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APPLICATION OF AN ON-MACHINE GAGE FOR DIAMETER MEASUREMENTS

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ABSTRACT

This paper describes the design analysis and application of a laser based gage made specifically for measuring parts on the machine tool to a high accuracy. The tri-beam gage uses three beams of light to measure the local curvature of the part in a manner similar to a V-block gage. The properties of this design include: calibration that is independent of the machine tool scales, non-contact damage free operation, low cost of the gage, and the ability to measure parts in motion.

INTRODUCTION

Increasing tolerances in machining have driven the need for closer and closer control of the process. To gain the greatest performance out of a machine tool, it is necessary to have the dimensional data available for minute adjustments to be made to machine offsets. In the past, many of these dimensional checks have been performed off-line, often some time after a part has been made. The time lag from part manufacture to measurement has meant that a drift or needed adjustment would not be made until many parts had already been manufactured at the previous settings. The most desirable place to make a measurement is right on the machine tool. Any measurement on the machine tool must be made with minimal affect on the cycle time of the machining least a cost be added on to the manufacturing cycle.

On-Machine Touch Probes

To facilitate on-machine gaging, many machine tool builders now supply a touch probe option. The touch probe is used either as a tool (put in place of the tool when measurements are made), or is otherwise attached to the machine. A measurement is typically made by first touching the touch-trigger probe to a reference datum on the machine tool. The probe is then moved by the machine mechanism to the points on the part to be measured.

The difficulties associated with making on-machine measurements with a touch probe are well known. In turning operations, the touch probe must measure the part along the radius of the part. To the extent that the measurement axis defined by the probe deviates from a line along the part radius, there will be an error in the measurement. That is, if the measurement line of the probe is off-set from the radius of the part, the probe will actually measure along a cord of the part, rather than the full radius. Once the part is sensed, the size and extend of the probe tip must be accounted for as an offset in the measurement. If the normal to the part is not know, this offset correction can be difficult.

Making a probe measurement with the machine tool system also has the problem that the part dimension is checked with the same mechanism which makes the part. If the scales on the machine tool are off, then the measurement may be wrong, to the same degree, for both making and measuring the part. Therefore, using the machine tool to make the measurement of the part does not provide an independent check of the machine accuracy.

A final difficulty with making measurements with an on-machine touch probe is the time involved. As the machine itself is used in the measurement, the time spent making the measurement adds to the effective machining time. Typically, the part must be stopped before making measurements. If multiple measures around the part is desired (as is sometimes the case), the part must be rotated to the those positions to be measured and held for the time it takes to approach the part with the touch probe to make the measurement. The touch probe can not be moved into the part quickly, as it can easily be damaged in collision with the part. The measurement speed of a touch probe type system is therefore typically limited to 1 to 2 points per second at best.

The problems described do not prevent the measurements from being made, but they do have three primary effects:

> the cycle time for the machine tool utilization is increased by the measurement time, which also limits the measurements made,
>
> the measurement is checked only against the machine tool itself, thereby not necessarily finding any error in the machine tool positioning that may have machined a part wrong,
>
> down time for the gage can be a problem because of damage of the touch-trigger probe.

These effects have been a limiting factor in supplying reliable, on machine gaging for offset corrections.

Off-Machine Gage Options

The alternative to on-machine gaging is to perform near machine gaging using such tools as machine vision, mechanical calipers, or laser micrometers.[1-7] Machine vision has been used to the accuracies desired (about 2.5 micron) by means of optically based versions of coordinate measurement machines. In these systems, a camera with a small field of view is moved across the field by a precision encoded stage system, which may be a gantry very similar to a traditional coordinate measurement machine (CMM). An off line measure, by even the faster optical CMM systems is still removed from the machine, and hence there is a temporal lag between the part completion and the availability of the measurement data, as described before.

The laser micrometer field is one which has become well established for near machine gaging. Laser micrometers offer the advantage of being a noncontact method, not prone to physical damage due to contact with heavy duty machines as many mechanical caliper systems suffer. A laser micrometer obtains it's measure by scanning or just shadowing a beam of light around the part, to create a silhouette of the part diameter. In the scanner based laser micrometers, the diameter is determined by the time it takes the beam to pass the object (the time during the scan for which the laser beam is shadowed by the part).

