Acoustic Sensing Using Radio Frequency Detection and Capacitive Micromachined Ultrasonic Transducers

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Abstract — **Broadband acoustic sensing over several decades of frequency has traditionally been difficult to achieve. Conventional condenser and electret microphones depend on membrane and cavity resonances to achieve maximum their maximum sensitivity. However, such resonant phenomena are inherently narrowband and limit the applicable frequency range of the acoustic sensor.**

New microphones using capacitive micromachined ultrasonic transducer (CMUT) technology and radio frequency (RF) detection achieve a relatively flat acoustic frequency response from frequencies below one hertz to hundreds of kilohertz. In this detection method, a high-frequency carrier signal is launched down a capacitively-loaded transmission line consisting of capacitive micromachined membranes and interconnects. The resulting phase modulation of the carrier due to impinging sound pressure can be measured. Preliminary experiments demonstrate microphone sensitivities of 50 dB/Pa/Hz ± 3 dB over a frequency range of 0.1 Hz to 300 kHz. Calculations reveal that sensitivities on the order of 100 dB/Pa/Hz, greater than the sensitivity of the human ear, may be possible with a 1 cm^2 device and a carrier frequency of several gigahertz.

I. INTRODUCTION

Capacitive microphones, or more generally capacitive transducers, consist of one or more conductive diaphragms suspended over a conductive backplate [1]. Sound detection is possible when the impinging pressure vibrates the diaphragm, thus changing the capacitance of the transducer. 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.

Recently, a new type of capacitive transducer has been developed, largely for ultrasound applications in air and water. The capacitive micromachined ultrasonic transducer (CMUT) consists of thousands of rectangular or circular silicon-nitride membranes electrically connected in parallel to form a capacitor [2]. This device behaves similarly to the conventional condenser microphone, except for its dimensions and different range of applications. CMUTs typically have membrane thicknesses of approximately 1 μm and membrane widths around 100 μm, with dimensions accurately controlled by lithography and semiconductor fabrication technology. The above device geometry results in a structure that resonates at 2-3 MHz, and is therefore useful for ultrasound applications [2]. However, such devices are narrow-band when operating in a low-impedance medium such as air.

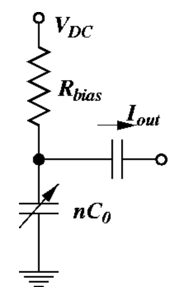

Fig. 1. Constant-voltage bias circuit capacitive transducer.

The trend in capacitive microphone technology has been to make the diaphragm thin and as large as possible for detection of low-frequency signals. The gap between the diaphragm and backplate is as small as possible for the maximum change in capacitance for diaphragm displacement. Unfortunately, such a structure suffers from squeeze-film effects, non-linearities, and durability issues. Most importantly, traditional capacitive microphone technology depends on mechanical resonance phenomena to achieve maximum sensitivity over a limited frequency range.

II. ANOTHER APPROACH TO MICROPHONES

A. Membrane Geometry for Flat Frequency Response

In an effort to broaden the frequency response of microphones, an alternative approach to microphone design is proposed. Instead of large, thin membranes with air-backing as in traditional microphones, we propose fabricating many small CMUT membranes with thicker, more robust diaphragms than usual. With stiffer membranes, the cavity behind these membranes may be vacuum-sealed during processing, and the membrane can still withstand atmospheric pressure. Because CMUT membranes resonate at a few megahertz, the displacement response of such membranes to pressure inputs is relatively flat up to several hundred kilohertz. If the cavity behind the membrane is evacuated, pressures variations near DC frequency (atmospheric pressure fluctuations) may be sensed by measuring the change in capacitance.

To better understand the advantages and disadvantages of acoustic sensors, it is useful to express the traditional definition of microphone sensitivity in volts per Pascal as a product of two terms: the mechanical sensitivity and the electrical sensitivity [1]. The mechanical sensitivity relates the membrane displacement to an incoming acoustic pressure while the electrical sensitivity relates the output voltage to the membrane displacement.

It is clear that utilizing capacitive membranes below resonant frequency will drastically reduce the membrane displacement for a given input pressure. This reduction in displacement can be compensated with an extremely sensitive method of detecting the slight changes in capacitance. Radio frequency (RF) detection is an alternative detection method to sense the change in capacitance due to membrane movement.

B. Overview of RF Detection Method

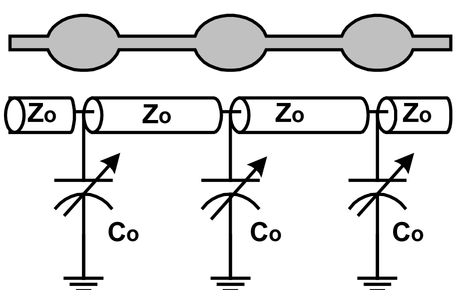

Fig. 2. Representation of a top metalization in a series string of membranes as a periodically-loaded tranmission line.

In RF detection, several hundred CMUT membranes are connected in series, thus creating a capacitively-loaded transmission line. The membranes form variable capacitors that are periodically spaced along the interconnecting microstrip transmission line as shown in Fig. 2. As the capacitive membranes in the line vibrate due to incoming sound, the propagation constant also changes, effectively modulating the electrical length of the transmission line.

If a radio frequency (RF) carrier signal that is launched down the artificial transmission line is phase modulated by the acoustic signal [3]. Subsequent detection or demodulation yields the acoustic signal. Fig. 3 shows a schematic representation of such a microphone system using RF detection.

