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Tilt sensitivity of an eddy-current position sensor for high-precision applications

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Abstract
To make eddy-current position sensors suitable for use in high precision applications they should operate at small standoff distances and high excitation frequencies. Currently, a new eddy-current sensor is being developed that works with excitation frequencies up to hundreds of MHz. However, operating at smaller standoffs increases the sensor's sensitivity to tilt. Therefore, it is necessary to investigate this tilt sensitivity and to derive specifications regarding the maximum acceptable tilt angle. A finite element model has been developed to find the change in the sensor's inductance as a function of the sensor standoff and tilt angle. The model has been validated by using experimental results. Based upon the results of the finite element model, an equation has been found for the inductance as a function of the standoff and the tilt angle. The equation shows that tilt of the eddy-current sensor leads to an offset error and a scale error. Based upon the equation, the sensor's tilt specification can be derived.

Keywords: position sensing, eddy-current sensor, sensitivity to tilt, tilt specifications

1. Introduction

In many high-precision machines the relative positions of the machine's parts need to be measured with high accuracy. For this function, various types of high performance position sensors may be used. If the required sensor range is small, e.g. below 1 mm, capacitive position sensors are often good candidates, as they have a high accuracy and are relatively low priced. However, an important drawback of capacitive sensors is their sensitivity to contamination of the gap between the sensor and the target. Alternatively, eddy-current sensors may be used, which do not have this drawback. Nevertheless, eddy-current sensors are still not as widely applied in high precision systems as capacitive sensors are, mainly due to their relatively poor resolution [1].

Due to their highly non-linear transfer characteristic, the sensitivity of capacitive and eddy-current sensors depends on the distance (standoff) from the target. That is why, for sensing very small displacement, the standoff has to be as small as possible. Unfortunately, the eddy-currents are formed inside the target, and not at its surface. This leads to additional standoff which further limits the sensor's sensitivity.

The effective depth of eddy currents can be characterised by the so-called skin depth. Skin depth is a function of the sensor's excitation frequency and the conductivity of the target. In earlier work the sensor's standoff was decreased by increasing the sensor's excitation frequency to tens of MHz, which significantly reduced the skin depth [2]. The small standoff, however, leads to a new challenge: the transfer characteristic of the eddy-current sensor becomes more sensitive to the tilt angle.

This paper shows how the sensor's tilt angle influences the sensor's performance. First, a sensor model and an experimental setup are introduced. The model is experimentally validated and is then used to derive the tilt angle specification of the sensor.

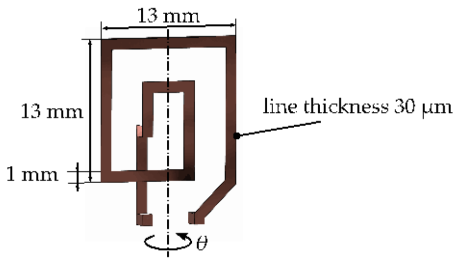

Figure 1. Geometry of the copper coil used for the experiments. The coil was manufactured on a PCB substrate.

2. Method

2.1. Finite element model

Figure 1 shows the geometry of the studied coil. The coil was made of copper and manufactured on a PCB. A Comsol finite element model of the coil and a copper target was developed. As the coil was asymmetric and had to be tilted, it was necessary to model the coil in 3D.

An excitation frequency of 100 MHz was used. The skin depth of copper at this frequency is around 7 μm. To describe the current distribution in the copper properly, excessive numbers of finite elements are needed. For this reason only the boundaries of the copper were modelled, using boundary elements in combination with lumped port excitation [3].

2.2. Experimental setup

The PCB coil of Figure 1 was mounted to the fixed world. The copper target was placed on a precision rotation stage on top of a translation stage. The inductance of the PCB coil was measured using an Agilent 4294A impedance analyser. As the impedance of the coil is also sensitive to its lateral alignment with respect to the target, a micrometre stage was added to the setup to be able to adapt the coil's lateral position.

3. Results and discussion

3.1. Inductance change as function of standoff position

Figure 2 shows the change in the coil's inductance, $\Delta L(x)$, as a function of its standoff. The results of the FE model and the measurement show a significant difference, possibly resulting from a standoff error or from the mesh of the FE model. However, the sensitivities $\partial L(x)/\partial x$ of the FE model and the measurements are close. At the sensor's nominal standoff of 100 µm, the FE model yields a sensitivity of 48 µH/m, and the experiment a sensitivity of 46 µH/m.

According to the FE model, the inductance of the coil at its nominal standoff is 11 nH. The sensor's electronic readout allows the measurement range L_{range} = 1.1 nH, which corresponds to a position range of x_{range} = 22 µm.

