ELECTRICAL RUNOUT USING AN EDDY-CURRENT SENSOR FOR ROUNDNESS MEASUREMENTS

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INTRODUCTION

Electrical runout is a commonly used term in the condition monitoring industry. It refers to the apparent displacement of a rotating shaft measured with inductive (eddy current) sensors caused by variations in the material electrical and magnetic properties [1]. Despite this unavoidable error in displacement measurement, inductive sensors remain the best choice when non-conductive contaminants such as dust, water, coolant or oil are present. In this work, actual roundness measured with a capacitance sensor and roundness plus sub-surface variation measured with an inductive sensor are compared for shafts of 6061-T6 aluminum, commercially pure Grade 2 titanium, and case hardened C1117 low carbon steel.

BACKGROUND

The theory behind inductive sensor operation relies on the relationship between electric current and magnetic fields. Inductive probes contain a coil that is excited with alternating current, creating an alternating magnetic field according to Ampère's law.

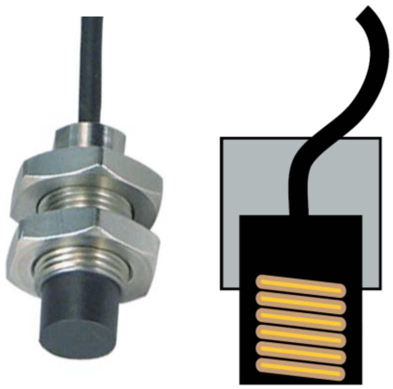


FIGURE 1. Inductive (eddy current) sensor with cross-section showing sensing coil.

According to Faraday, when time-varying magnetic fields interact with a conductive target, electric currents (eddy currents) are induced in the material. The eddy currents in the target create a reaction magnetic field in a direction opposite to the original magnetic field. This principle is known as Lenz's law.

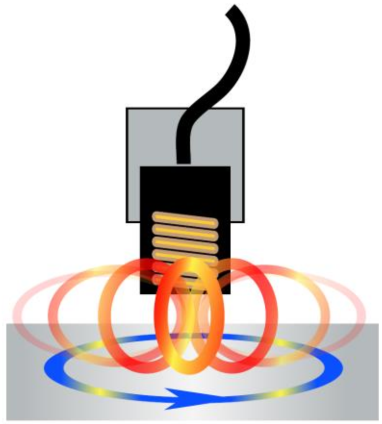


FIGURE 2. Alternating magnetic field produces eddy currents in the conductive target.

In order to maintain the original magnetic field around the sensing coil, the excitation current in the coil is increased to counteract the opposing magnetic field produced by the target. This interaction between the fields is used by the signal processing electronics to generate an output voltage proportional to the gap.

TARGET CONSIDERATIONS

Since the magnetic field of the sensor penetrates the target to induce eddy currents, anything that can disturb the current can cause errors in the gap measurement. The depth of field penetration is dependent on the frequency of excitation. If the target is too thin, the sensor will have reduced sensitivity and increased noise. Furthermore, the magnetic field covers an area on the target that can be 3-5 times larger than the probe tip. As a result, cylindrical targets should be 3-5 larger in diameter than the probe tip.

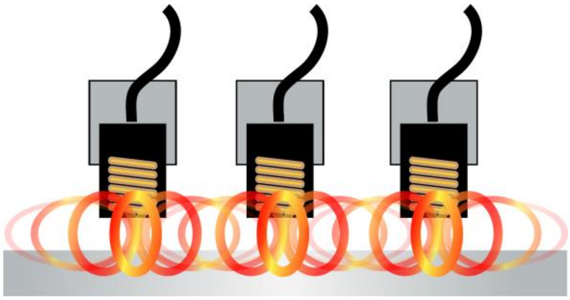


FIGURE 3.The field diameter can be 3-5 times the probe diameter. Multiple probes must be separated to avoid overlapping fields which create cross-talk between probes.

