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Auto-alignment of a High-Precision Eddy-current Displacement Sensor Using a Thermal Slider Actuator

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Abstract

Eddy-current displacement sensors can reach nanometre resolution by operating at high excitation frequency (~150 MHz) and low standoff (~50 µm). Alignment is more critical at lower standoff, requiring auto-alignment functionality. Auto-alignment of sensors can be performed using the Thermal Slider Actuator (TSA), which was until now only used in combination with capacitive probes. In this paper a new miniaturised design of the eddy-current probe is proposed that can be integrated in the TSA. The eddy-current coils are embedded in a PCB disk of 12-mm diameter, which is clamped between the fingers of the TSA. Although the PCB is relatively rough, the TSA was shown to produce net motion in both directions, attaining speeds of 13 µm/hour. Furthermore, in contrast to a capacitive probe, the eddy-current probe contains electronics, which generates heat, leading to a thermal gradient in the TSA. A thermomechanical model of the eddy-current probe and the TSA shows that the resulting deformation of the TSA is acceptable.

Eddy-current sensing, sub-nanometre displacement sensing, auto-alignment, Thermal Slider Actuator (TSA), thermal stability.

1. Introduction

Compared to capacitive sensors, Eddy-Current Displacement Sensors (ECDS) are relatively insensitive to environmental conditions and do not need an electric connection to the sensing target. Important limitations of ECDSs, however, are their relatively low resolution and relatively high sensitivity to thermal and mechanical drift [1]. In previous work, we have proposed a novel eddy-current sensor architecture that aims to mitigate these limitations. The architecture consists of a flat sensing coil, a reference coil and an on-chip readout that uses a much higher excitation frequency than state-of-the-art. A resolution of 1.85 nm at a bandwidth of 2 kHz over a range of 20 µm was reported [2].

To obtain a high displacement sensitivity, the sensor operates at low standoff of the target, around 50 µm. This leads to more stringent alignment requirements. Like in capacitive sensors, misalignment leads to both an offset and a gain error [3]. In literature, the Thermal Slider Actuator (TSA) was proposed, which was used to perform auto-alignment of capacitive electrodes. This actuator reached sub-micrometre positioning precision and a high stability (0.5 nm over 1 hour) [4]. It was, however not used in combination with eddy-current sensing.

This paper proposes a miniaturised eddy-current probe that can be integrated in the TSA (Section 2) and studies the performance of this design in terms of its actuation capabilities (Section 3) and the self-heating due to the integrated electronics (Section 4).

2. Integration of eddy-current sensor and thermal slider

In previous work, a high-precision eddy-current sensor prototype was shown that was realised on a multilayer PCB [2]. The prototype contains two coils: a sensing coil, whose inductance depends on its standoff distance from a conductive target and a reference coil with a constant inductance. The inductance of the coils is measured using a dedicated readout chip that excites the coils at 145 MHz and digitises the measurement value. The high excitation frequency makes it possible to use low-inductance, flat, mechanically stable coils. The high frequency also decreases the depth of the induced eddy currents, which leads to a lower cross-sensitivity to temperature variations.

Based on the earlier prototype, a new, much lower volume eddy-current probe is proposed (Figure 1, right). The prototype consists of a 12-mm diameter 6-layer PCB that contains the sensing and the reference coils and intermediate shielding layers. Using pins, the PCB is connected to a second, 11-mm diameter PCB that contains the readout chip and a few additional electronic components. This chip is placed close to the coils to minimise static inductance, but far enough to minimise self-heating of the electrode PCB. Due to the probe's low volume it is possible to integrate the sensor in a standard TSA (Figure 1, left).

During positioning of the eddy-current electrode, the position and the tilt of the electrode with respect to the measurement target is measured using three capacitive electrodes that are placed around the measurement coil.

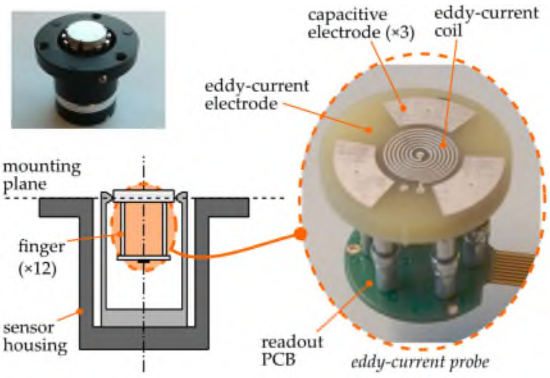

Figure 1. Standard TSA (top left). Cross-section of a TSA with an eddy-current probe (bottom left) and image of the eddy-current probe (right).

3. Measurements thermal slider

In literature, the TSA is used with capacitive electrodes, which are ceramic and have a polished side [4]. The 6-layer eddy-current electrode has been realised in FR4 PCB material, which is less stiff than ceramic. The electrode was made circular by water cutting, leading to a relatively rough sidewall. As PCB electrodes have not been used in combination with the TSA before, the stepping performance with the PCB electrode has been assessed.