Laser micrometer systems that use a simple shadow use a static sheet of collimated laser light which is shadowed onto a linear detector array. The edge of the shadow of the part has a distinct shadow shape to it cause by the diffraction of the laser light passing the part. The linear array can provide a sampling across the shadow edge diffraction pattern which allows the edge location to be determined to much less than a pixel. Typical accuracies for either type of laser micrometer are a part in 10,000 to a part in 20,000. Particularly with the laser scanning systems, diameter measurement resolutions of better that 0.25 microns (10 millionths of an inch) can be made though the use of a large number of measurement samples (one hundred measurements can be made in a second or less with these systems). A large degree of environmental stability is needed for measurements of less than a micron to be meaningful.

The laser mike has the advantage over a single touch probe in that it necessarily measures the greatest diameter of the part (as it is looking along parallel tangents on opposite sides of the part), and is noncontact, thus avoiding damage. As a noncontact probe, the laser micrometer can make measurements very quickly (a few hundred per second) as there is not danger of collision of the light beam with the part under test. In addition, the laser micrometer does not rely on the machine tool accuracy, but rather makes an independent measure of part diameters. Laser micrometers are currently established in industry for such applications a measuring wire and extruded tubing in-process. The measurement for wire production applications is made with the measured material in motion. Any multiple sampling of a moving product, of course, will produce an average measurement along some length of the product, but that is quite acceptable in this type of application.

For the application of the laser micrometer to machine tool operation, there are some drawbacks. Because the laser micrometer must surround the part (with instrumentation on both sides of the part), for an accurate measure, it is typically not practical to consider putting such a device in the machine tool itself. The long, open light path of the laser micrometer can also be a problem in dirty environments as air turbulence, heat, or other airborne material can deviate the light beam (as a function of how far the light must travel) and produce bad data. Maintaining the stability of the transmitter on one side to the receiver on the other side is an important structural and environmental concern which must be dealt with in using a laser micrometer. In typical applications where the laser micrometer can be rigidly mounted, the mechanical stability problems have been well addressed by the commercial vendors of this equipment (air environment has remained a problem). However, if the gage is to be moved, such as to measure a turned part in the chuck, these stability problems could be very limiting.

Therefore, there remains a need for a more effective gage for on-machine gaging of parts. The desirable features for such a gage for application of outer diameter turned part gaging would include:

high speed measurement capability,
accuracies of 2 to 5 microns,
only single side access required,
accuracy independent of machine scales,
high damage resistance for in-machine use,
limited sensitivity to heat and air contaminants of machine tool environment,
ability to measure moving parts (such as during spin down) to minimize time cost of the measurement.

The application we will be addressing is limited to outer diameter (OD) measurements.

TECHNICAL APPROACH

The tri-beam gage works on the same principle as the standard v-block gage. A v-block gage consists of a physical v-block, in which the cylinder to measure is placed. The line contacts of the v-block with the cylinder establishes two tangent points on the cylinder. A micrometer is mounted in the apex of the v. The micrometer is advanced till it just contacts the cylinder (this can be difficult to insure). The reading from the micrometer then permits a calculation of the cylinder curvature in that region, and hence a measure of the cylinder diameter.

Mechanical v-block gages are as well established as the caliper. V-block gages have the desired property that the measure is not dependent on any outside positioning of the gage. Mechanical v-block gages have typically be used on larger cylindrical objects where surrounding the part with a caliper or micrometer would require and impractiably large gage that may be difficult to manage. Therefore, the v-block gage only requires a small part of the surface of the cylinder to make the measure, and does not require surrounding the part (it need access only a single side). Examples of where this type v-block gage has been used includes large gun cylinders, trees, and optical components (where, of course, on a lens only part of the curve may exist).

The tri-beam gage is simply the optical equivalent of the v-block gage. As shown in Figure 1, in place of the V-structure we use two beams of light, detected by linear array detectors. In place of the vertex mounted micrometer we use a sheet of light and a detector array, similar to that used by commercial laser micrometers.