Eddy currents induced in the target are related to the electrical conductivity and magnetic permeability of the material. When calibrating the sensor, the actual material and alloy of the intended target must be used. However, even if the sensor is calibrated for a particular material, attributes such as the grain boundaries, crystal structure, chemical composition, quench profile, surface treatments, machining processes, residual magnetic field, and residual stress can all cause local variations in the material properties [2]. These inhomogeneities result in electrical runout, or measurement errors in target eccentricity and out-of-roundness.

APPROACH

The setup for demonstrating errors in roundness measurement due to electrical runout of various materials is shown in Figure 4. A cylindrical part is mounted to an air bearing roundness tester (Professional Instruments 4R Blockhead) with 512 line count encoder.

TABLE 1. Electrical and magnetic properties of materials used in this work [3].

Target material	Diameter (mm)	Volume resistivity (μΩ•m)	Relative permeability
aluminum 6061-T6	38	0.04	1.00002
commercially pure titanium	19	0.5	1.00005
steel C1117	19	0.2	3800

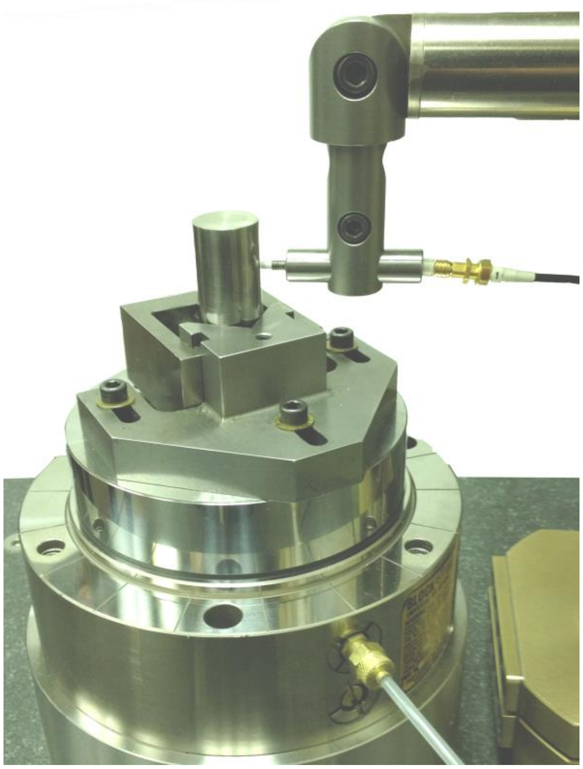


FIGURE 4. Electrical runout test using a Lion Precision U3 inductive sensor and ECL202 driver. The roundness tester uses a Professional Instruments 4R Blockhead air bearing spindle.

An inductive sensor and driver (Lion Precision U3 sensor and ECL202 driver) is calibrated for each of the three materials under test. The apparent out-of-roundness for each target material is measured for 8 revolutions using the inductive sensor at 512 angular locations provided by the encoder. The rotational speed is kept between 95-101 RPM to reduce speed-related variation in target inductance.

In the same setup, the inductive sensor is replaced with a capacitive sensor (Lion Precision C1-C probe and CPL290 driver) to determine the actual roundness using appropriate target corrections [4]. Comparing the two measurements demonstrates the roundness component of electrical runout for each of the three materials.

FIGURE 5. Measurement of the out-of-roundness of an aluminum target using a Lion Precision C1-C capacitive sensor.

RESULTS

The difference between the actual and apparent out-of-roundness shown in the polar plots (Figures 6, 7, and 8) demonstrates the "methods divergence problem" where two different types of displacement sensors produce significantly different results [5]. The divergence occurs because the capacitance sensor only measures the surface out-of-roundness and the inductive sensor measures the surface out-of-roundness and sub-surface material variation. The paramagnetic (small magnetic attraction) aluminum target results in the lowest error while the ferromagnetic steel target is the largest. This is a natural consequence given the differences in the material permeability shown in Table 2. The measurement error between aluminum and titanium is significantly less.

