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Evaluation of Sensitivity of Stiffness-Sensitive Electret Microphones

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***Abstract*— This paper presents an evaluation of the sensitivity of a new thin-film stiffness sensing technology that utilizes commercial electret microphones. The analysis allows comparison of commercial microphones for stiffness sensing applications. A mathematical method to estimate the stiffness sensitivity of a commercial microphone from its acoustic sensitivity is developed. Experimental results are presented on the use of the developed method in a sensor that estimates carbon dioxide concentration by utilizing a carbon nanotube thin film on an electret microphone.**

I. Introduction

SOLID state analyte sensors have been the focus of tremendous research in the last few decades, their potential advantages being low cost, size and power. Solid state sensors typically combine two elements, namely a sensing material and a measurement technique for monitoring property changes in the material. Sensing of different material properties has yielded a variety of solid-state analyte sensors. Types of material properties that have been used for sensing include electrical [1], mechanical [2], gravimetric [3] and optical [4] properties. Correspondingly a variety of measurement techniques have been used to monitor such material properties.

A useful material property that lacks a simultaneously cheap, portable and reliable measurement technique is elasticity/stiffness. Elasticity measurements have allowed characterization of several types of biological molecules [5-7]. Measurements of thin-film elasticity have also proven useful for chemical and gas sensing [8-10]. Some techniques used in the past for monitoring elastic properties of thin films include surface acoustic wave devices [11], micro-cantilevers [12] and capacitive membranes [13]. However each of these methods presents one or more challenges in the final development of a robust, inexpensive, small, low-power stiffness sensor [14]. The authors presented a novel stiffness measurement technique using a 'FET-less electret microphone' as a thin film stiffness sensor [14]. The complete description of the developed technology, along with comparisons to the above sensing technologies, has been provided in an earlier publication [14]. This paper develops a quantitative method to determine sensitivity of electret microphones for stiffness sensing applications. Before presenting the derivation of sensitivity for electret stiffness sensors, a brief description of this technology is provided below.

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This stiffness measurement technique uses electret microphones to monitor changes in the elastic properties of thin films. An electret microphone is a special type of microphone with inbuilt charges in the membrane or backplate. These charges result in the formation of opposite charges on the microphone's backplate or membrane correspondingly. This causes the membrane to pull in towards the backplate. However, membranes of electret microphones are designed with sufficient mechanical stiffness to resist this pulling and hence do not snap into the backplate. The final vertical position of the membrane is dictated by its mechanical stiffness and is altered by any changes to this stiffness.

It is possible to use this principle for sensing elasticity of thin films by coating the electret membrane with a sensitive thin film. An analyte-sensor would consist of two components: a stiffness-changing thin film sensitive to the analyte and a stiffness-sensitive electret microphone. Any changes to the stiffness of the thin film would result in a change in stiffness of the composite membrane. This change in stiffness would then result in corresponding vertical deflections of the membrane. Finally, capacitance measurements yield information about the membrane's vertical deflection. Figure 1 shows the elements that make a final analyte sensor.

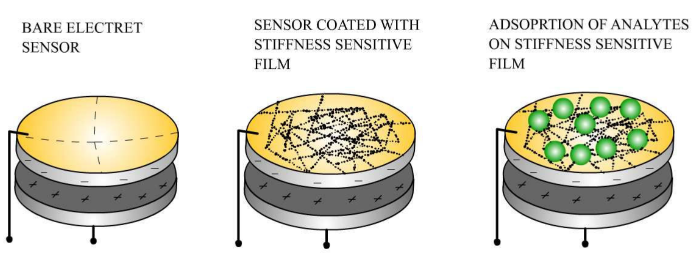

Figure 1. Schematic representation of electret stiffness sensor.

Designers can choose from several commercial electret microphones for stiffness sensing. Clearly, it is most beneficial to achieve maximum sensitivity within the choice of available commercial electret microphones. In this paper, a mathematical analysis is developed to predict stiffness sensitivity of commercial microphones based on manufacturer's specifications of acoustic sensitivity and a few simple measurements on a microphone.

