Capacitive micromachined ultrasonic transducer as a resonant temperature sensor

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Abstract: Resonant temperature sensors have drawn considerable attention for their advantages such as high sensitivity, digitized signal output and high precision. This paper presents a new type of resonant temperature sensor, which uses capacitive micromachined ultrasonic transducer (CMUT) as the sensing element. A lumped electro-mechanical-thermal model was established to show its working principle for temperature measurement. The theoretical model explicitly explains the thermally induced changes in the resonant frequency of the CMUT. Then, the finite element method was used to further investigate the sensing performance. The numerical results agree well with the established analytical model qualitatively. The numerical results show that the resonant frequency varies linearly with the temperature over the range of 20 ℃ to 140℃ at the first four vibrating modes. However, the first order vibrating mode shows a higher sensitivity than the other three higher modes. When working at the first order vibrating mode, the temperature coefficient of the resonance frequency (TCf) can reach as high as -1114.3 ppm/℃ at a bias voltage equal to 90% of the collapse voltage of the MCUT. The corresponding nonlinear error was as low as 1.18%. It is discovered that the sensing sensitivity is dependent on the applied bias voltages. A higher sensitivity can be achieved by increasing the bias voltages.

Key words: Resonant temperature sensor; CMUT; finite element method; bias voltages

1 Introduction

Resonant temperature sensors are widely studied due to their advantageous performances such as high sensitivity, digitized signal output and good precision [1-5]. Most of these sensors are based on silicon microbeam and quartz crystal resonators. For example, Leblois et al. [1] and Zhong et al. [3] investigated the performance of quartz resonators acting as resonant temperature sensors. Hsu et al. [4] and Jha et al. [5] studied the resolution and sensitivity of resonator beam based temperature sensors. However, both types of temperature sensors suffer from several shortcomings in their commercializing applications. For quartz crystal based temperature sensors, the temperature-frequency coefficient mainly depends on the cut type and fabrication accuracy of quartz crystals, which puts strict requirements into fabrication processes and thus results in a high cost [6-7]. In addition, the fabrication processes of quartz crystal are not compatible with micromachining technologies, which limit the wide application of quartz crystal based temperature sensors [7]. For the temperature sensor based on micro beam, its sensitivity is mainly determined by the thickness of the beam [4]. Although the sensitivity can be improved by reducing the thickness of the beam, yet this reduction may decrease the sensor's robustness and reliability. In comparison with the two types of resonator structures mentioned above, capacitive micromachined ultrasonic transducer (CMUT) presents more advantages when used as resonator, no matter in the fabrication processes or in the performances. Its batch fabrication based on MEMS technology and good compatibility with integrated circuit contribute to a reduced cost [8-9]. Its high resonant frequencies in the range of tens of megahertz and quality factors in the range of several hundred provide excellent sensitivity [10-11]. Additionally, compared with micro beam-based sensors, CMUT has a more robust structure, which allows more reliable operation in harsh environment. These advantageous characteristics enable CMUT as a platform for developing resonant temperature sensors.

In this study, we used the CMUT as a resonant temperature sensor and investigated its performance for temperature measurement. Firstly, we presented a schematic of CMUT based temperature sensor and established a lumped electro-mechanical-thermal model for its working principle. Then, the finite element method (FEM) was employed to simulate the effects of vibrating modes and bias voltages on the sensing performance (such as linearity and sensitivity). Finally, several suggestions on the design of CMUT based temperature sensor were proposed.

2 Working principle

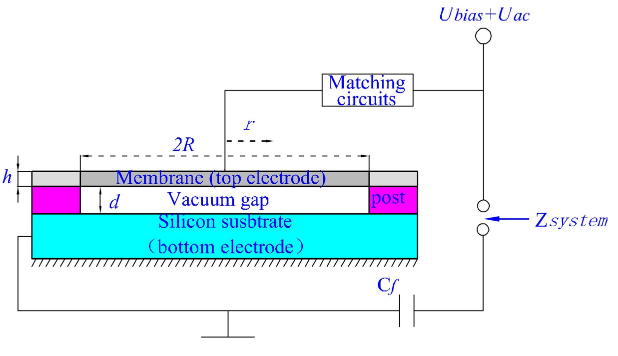

Fig. 1 Schematic of a CMUT cell for temperature measurement

Figure 1 shows the schematic of a CMUT used for temperature measurement. The membrane with clamped periphery works as a temperature-sensing element, and simultaneously as the top electrode of the CMUT. The substrate parallel to the membrane acts as the bottom electrode, and is fully fixed so that the change in its sizes can be neglected in a temperature-changing environment. The post between the upper membrane and lower substrate is assumed to have a very small coefficient of thermal expansion (CTE) compared with that of the membrane. So, the size change of the post caused by thermal expansion can be neglected. Based on these simplifications, the effects of the substrate and post on the thermal expansion of the membrane are negligible.