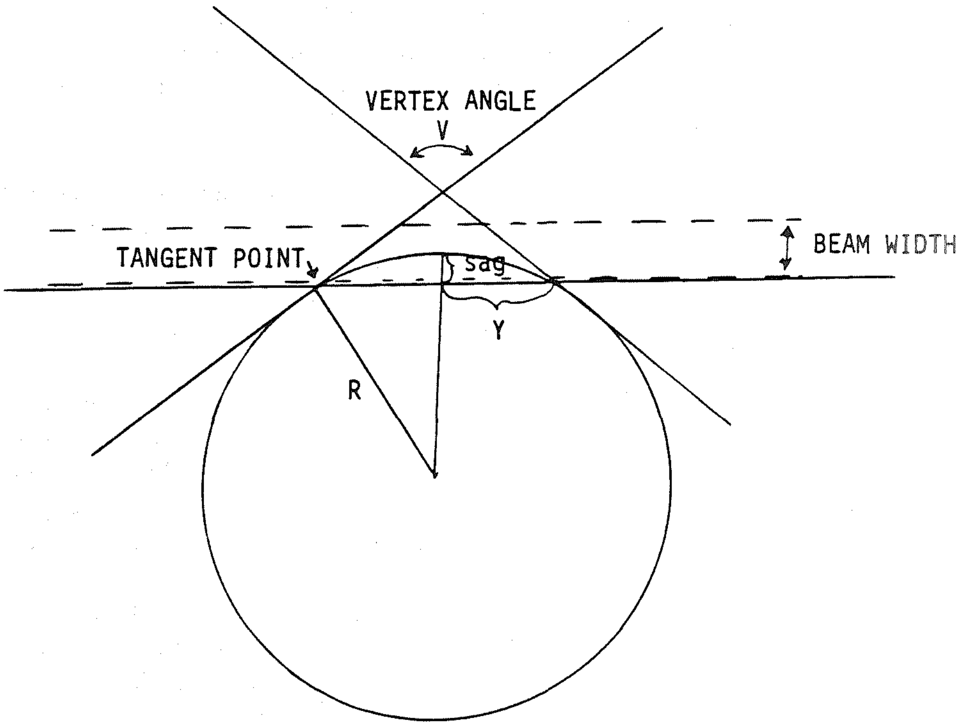

Figure 1. Diagram of the tri-beam gage concept.

For the purpose of establishing the two tangent points, the tri-beam gage simply shadows the light onto the two side detectors. The measurement range of motion of the position of the cylinder edge need not be very large, as the purpose of the two side detectors is simply to establish the two tangent points at the time we make the center measurement which will be equivalent to the vertex micrometer. The third beam used to replace the vertex mounted micrometer must have the accuracy, and range of geometric measurement to accommodate the various diameters of interest for the particular gage.

There are a number of parameters which affect the performance of the tri-beam gage. The primary parameters include gage geometry, and gage stability in use. The gage mechanical stability is driven by the mounting of the three detectors and light sources with respect to each other. By mounting these components rigidly in close proximity to each other, the effects of vibrations or thermal expansion of the unit can be minimized. For example, mounting the components with a linear offset from each other of 5 centimeters on steel would produce a drift of 0.5 microns (20 microinches) per degree C. However, mounting these components in a symmetric configuration in a 30 degree cross configuration would reduce this drift to 0.2 microns for a temperature differential across the 5 centimeters of a degree centigrade. Therefore, it becomes only necessary to compensate for uneven heating by means of controlled radiative heating to maintain negligible mechanical drift with temperature.

