Enhancement of unsteady frequency responses of electro-thermal resonance MEMS cantilever sensors

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Abstract. Unsteady frequency response of in-plane electro-thermal MEMS-based cantilever sensors can cause up-/down-shifting of the resonance phase, which becomes an inhibitive factor in resonance locking using a phase-locked loop setup. Moreover, the inconsistency of resonance phase during real-time measurement potentially causes inaccuracy in resonant-frequency locking. In this work, reference parameters are differentially subtracted from the sensor output signals to enhance the characteristic of frequency response. As a calculation result, a constant resonance phase can be successfully achieved by adjusting the reference parameters close to the sensor baseline, both in sensor amplitude and phase.

1. Introduction

Micro-electro-mechanical systems (MEMS) are today already an indispensable part of our daily life. In recent years, silicon MEMS-based sensors have shown a capability to measure in a high resolution some numbers of particles and agglomerations [1–5]. Silicon micro-machined sensors have good characteristics of small size, lightweight, high precision, and good stability [6, 7]. An electro-thermal silicon piezoresistive cantilever sensor is one kind of these devices, to which measured various target analytes making regular changes in natural frequency of the resonant beam. The excitation part is a key component of a resonant sensor, where electro-thermal excitation is having certain advantages, e.g., simple fabrication. We fabricated this type of sensor using bulk silicon wafers and a bulk micromachining technique that leads to lower cost of materials and fabrication processes with respect to surface micromachining [8]. This MEMS-cantilever sensor comprises two main parts, i.e., a heating resistor (HR) and a U-shaped full Wheatstone bridge (WB) configuration, which act as mechanical actuation and electrical sensing, respectively [9–11]. Both are realized in the form of diffused p-type silicon resistors as illustrated in figure 1.
Thermally actuated compliant mechanisms are those onto which thermal loading is applied in order to deform a structure. A typical way of obtaining a thermal load is to apply a current through a resistive material, which is subsequently converted into heat by the Joule heating effect. The resulting temperature gradient yields a bending deformation, which is then detected by the sensing component. However, small distance between actuation part (HR) and sensing part (WB) can cause a direct thermal crosstalk between HR and WB that leads to asymmetry and reversed shape of resonance amplitude and phase characteristic, respectively [12, 13]. Moreover, a phase delay between the signal induced by the cantilever deflection and the direct thermal parasitic is expected, which may have an impact on the occurrence of up-/down-shifting of the phase in the sensor output signal. Therefore, this report deals with an improvement of the frequency response of electro-thermal silicon piezoresistive cantilever sensors, especially on removing instabilities of the resonance phase \( \theta_R \) during online measurement of an analyte. A steady phase response becomes an important requirement to establish real-time resonant-frequency tracking using a phase-locked loop (PLL) setup.

2. Frequency responses of electro-thermal resonance cantilever sensor

Frequency responses are amplitude and phase responses that are measured in the frequency domain. Frequency response of cantilever sensor can be acquired using a lock-in amplifier instrument that can extract a signal on a known carrier wave by operating a multiplication of its input with a reference signal (carrier) and then applying a low-pass filter to the result. Figure 2 shows how a lock-in amplifier works out resulting amplitude \( R \) and phase responses \( \theta \). The input signal from the WB of the cantilever is split and separately multiplied with the reference signal and its 90° phase-shifted copy. The outputs of the mixers pass through low-pass filters, resulting in the two outputs \( X \) and \( Y \), termed the in-phase and quadrature components, respectively. A low pass filter picks out the part of the signal that is correlated with the reference essentially by averaging the output of the mixer. Furthermore, the amplitude \( R \) and the phase \( \theta \) are easily derived from \( X \) and \( Y \) by a transformation from Cartesian coordinates into polar coordinates using the relations:

\[
R = \sqrt{X^2 + Y^2} \tag{1}
\]

\[
\theta = \text{atan2}(Y, X) \tag{2}
\]

where \text{atan2} is an extension of the inverse angle function arctangent and is used to have an output range for the phase angle that covers all four quadrants, i.e., \((-\pi, \pi)\).
Figure 2. Schematic of the lock-in amplification: the input signal is multiplied by the reference signal and a 90° phase-shifted version of the signal source. The mixer outputs are low-pass filtered to reject the noise and the 2ω component, and finally converted into polar coordinates, i.e., amplitude $R$ and phase $\theta$.

We use an MFLI lock-in amplifier from Zurich Instrument to characterize the frequency responses of the resonance cantilever sensor. A sinusoidal signal with $2\, V_{\text{pk-pk}}$ and $+5\, \text{VDC}$ offset were generated to actuate the cantilever beam through the heating resistor (HR). Due to the Joule effect, there is a bending deformation around HR which subsequently actuates the cantilever beam into lateral deflection. The induced bending strain is sensed by the WB and converted into an electrical signal. The WB output signals were amplified by an instrumentation amplifier AD8429 at $G = 61$. In addition, the silicon substrate ($n$-type) was connected to the ground pole of the supply of WB ($V_{\text{WB}}$) and HR, which was purposed to avoid a current leaking along the piezoresistors and HR.