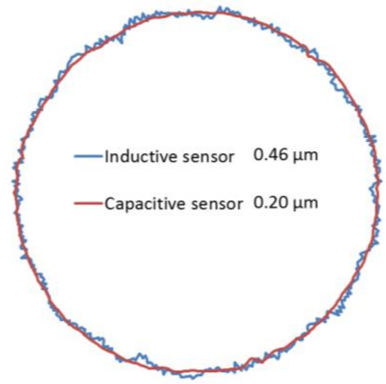


*FIGURE 6. **Aluminum** target out-of-roundness. The 0.26 micrometer difference between the two sensors is attributed to electrical runout.*

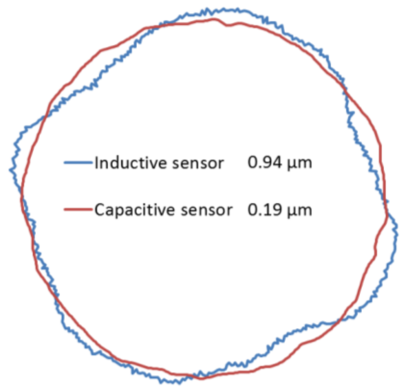


*FIGURE 7. **Titanium** target out-of-roundness. Slightly larger than the effect in aluminum, the electrical runout is 0.75 micrometers.*

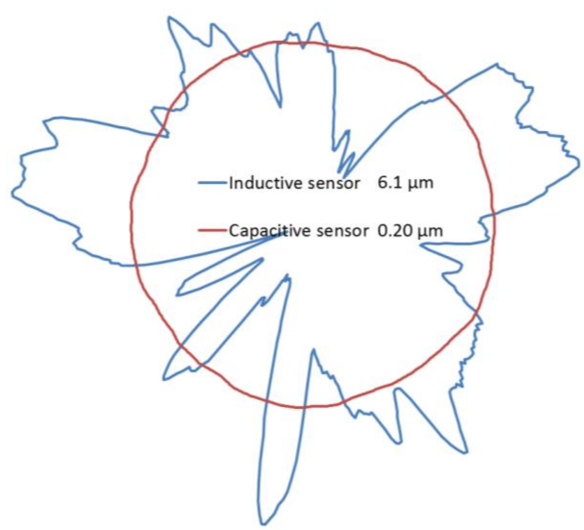
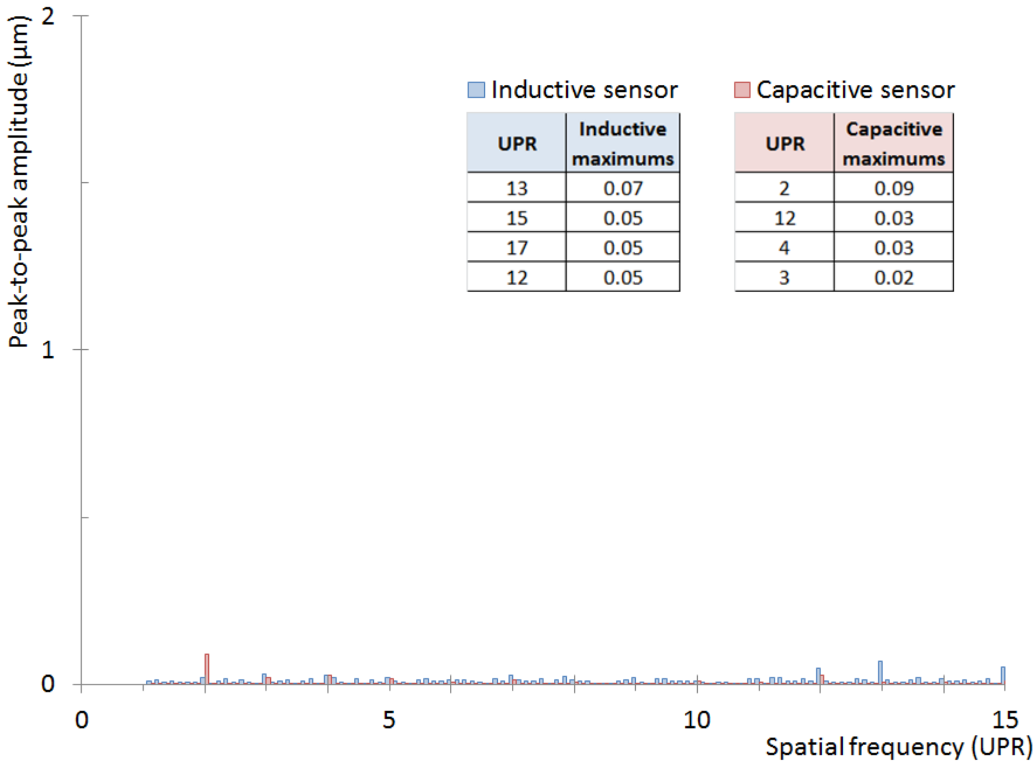