The working principle of the CMUT based temperature sensor depends on the resonant frequency shift caused by the thermally induced changes in electrical stiffness across the capacitive transducer. Initially, the CMUT vibrates at a certain resonant frequency under the co-action of a bias voltage U_{bias} and a small voltage U_{ac}. When there is a variation in environmental temperature, a thermal stress in the clamped membrane produce, which will further produce a small change in the gap of the CMUT. As a result, the electrical stiffness of the membrane changes, leading to a corresponding shift in resonant frequency.

2.1 Theory analysis

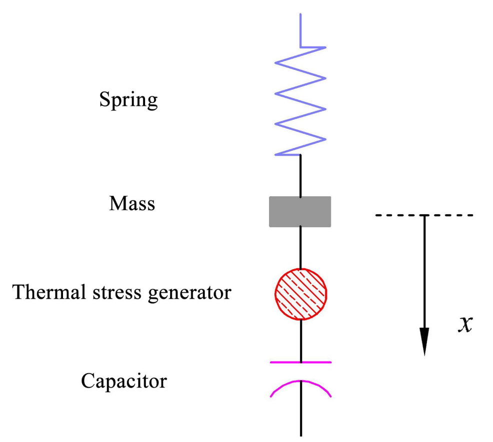

Fig. 2 a lumped electro-mechanical-thermal model for a CMUT cell

In order to simplify the theory analysis, several approximations are proposed. The membrane is assumed to be circular with a radius R, thickness h. The restoring force of the membrane is assumed as a linear function of its displacement. The electrical fringing fields between the top and bottom electrodes are neglected when considering the electrical forces applied to the membrane. Furthermore, the temperature distribution of the membrane is assumed to be uniform at a certain time. Then we assume that the CMUT operates in a vacuum, which is equivalent to neglecting any other loading of the membrane such as air damping [12]. Thus, we obtain a lumped electro-mechanical-thermal model consisting of a linear spring, a mass, a thermal stress generator and a parallel plate capacitor, as shown in Figure 2.

For a clamped membrane with a uniform temperature distribution, the thermal stress can be given as [13]

$$\sigma_{\mathrm{r}}=\sigma_{\theta}=-\frac{E\alpha}{1-v}\Delta T \tag{1}$$

where E is the Young's modulus, ν is the Poisson ratio and ΔT is the change of temperature; $\Delta T = T\text{-}T_0$, T_0 is the reference or initial temperature, T is the measured temperature; σ_{r} is the radial thermal stress and σ_θ is the tangential thermal stress.

Then, the radial and tangential tensile or compressive forces per unit length of the undeformed membrane can be obtained by an integration of the radial and tangential stress from 0 to h. Their expressions can be expressed as

$$N_r=-\frac{E\alpha}{1-v}\Delta Th \tag{2}$$

$$N_\theta=-\frac{E\alpha}{1-v}\Delta Th \tag{3}$$

where the terms N_r and N_θ represent radial and tangential forces respectively. When the membrane is deflected towards the lower substrate under an applied voltage, the radial force N_r will produce a small lateral force component which will lead to an additional deformation. This deformation under the applied voltage will further cause an increase in the electrostatic force and then the deformation. This phenomenon can be interpreted as a thermally induced stiffness softening. The lateral force component of N_{r} can be expressed as [13,14]

$$N_{rl}=N_r\frac{\partial^2 w(r)}{\partial r^2} \tag{4}$$

where N_{rl} is the lateral force component of N_r, $w(r)$ represents the deflection at any radial position r. This deflection function satisfies the conditions of the clamped thin plate such as $w(R)=0$, $dw(R)/dr=0$ at the edge and $dw(0)/dr=0$ in the center [15]. Then the sum of N_{rl} over the entire circular membrane can be calculated by

$$F_T=\int_0^R\int_0^{2\pi}N_{rl}\mathrm{r}\mathrm{d}\mathrm{r}\mathrm{d}\theta=2\pi N_r w(0) \tag{5}$$

