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Practical in-situ calibration method for the non-linear output from a low cost eddy current sensor

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Abstract. Increasing demand on manufacturing industry to produce tighter tolerance parts at a consistent rate means it is necessary to gain a greater understanding of machine tool capabilities, error sources and factors affecting asset availability. The machine tool spindle can be a significant contributor to both machine tool errors and failures resulting in a requirement for spindle error measurement.

The use of eddy current non-contact displacement transducers is currently a popular method for measuring spindle error in a manufacturing environment. This is due to their resistance to harsh conditions where dust and coolant may be present. Unfortunately, many eddy current sensors have non-linear outputs that vary with target material and dimension. Typically, adjustments in the signal conditioning are provided to linearise the output, and calibrate the sensors for a specific target material.

It is the purpose of this paper to assess current sensor calibration methods and highlight the potential for error in practical situations. To solve the problem, a method of in-situ calibration is presented, which uses the short range positional accuracy of the machine as a reference and least squares best fit of a low order polynomial. Validation is provided through the use of calibration test results and a practical example.

Keywords: Non-contact measurement, eddy current sensors, calibration methods, spindle error measurement

1.0 Introduction

Spindle error measurement is becoming increasingly important to machine tool users in high precision manufacturing, as they look to charcterise their spindle performance capabilities.

The requirement to measure and quantify these errors has resulted in the production of an international standard. ISO 230 part 7 'Geometric accuracy of axes of rotation' specifies test procedures and test equipment type for determining the effects of spindle errors [1].

The standard describes tests for measuring spindle radial, axial and tilt error motion which can be categorised into synchronous and asynchronous error motion. Synchronous errors are once per revolution and essentially result in the out of roundness of the spindle rotation. Asynchronous errors are non-repeating with spindle rotation and are directly responsible for part surface finish quality.

1.1 Non-contact sensing technology

The standard suggests the use of non contact measurement to analyse the spindle behaviour. The ability to monitor a target without physical contact offers several advantages over contact measurement, including the ability to achieve higher measurement resolution and increased dynamic response to moving targets. They are also virtually free of hysteresis and there is limited risk of damaging fragile targets because of contact with a measurement probe. Three typical non contact measurement sensing technologies (as suggested by ISO) are [2]:

- Capacitance
- Eddy Current
- Laser triangulation

Each of these technologies has its advantages and disadvantages for use in spindle analysis [3]. Laser triangulation sensors have a large offset so there is a reduced risk of damage during setup. However, they are susceptible to environmental influences such as humidity and material in the gap between the sensor and the target.

Capacitance sensors can achieve nanometer resolutions with high accuracy measurement however; they too are affected by use in dirty environments where dust, oil and coolant may be present.

Eddy current or inductive sensors, unlike the other sensors, are not affected by material in the gap between the sensor and the target and so are well adapted to use in hostile environments. Although the spindle in figure 1.1 is not typical, it does show a typical manufacturing environment where spindle analysis might take place.

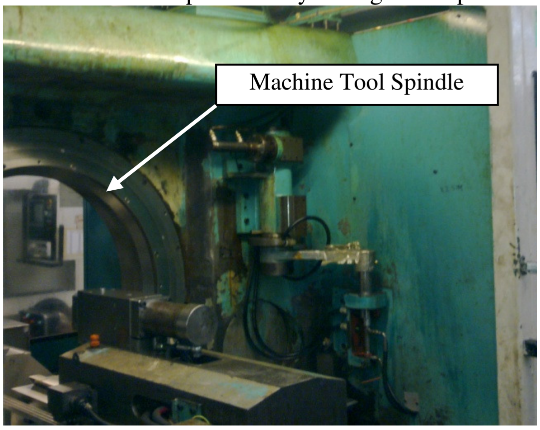

Fig. 1.1. Typical Manufacturing Environment

When compared to the other sensing technologies, eddy current sensors are also the cheaper option. The sensors used in this paper are from a simple low cost system. They are however not without their disadvantages and it is the purpose of this paper to address these disadvantages and offer a simple solution through the use of real case studies.

