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A NEW ELECTRO-MAGNETIC CONTACT SENSING TECHNIQUE FOR ENHANCING MACHINING ACCURACY

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Abstract

This paper describes a new electromagnetic sensing technique which enables the cutting tool itself to be used as a probe during on-machine measurement of the workpiece. The simple sensor design for the probe (the cutting tool) has resulted in a low cost system for workpiece set-up and inspection. Tests have shown that the sensor precision is of the order of 0.01 μm and, hence, could be used on CMMs as well. The sensor is effective irrespective of variations in cutting tool geometry, cutting insert coatings, insert geometry and size, cutting fluids, and workpiece material.

Keywords: Electromagnetic Sensor, Measurement, Precision.

1. Introduction

Owing to increasing demand for higher precision coupled with lower costs in the machining industry [1], there is a growing need for automatable techniques leading to enhanced machining accuracy. In response to this demand, much progress has been made in recent times with regard to the development of high precision machine tools and novel machining techniques capable of yielding sub-micron level and, even, nanometer level machining accuracies. However, very few breakthroughs appear to have been made in terms of cost effective techniques capable of significantly enhancing machining accuracies achievable on *commonly used* machine tools (conventional, NC, or otherwise). As a result, the dimensional errors on the parts produced on most industrial machine tools continue to be several times larger in magnitude than the theoretically achievable highest machining accuracy on the given machine tool. For instance, in recent experiment on a CNC turning center, the maximum error on workpiece diameter was 20 times larger than the resolution of the machine axes.

The theoretical upper limit to the achievable machined part accuracy on a machine tool is basically determined by the random error profile of the specific machine. The gap between the actually achieved accuracy and the theoretical limit often arises due to assignable causes such as the errors in workpiece set-up; errors in tool set-up; regular geometric, kinematic and thermal errors inherent within the machine tool; errors due to dimensional wear of the cutting tool; and errors due to the deflection of the machine-fixture-workpiece-tool system under the cutting load. Good machining practice requires these errors due to assignable causes to be anticipated and corrected (or compensated for). A prerequisite to such anticipation and correction is the availability of cost-effective and robust techniques and the associated devices for measuring the errors. Contact sensing is one such technique.

Contact sensing refers to any technique capable of detecting the event of contact between two bodies approaching each other. In machining practice, one of the bodies is a probe attached to one of the machine's slides (axes) and the other is either a reference surface or the workpiece surface.

The contact sensing probe predominantly used in current industrial practice is the touch-trigger probe which has been particularly popular on coordinate measuring machines (CMM). In recent years, the touch trigger probe is also being used to perform on-machine inspection of machined parts and to assist in tool and workpiece set up.

A touch-trigger probe is usually mounted on one of the slides of the machine and the probe is moved relative to the part to be measured until the probe-tip establishes contact with the part at the desired point on the probe surface. Upon contact under continued (slow) relative motion of the probe, the probe deflects by a small known amount until a pair of electrical contacts are closed. This generates an electronic signal (trigger) which informs the CNC controller of the machine to record the axis positions of the machine at the moment of contact.

As with any shop floor level instrument, a contact probe should be (i) adequately accurate, (ii) versatile in application, (iii) simple construction, (iv) inexpensive, (v) robust and easily maintainable. The touch trigger probes in use today, while being attractive in terms of criteria (i) and (ii), seem to be inadequate in terms of criteria (iii), (iv), and (v).

The present paper describes a new technique of contact probing, called the “Fine Touch” which is capable of yielding a measurement accuracy comparable to that of the best touch trigger probe in use today while being significantly superior in terms of the other criteria. The principle of operation and construction of “Fine Touch” is extremely simple. Unlike with the touch trigger probe, Fine Touch has no time delay between the events of “touching” and “triggering”. The technique obviates the need for complex probes[3] such as the commonly used touch trigger probes by facilitating the use of the cutting tool itself as a contact-probe[4]. This eliminates the need for changing the tool for a probe before workpiece measurements could be made. This unprecedented feature opens up new applications of contact probing.

