Using Capacitance Probes to Measure the Limit of Machine Contouring Performance

Don Martin,
Lion Precision, 563 Shoreview Park Road, St. Paul, NIN 55126

Most machine tools used for discrete part manufacturing have the ability to create contoured surfaces. Generating a contoured surface usually requires the coordination of two or more axes of the machine. The increased use of CAD/CAM and integration of engineering and manufacturing systems has put increased pressure on contouring accuracy. This paper examines the nature of contouring errors, and presents a simple approach using capacitance displacement probes to determine the contouring speed limit of a machine tool.

Contouring Error and How It Is Measured

A machine is programmed to travel in a predetermined path or contour. Any deviation from the programmed path is referred to as contouring error. For simplicity of implementation and analysis, most contouring tests use a circular path. A machine is programmed to travel in a circle, the resultant path is measured and the difference between the programmed path and the actual path is compared. Not only is the error of interest, but by studying the characteristics of the error, many times the cause can be found and the problem eliminated. **ANSI/ASME BS.54 "Methods for Performance Evaluation of CNC Machining Centers"** recommends the use of the telescoping ball bar to measure contouring performance of a machine tool. The method presented in this paper is an alternative to this approach and it allows an arbitrary path and much smaller distances.

Contributors to contouring error

Machine alignment: if two axes are not perpendicular to each other, an oval pattern will replace the desired circular pattern

Axis accuracy and drive mechanism adjustment and condition: backlash in lead screws, scale mis-alignment, axis straightness, pitch, roll and yaw errors will all have an effect on contouring performance.

Servo tuning and response time: A machine tool must be able to accelerate and decelerate without overshoot to generate accurate contours - with a variety of load conditions.

Processor calculation time: The desired position must be calculated and fed to the servo amplifiers to drive the axes toward the correct target position. The point where the calculations cannot keep up with the desired motion is sometimes called “data starvation.”

What can be done to push a machine to its (speed) limit?

All machines have an upper limit on contouring speed. It is related to how fast themachine can accelerate (servo response) and how fast the processor can calculate target positions. It makes sense that the ideal contouring test would require a situation with maximum accelerations. One approach to generate demanding accelerations and high calculation rates is to program the machine to contour a very small circle. Even at moderate speeds, tracing small circles is a very difficult test for a CNC machine tool.

Consider what is going on with two axes that are performing a circular contour motion: Each axis is being driven with a sinusoidal function. The position, velocity and acceleration formulas for an 'x' and 'y' axis are:

$$x = K \sin(\omega t) \qquad v_x = \omega K \cos(\omega t) \qquad a_x = -\omega^2 K \sin(\omega t)$$

$$y = K \cos(\omega t) \qquad v_y = -\omega K \sin(\omega t) \qquad a_y = -\omega^2 K \cos(\omega t)$$

At a feed rate of 250mm (10 inches) per minute and a radius of 250mm (10 inches), the maximum acceleration works out to be 0.000,069m/s^2 or 0.000,007 g_n.

For each order of magnitude of reduction of radius, the acceleration increases by one order of magnitude (if the speed remains constant). See table I for examples:

Path Dia	Acceleration	Acceleration
mm	m/s^2	g_n
250	0.000,069	0.000,007,1
25	0.000,69	0.000,071
2.5	0.006,9	0.000,71
0.25	0.069	0.007,1

Table 1: Diameter vs. Acceleration at constant feed rate of 250 mm/minute

By changing the path diameter from 250mm to 0.25mm acceleration increases by a factor of 1,000. From a technicians standpoint, I can assure you it is much more comforting to be observing a machine going in 0.25mm circles at 250mm/minute than one going in 250mm circles at 250,000 mm/minute!

From the above analysis, it is apparent that by reducing the path diameter, it will be possible to determine the limitation of a high speed machine tool by measuring over a small displacement range.

Test setup

Whenever possible, measurements on machine tools should simulate measurement at “the point of machining” which represents motion between the “tool” and the “workpiece” during normal operation. On a machining center this involves mounting probes on the machine table and mounting a target on the spindle or spindle housing.

