ELECTRICAL RUNOUT USING AN EDDY-CURRENT SENSOR
FOR ROUNDEDNESS 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 \cite{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 subsurface 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. 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.

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.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Inductive (eddy current) sensor with cross-section showing sensing coil.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Alternating magnetic field produces eddy currents in the conductive target.}
\end{figure}
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>
<thead>
<tr>
<th>Target material</th>
<th>Diameter (mm)</th>
<th>Volume resistivity (µΩ•m)</th>
<th>Relative permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum 6061-T6</td>
<td>38</td>
<td>0.04</td>
<td>1.00002</td>
</tr>
<tr>
<td>commercially pure titanium</td>
<td>19</td>
<td>0.5</td>
<td>1.00005</td>
</tr>
<tr>
<td>steel C1117</td>
<td>19</td>
<td>0.2</td>
<td>3800</td>
</tr>
</tbody>
</table>

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.
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 10. Frequency content of titanium 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.

REFERENCES