An eddy-current electrode was placed between the fingers of a standard TSA with 12 fingers of 15 mm length. The fingers were equipped with resistors of 240 Ω. To heat up a finger, a potential of approx. 11 V was applied to the resistors. Thermal cycles, as described in [4], were applied to the TSA to produce a net upward motion (toward the measurement target) and downward motion. The cycles consisted of a heating or a cooling step of 10 s, followed by one-by-one cooling or heating of each individual finger for 10 s. The average power consumption of the thermal cycle was 3.0 W.

The position of the electrodes was measured using the capacitive plates. Figure 2 shows the translation during an experiment in which forty upward thermal cycles and forty downward cycles were repeated alternately. The results show that the motion generated by the TSA is repeatable in the tested range of about 20 µm and that the net speed in the two directions is almost equal, around 13 µm/hour.

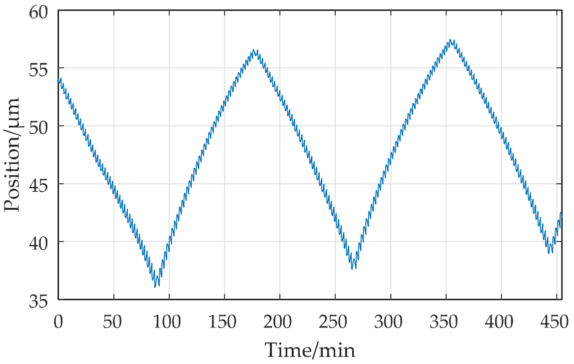

Figure 2. Standoff change when applying alternatingly forty upward and fourth downward thermal cycles.

4. Effect of sensor self-heating

Previously, the TSA was used in combination with capacitive probes, which are inherently non-dissipative and make use of external electronics. For eddy-current sensing, however, the readout electronics, which consumes 9.1 mW of power [2], need to be close to the coils to minimise offset inductance due to wiring, which leads to higher self-heating of the sensor.

When the TSA is turned off, any expansion of the fingers is compensated by the expansion of the housing, as long as the fingers and the housing have equal temperature. Due to self-heating, however, the fingers might attain a higher temperature than the housing, leading to displacement of the probe.

A finite element model of the TSA in air was developed using the solid mechanics, the heat transfer and the laminar flow toolboxes in Comsol. The model consists of a 1/24th sector of the full sensor. A heat source is placed at the location of the chip. The thermal contact between the finger and the electrode is modelled as perfect. Further boundary conditions are indicated in Figure 3.

Figure 3 shows the resulting thermal response. The area around the chip heats up significantly, but the average finger temperature rises by only 0.016 K, leading to 4.8 nm finger elongation. As this is in the order of the sensor's resolution at 2 kHz bandwidth, this is acceptable. More importantly, in the model, most deformation is caused by the expansion of the readout PCB, leading to bending of the eddy-current electrode. This must be taken into account in the final probe design.

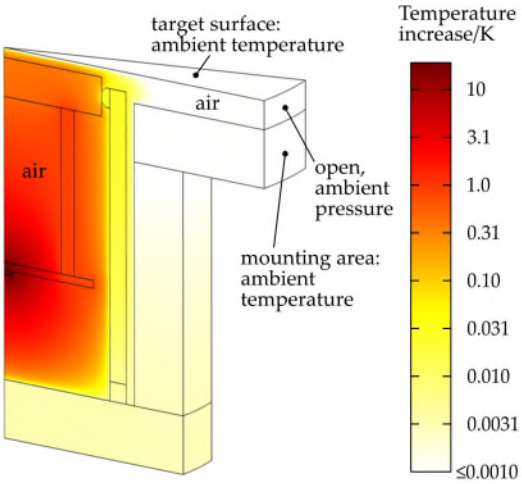

Figure 3. Thermal response of a sector of the TSA and the eddy-current probe due to the heat input of the readout chip.

5. Conclusion

When operated at low standoff, alignment of the eddy-current probe becomes more critical. The Thermal Slider Actuator (TSA) can be used to perform this alignment. A design of a miniaturised eddy-current probe is proposed that facilitates integration in the thermal slider actuator (TSA). The design consists of a 12-mm diameter PCB disk that contains the eddy-current coils and shielding layers. To this PCB a second PCB is attached that carries the readout electronics. The 12-mm PCB is placed between the fingers of the TSA.

Although the sidewall of the PCB was not polished, measurements showed that it is possible to generate net motion. The translational speed in the two directions is almost equal, around 13 µm/hour.

The dissipation in the integrated readout electronics causes self-heating of the sensor. Simulation results showed that this leads to 4.8 nm displacement of the electrode, which is acceptable. More important is the internal deformation in the probe. A more detailed thermomechanical analysis is required to investigate whether design changes are needed to more optimally thermally isolate the measurement electrode and the electronic readout.

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