The setup for this test is shown in Figure 1. A square target is mounted to the spindle so that it does not rotate and is aligned in the X and Y directions. Capacitance probes are fixtured to measure along the X and Y edges of the square. The input of the probe drivers is output directly to an oscilloscope where the machine tool motion is directly displayed (and printed). Figure 2 shows more detail of the probe and target mounting. The “square” was a piece of precision ground steel, the probes, probe drivers, and mounting fixture were parts of a commercial spindle analyzer from Lion Precision, and the oscilloscope was a commercially available unit from Fluke.

The machine tested was in good operating condition and was used in regular production. It is a Matsura MC760V manufactured in 1982. It is specified to have 118 inches per minute linear interpolation and 40 inches per minute circular interpolation capability. The machine was programmed using the circular interpolation command, using various path diameters and speeds.

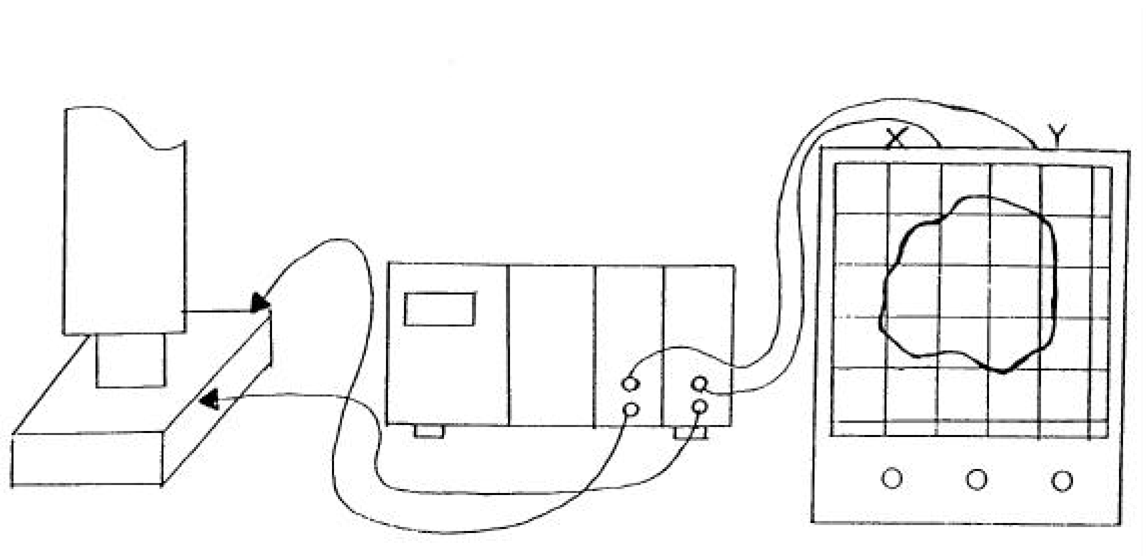
Tests Performed:

Table 1 provides the various path diameters speed and subjective judgment of the results.

Summary of Tests:

Path Diameter (Inches)	Speed (Inches/Minute)	Results
0.005	0.1 5	Round Square
0.010	0.1 1 2 5	Very round 8 sided (not symmetrical) 8 sided (not symmetrical) Almost square
0.015	5	Better than 0.010 at same speed

CAP GAGE CONTOURING TEST FOR MACHINE TOOLS



Machine Spindle	2 Channel Cap Gage	Oscilloscope
Target	Measuring Range	w/ X-Y Display
Two Cap Gages (X,Y)	0.060 - 0.080 Inches	Storage/Print Capability

Machine Tested:

Matsura MC760V 1982
118 Inches/Minute Linear
40 Inches/Minute Circular Interpolation

