The Laser/Ballbar is a 2-dimensional measurement; both the X-coordinate, and Y-coordinate are measured to generate the circular path. The telescoping ballbar is a 1-dimensional measurement; only the radius changes along angular positions are measured. Futhermore, the angular positions are not measured but calculated by assuming the machine feed rate is a constant. Additionally, the 2-dimensional Laser/Ballbar measurement will provide much more information, such as feed rate or tangential velocity and acceleration. Also, the tool paths are not limited to a circular path. For example, a tool path with decreasing radius or a spiral path, is entirely possible.

The Laser/Ballbar measurement is non-contact. Hence a circular path with many revolutions can easily be measured, and the radius of the circular path can be continuously varied. For a telescoping ballbar, there is a cable between the transducer (inside the telescoping bar) and the electronic processor. This cable makes the circular path with multiple revolutions very difficult if not impossible. Also, because the length of the telescoping bar is fixed, the radius of the circular path is fixed. Furthermore, because of the size of the transducer, it is very difficult to do a circular path radius much smaller than 50mm.

The Laser/Ballbar uses a Laser Doppler Displacement Meter for the measurement. Hence the accuracy and stability are very high, typically 1PPM for linear displacement with a stability better than 0.1PPM; the system is also traceable to N.I.S.T. The telescoping ballbar uses a transducer for the measurement; hence the accuracy is lower, needs periodic calibration, and it is sensitive to temperature changes. Also, since a Laser Doppler Displacement Meter is used in the Laser/Ballbar, the system can also be used for the linear calibration of the machine and to generate the compensation file.

Of course, two sets of measurements with two setups are needed for the Laser/Ballbar to generate the circular path as compare to just one for the telescoping ballbar. But, to reduce the setup time of the Laser/Ballbar, a steering mirror and optical adapter are provided to ease the alignment and to increase the misalignment tolerance. A typical setup time is less than a few minutes. A performance comparison is shown in the following.

Table I. Performance Comparison

Performance	Laser/Ballbar	Telescoping ballbar
Measurement Sensor	Laser Doppler Displacement Meter	Transducer
Measurement Method	Measures x-coordinate and y-coordinate to generate the circular path. 2-dimensional measurement	Measures the radius changes along angular positions on a circular path. Angular positions are not measured. 1-dimensional measurement.
Sensor Calibration	Linear accuracy is calibrated and traceable to N.I.S.T.	Transducer needs periodical calibration
Sensor Range	Up to a few meters	Up to a few mm
Non-contact measurement	Yes	No
Radius of circular path	Continuously variable from 1 mm to 150 mm (or longer with optional mirror)	Fixed radius
Measures feed rate	Yes	No
Sampling rate	1000 data/sec	250 data/sec
Maximum feed rate	Up to 240m/min.	Up to a few m/min.

I. Summary and conclusion

To evaluate or to optimize the performance of a machine tools, it is important to check both the static position errors and the dynamic tool path errors. A laser interferometer or a Laser Doppler Displacement Meter can be used to check the static position errors and to generate a compensation file for the controller. A telescoping ballbar or Laser/Ballbar can quickly assess machine dynamic characteristics such as servo mismatch, axis reversal spike or backlash, scale mismatch, squareness errors, vibrations, etc. Hence, a Laser/Ballbar can be used to optimize the machine performance by both generating a static displacement compensation file and dynamic tuning of the servo controller.

Figure captions

1. Schematics of a laser circular test.
2. A typical Laser/Ballbar setup
3. Schematics showing combine x-coordinate data and y-coordinate data to generate a circular path.
4. A typical polar plot of the deviations from a perfect circle.
5. A typical simulation polar plot using the PolarCheck program.