II. DERIVATION OF SENSITIVITY

In this measurement technique, stiffness changes in a thin film are estimated by measurement of changes in a microphone's capacitance. Sensitivity is then defined as the incremental change in capacitance for a given change in film stiffness. The force balance equation for a membrane subjected to a voltage potential V_{DC} shown in Figure 2 is given by,

$$\frac{\varepsilon A V_{DC}^2}{2x^2} = k(d_0 - x)$$

where ε is the dielectric constant of the medium, A is the metallic electrode area, V_{DC} is the electret-charge-induced internal potential between the membrane and back-plate, k is the membrane-stiffness, d_0 is the original vertical separation between the membrane and the back plate (in the absence of electrical forces), and x is the actual vertical separation between the membrane and the backplate.

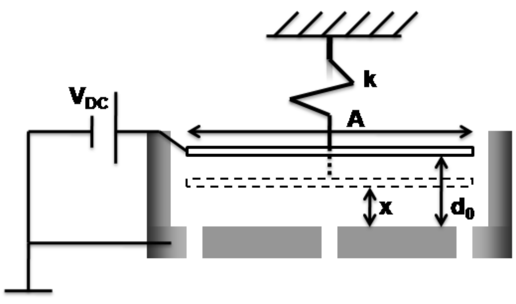

Figure 2. Schematic representation of electrostatically acutated membrane capacitor [14]**.**

Simplifying and differentiating,

$$2x^3 - 2d_0 x^2 + \frac{\varepsilon A V_{DC}^2}{k} = 0$$

$$\Rightarrow \frac{\partial x}{\partial k} = -\frac{\varepsilon A V_{DC}^2}{k^2(4xd_0 - 6x^2)}$$

Sensitivity of capacitance change to stiffness change is given by

$$\frac{\partial C}{\partial k} = \frac{\partial C}{\partial x} \cdot \frac{\partial x}{\partial k}$$

where $C = \frac{\varepsilon A}{x}$ is the measured capacitance. Since, $\frac{\partial C}{\partial x} = -\frac{\varepsilon A}{x^2}$, sensitivity can be expressed as

$$\boxed{\frac{\partial C}{\partial k} = \frac{\varepsilon^2 A^2 V_{DC}^2}{6k^2 x^3 (x - \frac{2}{3} d_0)}} \quad (1)$$

While Eq. (1) provides an analytical expression for sensitivity, constants V_{DC} and k in this equation are typically unknown for commercially manufactured microphones. A numerical value for sensitivity to stiffness changes cannot be computed without prior knowledge of these constants. Constants A and d_0 can be estimated simply by physical measurements on a microphone. Separation distance x could possibly be calculated from the microphone's capacitance. To eliminate the need for knowledge of constants V_{DC} and k, an alternate expression will be derived that utilizes the expression for acoustic sensitivity (provided by microphone manufacturer) and capacitance of the microphone.

To begin this derivation, the expression for acoustic sensitivity, a commonly specified parameter, is first considered. Acoustic sensitivity of an electret microphone is given by the change in voltage across a load resistor for a given change in acoustic pressure. Acoustic sensitivity is proportional to the voltage across the microphone's capacitance; the proportionality constant depending upon supply voltage, load resistance and amplification factor of pre-amplifier (these parameters are standard for many microphones making the proportionality constant same for such microphones).

The acoustic sensitivity is then given by:

$$Acoustic\ sensitivity\ \alpha \frac{dV}{dP} = \frac{d\left(\frac{Q}{C}\right)}{dP} \quad (2)$$

where V is the voltage across the microphone, P is the acoustic pressure acting on the microphone membrane and Q is the approximately constant charge on the microphone whose magnitude depends upon the supply voltage. It can be absorbed into the proportionality constant γ to express the acoustic sensitivity as

$$Acoustic\ sensitivity = \gamma . \frac{d\left(\frac{1}{C}\right)}{dP} = \gamma . \frac{d\left(\frac{x}{\varepsilon A}\right)}{dP} = \gamma . \frac{1}{\varepsilon A} . \frac{dx}{dP} \quad (3)$$

To derive an expression for $\frac{dx}{dP}$, consider the force balance equation in an acoustic microphone,

$$\frac{\varepsilon A V_{DC}^2}{2x^2} + A.P = k(d_0 - x) \quad (4)$$

(electrical force + acoustic force = mechanical restoring force)

Differentiating, $$-\frac{\varepsilon A V_{DC}^2}{x^3} dx + A.dP = -k.dx \quad (5)$$

$$\Rightarrow \frac{dx}{dP} = \frac{A}{\left(\frac{\varepsilon A V_{DC}^2}{x^3} - k\right)} \quad (6)$$

