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Evaluation of Machine Tool Contouring Accuracy at High Feed Rates

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Recently, 5-axis high-precision high-speed milling machines have been developed specifically for die mold applications. To achieve the high precision and super-finishes, static positioning accuracy or repeatability is not enough. The acceptable contour will depend on several factors including cutter path complexity, machine static and dynamic accuracy, the machine acceleration and deceleration rate, the machine control system and compensation, data processing rate, etc.

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. 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.

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. The standard verification of machine contouring accuracy is the use of circular tests. However, traditional test equipment is rather limited in its capability to measure small radius contours at high speed. For example, for most dies and molds the radius of curvatures are less than 50 mm and the feed rates are a few meters per minute, and it is more desirable to perform the contour tests at smaller radius and at high feed rate.

For the study here, a Laser/Ballbar developed by Optodyne is used. The Laser/Ballbar is based on a single-aperture Laser Doppler Displacement Meter (LDDM) and a flat mirror target. The major features are: the measurement is non-contact; the circular path radius can be varied continuously from less than 1 mm to 150 mm; all linear accuracy are traceable to NIST; the feed rate is up to 4 m/sec; the data rate is up to 1000 Hz; and the actual feed rate, velocity, and acceleration profiles can all be determined.

As compared to conventional telescoping ball bars, the Laser/Ballbar makes a 2-dimensional measurement. Both the x-coordinate and y-coordinate are measured to generate the circular path. The telescoping ball bar is a 1-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 2dimensional Laser/Ballbar measurement will provide more information, such as feed rate or tangential velocity and acceleration.

1. Velocity control and acceleration/deceleration limitations:
Moving along a contour, the axis velocity and axis acceleration is continuously changing. For a circular path, the axis motion is a simple harmonic or sinusoidal motion. That is:

$$X(t) = R \sin \omega t$$

$$V(t) = dX/dt = \omega * R \cos \omega t = F \cos \omega t \qquad (1)$$

$$A(t) = dV/dt = -\omega * \omega * R \sin \omega t = -F * F/R \sin \omega t$$

Where X is the position, V is the velocity, A is.the acceleration, R is the radius, ω is the angular velocity, F is the feed rate and t is the time.

For a constant feed rate F, the required acceleration is proportional to the square of the feed rate and inversely proportional to the radius of the circular contour. Hence, for a small radius or at high feed rate, the required acceleration/deceleration becomes very large. With a fixed maximum driving force, it is important to reduce the moving mass of the machine to achieve the required high acceleration.

2. Decrease in radius caused by response lags and acceleration/deceleration time:
For a circular contour of radius R and at a constant feed rate F, the decrease in radius dR caused by the response lags can be expressed as

$$dR = -(Tp*Tp/2 + Ts*Ts/2 + Ta*Ta/24) * F*F/R \qquad (2)$$

where Tp is the time constant for the position loop in sec, Ts is the time constant for the controller filtering circuit in sec, Ta is the time constant for acceleration/deceleration in sec, F is the feed rate in mm/sec, and R is the radius in mm.

To reduce the decrease in radius, it is important to keep the response time as short as possible. However, sometimes the smaller servo loop response time or larger servo loop gain may cause oscillations or vibrations. There are many methods, such as path error compensation, feed forward control, look ahead, etc that may be used to minimize the decrease in radius.

3. Decrease in radius caused by block processing delay or programming methods:
Two methods are available to program a machine to follow a circle. One is using the NC command G02/G03 or circular interpolation. The advantage of using circular interpolation is that the CNC does not process a large amount of NC blocks and rather dedicates its resources to moving the axes and tracking their positions.

The other method is the use of the command GO1 or linear interpolation. Here many linear segments define the circular path. If the accuracy requirement of the circle is high, a large number of points will be needed. The CNC must continuously process this data while the machine is attempting to follow the path. Very often highly dense data is necessary to define a curve; hence the machine control system must manage this high data flow. In many cases, this high data rate may cause data starvation or the reduction in feed rate. Hence, the positioning accuracy of motion-control systems depends on how well controllers can execute linear and non-linear interpolation programs at high rates. The key is how to verify the effect.

Described here are tests performed at one of GM Metal Fabrication Division plants. Most of the tests were performed on a vertical spindle bridge design machining center with a work volume of 6.250 X 3.700 X 1.200 cubic meter. The maximum travel speed is 333 mm/sec. The controller is a Fanuc 15MB. Circular contours at various radii from 6.25 mm to 150 mm and at 20 mm/sec to 80 mm/sec have been performed.

1. Velocity and acceleration profiles:
For a circular contour, the axis motion is a sinusoidal function. Similarly, the velocity and acceleration are also sinusoidal. The shapes of these curves are very close to sinusoidal. This indicates good velocity and acceleration control. The peak displacements correspond to the radius of the circular path, the peak velocities correspond to the tangential velocity or feed rate, and the peak accelerations correspond to the centrifugal acceleration.

For circular path without velocity feedback or control, data was collected on a different machine. The displacement, velocity, and acceleration were measured. Although the displacement is close to sinusoidal, the velocity profile is close to a triangular shape and the acceleration profile is similar to a 2-level acceleration.

2. Various radii at a constant feed rate:
We have performed circular tests at radii of 6.25, 12.5, 25, 50, 75, 100, and 150 mm at a constant feed rate of 80 mm/sec. As shown in Table 1, the variations in circularity or non--roundness are relatively small, they vary from 28~tm to 35pm. However, the decrease in radius is rather large, up to 403pm at 6.25 mm radius. Note that the measured radius error is inversely proportional to the nominal radius as expressed in Eq. 2. Also, the feed rates varied from +0.5 to -1.42 mm/sec.

3. Various feed rate with a constant radius:
We have performed circular tests of radius 100 mm at three different feed rates, 16.7, 50 and 133 mm/sec. The results are shown in Table 2. The differences in circularity are relatively small from 58 µm at 50 mm/sec to 84 µm at 133 mm/sec, while the decreases in

radius are relatively large from 75 µm at 50 mm/sec to 276 µm at 133 mm/sec. These results agree with the Eq. 2 very well.

In summary, using Optodyne's Laser/ballbar system, we have performed the circular contour tests at various radii down to 6.25 mm at high feed rates up to 80 mm/sec. The results agree with the theory very well. Because the measurement is non-contact, the circular contour radius can be varied continuously down to a few mm at a high feed rate up to a few m/sec. .The setup time is short and the data rate is high. Because of these capabilities, the Laser/ballbar should be an essential tool for servo system, machine tool, and NC manufacture, for optimizing the motion control parameters and verifying the contouring accuracy.

Table 1. Changes in radius, circularity and feed- rate versus various radii of the circular contour at a constant feed rate of 80 mm/sec.

Test #	Nominal radius mm	Changes in Radius µm	Circularity µm	Changes in feed rate mm/sec
1	6.25	-403	32	-1.37
2	12.5	-216	31	+0.22
3	25	-109	28	+0.53
4	50	-.52	29	+0.53
5	75	-32	35	+0.48
6	100	-21	32	+0.05
7	150	-8	35	+0.12
8	150 linear	+10	499	-4.6

Table 2. Changes in radius and circularity versus various feed rates of the circular contour at a constant radius of 100 mm.

Test #	Feed Rate mm/sec	Changes in radius µm	Circularity µm
1	16.7	+3	71
2	50	-35	58
3	133.3	-276	84

Key words: Dynamic testing, contouring accuracy, circular tests, small radius, and high