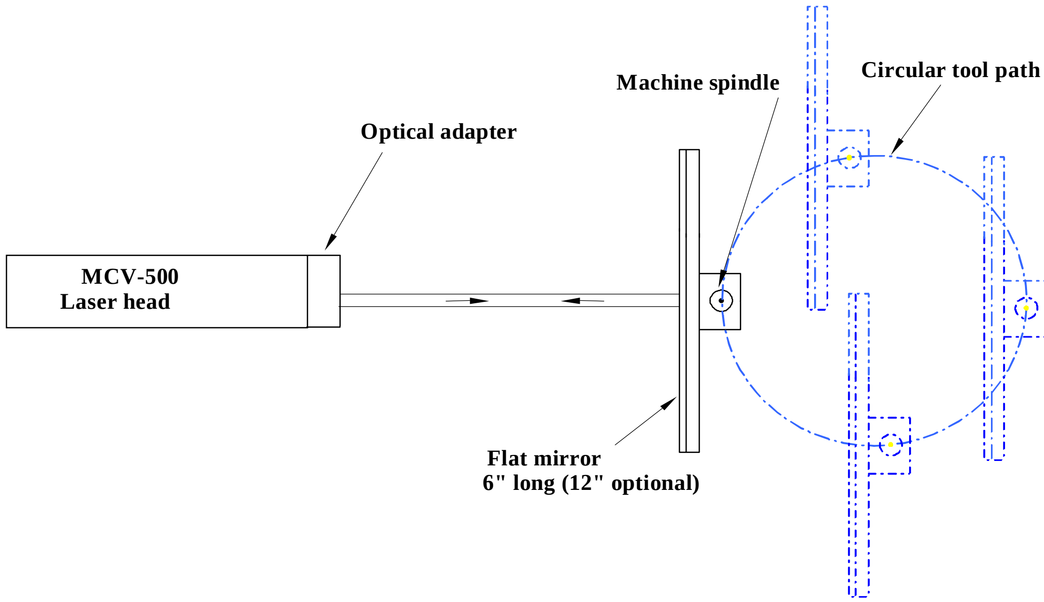

FIG. 1   SCHEMATIC OF LASER CIRCULAR TEST

FIG. 2 A TYPICAL LASER/BALL-BAR SETUP

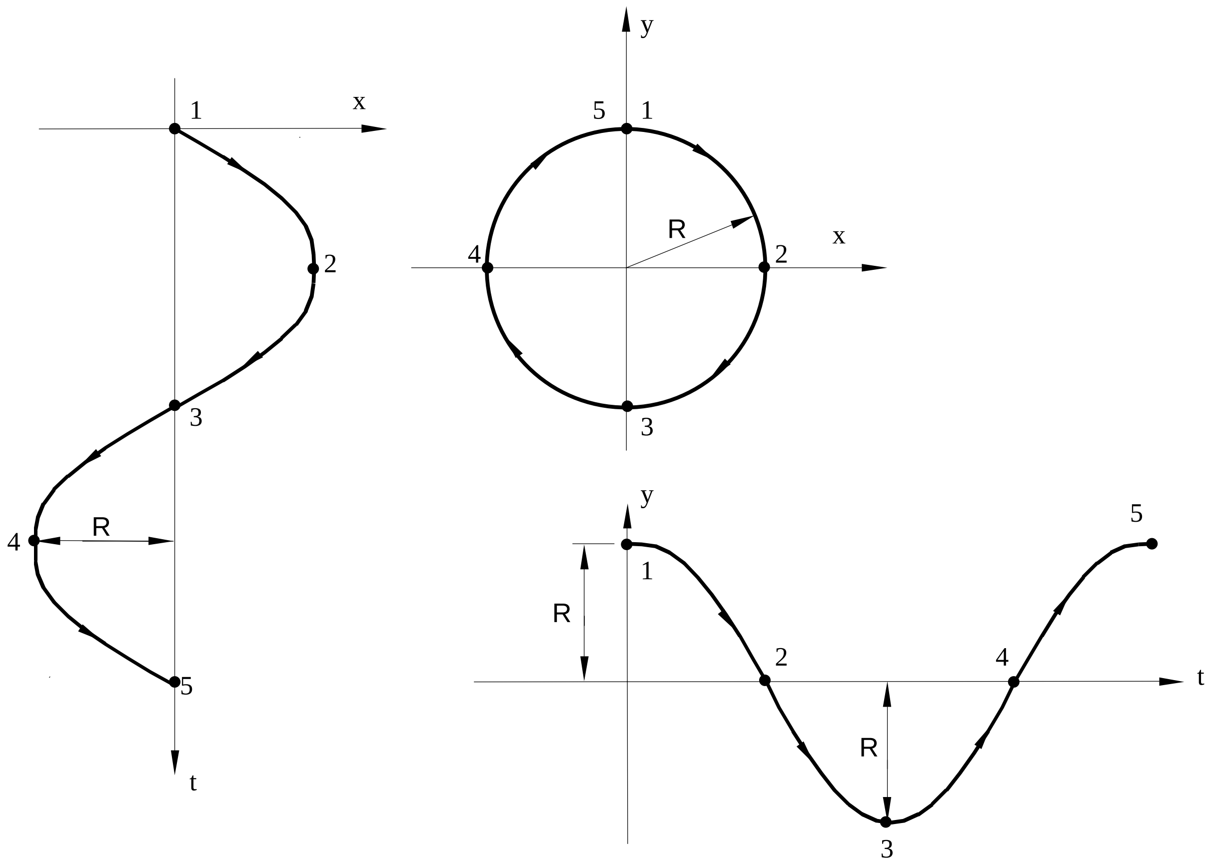

