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Novel MEMS Sensor for Detecting Magnetic Particles in Liquids †

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Abstract: We present a novel MEMS sensor for the detection of magnetic particles in liquids, which consists of a microcantilever excited piezoelectrically in resonance and having an integrated planar coil on its free end. Due to the latter component, magnetic particles are attracted and accumulate on the sensor surface. The additional mass introduced by the particles changes the resonance frequency of the microcantilever serving as measured quantity. To evaluate our design, we dispersed 250 nm iron-oxide particles in de-ionized water and monitored the resonance frequency during particle accumulation. 100 min after measurement start, a total resonance frequency shift of 6 kHz was found, which can easily be measured and shows the high potential of the proposed sensor design.

Keywords: MEMS sensor; microcantilever; magnetic particles; resonant mass sensing

1. Introduction

The detection of magnetic particles in liquids is critical in e.g., lubricating systems, where ferrous wear debris is a measure for the actual condition of machinery. To avoid the time-consuming standard procedure when sending samples of used lubricants to a laboratory for analysis, numerous real-time monitoring systems have been developed. These systems use various physical principles to detect wear debris, such as changes of the magnetic inductance [1] and electrical capacitance [2]. In addition, echo detection using ultrasonic transducers [3] and optical detection and characterization even down to single particle level are possible [4]. Despite their real-time monitoring capabilities, these methods suffer from low throughput and/or low sensitivity, as the minimal detectable particle size is in the range of 10 µm or above [5]. Especially in fuel-lubricated systems, such as the injection pump of modern diesel engines, the size of wear particles is much smaller, revealing the limits of established wear debris sensors.

Our design allows for the measurement of particles even in the sub-µm range, by taking advantage of the high mass responsivity of resonating MEMS sensors. While mass sensing MEMS resonators are an established tool to detect e.g., pathogens or similar species in bioanalytics [6], their use in the field of lubricant monitoring is limited to viscosity and density sensing [7]. In this work, we present our novel MEMS sensor design and show its particle detection capability.

2. Measurement Principle and Sensor Design

The measurement principle of microcantilever-type sensors is based on the dependence of a given resonance frequency on the oscillating mass. When a mass Δm is added on the surface of an oscillating cantilever, the induced resonance frequency shift is given by [8].

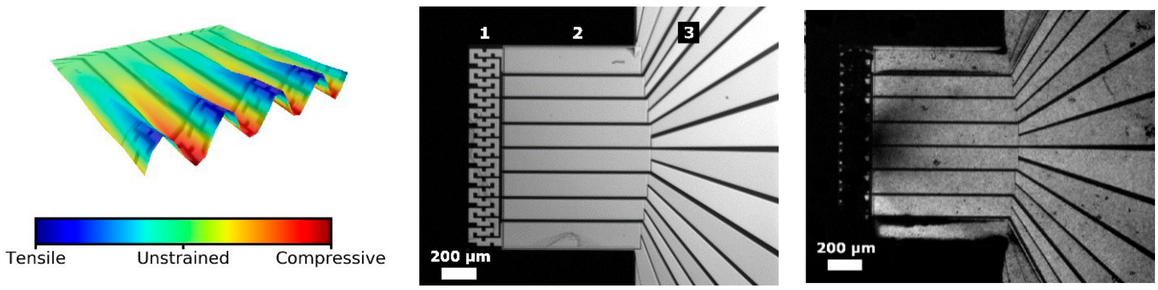
$$\Delta f = -\frac{1}{2}\frac{\Delta m}{M} f_{res} \phi^2 (x, y). \quad (1)$$

Here, φ(x, y) is the value of the mode shape function at the position of the added mass, f_{res} is the resonance frequency of the microcantilever and M is the oscillating mass. In vacuum, M is equal to the mass of the cantilever, whereas in a liquid environment the mass of the displaced fluid has to be added [9]. Depending on the sensor geometry and surrounding fluid, this additional fluid mass can be a multiple of the cantilever mass and therefore greatly deteriorate the mass sensing performance. To minimize the impact of the surrounding fluid, our sensor vibrates in the 8th order of the so called-roof tile mode (see Figure 1a), which shows very low damping (quality factor ≈ 300 in water [10]) and was already successfully used to measure the dynamic viscosity and the density of various liquids [11].

Figure 1b shows the design of our sensor, which is based on a 1000 × 1250 × 20 µm silicon cantilever, fabricated using standard micromachining techniques. The cantilever is actuated by a sputter-deposited aluminum nitride layer, which is connected via gold electrodes. The patterned electrode design is optimized to excite the 8th order roof-tile mode [12]. To generate the magnetic field needed to accumulate the particles, we integrated a meander-shaped planar coil on the free end of the cantilever. An identical sensor is fixed next to the active sensor and serves as a reference element. Since current is only fed into the planar coil of the active sensor, no particles are magnetically attracted to the reference element. Doing so, it is possible to cancel out environmental effects, such as temperature variations of the surrounding liquid.

3. Measurements and Results

The measurement procedure was as follows: the sensor was placed under a Laser Doppler Vibrometer (MSA 500; Polytec GmbH, Waldbronn, Germany) and both, the active and the reference element, were connected to a signal generator to excite the oscillation. To test our sensor design, we dispersed 250 nm iron-oxide particles in deionized water with a concentration of approximately 350 µg/mL. The sensor elements were immersed in the dispersion and the planar coil of the active sensor element was powered with an electric current of 150 mA.

