MEMS wireless temperature sensor for combustion studies

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Abstract. A MEMS wireless wall temperature sensor for combustion studies is proposed. Electrical resistance change in a LCR circuit is used to measure the temperature through inductive coupling the sensor coil and the read-out coil. Equivalent circuit model and 3-D electromagnetic simulation are employed to design sensor configuration. The resonant frequency is increased with increasing the resistance due to the temperature increase. The prototype sensor was successfully fabricated with MEMS technologies. The impedance phase angle shows a sharp dip at the resonant frequency, which is in good accordance with the equivalent circuit model. The measured temperature sensitivity is found to be as high as 6 kHz/K, when the distance between the read-out and the sensor coils is 0.71 mm.

1. Introduction

Precise wall temperature measurement is crucial in various combustion studies, such as wall-flame interaction [1], catalytic combustion [2], and the thermal/chemical wall quenching phenomenon [3]. Contact thermometry using thermocouple or RTD (Resistance Temperature Detector) has been widely used for measuring the wall temperature in combustion fields. However, physical contact with the target easily introduces disturbances to the temperature field, which makes the precise measurement difficult. On the other hand, non-contact thermometry based on infrared radiation or temperature-dependent fluorescent material can only be applied when the optical access is allowed [4].

We previously proposed a wireless temperature sensor using a LCR circuit, in which the resonant frequency is changed by the capacitance change [5]. We employ Al₂O₃ for dielectric material of the capacitor in the LCR circuit, by which the temperature coefficient of permittivity (TCP) is around 0.3%/K. However, the impedance phase did not exhibit a sharp dip because the resistance of the sensor coil was around 10 times higher than the designed value. Moreover, considering the temperature coefficient of resistance (TCR) of the electrodes, the resistance change will cancel out the capacitance change on the resonant frequency. For a wide temperature range used in combustion studies, the effect of resistance change is much larger than that of the capacitance change. In the present study, a MEMS wireless wall temperature sensor based on TCR of electrodes is proposed, and performance of a prototype sensor is evaluated for a non-contact wall temperature measurement.
2. Design of the sensor

Figure 1 shows the concept of non-contact wall temperature measurement using the MEMS wireless temperature sensor. The sensor consists of a thin-film coil and a capacitor and is attached on the target wall surface. A read-out coil is placed on the other side of the wall. The wall temperature change results in the resonant frequency change of the LCR circuit, which is measured by inductive coupling between the sensor and the read-out coils [5-7].

The present sensor is essentially a LCR resonant circuit. The sensor coil is inductively coupled with the read-out coil with a coupling coefficient $k$ as described later. The read-out coil is connected to a network analyzer (NA), and the impedance phase dip that appears at the resonant frequency of the LCR circuit is measured. Based on the resonant frequency, the resistance of the sensor and thus the wall temperature are estimated. The equivalent circuit model for the read-out coil and the sensor is shown in figure 2. $R$, $L$, $C$, $M$, and $v$ are the resistance, the self-inductance, the capacitance, the mutual-inductance and the voltage, respectively. Subscript e and s denote the values for the read-out coil and the sensor, respectively. The circuit equations can be written as follows:

$$
\begin{align*}
\dot{v}_e(t) &= R_e i_e + L_e \frac{di_e}{dt} + M \frac{di_s}{dt} \\
0 &= R_s i_s + L_s \frac{di_s}{dt} + \frac{1}{C_s} \int i_s dt + M \frac{di_e}{dt}
\end{align*}
$$

Figure 1. Principle of MEMS wireless wall temperature sensor. Wall surface temperature can be measured without contact from the backside of the wall.

Figure 2. Equivalent circuit model for the read-out coil (left) and the sensor (right).
By solving these simultaneous equations, the ratio of the external voltage to the external circuit current, i.e., the impedance of the external circuit \( Z_e(\omega) \) is calculated. \( R_e \) is much smaller than \( R_s \), and can be neglected. The impedance phase angle can be found as follows:

\[
\angle Z_e(\omega) \approx \arctan \left( \frac{1 - k^2}{k^2 R_s L_s C_s^2 \omega^2 + 1} \right)
\]

(2)

We can define the resonant frequency by getting the extreme value of equation (2):

\[
\omega_0 = \sqrt{\frac{\left(R_s L_s^{-1} C_s + (k^2 - 2)\right)^2 + 12 \left(1 - k^2\right)}{2 \left(1 - k^2\right)}}
\]

(3)

Note that \( k \) is the coupling coefficient representing intensity of the coupling between two coils [6], which strongly depends on the distance between the coils:

\[
k = \frac{M}{\sqrt{L_s L_t}}
\]