The other consideration relating to gage geometry is the actual angles between the beams of light used to form the optical V-block. As the V configuration becomes shallower, a greater accuracy is needed in the measurement at the vertex point to maintain the same accuracy on the diameter measurement, and the greater the significance of any errors in the optical V measurements. For example, a standard array sensor could be used to measure a radius range of 50 millimeters (diameter range of 100 millimeters or 4 inches) with an angle of the V of 60 degrees. The detector in this case would need to measure to an accuracy of twice as good as the desired radius measure (4 time the diameter). The same sensor could measure a radius change of 100 millimeters (diameter range of 200 millimeters or 8 inches) with a V angle of 120 degrees, but would need to be 4 times more accurate than the desired radius measurement accuracy (8 times better than the diameter). Therefore, to obtain 2.5 micron accuracy, the sensor would need to be accurate to about 0.3 microns. This accuracy is within the limits of state-of-the-art detector systems.[8-10]

As with any device of this type, the part needs to be clean to make a reliable measurement. If any chips or other debris are present, they may be measured along with the part to produce an erroneous measurement. This need for some degree of cleanliness is actually true for any diameter measurement (even a chip in a mechanical V-block will lead to a wrong measurement). Cleaning of the part can easily be accomplished by blowing off the surface. Such a provision can be built right into the gage head itself.

Coolants and other debris in the air is not of major concern with the tri-beam gage concept. As the gage detects edges, rather than a light level to determine diameter, as long as there is some light getting through, the measurement is possible to make. If there is noticeable debris present on the gage, this may contribute to the measurement noise. A standard way of dealing with contaminants with this type of gage is to use a regular air flow or "air curtain" to keep any contaminants moving, and therefore preventing any buildup.

The performance objective for this gage were based upon input from machine tool builders and users. We found that large numbers of data point are not needed because the controllers can not use the extra data anyway. Most on-machine measurements are made to provide just simple offsets from some known dimension. The speed fo the tri-beam gage may provide additional data relating to ovality, and permit multiple sampling locations in a short period of time. The performance objective derived are summarized as follows:

Table 1. PERFORMANCE OBJECTIVES

- Accuracy: 1-2 micron (0.00004 inches)
- Speed: 10 measures per second or better
- Environment: ± 30 degrees C
- Part Sizes: 5 cm to 15 cm (2 to 6 inches)
- Calibration: internal
- Environmental: chips, coolant (between cuts)
- Price: under $10,000

The system we built uses the simplest configuration of optics and mechanics. Based upon a 60 degree vertex angle, we were able to design the system to cover a range of diameters of 2 to 6 inches (5 to 15 centimeters). A diagram of this system is shown in Figure 2. The laser light is collimated and is shadowed directly onto the detectors. The interference pattern produced is shown in Figure 3. By matching to the well defined pattern, the position of the edge can be found very precisely. This allows for a measurement resolution of a few microns over a range of 4 inches of diameter. A picture of the sensor is shown in Figure 4. The structure was made very solid to minimize the effects of vibrations, heating, and minimize the chance of damage when operating on the tool carosel.