Figure 1
Instrumentation Test Setup

CAP GAGE CONTOURING TEST FOR MACHINE TOOLS

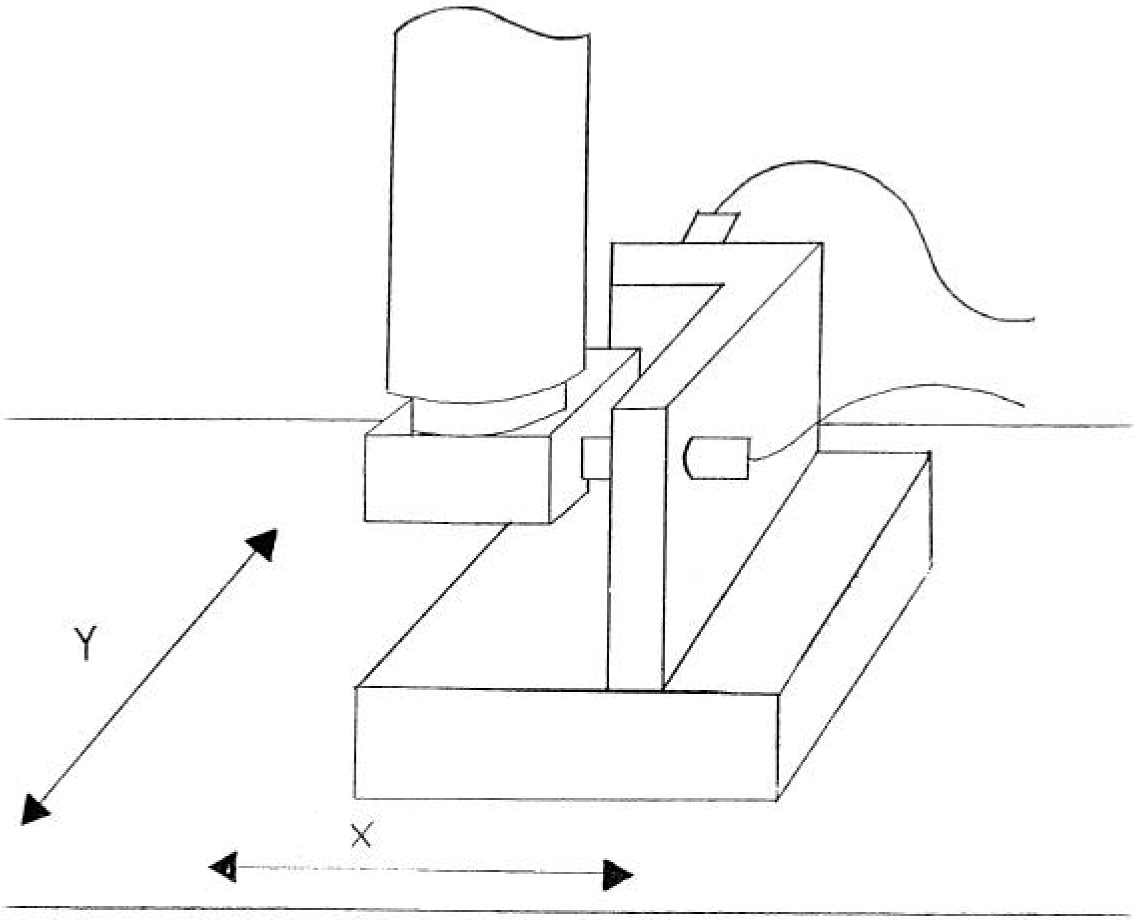
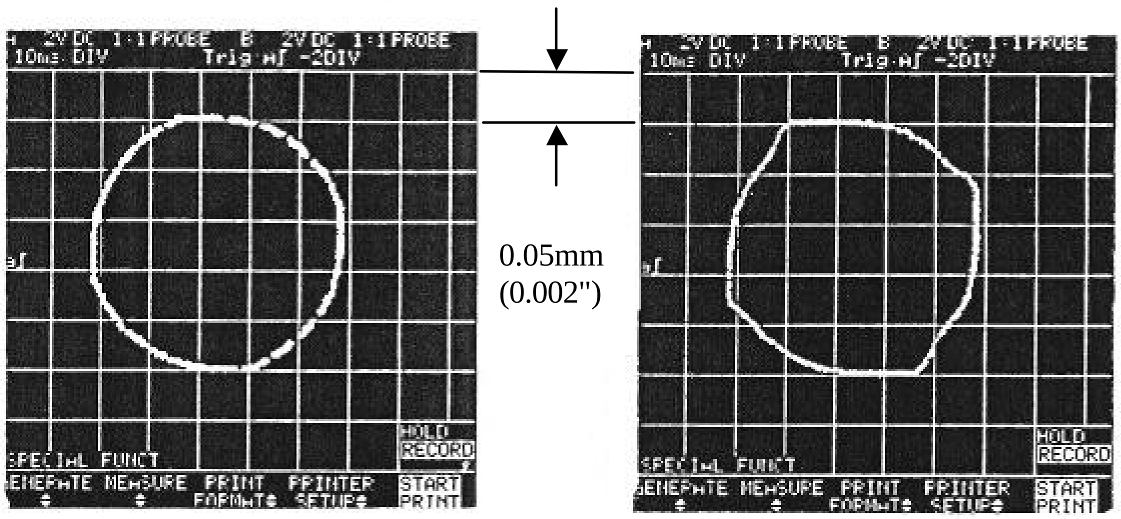