FIG. 3 COMBINE DATA IN X-COORDINATE AND DATA IN Y-COORDINATE
TO GENERATE THE CIRCULAR PATH

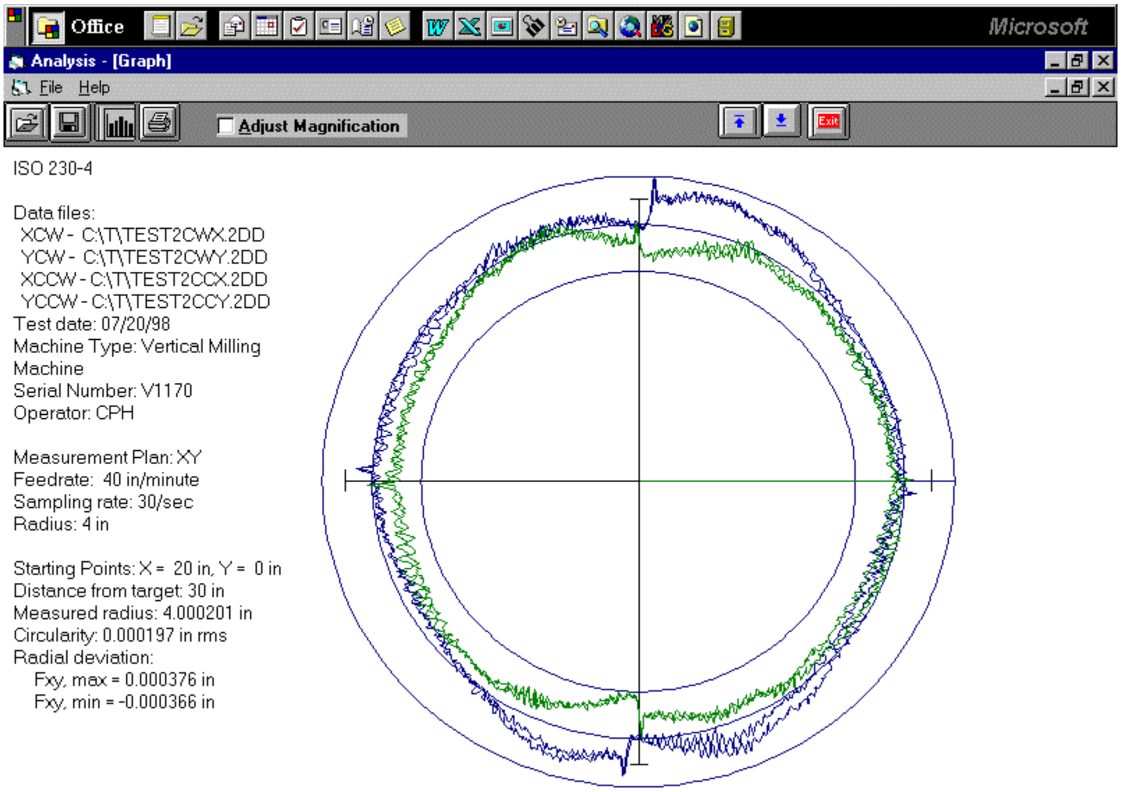