where F_T is the sum of N_{rl}, $w(0)$ is the maximum displacement of the membrane. For a circular membrane with axisymmetric transverse deflection, the average deflection is equal to one third of its maximum displacement $w(0)$ [15]. In the lumped model, we used the average deflection to represent the displacement x as shown in Figure.2. Then equation (6) can be rewritten as

$$F_T=6\pi N_r x \tag{6}$$

This expression can facilitate the analysis of the lumped electro-mechanical-thermal model. Then, the equation governing the balance of this lumped model can be given as

$$F_{\mathrm{S}}+F_{\mathrm{E}}+F_{\mathrm{T}}=F_{\mathrm{M}} \tag{7}$$

where the terms F_{S}, F_{E}, F_{T} and F_{M} are the spring, capacitor, thermal and inertial forces respectively. The capacitor and spring force can be given as [12]:

$$F_{\mathrm{E}}=\frac{\varepsilon SV^2}{2(d-x)^2},\qquad F_S=-kx \tag{8}$$

where V is the voltage across the capacitor, ε is the electric permittivity, S is the area of the capacitor plate. Taking the time variable t into consideration and substituting for the force terms, the vibrating equation governing this lumped model is given

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}-\frac{\varepsilon SV^2(\mathrm{t})}{2(d-x(t))^2}-6\pi N_r x+kx=0 \tag{9}$$

where the $V(t)=U_{bias}+U_{ac}(t)$. In general, as the amplitude of $U_{ac}(t)$ is far less than U_{bias}, $V(t)$ can be replaced by U_{bias} for a simplified analysis. Expanding the nonlinear term in equation (9) with a Taylor expansion about the point $x(t)=0$ and neglecting the high order terms, a linearized form of equation (9) can be obtained

$$m\frac{d^2x(t)}{dt^2}-(\frac{\varepsilon SU_{bias}^2}{2d^2}+\frac{\varepsilon SU_{bias}^2}{d^3}x(t))-6\pi N_r x(t)+kx(t)=0 \quad (10)$$

Simplifying equation (10), a significant qualitative expression is obtained as

$$m\frac{d^2x(t)}{dt^2}+K_{eff}x(t)=\frac{\varepsilon SV_{DC}^2}{2d^2} \quad (11)$$

and

$$K_{eff}=k-\frac{\varepsilon SV_{DC}^2}{d^3}-6\pi N_r \quad (12)$$

If $T>T_0$, the radial thermal stress N_r is compressive, which produces a lateral force component in a same direction with the capacitor force. So, substituting for the absolute value of equation (2), equation (12) can be rewritten as

$$K_{eff}=k-\frac{\varepsilon SU_{DC}^2}{d^3}-6\pi\frac{Eha}{1-v}\Delta T \quad (13)$$

This expression provides an explicit explanation for the influences of voltage and temperature on the electrical stiffness of the membrane. The second term of the right side of equation (13) denotes the effect of applied bias voltage. The third term of the right side of equation (13) denotes the effect from temperature change. It is obvious that the resonant frequency of the CMUT can be changed by the voltage and temperature. Actually, the resonant frequency reduces with the voltage and temperature.

The temperature coefficient of the resonance frequency (TCf) of CMUT-based temperature sensor can be defined as

$$TCf=\frac{1}{\text{fv}}\frac{\partial f}{\partial T} \quad (14)$$

where f_V is the resonant frequency under an applied voltage U_{bias}, and f is resonant frequency under different temperature at the fixed voltage.

2.2 Frequency detection

The related circuits used to detect the resonance frequency of a CMUT are shown in Figure.1. The matching circuits are designed to protect the CMUT cell and track the changes in its electrical parameters. The bias voltage U_{bias} and small alternate signal U_{ac} can be provided by a digital power. The system impedance Z_{system} can be measured using an impedance analyzer.