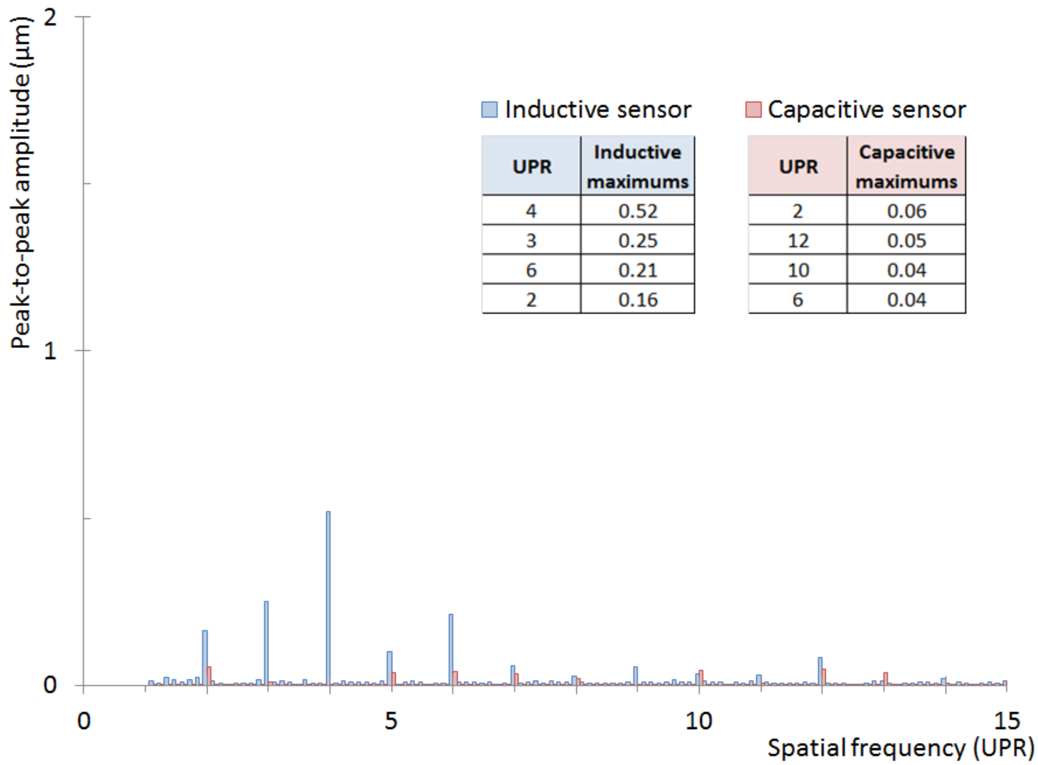
*FIGURE 8. **Steel** target out-of-roundness. The electrical runout in steel is significantly larger at 5.9 micrometers.*