FIG.4 A TYPICAL POLAR PLOT OF THE DEVIATIONS FROM A PERFECT CIRCLE

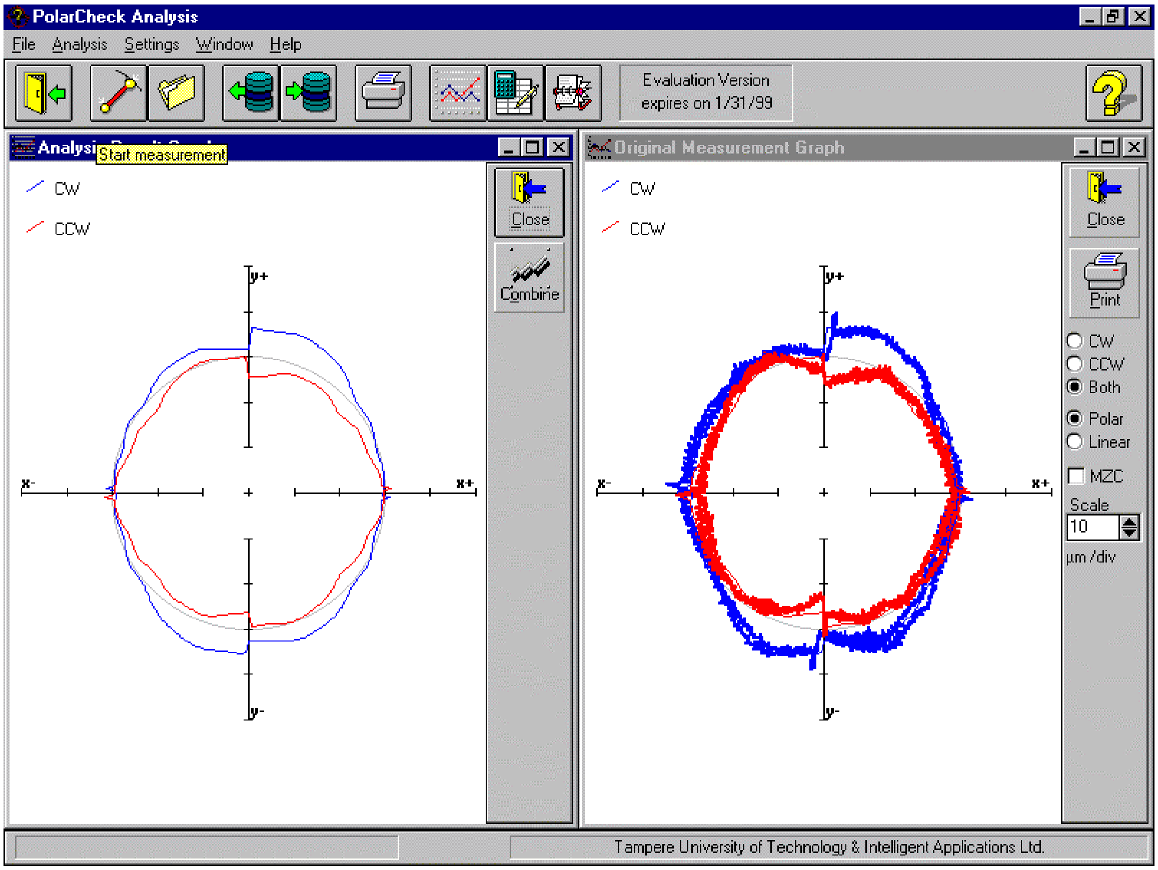

FIG.5 A TYPICAL SIMULATION POLAR PLOT
USING THE POLARANALYSER PROGRAM