IMPROVED MODELING AND DESIGN OF MICROPHONES USING RADIO FREQUENCY DETECTION WITH CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS

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Abstract – Broadband acoustic sensing, over several decades of frequency, has traditionally been difficult to achieve. An alternative approach to conventional condenser microphones is to use capacitive micromachined ultrasonic transducer (CMUT) membranes with a sensitive radio frequency (RF) detection method. Since the resonant frequency of a typical CMUT membrane is several megahertz, the membrane response to acoustic frequencies below resonance, from DC to several hundred kilohertz, is constant.

This paper presents the theory, modeling, and sensitivity predictions of the RF detection method. Electrical thermal noise is now incorporated in the model and ultimately limits the sensitivity. In addition, we present experimental results showing the flat frequency response, from 0.1 Hz to 100 kHz, of a microphone using RF detection. Present measurements demonstrate a sensitivity of 53 dB/Pa/Hz, though improvements to the design are expected to achieve sensitivities approaching 100 dB/Pa/Hz.

I. INTRODUCTION

Much of the development of miniature acoustic pressure sensors has focused on hearing aid applications, and therefore is concerned with detecting sound from several tens of hertz to 100 kHz [1]. Some industrial and military applications, such as condition monitoring of equipment, require acoustic data collection over larger bandwidths for proper signal identification [2, 3]. Furthermore, such sensors should be robust, as they may be subjected to harsh environments that include dust and moisture.

Most acoustic sensing devices, such as condenser microphones, piezoelectrics, or capacitive micromachined ultrasonic transducers (CMUTs) depend on membrane resonance to achieve sensitivity. While this results in large membrane displacements and very sensitive devices, these resonance phenomena are inherently narrowband. While the addition of dampening or any loss mechanism will broaden the frequency range, it does so at the expense of sensitivity.

Condenser microphones and capacitive transducers generally consist of one or more conductive diaphragms suspended over a conductive backplate [4]. Sound detection is possible when the impinging pressure vibrates the diaphragm, thus changing the capacitance of the transducer. For conventional microphones, the change in capacitance is detected by measuring either the output current under constant-voltage bias or the output voltage under a constant-charge on the diaphragm electrode. Fig. 1 shows such a constant-voltage bias circuit, where the transducer is represented as a variable capacitor.

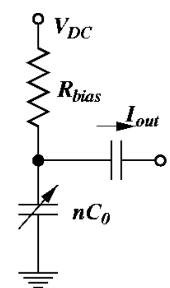

Figure 1: Constant-voltage bias circuit for a capacitive transducer.

II. AN ALTERNATIVE MICROPHONE DESIGN

CMUT Membranes

As depicted in Fig. 2, CMUTs for use in air applications typically have a membrane thickness of approximately 1 µm and membrane width or diameter of around 90 µm, with dimensions accurately controlled by lithography and semiconductor fabrication technology [5]. These membranes can be vacuum-sealed; that is, the area beneath the membrane can be evacuated during fabrication. This seals out moisture and particles which otherwise might affect or restrict the membrane's movement, while also eliminating squeeze-film effects. Since the above device geometry results in a structure that resonates at 2-3 MHz, the displacement response of such membranes to pressure inputs is relatively constant up to several hundred kilohertz. This results in a sensor with a very flat frequency response below the membrane resonance. If the cavity behind the membrane is evacuated, pressure variations near zero frequency (atmospheric pressure fluctuations) can be sensed by measuring the change in capacitance.

It is clear that utilizing small, stiff membranes below their resonant frequencies will drastically reduce the membrane displacement for a given input pressure. To obtain a reasonably scaled signal output, this reduction in displacement sensitivity must be compensated with an extremely sensitive method of detecting slight changes in capacitance. Radio frequency (RF) detection is an alternative detection method for sensing the slight changes in capacitance due to membrane movement.

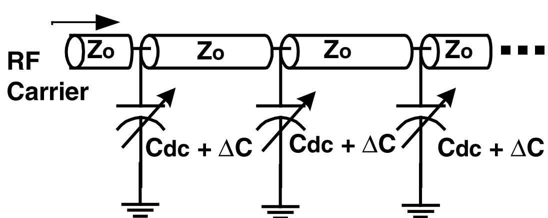

Figure 2: A transmission line that is periodically loaded with capacitive membranes.