2. A new electromagnetic contact sensing technique

Fig. 1 shows the application of a novel contact sensor (USSR patents 1713338 & 1740983 by the first author) on a CNC turning machine. The sensing strategy utilizes the fact that the machine-fixture-workpiece-tool (MFWT) system is invariably subject to an electromagnetic field generated by diverse electromagnetic sources (electric motors, transformers, radio waves, etc.) generally present in a shop floor environment. It is assumed that the MFWT loop is electrically conductive (as is the case generally when machining metals which dominate the machining industry). Thus, when the tool is advanced to touch the workpiece during a probing cycle, the electrically conductive MFWT loop is closed and an electromagnetically induced alternating current I with a certain frequency spectrum consistent with that of the ambient electromagnetic field flows around the loop. The presence of this current signals contact between the tool and the workpiece. To detect the presence of this current, a simple electrical coil wound on an electromagnetic toroid (see Fig. 2) is mounted at a convenient location on the machine such that the loop current, I, passes through the central opening in the coil. Experience has shown that the best possible location is to have the coil “wrapped” machine’s spindle nose (see Fig. 1). Alternatively, the coil may be mounted around the tool shank. However, in this case, the coil needs to be remounted whenever the tool is changed. In either case, the MFWT system acts as the single turn primary winding of a transformer and the detecting coil acts as the secondary winding. The voltage, E_m, induced across the detecting coil due to this transformer effect is obviously proportional to the number windings in the detecting coil. A detecting coil with 500 to 1000 turns has been found to provide adequate output after suitable amplification. A separate electric circuit gives an “ON” signal when the amplifier output exceeds a carefully set threshold magnitude. The signaling circuit is easily wired to the controller of the CNC machine tool via a system PC such that the controller registers the axis positions at the instance the “ON” signal appears (as is common while using touch trigger probes). Considerable effort has been put into the fine tuning of the signal processing system — these details are not discussed here to protect the integrity of the patents.

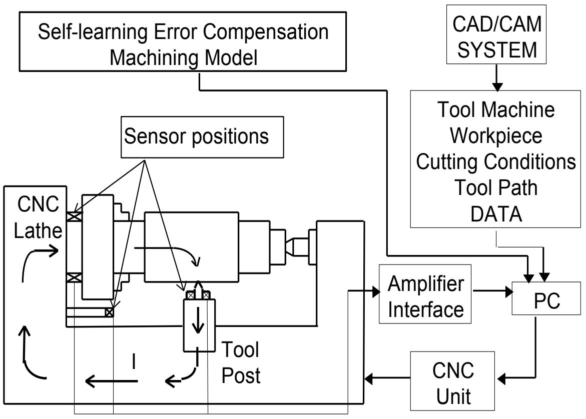

Fig. 1 The application of the electromagnetic contact-probe in CNC turning.

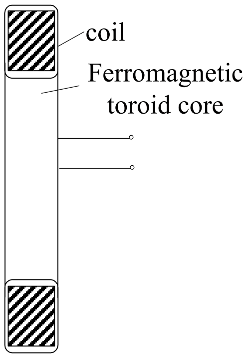

Fig. 2 Detection coil (secondary coil) design.

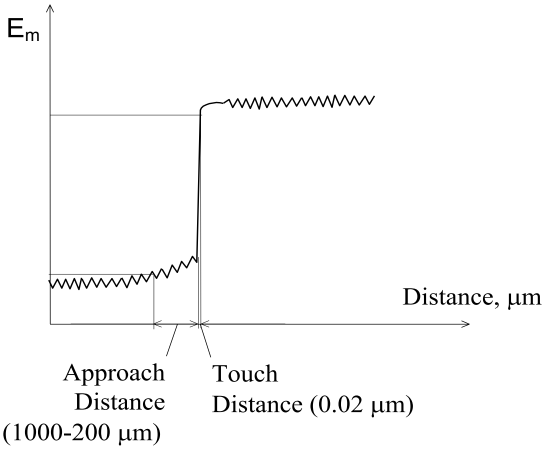

Fig. 3 Variation of voltage output, E_m, across the detection coil as the tool (contact probe) approaches the surface being probed

Fig. 3 shows the typical variation of Em as the gap between the tool and the workpiece decreases, i.e. as the tool approaches the work surface from a distance. As observed from this graph, there is a small but detectable voltage across the detector coil even when there is a small gap of the order of 0.005 to 1000 μm in the MFWT electrical loop. This voltage increases slowly as the gap decreases. Thus, by setting a second threshold voltage at a suitable level, a proximity signal could be transmitted to the CNC controller when the gap between the tool and the surface being probed is of the order of 0.1 to 1.0 mm. The controller could be programmed to slow down a rapidly moving probe upon receiving this signal. Thus, the actual contact could be made at a speed sufficiently small to guarantee a high contact detection accuracy.

3. Tests to assess the precision of the contact-probe

Consider now the possible sources of error in the contact detection described above.

We assume that either the tool itself or a specially designed probe with a spherical or prismatic tip is used as the probe.