UPR	Inductive maximums
13	0.07
15	0.05
17	0.05
12	0.05

UPR	Capacitive maximums
2	0.09
12	0.03
4	0.03
3	0.02

FIGURE 9. Frequency content of ***aluminum*** *target out-of-roundness.*



UPR	Inductive maximums
4	0.52
3	0.25
6	0.21
2	0.16

UPR	Capacitive maximums
2	0.06
12	0.05
10	0.04
6	0.04

FIGURE 10. Frequency content of ***titanium*** *target out-of-roundness.*

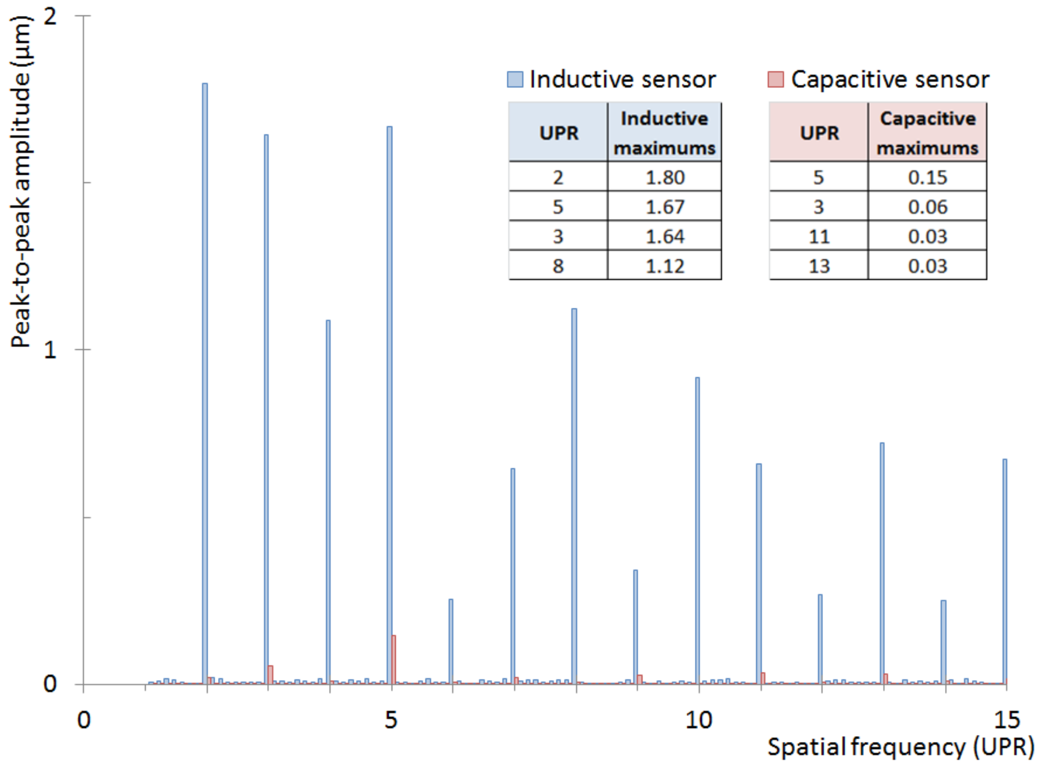


*FIGURE 11. Frequency content of **steel** target out-of-roundness.*

Figures 9, 10, and 11 show the synchronous and asynchronous frequency content of the out-of-roundness measurement. Content at and below 1 UPR has been filtered out. The asynchronous error is not material dependent and it was approximately 0.6 µm for the inductive measurements and 0.02 µm for the capacitive measurements. It is worth noting that the inductive measurement of the titanium exhibits a strong 4th harmonic not seen with the capacitive measurement. This is a remnant of the forming process and the resulting grain structure.

CONCLUSIONS

Inductive (eddy current) sensors are commonly used for radial vibration condition monitoring of rotating shafts in dirty environments. However, when using inductive sensors with rotating targets, displacement measurement errors exist associated with variations in electrical and magnetic properties of the target. It is demonstrated that measurement errors on the order of 10 µm can exist when using an inductive sensor and a rotating steel target. Aluminum and titanium showed reduced measurement errors on the order of 1 µm. Asynchronous error due the resolution of the inductive sensor was independent of material and was approximately 0.6 µm.

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