RF Detection

In RF detection, several hundred CMUT membranes are connected in series by short sections of transmission line, thereby creating a capacitively-loaded transmission line. The membranes form variable capacitors that are periodically spaced along the transmission line as shown in Fig. 2. As the capacitive membranes in the line vibrate due to incoming sound pressure, the propagation constant of the loaded transmission line also changes, effectively phase modulating a radio frequency (RF) carrier by the acoustic signal [8]. The microphone itself operates in a phase detection circuit such as the one shown in Fig. 3. The output signal represents the acoustic pressure signal on the microphone.

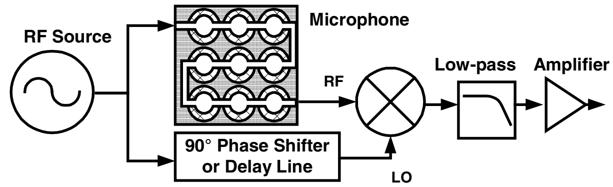

Figure 3: The phase-detection circuit used in RF detection.

By neglecting the conversion loss of the mixer and subsequent amplification stages, a simple approximation for the signal output of the mixer is possible:

$$I_{Out} = \frac{V_{RF}}{4} e^{-\alpha n} n C_0 \omega_{RF} \frac{\Delta x}{x_0}. \quad (1)$$

In equation (1), n is the number of membranes or sections in the line, C_o is the capacitance of single membrane, x_o is the initial separation between capacitor electrodes, Δx is the membrane's amplitude of vibration, V_{RF} is the RF voltage, α is the attenuation constant per section in nepers, and ω_{RF} is the RF radian frequency [8].

III. Noise Considerations

As mentioned earlier, microphone sensitivity is traditionally described in terms of output voltage response for an input pressure. This information alone will not completely describe the performance of the microphone unless accompanied by figures describing the noise performance of the microphone. Therefore, in this paper we commonly use the signal-to-noise-ratio (SNR) of the system as a measure of the microphone sensitivity in an electrical system, often quoted in decibels (dB) relative to a 1 Pa pressure input.

Very often, the mechanical noise of a condenser microphone limits the performance of the sensor, regardless of the quality of the amplifying electronics. Squeeze-film damping due to air behind the membrane in unsealed membrane devices is the dominant noise mechanism for many high-quality condenser microphone designs [7]. By eliminating the major source of acoustical resistance, vacuum-sealed CMUT membranes have a much lower mechanical noise floor. Radiation resistance of the membrane is the remaining loss mechanism, and calculations indicate that mechanical noise in sealed CMUT membranes is small enough to be neglected at low frequencies. Instead electrical thermal noise actually limits the sensitivity of the device.

There are several sources of electrical noise in the system. First, there is the thermal noise power on the transmission line given by kT_o in a 1 Hz bandwidth, where k is Boltzmann's constant (1.38 x 10^{-23} J/K) and T_o is the absolute temperature of the system. The quadrature component of this thermal noise is mixed to baseband and again has value kT_o in a 1 Hz bandwidth [8]. Furthermore, the mixer introduces its own thermal noise due to the conversion loss between the RF port and the intermediate frequency (IF) port. Subsequent amplification of the baseband signal also introduces additional thermal noise into the system.

IV. EXPERIMENTAL RESULTS

Measurements

In the absence of elaborate acoustic measurement equipment, acoustic performance in initial devices is evaluated by vibrating the membranes electrostatically with an applied voltage. The actual displacement of the membrane under this electrostatic actuation is measured using an optical interferometer. Analysis of the output signal permits measurement of the electrical sensitivity of the RF detection method. By calculating the equivalent pressure input that results in the same applied displacement, a measurement of the overall sensitivity of the microphone system is possible.

The microphone consists of 258 rectangular membranes periodically loading a microstrip line at distances of 114 µm. The membrane thickness is 1.3 µm and has dimensions of 100 µm x 800 µm, suspended 1 µm above the substrate. The area of the device is approximately 4 mm x 4 mm. With an RF frequency of 113 MHz, the SNR at 10 kHz is 82 dB/Hz for a measured membrane displacement of 7.5 Angstroms. This suggests that the minimum detectable displacement using this RF detection configuration is $6.4 \cdot 10^{-4}$ Å/√Hz.