The probe tip (the tool) needs to be pointed in the direction of probing motion so as to avoid uncertainty regarding the exact location of the contact point on the probe surface. However, fortunately, as most cutting tools are pointed by nature. Experience shows that a spherical probe tip of 3 to 5 mm diameter is sufficiently pointed to provide adequate contact detection accuracy. A hardened prismatic tip with a corner acting as the probe apex of course is the best.

Further uncertainties may arise with regard to the appropriate level of output threshold, and the influence of the presence of coolant and other contaminants (e.g. rust) on work or probe surfaces.

A number of tests were conducted to assess the level of measurement accuracy achievable by the new contact sensing technique and the sensitivity of measurement to various error sources. These are discussed below.

Firstly, in order to assess the best possible accuracy, specially designed probes with a hardened and ground square based half-pyramid-point and a 3 mm. diameter sphere were used. The probe was mounted on a metrological height measuring instrument with 0.2 μm resolution. The thickness of a metrological gage block was first measured (see Table 1) using the dial indicator on the instrument. Next, the measurement was repeated with the dial indicator (of 0.2 μm resolution) replaced by the special probe. The measurements were repeated several times to obtain statistically significant conclusions. It was found that there was no significant difference between the accuracy levels achievable by the pyramid point or spherical point probes. Each of these probes yielded a standard deviation of around 0.3 μm which was significantly superior than the standard deviation of 0.5 μm observed by using the dial indicator. This showed that the precision achievable through the use of the Fine Touch probe is superior to that achievable by a meteorological dial indicator of 0.2 μm resolution. This also meant that an assessment of the full accuracy potential of Fine Touch required tests performed with an instrument with a smaller resolution than that of metrological dial indicator.

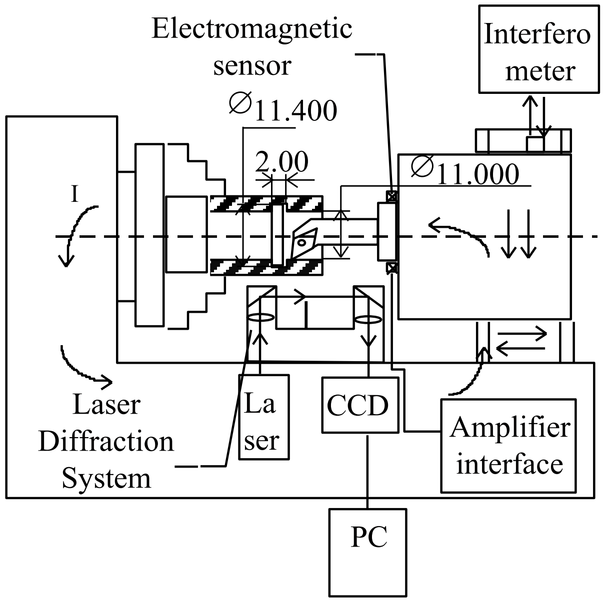

Fig. 4 Electromagnetic sensor calibration setup.

The second set of tests used a laser interferometer (see Fig. 4). The detection coil was clamped around a standard carbide tipped cutting tool (see Fig. 2) on a precision lathe with a dimensional accuracy capability of ±0.5μm. The lathe provided a numerical display of axis positions for easy positioning of the tool. A previously machined work surface was repeatedly probed (manually) using the cutting tool itself as the contact probe. In each case, the movement of the cutting tool movement was monitored using a high precision interferometer which, in turn, was set up and calibrated using a laser diffraction system ("LIR"). This elaborate method of monitoring the actual tool position at the time of contact was considered essential to provide a reliable assessment of the full accuracy potential of Fine Touch. These tests were repeated over different combinations (drawn from common practice) of cutting tool materials, cutting tip coatings and geometries work materials, cutting fluids, and work surface conditions. For each combination, achievable contact detection accuracy was taken as 6 times the standard deviation associated with tool position at the instant of tool-work contact as detected. The following conclusions could be drawn from these tests (see Table 1):

- The best contact detection accuracy (0.011μm) was found with the HSS tool-brass workpiece couple.
- The worst accuracy (0.0125μm) was obtained with a carbide-carbon steel couple.

- The mean contact detection accuracy across the range of tests was equal to 0.012μm .

The third set of tests aimed to compare the performance of Fine Touch probe principle with that of a popular brand of touch-trigger probe commonly used with a CMM in industrial practice. The test procedure adopted was similar to that used in the first set of tests except for the fact that the measurements were made on a metrological CMM. Measurements obtained with the electromagnetic probe were compared with those obtained using a standard touch-trigger probe. A statistical analysis of the test results indicated that the electromagnetic probe was superior by 2 to 2.5 times in terms of precision.