2.0 Eddy Current Technology

Eddy current sensors operate on a principle based on Lenz's law [4]. Most eddy current sensors are constructed with a sensing coil, which is a coil of wire in the head of the probe. When an alternating coil is passed through the coil it creates an alternating magnetic field. When a metallic target is present in this magnetic field the electromagnetic induction causes an eddy current in the target material in a perpendicular plane to the magnetic field of direction. This induced eddy current generates an opposing magnetic field which resists the field generated by the sensing coil. The interaction of the two magnetic fields is sensed using electronics and converted into an output voltage that is directly proportional to the distance between the sensor and the target.

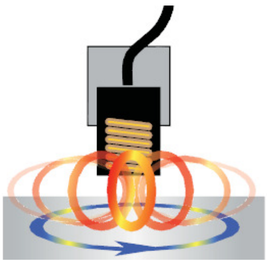

Fig. 2.1. Principle of eddy current sensor [5]

As previously mentioned, eddy current sensors are not without their disadvantages. The main challenge is that the output changes with the use of different target materials. This leads to a requirement for careful calibration of the sensors.

2.1 Sensor Calibration

It is normal practice that the sensors are calibrated by the manfacturer before they are delivered to the customer. Each sensor is calibrated to its own individual signal conditioning unit, these cannot be interchanged between sensors without effecting the output. The length of cable used to connect the sensor to the signal conditioning unit also has an effect on the output, so once calibrated cannot be exchanged for a cable of differing length. The main challenge for high-end specifiction eddy currenet sensors with linear outputs in the region of 0.2% is that they must be calibrated to a specific target material. There is a significant difference in the output of the sensors when used with a ferrous target compared to a non-ferrous target and as such the sensors are usually calibrated to either one or the other.

This leaves room for a certain amount of measurement uncertainty between materials of a similar nature. For example the output from an aluminium alloy target would be different to that of pure aluminium. Some sensor manufactures provide a method for self calibration for fine adjustment [6]. However, if it is necessary to use the sensors on both ferrous and non-ferrous target then either a new set of sensors will be required or they will continuously need to be sent back to the manufacturer for re-calibration to a new target material.

Alternatively low cost eddy current sensors are available that are not calibrated to a specific target material. However, the output from these sensors is very non-linear and as such requires careful calibration.

From practical experience, it is not always possible to use the same target material when performing spindle measurements. In many cases different machines will have differing test bar material. In certain situations it may be necessary to perform a measurement against a component mounted in a spindle.

With this in mind a simple in-situ method for calibrating the sensor to the necessary target material is extremely beneficial. The next section of this paper offers a possible solution to this challenge.

3.0 Impementation and Results of New Calibration Method

For the calibration of the eddy current sensor to a specific target material to take place, a linear profile of the output must first be established. This paper proposes setting up the sensor and required target material on a machine tool to measure the output when the machine is moved in one micron steps over the range of the sensor.

The linear scale of a machine tool is specified with linear errors on a typical modern machine in the region of 5µ/m, so when calibrating over 0.1 mm, any error can be considered negligible. There is a possibility of stiction error when moving the machine in small increments but experience shows that this is also negligible. This is not necessarily true for older machines and as such, calibration, where possible, should take place on newer machine tools.

To ensure the stability and accuracy of the measurement the following is taken into consideration:

- The accuracy and responsiveness of the axis over the region to be used must first be established by standard methods.
- Before any measurement is taken, it is important to move the axis of the machine over the region in which the measurement is to be taken in to ensure oil flow to the linear guide ways to counter the stiction.
- All calibration measurement is taken when approaching the target from the same direction so that no reversal error is introduced; an axis over-run [7] before the test ensures unidirectional calibration.

The measurement range of the eddy current sensor is 500µm. However, only the first 100µm was required for the case study in this paper. This was due to the most sensitive section of the sensor appearing in this part of the range. The blue trace in figure 4.1 shows the output over the first 100µm and as can be seen the output is very non-linear.