To eliminate unknown V_{DC} from this equation, substitute from Eq. (4)

$\frac{\varepsilon A V_{DC}^2}{2x^2} \approx k(d_0 - x)$ (assuming that force due to electrical attraction is much larger than that due to acoustic pressure)

$$\Rightarrow \frac{dx}{dP} = \frac{A}{\left(2\frac{k(d_0-x)}{x} - k\right)} \quad (7)$$

$$\Rightarrow \frac{dx}{dP} = \frac{Ax}{3k\left(\frac{2}{3}d_0 - x\right)} \quad (8)$$

Thus,

$$\boxed{Acoustic\ sensitivity = \gamma . \frac{x}{3\varepsilon k\left(\frac{2}{3}d_0 - x\right)}} \quad (9)$$

Now, Eq. (1) can be rewritten as

$$\frac{\partial C}{\partial k} = \frac{\varepsilon^2 A^2 V_{DC}^2}{6k^2x^3(x-\frac{2}{3}d_0)} = \left(\frac{\varepsilon A}{x}\right).\left(\frac{\varepsilon A V_{DC}^2}{2x^2}\right).\left(\frac{x}{3\varepsilon k(x-\frac{2}{3}d_0)}\right).\frac{\varepsilon}{kx} \quad (10)$$

Substituting from Eqs. (4), (9)

$$\frac{\partial C}{\partial k} = C.\left(k(d_0 - x)\right).\left(\frac{Acoustic\ sensitivity}{\gamma}\right).\frac{\varepsilon}{kx} \quad (11)$$

Thus the final expression for sensitivity can be written as

$$\boxed{\Rightarrow \frac{\partial C}{\partial k} = \varepsilon . C\left(\frac{d_0}{x} - 1\right)\left(\frac{Acoustic\ sensitivity}{\gamma}\right)} \quad (12)$$

Eq. (12) suggests that a microphone with a larger nominal capacitance, larger acoustic sensitivity and smaller vertical separation x would be more sensitive to stiffness changes. All terms in Eq. (12) are comparable except $\left(\frac{d_0}{x} - 1\right)$. But, the ratio of $\left(\frac{d_0}{x} - 1\right)$ between microphones will always be larger than the respective ratio of $\left(\frac{d_0}{x}\right)$ or the ratio of $\left(\frac{d_0 C}{A}\right)$, since $1 < \left(\frac{d_0}{x}\right) < \frac{3}{2}$.

Summarizing, the sensitivities of microphones to stiffness changes can be compared using the product of the ratio of (a) capacitance, (b) acoustic sensitivity and (c) $\frac{d_0 C}{A}$.

III. RESULTS AND DISCUSSION

An illustrative example using commercially available microphones is used to show the application of the above techniques to compare the sensitivities of two microphones for stiffness sensing. Two commercially available no-FET electret microphones are chosen for this purpose. The ICC-MEO-96PD-00-604-NF is a front-electret while the Transound TSB 160A is a back-electret microphone. Table 1 provides a comparison of relevant parameters for these two no-FET electret microphones. As described in the previous section, these include (a) capacitance, (b) acoustic sensitivity and (c) $\frac{d_0 C}{A}$.Since membrane area is proportional to the square of diameter $\frac{d_0 C}{D^2}$ is used instead of $\frac{d_0 C}{A}$, where D is the diameter of the membrane.

Table 1. Comparison of parameters for ICC Intervox and Transound no-FET electret microphones.

Parameter	***ICC – MEO-96PD-00-604-NF***	***Transound – TSB 160A***
d_0	20 μm	20 μm
D	9.7 mm	16 mm
C	16.8pF	23.19pF
Acoustic Sensitivity	10 mV/Pa	5 mV/Pa
Acoustic Sensitivity * $C * \frac{d_0 C}{D^2}$	**599.76** (arbitrary units)	**209.87** (arbitrary units)

Table 1 shows that ICC electret microphones are at least 3 times as sensitive to stiffness changes as TSB microphones. To compare the sensitivity of microphones, a thin film that responded with stiffness change in presence of analytes was required. Single walled carbon nanotube (SWNT) thin films were chosen for this purpose. SWNT films are known to alter their stiffness in the presence of carbon dioxide (CO_2) gas [15]. Stiffness of single walled carbon nanotube (SWNT) films has been shown to vary with the concentration of CO_2 gas [15]. Hence, similar SWNT films were coated on the two microphones and carbon dioxide gas was introduced to alter their stiffness.