The aim of the fourth set of tests was to assess the precision obtainable by using practical cutting tools themselves as probes in bar turning. The tests were performed on the same precision lathe used in the second set of tests. Test measurements using the probe were compared with those obtained using a precision dial indicator. Tests were repeated with tools with different geometry (γ_n = -10° to 45°,αn = -3° to 10°, ψr= -3° to 10°, K'r = 10° to 45°, and nose radius = 0.5 to 5 mm). The tests were replicated with different tool materials, work materials and cutting fluids (water and oil based). Other test conditions were essentially same as those used in the second set of tests. All tests yielded a repeatability better than 1 μm. No statistically significant differences were found to be arising from differences in tool geometry and tool materials except for the fact that the standard deviation obtained while probing brass and aluminum workpieces with TiC coated tools was 10-15% higher. The best repeatability was obtained while probing copper and carbon steel workpieces with HSS cutting tools. However, a big error in the range 25-30 μm was found while probing heavily rusted carbon steel workpieces—probably due to the extremely rough work surface. The difference between probing in air and in the presence of cutting fluids was only in the range of 5 to 7%.

The fifth set of tests were aimed at assessing the effectiveness and utility of the Fine Touch principle in boring and measuring holes and grooves. These tests also aimed to demonstrate the fact that the machining accuracy achieved in the final pass can be signficantly improved by incorporating judicius probing of the surfaces produced in in earlier passes with the tool itself acting as the probe. The tests consisted of machining a bore of 11.000 mm bore with a 0.2 mm deep and 2 mm wide rectangular groove in brass workpieces. Machining was performed with standard carbide tipped boring bars on the same precision lathe used in the fourth set of tests. The following cutting conditions were used: depth of cut 0.05 mm, feed 0.026 mm/rev. and cutting speed 32 m/min. Boring was done in two equal passes. After the first pass, the boring tip was re-referenced using a laser diffraction system in order to compensate for tool wear and thermal deformation/extension. The resulting bore surface was then contact sensed using the boring tool itself as the probe. The measurement results (see Fig. 5) indicated that the average hole diameter was equal to 10.9773 mm. instead of the intended 10.990mm. This difference was attributable to the deflection of the boring bar under the cutting load. This difference was then added to the previously palnned depth of cut for the second pass. The resulting hole dimensions were then independently measured using the contact probing technique, a CMM, a Digimatic Hole Test device, and an optical microscope. The results are summarized in Fig. 5.

he comparison measurement results presented on Fig.3. shows the diameter measurement difference is 1.7μm for the electromagnetic sensor and 2.7μm for digital gadge Digimatic Holtest (HTD series 468). Consequently the hole form error was 0.0056 mm by the sensor on the lathe measurement and 0.0050mm by CMM. This technology permits to get also precision hole groove diameter with width 2mm and less. The average groove diameter was measured on the lathe was 11.4068 mm and CMM measurement gave 11.0082.(Fig.3). The last experiment had been made for small through hole boring from drilled diameter 1.00mm to 1.200 mm.and length 3.00mm. The boring tool is a very flexible and this kind of boring has some problems usually. The boring tool had been set up by diffraction system and following electromagnetic sensor usage around the tool holder. The lathe measurement result after compensation boring for average hole diameter was 1.205mm and the optical measurement on microscope gave average diameter value 1.203mm. The final set of tests consisted of measuring aluminum workpieces produced by end milling on a vertical machining center Yamazaki Mazak STD (B-6336) AJV-25/405. The dimensions measured were in the range 8 to 70 mm and were distributed over the X and Y directions of the machine table. The electromagnetic sensing coil surrounded the end mill (of 10 mm diameter) so that the end mill itself could be used as the contact probe during on-machine inspection. The same set of dimensions were then measured again using a standard touch-trigger probe mounted on the machining center. Finally, the dimensions were measured on a CMM. A statistical analysis of the data obtained from these three sets of measurements showed that the standard error (standard deviation of the difference between means) between CMM measurements and on-machine measurements obtained with the standard probe was in the range of 0.5 to 1.1 μm. In contrast, the standard error between CMM measurements and the on-machine measurements obtained with the end mill itself were nearly half (0.39 to 0.52 μm).