Figure 2
Detail of Setup on Machine

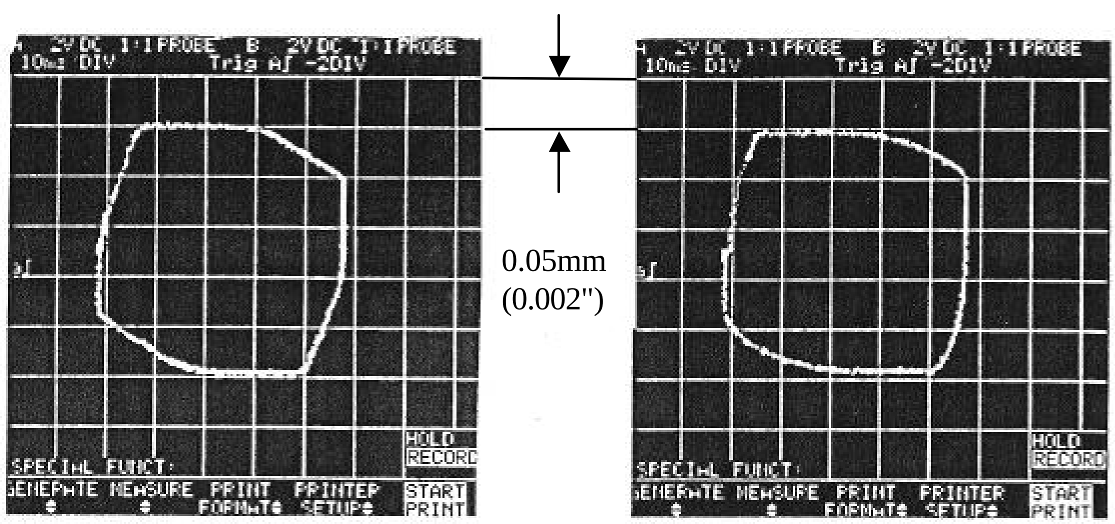
CAP GAGE CONTOURING TEST FOR MACHINE TOOLS

PATH DIAMETER 0.010 INCHES



2.5mm/min (0.1 ipm)

25mm/min (1.0 ipm)

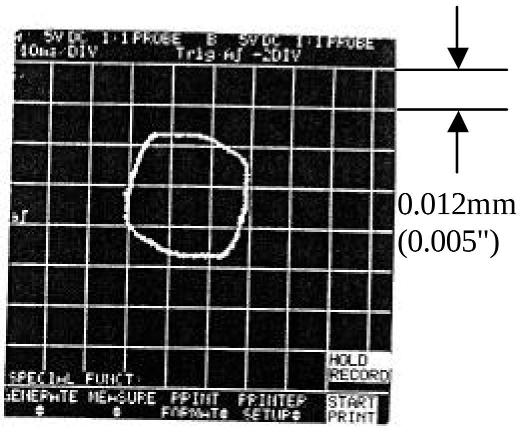


50mm/min (2.0 ipm)

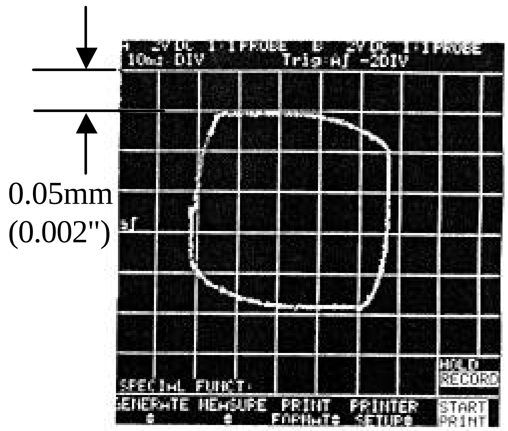
125mm/min (5 ipm)