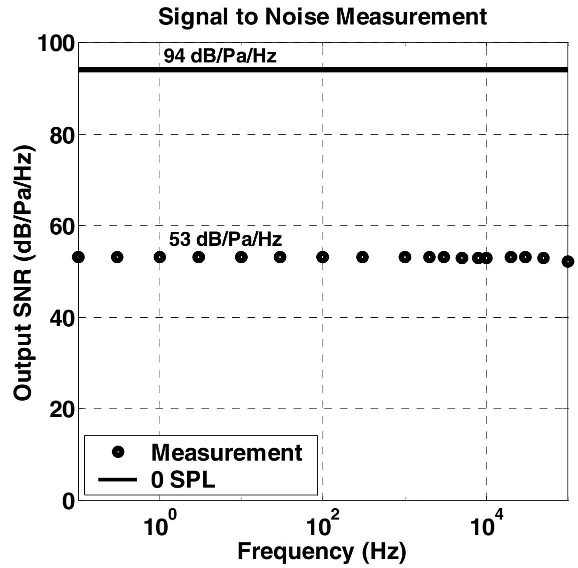

Fig. 4. Measured output SNR (dB) compared to reference level of 0 SPL for the human ear. The frequency range is from 0.1 Hz to 100 kHz.

Collecting signal outputs at a variety of frequencies demonstrates the relatively flat frequency response that is possible with RF detection and CMUTs. Fig. 4 shows the microphone's SNR based on the equivalent acoustic pressure input from 0.1 Hz to 300 kHz. This is compared to the commonly accepted reference of 0 sound pressure level (SPL) for the human ear, which is equivalent to 94 dB SNR relative to 1 Pa. The sensitivity of the microphone over the frequency range is 53 dB/Pa/Hz ± 1dB.

Discussion of Results

The device tested in the results of Fig. 4 was designed for conventional ultrasonic applications, and therefore was not optimized for use with RF detection in terms of membrane geometry or for reduction of RF loss on the connecting microstrip transmission line. In fact, the RF loss of the transmission line was prohibitively large at high frequencies, so a relatively low RF frequency of 113 MHz was used in these experiments. For the device tested, the transmission line loss at 100 MHz is 14 dB, and increases to 44 dB at 1 GHz for the 3 cm-long line. This transmission line loss reduces the output signal level and overall SNR proportionally as seen from Equation (1). In addition, high transmission line loss prevents the use of higher RF frequencies, which could further increase the signal level.

Strategies for Improvement

The greatest improvement to the microphone sensitivity is possible by reducing the high levels of transmission line loss in the devices. A coplanar waveguide (CPW) transmission line geometry reduces the conduction loss of the line since it permits wider signal lines while maintaining a high characteristic impedance [9]. Loss can be further decreased by burying the transmission lines underneath the membrane, which permits arbitrarily thick metal lines without adversely affecting the CMUT membrane movement. Based on other literature results, we expect that transmission lines with less than 0.4 dB/cm loss at 1 GHz can be fabricated on high resistivity silicon substrates [10]. For the device measured in Fig. 4, the expected SNR with such a low-loss line and an RF frequency of 1 GHz is 90 dB/Pa/Hz.

Improvements to the phase detection circuit can further improve the sensitivity of the RF microphone. Insertion of a low-noise RF amplifier before the mixer in the phase detection circuit Fig. 3 compensates for some of the loss of the RF microphone's transmission lines, thus permitting longer transmission lines in the RF microphone for more phase modulation. In addition, many commercially available RF amplifiers have very low noise figures, some below 1 dB. Since the mixer's noise performance is likely poor, it's noise is discounted by the gain of the RF amplifier. Futhermore, the gain and noise specifications of the baseband amplifier are relaxed by boosting the signal level before demodulation. This simple modification to the detection circuit, coupled with low-loss transmission lines could yield an SNR above 100 dB/Pa/Hz. The resulting device would be sensitive, robust, and only a few millimeters in size.

V. ACKNOWLEDGEMENTS

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