SWNTs were purchased from Timesnano, China. Acid-treated negatively charged single walled CNTs (SWNTs) were drop coated onto the microphone membranes and allowed to dry. Experiments on SWNT stiffness sensing were performed by sealing the electronics and microphone leads away from the environment. This ensured that measured capacitance changes were not affected by gas seepage between leads connecting the microphones to the electronics. Capacitance measurement for ICC microphones was performed using programmable chips (MS3110) from Irvine sensors and that for TSB microphones using programmable chips (AD7746) from Analog Device Inc. Labview™ software was used for acquiring and storing data. Ultra pure CO_2 and N_2 gas were mixed and bubbled through a saturated salt solution of sodium chloride (to maintain constant relative humidity). The concentration of CO_2 was altered by changing the relative flow rates of the gases. This synthetic mixture ensured that no unwanted gas species existed in the sensing chamber. This helped eliminate spurious stiffness changes due to adsorption of unknown gases.

Figure 3 shows that the capacitance of SWNT coated ICC microphones varied with CO_2 gas concentration (earlier tests confirmed that similar uncoated ICC microphones were unresponsive to CO_2 gas). Figure 4 shows that SWNT-coated TSB microphone showed no changed in capacitance upon introduction of CO_2 gas. The long-term drift observed in Figure 4 is believed to be due to slow seepage of humid air into the microphones' dielectric gap. These results show that ICC microphones respond to stiffness changes in SWNT films deposited on their membranes while TSB-165 microphones show little or no response. Since similar SWNT films were coated on both microphones, it is concluded that ICC microphones display much higher sensitivity to SWNT film-stiffness changes.

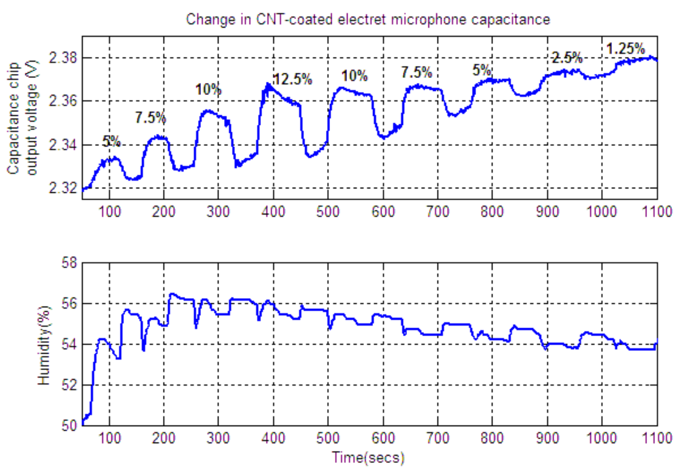

Figure 3. Response of SWNT coated ICC microphone to humidity and CO_2 gas

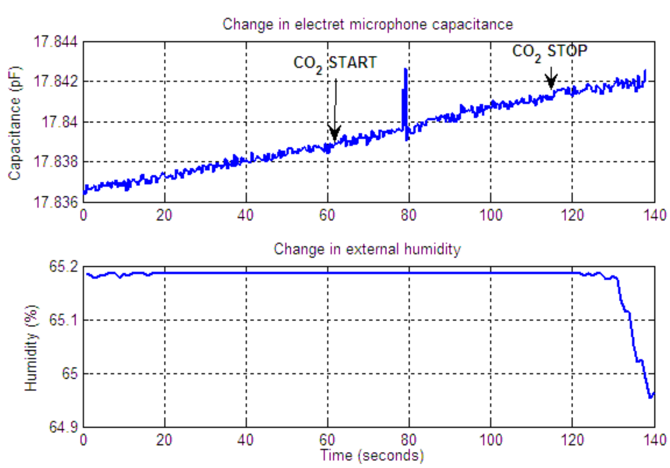

Figure 4. Response of SWNT coated TSB 165 microphone to CO_2 gas.

IV. CONCLUSION

A mathematical method has been provided to compare the relative sensitivities of commercial microphones. This analysis allows direct comparison of commercial electret microphones for stiffness sensing. The proposed method requires physical measurements on microphones and would need testing for determination of sensitivities. Microphones with larger acoustic sensitivity and membrane areas as well as thinner diaphragms and smaller inter-electrode gaps are found to be more sensitive for stiffness sensing applications.

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