CAP GAGE CONTOURING TEST FOR MACHINE TOOLS

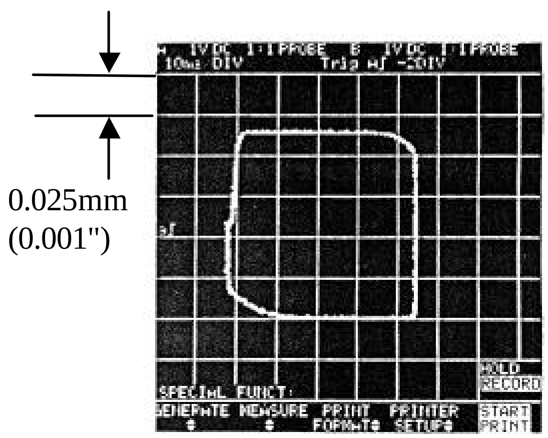
SPEED 5 INCHES/MINUTE FOR VARIOUS PATH DIAMETERS



0.38mm (0.015") Diameter



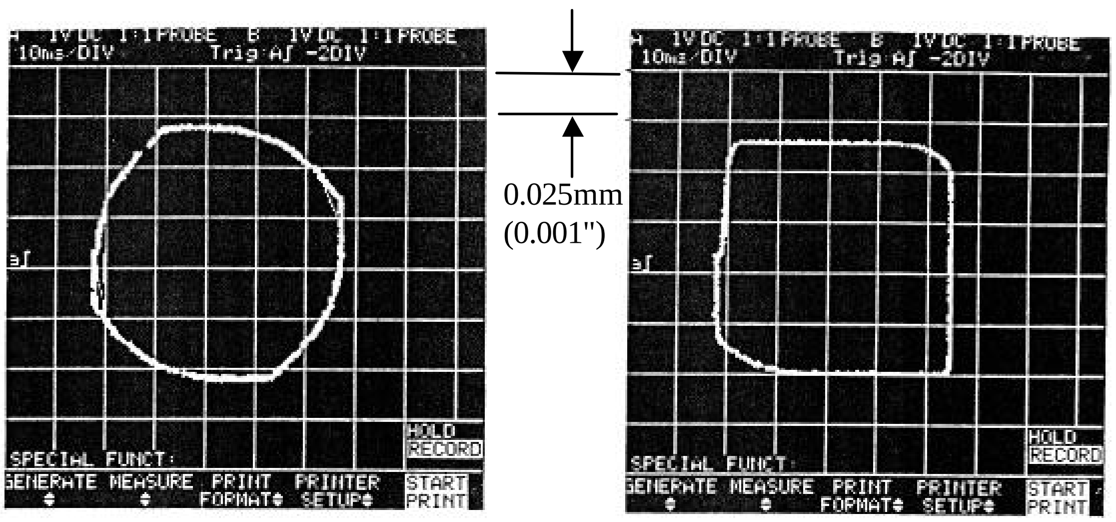
0.25mm (0.010") Diameter



0.012mm (0.005") Diameter

CAP GAGE CONTOURING TEST FOR MACHINE TOOLS

PATH DIAMETER 0.005 INCHES



2.5mm/min (0.1 ipm)

125mm/min (5.0 ipm)

Conclusion

This test is very capable of finding the limit of contouring speed for a machine tool.

Advantages

Test set-up is simple
CNC programming is trivial
Capable of finding limits of performance
Very safe and low-key compared to other “speed limit” tests
Accommodates small work zones
Works at speeds up to 10,000 circular contours/second (1,000,000 inches per minute for 0.5 inch diameter or 10,000 ipm for 0.005 inch diameter path)
Provides calibrated, traceable output

Disadvantages

Short range: 0.5 inches is maximum practical range
Requires target mounted in or on spindle

Further Research and Application

This capacitance sensing approach allows for arbitrary paths - the test setup does not dictate a circular path. This fundamental difference from current contouring tests such as the telescoping ball bar and the circle trace test provides more flexible testing and shorter set up times. In addition, a third probe could be mounted in the 'Z' direction and position in all three directions detected simultaneously.
This same concept allows for use of plane mirror interferometry for larger ranges. Again Y, Y, and Z position could be detected simultaneously. This would provide interferometric accuracy, speed and range with arbitrary path capability.

Summary

A method has been presented to determine the limit of contouring speed on CNC controlled machine tools. All the instruments used to make the measurement are readily available and straightforward to apply. Results of measuring a typical machine tool are presented. Advantages, disadvantages, and further application of the measurement technique are discussed.

Acknowledgments

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