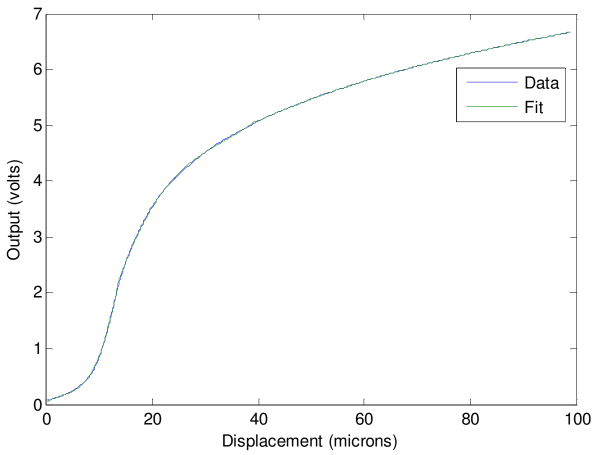

Fig. 4.1. Comparison of eddy current sensor output and calibration

The output data file from this test was then input into Matlab and a curve fitting tool used to fit to the data. A low order polynomial was used to ensure robustness of the fit and to enable the fit to be performed to within 0.1µm the curve was chopped into sections. The end result is a calibration file for each individual part of the curve to within 0.1µm and can be seen from the green trace in figure 4.1.

The data in figure 4.1 was captured using a 16-bit National Instruments (NI) data acquisition device and a bespoke computer application which uses standard NI APIs. The low order polynomial calibration file can then be loaded into the software whenever the sensor is being utilised with the target material for which it has been calibrated.

With the calibration file input into the windows application the repeatability of the calibrated sensor can be tested. The axis was moved in steps of 10 µm in the same direction from the same starting position for five separate runs and the deviation from linearity plotted in figure 4.2. As can be seen the sensor measured repeatably to within 0.2 µm over the 100µm range.

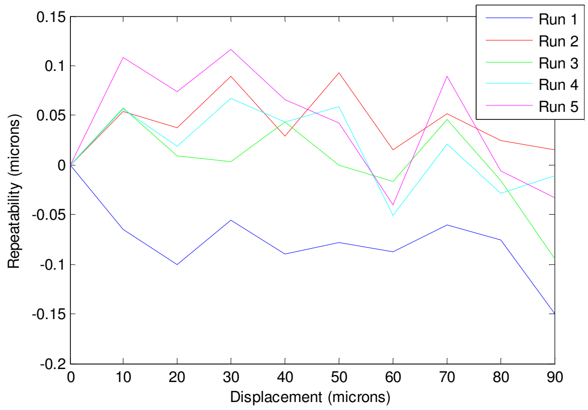

Fig. 4.2. Repeatability reuslts for eddy current sensor output

4.0 Practical Validation

To ensure the calibration method worked in a practical application, a dyanmic measurment was taken using a high resoultion piezo platform flexure rig. The eddy current sensor was set up to measure against the same target and the software loaded with the calibration file captured on a standard milling machine using the proposed method. A Renishaw XL80 laser interferometer was used as a traceable reference device (see figure 5.1).

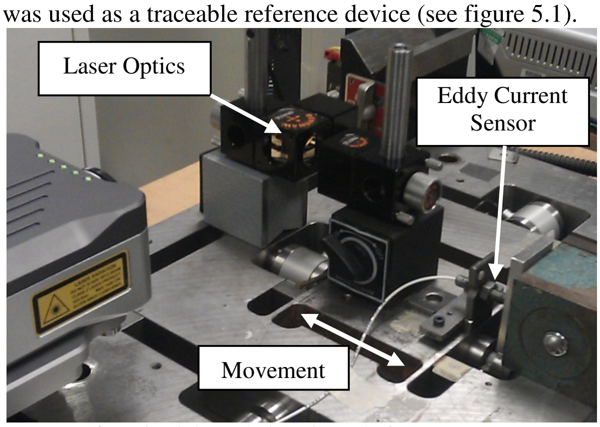

Fig. 5.1. High resolution piezo platform test setup

The rig was set to vibrate at 100Hz and the magnitude of the oscillation adjusted to be approximately 0.008 µm. Figure 5.2 shows the output from the Renishaw XL80 laser interferometer. There are some imperfections of the sine wave but this is to be expected at this level of resolution and can be attributed to the stability of the setup.