Table.1

No	Calibration equipment resolution in μm.	Comparison gage resolution in μm.	Probe	Meaning Accuracy in μm.
1	Instrument for height measurement with dial indicator- 0.2 .	Standard block gage - 0.01 .	Half-pyramid-pointed probe, 3 mm diameter sphere	0.3 0.3
2	CMM with contact trigger probe - 1.0	Standard block gage - 0.01 .	3 mm. diameter probe	1.0
3	Precision machine tool Schaublin - 150 -0.5	Laser interferometer - 0.001	Cutting tool for turning with carbide tip HSS	0.012 0.011
4	Precision machine tool Schaublin 150 - 0.5	Laser interferometer - 0.001	Carbide cutting tool for hall boring from 6.0 to 100.0 mm.	0.0125
5	Precision machine tool Schaublin 150 - 0.5	Laser interferometer - 0.001	HSS cutting tool for hall boring from 0.9 to 3.0 mm.	0.011

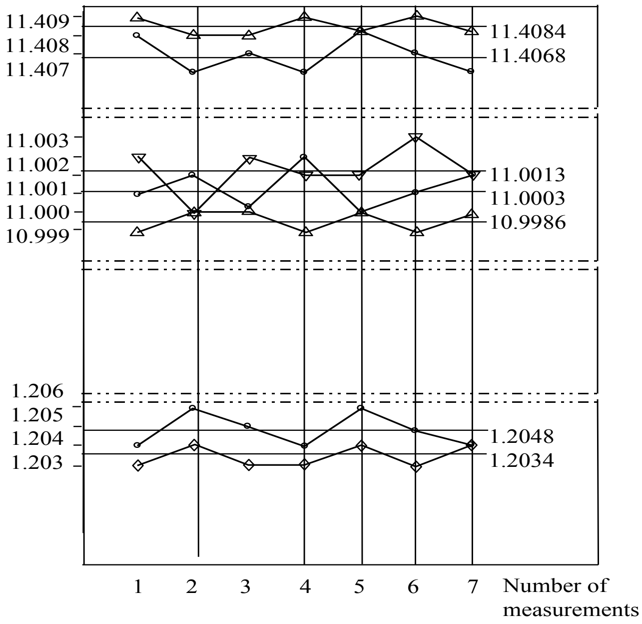

Fig.5 Hole measurement results.
o - electromagnetic sensor, ∇ - digital gadge,
Δ -CMM, ◊-optical microscope.

It is therefore concluded that the new electromagnetic sensing strategy not only enables the use of the cutting tool itself as a contact-probe but also improves the precision of measurement by a factor of 30 (Table2). Another advantage of the new approach is that no time need be wasted in removing the cutting tool from the machine and replacing by the standard probe during on-machine inspection. Thus, the new system is capable of achieving higher productivity and accuracy in measurement while maintaining simplicity of operation and the equipment used. Finally, further experiments have shown that tool breakage could be detected by monitoring fluctuations in the loop current._

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Table2

Comparison FINETOUCH System with Contact Trigger Probe.

N	INDEX	FINETOUCH SYSTEM	Contract Trigger Probe	Comparison of of two devices
1	Uni-directional repeatability at stylus tip	from 0,01μm to 0.02 μm	from 0.35μm to 1.00 μm	Better in 35-50 times
2	Measurement force	Absent	from 7g to 15 g	Better for accuracy
3	Distance for workpiece recognition	from 5.00 μm to 1,000.00 μm	Lack of opportunity	Priority
4	Measurement time	from 10 to 500 macroseconds	10 microseconds	Better in 50-1000 times
5	Stylus overtravel	The system recognizes a probe approach	from ± 20.0° to ± 14.0°	Better for machine tool safety
6	Max extension	from 300mm to 750mm	from 100mm to 300 mm	Better in 2-3 times
7	Stylus velocity	up to 1000 mm/min.	from 450 mm/min. to 500 mm/min.	Better in 2 times
8	Cutting tool breakage	while cutting	after cutting	Better for machine tool safety
9	Measurement by cutting tool	the same resolution 0.01-0.02 μm	Lack of opportunity	Better of machining accuracy
10	Autonomous action time	1000 hours	80 hours	Better in 10-12 times
11	Sense directions	No limit	limit in -Z	Better
12	Small hole and hole groove measurement	up to 0.3 mm any kind of hole groove	from 2.00 mm limited size of hole groove	Better
13	Pre-travel variation	±0.02 μm	from ±0.15μm to ± 0.20μm	Better in 10 times
14	Measuring temperature range	from -50°C to + 80°C	from 0°C to + 50°C	Better
15	Humidity admission	up to 100%	up to 100%	Same
16	Material for measurement	Electriconductive	All type of materials	Lack of measurement of nonconductive materials
17	Design complexity	Simple electronic and mechanic with few precision parts.	Simple electronic, high precision and complex mechanics	More simple, reliable and easy manufacturing