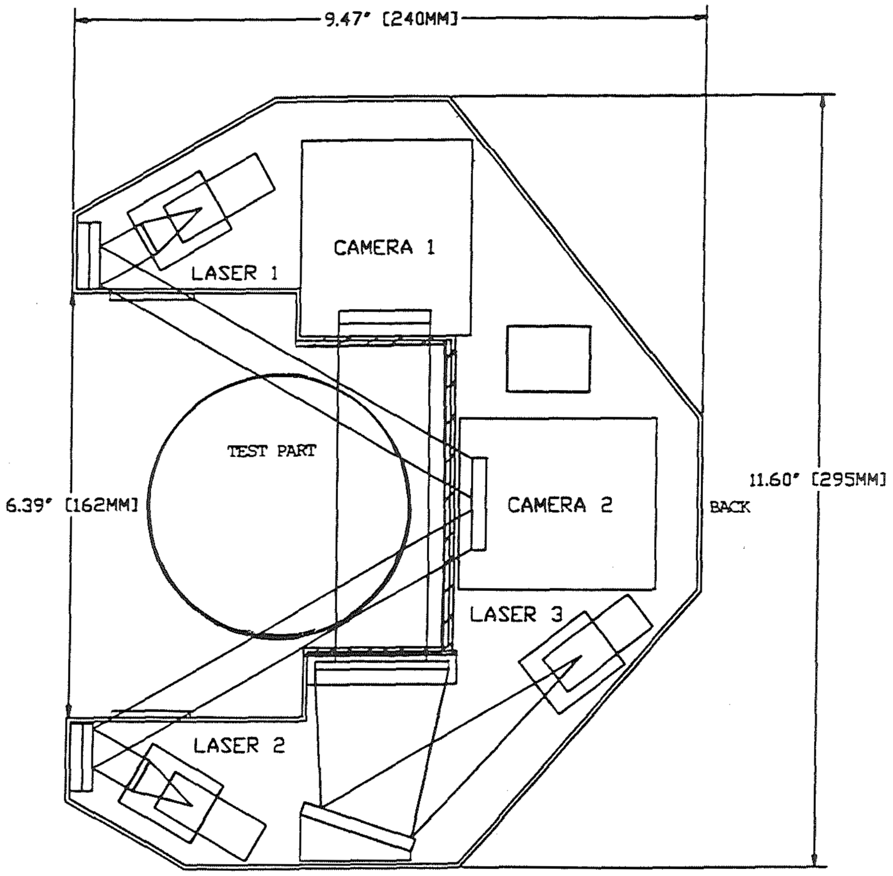

Figure 2. Diagram of 4 inch range tri-beam gage made by ITI.

APPLICATIONS AND CONCLUSIONS

The primay application for this gage is as a means to obtain immediate feedback to the machining process. When measurements are taken after the fact, compensations may be made which over correct the offset of the tool, leading to a continued swing plus and minus of the ideal. With information available while the part is on the machine, potentially subsequent cuts can be adjusted to correct errors on that particular part.

In general, the primary application motives for this gage are as summarized below:

- Provide On-Machine Gaging for Immediate Feedback
    - Compensate Subsequent Cuts
    - Monitor Machine/Tool Condition

- Obtain a Measure Independent of Machine Scales
    - Find Centering Errors
    - Monitor Machine Drifts

- Minimize Machine Time Interruption of Measurements
    - Measure During Spin-down
    - Provide High Measurement Speed

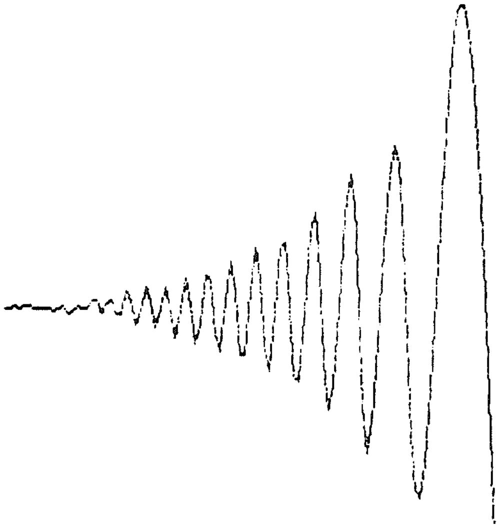

Figure 3. Interference pattern from the part edge used to make the measurements.

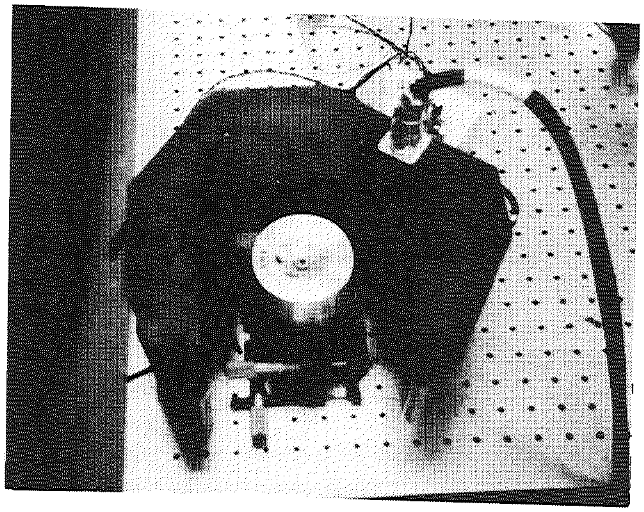

Figure 4. Picture of the prototype tri-beam gage made for on-machine tests.

As with any new gage, the ultimate applications will depend on the performance and final operational parameters of the gage system. With increasing abilities for machine controllers to use real-time data, on machine gaging such as this is expected to become an important tool for producing quality parts in the future.

ACKNOWLEDGEMENT

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