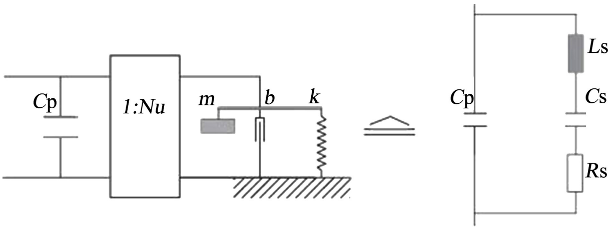

Fig. 3 Equivalent circuit of a CMUT cell

An equivalent circuit model for a CMUT cell is shown in Figure.3. It can be used as the basis for the design and analysis of the circuit system in Figure.1. This model consists of the electrical capacitance of the structure C_P in parallel with a series combination of an inductor representing the mass of the membrane L_S, a capacitor representing the stiffness of the membrane C_S, and a resistor modeling the motional resistance including the radiation into the medium R_S[10,16]. When the CMUT works in a temperature-changing environment, the thermally induced change in the stiffness of the membrane will finally result in a change in C_S. Then, a shift in the resonant frequency of the circuit system will produce correspondingly. In order to find the resonant frequency, we can adjust the frequency of U_{ac} within a frequency range. When the varying frequency equals to the resonance frequency, the equivalent circuit resonance occurs with minimum electrical impedance. This impedance value and the corresponding resonance frequency can be captured by the impedance analyzer accurately. Then, the measured temperature can be calculated through the relationship between temperature and resonant frequency.

3 Modeling and simulation

In this section, a finite element model was established to simulate the situation of a CMUT for temperature sensing by the finite element software ANSYS12.0. Due to symmetry of the structure and loads shown in Figure.1, the CMUT structure was modeled as 2D-axisymmetrical. The membrane and membrane support structures were constructed using plane structural elements PLANE42. The vacuum cavity and the electrostatic effect between top and bottom electrodes were modeled by using electromechanical coupling elements TRANS126, which were basically parallel plate capacitors and apply opposite electrostatic attraction forces to the nodes to which they were attached. The top nodes of these TRANS126 elements were attached to the section of the membrane where the electrode was located; the bottom nodes were simply clamped, which represented the bottom electrode. The detail parameters used for the simulation are shown in Table. 1.

Table 1 Geometry and material parameters for simulations

Parameters	Value
Membrane radius *R* (mm)	20
Membrane thickness *h* (mm)	1
Cavity gap *d* (mm)	0.4
Membrane Density *r* (kg/mm^3)	2.332×10^{-15}
Membrane Young's modulus *E* (MPa)	1.69×10^5
Membrane Poisson's ratio *v*	0.29
Coefficient of thermal expansion a (10^{-6}/℃)	2.33

Via the model constructed above, we studied two types of behavior characteristics of the CMUT-based temperature sensor: firstly, the relation of the resonant frequencies under different vibration modes with temperature at a fixed bias voltage; secondly, the effects of different bias voltages on the *TCf*. To this end, static and prestressed modal analyses were carried out sequentially under different temperatures at a fixed bias voltage. The collapsed voltage U_{colla} was 146V, the reference temperature was 20℃ and the coefficient of thermal expansion of the membrane was assumed to be a constant in the simulated temperature range. The results of simulations are shown in Figures 4, 5 and 6.

4 Results and discussion

Figure 4 shows the results of frequency shift to temperature under different vibration modes. It is obvious that the frequency shift varied linearly with the temperature at the first four order vibration modes. The frequency decreases with the temperature. The *TCf*s of the first, the second, the third and the fourth order modes were -739.8 mg/kg/℃, -162.4 mg/kg/℃, -78.7 mg/kg/℃, -48 mg/kg/℃ respectively when temperature varying from 20 ℃ to 140 ℃. It can be concluded that the frequency shift has a linear relationship with the temperature and the fist order vibration mode holds a higher sensitivity than the other three modes.

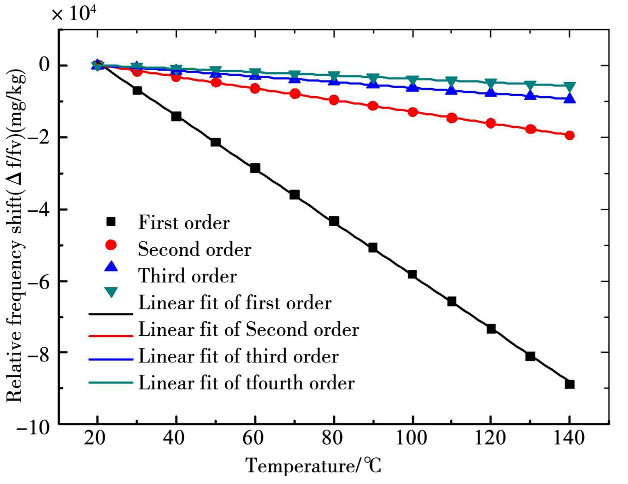

Fig. 4 Relative frequency shift VS temperature under different vibration modes of the membrane.