A resonance cantilever sensor experiences a resonant-frequency shift $\Delta f_R$ induced by the added mass of a certain analyte target that descends and sticks on its surface. We functionalized a cantilever beam with $\sim 2\, \mu\text{m}$ sized polymethyl methacrylate (PMMA) particles (from Sigma-Aldrich Inc.) to increase its capability for collecting target analytes in cigarette smoke. The characteristics of PMMA, which has carbon atom on the backbone chain and has low hydrophobicity, are desired to foster collecting of carbon and hydrogen-based molecules comprised in the smoke. A frequency-sweep method was used to exhibit the frequency responses and deliver its $Q$-factor before and after smoke exposure. Sinusoidal signals generated by the MFLI in a certain bandwidth of frequency were then fed into the actuation part (the HR) and subsequently the amplitude $R$ and phase response $\theta$ were measured. Figure 3 delineate the frequency responses at the two different conditions showing a frequency shift $\Delta f_R = \sim 40.45\, \text{Hz}$. On the other hand, the $Q$-factor decreased from 2666.5 to 2105.1.

Figure 3. Measured frequency response in (a) amplitude $R$ and (b) phase of an electro-thermal MEMS cantilever sensor. Resonant-frequency shift $\Delta f_R$ due to smoke exposure is accompanied by an increase of resonance amplitude and a decrease of resonance phase from $\theta_{R1}$ to $\theta_{R2}$. 
However, unsteady frequency response causes a decrease of resonance phase from $\theta_{R1}$ to $\theta_{R2}$. A steady resonance phase is necessary, however, if we intend to track the resonant-frequency in real-time using a PLL-based system. In a PLL setup, frequencies are controlled based on a phase error that refers to the resonance phase at a set-point. Therefore, $\theta_k$ should be constantly standing for precise measurement of analyte exposure.

3. Reference parameter subtraction

In this study, a reference parameter is investigated to improve the frequency response to yield a steady resonance phase. Basically, a reference parameter is a constant value near the baseline values of amplitude $R$ and phase $\theta$, which are differentially subtracted from the sensor responses using Eqs. (3) to (5):

$$x_1 = R_s \cos \theta_s; \quad y_1 = R_s \sin \theta_s; \quad x_2 = R_r \cos \theta_r; \quad y_2 = R_r \sin \theta_r,$$

$$\Delta x = x_1 - x_2; \quad \Delta y = y_1 - y_2,$$

$$R_{opt} = \sqrt{\Delta x^2 + \Delta y^2}; \quad \theta_{opt} = \text{atan2}(\Delta x, \Delta y),$$

where $R_s$, $R_r$, and $R_{opt}$ are amplitudes of sensor, reference and optimized response, while $\theta_s$, $\theta_r$, $\theta_{opt}$ are phases of sensor, reference, and optimized response, respectively.

Figure 4 illustrates how the reference parameters are configured relative to the sensor baseline, both on the amplitude $R$ and the phase $\theta$. At the first condition (i.e., without smoke), the reference parameters are adjusted to 1.3 V and -7.2° for amplitude and phase, respectively. While after being exposed with smoke, the reference parameters are re-adjusted to the new values, i.e., 1.39 V for amplitude and -10.5° for phase. As shown in figure 5, the implementation of the reference parameter dramatically improves the frequency response, especially for resonance phase $\theta_k$ that is kept constant at $\sim -12.2^\circ$.

![Figure 4](image.png)

**Figure 4.** Measured frequency response in (a) amplitude $R$ (black plus line) and (b) phase (blue crossline) of an electro-thermal MEMS cantilever at different conditions (without and with smoke), with constant reference parameters shown in black open circle and blue open square line for reference amplitude and reference phase, respectively.
Figure 5. Calculated frequency response in (a) amplitude $R$ (black full line) and (b) phase (red dash line) of an electro-thermal MEMS cantilever sensor showing a steady spectral phase response with a constant resonance phase of $\sim -12.2^\circ$.

However, it is challenging for determining reference values simultaneously with the changing of sensor response during a real-time measurement. Reference parameters should be kept at an optimum value in order to yield the desired resonance phase. To realize it, the implementation of a prediction algorithm will be further investigated. This prediction algorithm will be incorporated in the digital-PLL program and thus result in accurate resonant-frequency locking in real time.

4. Conclusion
Unsteady phase responses occurring with the electro-thermal cantilever sensors can be improved by implementing reference parameters involving a differential calculation method. This method can provide monotonic phase responses that are suitable for an implementation in a digital phase-locked-loop (PLL) system for tracking the resonant frequency of the sensor at changing conditions of analyte exposure (e.g., smoke). A method for involving adaptive reference parameters, however, is still necessary to be developed in the next further works.

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