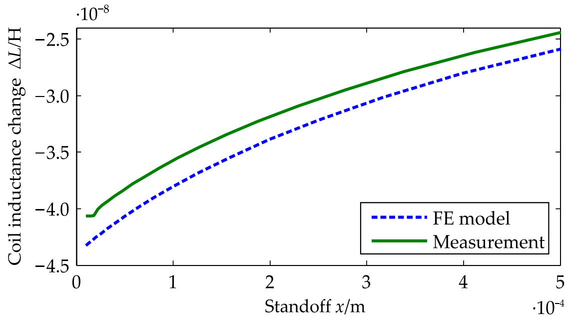

Figure 2. The coil's inductance change as a function of its standoff from a copper target. Inductance change was measured with respect to the absence of the target. An excitation frequency of 100 MHz was used.

3.2. Inductance change as function of tilt angle

Figure 3 compares the additional inductance change of the coil, ΔL_{tilt}, resulting from the tilt angle at a standoff of 100 µm. The graphs are centred around the point (ΔL_{tilt} = 0, θ = 0) for better comparison. The inductance change was very low. That is why the experiments were repeated 450 times and the results were averaged to decrease the random noise level.

The inductance change can be described well by a parabola, $\Delta L_{tilt} = S_{tilt}\theta^2$, where S_{tilt} = –1.5 H/rad^2 for the FE model and S_{tilt} = –1.8 H/rad^2 for the measurements.

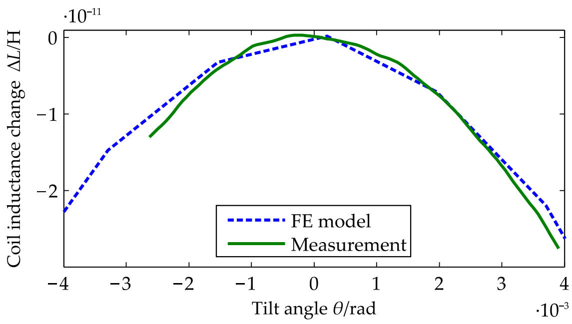

Figure 3. Inductance change of the coil as a function of the tilt angle at a standoff of x = 100 µm.

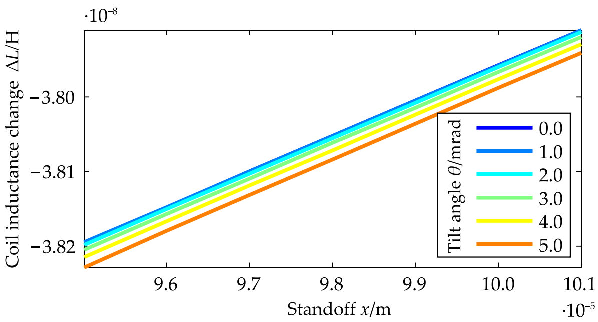

Figure 4. Inductance change of the coil as a function of standoff at different tilt angles (colours, in mrad).

3.3. Inductance change as function of standoff and tilt angle

Figure 4 shows the coil's inductance change as a function of its standoff, as obtained with the FE model. The colours indicate different tilt angles. As seen in Figure 3, the coil's inductance decreases with increasing tilt.

Starting at 48 µH/m for 0 tilt, the slope of $\Delta L(x)$ increases proportionally to the tilt angle squared. With slope variation 0.014 H/(m·rad^2) this is a small effect that is almost indiscernible in the figure. In addition, $\Delta L(x)$ has some non-linearity for 0 tilt angle, which can be compensated for after an initial calibration. More importantly, the additional non-linearity due to tilt is not significant.

3.4. Derivation of tilt angle specification

Using the results obtained with the FE model, an equation for the inductance change of the coil as a function of the change in standoff and tilt angle can be formulated as:

$$\Delta L(\Delta x,\theta) = 48\cdot 10^{-6}\,\Delta x + \left(0.014\Delta x - 1.5\cdot 10^{-6}\right)\theta^2 . \qquad (1)$$

The formula shows that a tilt angle of the sensor causes, like in capacitive sensors [4], both an offset error and a scale error.

Table 1 provides the equations for the offset error and the scale error, along with examples for tilt angles of 0.1 mrad and 1 mrad. Of the two, the offset error is the most significant. If the offset error is allowed to be 0.1 nm, the resulting tilt specification is 0.18 mrad.

Table 1. Errors due to a tilt angle θ. The errors are given as a fraction of the full sensor range and are thus dimensionless.

		Tilt angle	
		0.1 mrad	1 mrad
Offset error	$\frac{1.5\cdot 10^{-6}}{L_{range}}\theta^2$	1.7·10^{-5}	1.7·10^{-3}
Scale error	$\frac{0.014 x_{range}}{2L_{range}}\theta^2$	1.3·10^{-6}	1.3·10^{-4}

4. Conclusions

A tilt analysis of an eddy-current sensor was presented using a FE model. Both the sensor's position sensitivity in terms of inductance over position, and its tilt sensitivity were experimentally validated. The results of the FE model were used to formulate an equation for the inductance change as function of the sensor's standoff and tilt angle. This equation shows that a nonzero tilt angle error leads to an offset error and a scale error. Of the two, the offset error is dominant. If the offset error needs to be smaller than 0.1 nm, the corresponding maximum allowed tilt angle for the sensor parameters and geometry used, is 0.18 mrad.

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