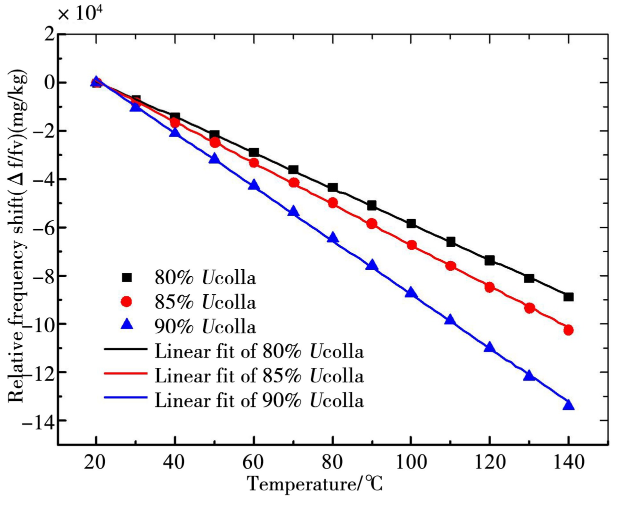

Fig. 5 Relative frequency shift VS temperature at different bias voltages.

Figure 5 shows the relationships between the fundamental (first order) frequency shift and the temperature at different bias voltages U_{bias}. The U_{bias} was set to 80%, 85% and 90% of the collapse voltage U_{colla}, and the corresponding *TCfs* were -739.8 mg/kg/℃, -851.8 mg/kg/℃, -1114.3 mg/kg/℃ respectively. The nonlinear error was 1.18% when the U_{bias} was 90% of the U_{colla}. These results show that the sensitivity increases with U_{bias}. In other words, the sensitivity can be adjusted by changing the U_{bias}. In addition, with a comparison between the simulated results and the analytical expressions (13) and (14), it is easy to find that the numerical simulations agree with the theoretical analysis qualitatively.

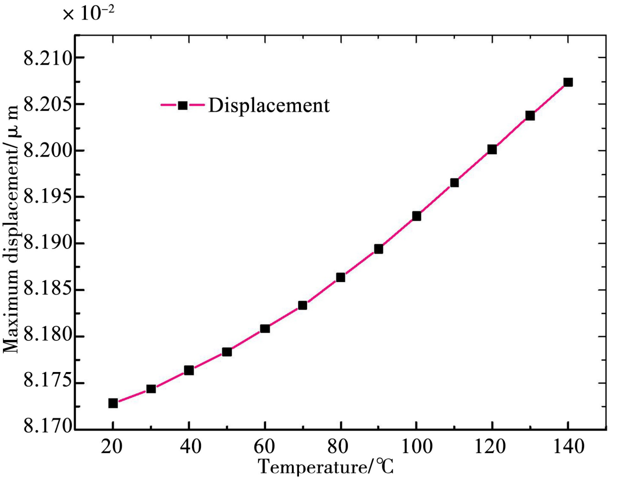

Fig. 6 Variation of the maximum deflection of the membrane with respect to temperature at a bias voltage 80% of the U_{colla}.

The results shown above demonstrate the linear relationship between the resonant frequency and temperature, and the superiority of the first-order mode vibration for temperature measurement. It also is proved that a high TCf can be achieved by increasing the bias voltage. However, as shown in Figure 6, the increased temperature will lead to an additional deflection of the CMUT membrane, which will enable the CMUT easy to collapse and thus reduce the collapse voltage. So if we want to improve the sensitivity by increasing the bias voltage, the temperature range should be reduced. A trade-off between the sensitivity and temperature measurement range should be considered when we design a CMUT based temperature sensor.

5 Conclusion

In this study, we made an investigation on the CMUT based resonant temperature. A lumped electro-mechanical-thermal model was established for the theoretical analysis. It provides an explicit explanation for the thermally induced changes in electrical stiffness and resonant frequency of the CMUT. Based on this model, the corresponding detection circuits and method were presented. Then, a 2D axi-symmetric model was established to simulate the working performance by the finite element method. The numerical results show that the resonant frequency varies linearly with the temperature over the range of 20 ℃ to 140℃ at the first-four vibration modes, and the first order mode vibration had a higher sensitivity than the other three higher modes. The sensing sensitivity can be adjusted by the applied bias voltages. Those numerical results also agree well with the established model qualitatively.

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