(4)

From equation (3), we can notice that the resonant frequency \( \omega_0 \) is increased when the sensor resistance \( R_s \) is increased. In the present analysis, the coupling coefficient is assumed as \( k = 0.3 \), which is reasonable for near-distance inductive coupling. Figure 3a shows the analytical results based on the equivalent circuit model when resistance is in range of 10 ~ 20 \( \Omega \). The resonant frequency is increased with the resistance, while the dip is decreased. 3-D electromagnetic simulation using ANSYS HFSS (High Frequency Structure Simulator) is also made for comparison. The sensor is modelled as a closed LCR circuit as designed and both ends of the read-out coil are connected to a lumped port, which functions as a NA. Metal layers on the sensor are assumed as a 2-D plate to reduce computational loads. To change the sensor resistance value, a lumped resistor element is connected to the sensor circuit in series. The frequency is swept from 1 MHz to 100 MHz with a step size of 1 MHz. The results are plotted in figure 3b. Although the 3-D simulation results are somewhat different from the analytical solution, both results show similar resonant frequency shifts due to the resistance change.

3. MEMS fabrication of the sensor

The microfabrication process starts with sputtering of a 500 nm-thick Au layer on the glass substrate with a 50 nm-thick Cr or Ti film as the adhesion layer. The Au layer was then patterned into the bottom electrode using standard lithography. Then, a 100 nm-thick SiO\textsubscript{2} layer was deposited as a
dielectric layer by plasma CVD with TEOS (tetraethyl orthosilicate) as a precursor. A contact hole for connecting two metal layers was etched using buffered HF. Finally, another 1.5 μm-thick Au layer was sputtered and patterned to form a counter electrode and a 5-turn spiral coil. Figure 5 shows a photograph of the completed sensor with a size of 10 mm squared.

4. Results and discussion
The read-out coil was made by winding Cu wire (diameter: 1.12 mm) in a spiral shape. The prototype sensor and the read-out coil were attached to each side of a resin film. The distance between two coils is 0.68 mm. The read-out coil is connected to a NA (ZVL6, Rohde & Schwarz), and the resonance profile was measured. Figure 7 shows the impedance phase angle changes measured in the frequency range up to 100 MHz. A sharp impedance phase dip over 35 degrees is clearly seen near the resonant frequency. The measured results are well fitted with the equivalent circuit model (equation (2)), proving the effectiveness of the present circuit model analysis. The fitting value of the coupling coefficient $k$ is approximately 0.6 when the distance between coils is 0.68 mm, while it decreases below 0.1 when the distance is beyond 5.6 mm. With decreasing coupling coefficient, the sensitivity is also decreased because the impedance phase dip becomes dull. Improvement of the sensitivity for longer distance can be achieved by changing the coil shape or by improving the measurement.

![Figure 4. MEMS Fabrication process; (a) Sputtering and resist-coating, (b) Bottom metal layer patterning, (c) SiO2 layer deposition, (d) SiO2 patterning, (e) Sputtering and resist-coating, (f) Upper metal layer patterning.](image)

![Figure 5. Prototype of the wireless temperature sensor. Dimensions are 10 mm × 10 mm.](image)

![Figure 6. Experimental set-up to evaluate sensor performance. The read-out coil is coupled with the sensor and its impedance phase angle is measured by NA.](image)
Figure 7. Impedance phase angle versus frequency. Solid line is a curve-fitted circuit model with $R_s=22.4 \, \Omega$, $L_s=0.25 \, \mu H$, and $C_s=0.23 \, nF$.

Figure 8. Resonant frequency versus temperature. A measured sensitivity against temperature changes is about 6 kHz/K.

algorithm.

Figure 6 shows the experimental set-up to evaluate the performance as a wireless temperature sensor. The sensor and the read-out coil were fixed on a 0.15 mm-thick slide glass, which corresponds to the distance between coils of 0.71 mm. The device was put into an electric oven for the measurement at different temperatures from 26.5 to 150 °C. The resonant frequency at each temperature is plotted in figure 8. The frequency sensitivity is found to be around 6 kHz/K. When the measurement error in determining the resonant frequency is assumed to be ~ 50 kHz, the temperature accuracy is ±10 K, which is high enough for most combustion studies.

5. Conclusion
A novel MEMS wireless temperature sensor for combustion studies is proposed. Resonant frequency change due to the resistance change is employed. A prototype sensor is successfully microfabricated using MEMS technologies. A sharp impedance phase dip in a good accordance with the equivalent circuit model has been observed. Frequency sensitivity around 6 kHz/K is achieved, which corresponds to the temperature accuracy of ±10 K.

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