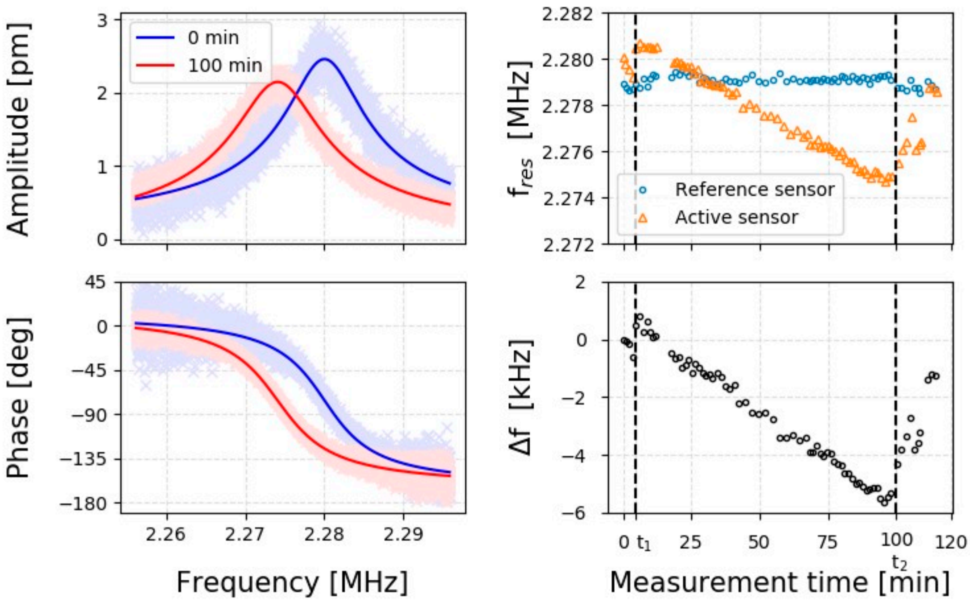


(**a**) (**b**) (**c**)

Figure 1. (**a**) Laser Doppler Vibrometer measurement showing the mode shape of the 8th order roof-tile mode. The red and blue colored areas represent the strain distribution (tensile, compressive) on the surface. (**b**) Optical micrograph of the sensor element. The planar coil (1) accumulates the magnetic particles on the cantilever (2) which is fixed to a substrate (3). The patterned electrode design is optimized to excite the 8th order roof tile mode. (**c**) Optical micrograph of the sensor element during the experiment. The accumulation of the 250 nm iron-oxide particles especially at the free end area of the cantilever is clearly visible.

During the measurement duration of 120 min, the amplitude and phase response of the active and reference element were recorded and a least square fitting algorithm was applied to determine the change in resonance frequency (see Figure 2a). The resonance frequency is approximately 2 MHz, while the Q-factor is in the order of 225, demonstrating the superior performance of the roof-tile shaped mode in liquid environments.

Figure 2b shows the resonance frequency of both the active and the reference element during the measurement duration of 2 h. The accumulation of particles starts at $t = t_1$ by powering the planar coil of the active element. The sudden jump of the resonance frequency can be explained by the heat produced by the coil current and the consequent change of mechanical properties of the cantilever material and liquid properties. Note that the reference sensor stays unaffected by this parasitic effect. The bottom figure shows the frequency shift Δf of the active sensor relative to the reference sensor. The continuous accumulation of particles leads to a linear decrease of the resonance frequency and can also be observed optically (see Figure 1c). After 100 min ($t = t_2$) we observed a total frequency shift of almost 6 kHz. By turning off the coil current and rinsing the sensor with fresh deionized water, the particles start to detach and the resonance frequency drifts towards its initial value. This allows for the reuse of the sensor for subsequent measurements. By using Equation (1), we were able to determine the accumulated mass during the experiment as about 1.5 µg.



(**a**) (**b**)

Figure 2. (**a**) Measured amplitude and phase response of the active element before and after the experiment. A least squares fit algorithm was applied to determine the resonance frequency (solid lines. The total resonance frequency shift is approximately 6 kHz. (**b**) Measured resonance frequency f_{res} of the active sensor element and the passive reference which is used to compensate environmental effects. The coil current was turned on at $t = t_1$ and was stopped at $t = t_2$. The bottom image shows the frequency shift relative to the reference element.

4. Conclusions and Outlook

In this study, we showed that our novel sensor design is capable of detecting magnetic particles in liquids, as the accumulation of particles leads to a continuous shift of the sensors resonance frequency. We observed a total resonance frequency shift of approximately 6 kHz after a measurement time of 100 min. In the field of lubricant condition monitoring, the temporal change in frequency can be used to detect abnormal conditions of the machinery. Future work will focus on experiments in a more realistic environment, e.g., oil samples from real machinery. Finally, the detection limit in terms of particle size and concentration is of future interest.

Author Contributions: F.P., S.S., M.S. (Michael Schneider) and U.S. conceived and designed the experiments; M.S. (Matthias Schlögl) performed the experiments; F.P., M.S. (Matthias Schlögl), U.S. and M.S. (Michael Schneider) analyzed the data; M.S. (Michael Schneider) and U.S. contributed materials/analysis tools; F.P. wrote the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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