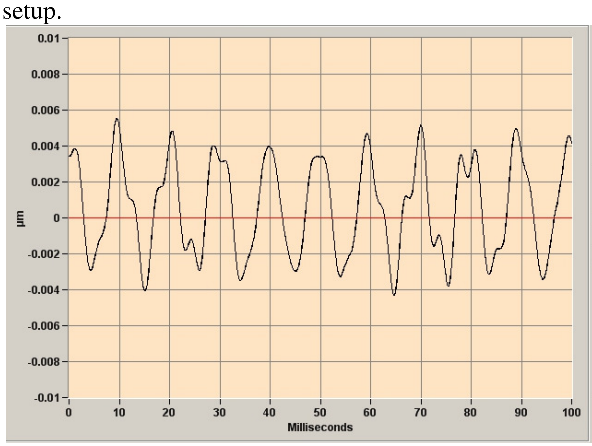

Fig. 5.2. Renishaw XL80 laser output on vibration rig

Figure 5.3 shows the output from the eddy current sensor sampling at 10 kHz. As is expected at this resolution there is some noise on the output signal but a sine wave can still clearly be seen at a magnitude of between 0.008µm and 0.01µm.

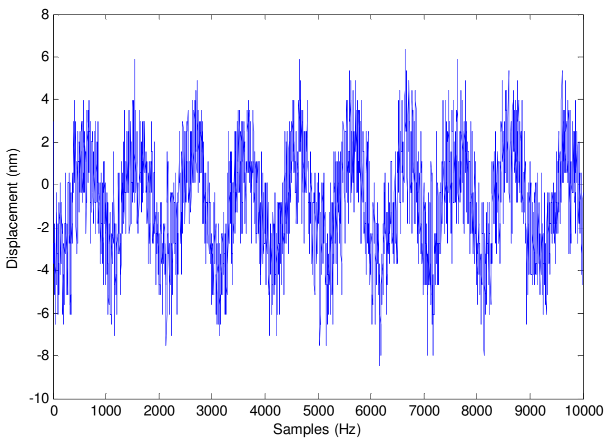

Fig. 5.3. Output from eddy current sensor on vibration rig

The standard deviation of the data in figure 5.3 shows the noise level to be at approximately 0.0037 µm. Since the data was sampled at 10 kHz averaging could be applied to clean up the signal, if this does not impinge on the required sampling frequency of the application.

5.0 Conclusions

The need of the manufacturing industry to understand machine tool capabilities and error sources has led to the production of an international standard for measuring spindle error motion. Measuring a spindle dynamically requires the use on non-contact displacement sensors.

This paper provides evidence to support the use of eddy current non-contact sensors for use in a manufacturing environment and assesses current calibration methods. The problem of needing to calibrate the sensors while working on the shop floor is highlighted.

A new methodology for in-situ calibration of low cost eddy current sensors is presented which allows the sensor to be calibrated to a specific target material, while in the field, to a linear accuracy of 0.3µm and a repeatability of 0.2µm.

A practical validation of the sensors is described and demonstrates the good resolution capability in the nanometre range.

Due to the non-linear output of such sensors, they are very sensitive over a small range. This offers other measurement capabilities for the sensor, such as vibration monitoring.

6.0 References

[1] ISO 230-7, Test code for machine tools – Part 7: Geometric accuracy of axes of rotation.2006.

[2] ISO 230-3, Test code for machine tools – Part 3: Determination of thermal effects.2007.

[3] Wilson, JS. "Sensor technology handbook", Elsevier, 2005.

[4] Nabavi, MR "A novel interface for eddy current displacement sensors", IEEE transactions on instrumentation and measurement, vol. 58, no.5, May 2009.

[5] Lion Precision, "Difference between capacitive and eddy current sensors", TechNote LT05-0011, 2009.

[6] Lion Precision, "Calibration of eddy current sensors", Eddy current TechNote LT02-0013, 2007.

[7] ISO 230-2, Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes.2006.

[8] Lai. Y, "Eddy current displacement sensor with LTCC technology," Ph.D. dissertation, Universität Freiburg, Switzerland, 2005.

[9] Tian. G. Y, Zhao. Z. X and Baines. R.W, "The research of inhomogeneity in eddy current sensors", *Sens. Actuators A, Phys.*, vol. 69, no. 2, p148– 151, Aug. 1998.

[10] Zhang, H. "An approach of eddy current sensor calibration in state estimation for maglev system", Electrical machines and systems, p1955-1958, 2007.

[11] Rao, BPC. "Practical eddy current testing", Oxford: Alpha Science, 2007.

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