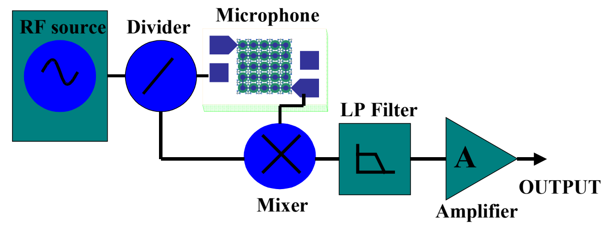

Fig. 3. Complete microphone system including demodulation.

The electrical length of the transmission line in radians, as well as the phase modulation index of the transmitted RF signal in radians/Pascal, is proportional to the number of membranes and the frequency of the RF signal. Clearly, higher RF frequencies will boost the electrical sensitivity until transmission line losses, which increase with frequency, affect the system's ability to detect the phase changes.

Narrowband phase-modulation of the transmitted RF can be demodulated by mixing the modulated signal with a reference RF signal obtained from the original RF generator. Neglecting the conversion loss of the mixer, a simple expression for the current output of the mixer is possible:

$$I_{RF} = \frac{V_{RF}}{4} N C_0 \omega_{RF} \frac{\Delta x}{x_0}. \quad (1)$$

In equation (1), N is the number of membranes, 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, and ω_{RF} is the RF frequency [3]. For comparison, the output current of a conventional constant-voltage bias detector, as shown in Fig. 1, is given by:

$$I_{RF} = V_{DC} N C_0 \omega_A \frac{\Delta x}{x_0}. \quad (2)$$

Two differences are evident from equations (1) and (2). First, the RF voltage takes the place of the DC voltage in RF detection. Typically, the DC voltage bias can be made an order of magnitude larger than the RF voltage that can be applied to the RF detection system. Secondly, and more importantly, the output current in RF detection is directly proportional to the RF frequency, whereas the conventional detection output signal is proportional to the incoming sound frequency. If the RF frequency is several gigahertz, the electrical sensitivity of the RF detection method can be many orders of magnitude larger than the constant-voltage detection method sensitivity. Furthermore, the output current in RF detection is independent of the acoustic signal, as long as the amplitude of vibration is frequency-independent as it will be below membrane resonance. Because of the dependence on acoustic frequency, ω_A, of the constant-bias voltage detection, it is difficult to detect the membrane response at very low frequencies of a few hertz. RF detection on vacuum-sealed devices permits sensing of arbitrarily low frequency membrane displacements.

C. Sensitivity and Figures of Merit

As mentioned earlier, microphone sensitivity is traditionally described in terms of output voltage response for an input pressure. This definition for sensitivity can be a misleading measure of a device since subsequent amplification can always increase the output voltage without any apparent tradeoffs. A more complete figure of merit is one that incorporates both mechanical and electrical noise generated by the microphone and the amplifying electronics, respectively. Therefore, in this paper we commonly use the signal-to-noise ratio (SNR) of the system, quoted in decibels relative to a 1 Pa pressure input, as a measure of the microphone sensitivity in an electrical system. Since the first stage of amplification dominates the electrical noise of the system, the SNR is measured after the amplifier.

As can be seen from a microphone design using RF detection, the mechanical sensitivity in terms displacement for input pressure is drastically reduced. However, the mechanical SNR is actually improved since mechanical losses are minimized with vacuum-sealing of the devices. RF detection can potentially increase the electrical sensitivity to the point where the mechanical noise dominates the electrical noise, therefore allowing detection at the mechanical noise limit of the system. The resulting microphone will have a better SNR than conventional capacitive microphones while still achieving a very broad frequency response.

III. SNR Estimation with RF Detection

The noise for a microphone system using RF detection can be divided into two parts: mechanical noise is due to mechanical losses in the transducer and electrical noise due to lossy circuit components and the amplifier electronics. Nearly all of the mechanical noise is generated from the air and can be calculated from the radiation impedance of the microphone into air [3]. As long as the transmission line loss is low enough to be neglected, mechanical noise will dominate electrical noise for many amplifier systems. For a commercially available, low-noise amplifier with 1 nV/√Hz noise voltage and 0.1 pA/√Hz noise current, the mechanical noise of a 1 mm^2 transducer dominates at -179 dB relative to 1 V_{rms}/√Hz. Although the mechanical noise produced by a transducer will increase as the square-root of area, the signal level will increase proportionally with area resulting in an improved SNR for larger transducers. Because sound detection at the mechanical noise limit is possible, a microphone with 1 cm^2 area using RF detection has the potential to detect signals below 20 µPa, the often-cited minimum detectable pressure for the human ear.

IV. Experimental Results

The experimental setup shown in Fig. 4 is used to test the RF detection method. In this configuration, a low frequency voltage signal is applied through a bias-T to the membranes to actuate them a known, controlled distance. 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, an estimation of the overall sensitivity of the microphone system is possible in the absence of elaborate acoustic measurement equipment.

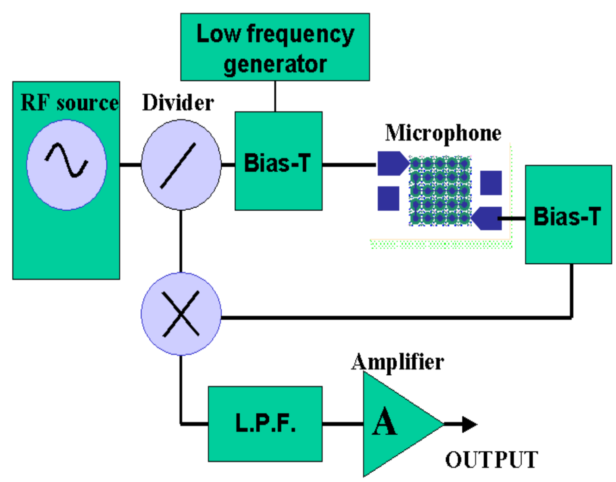

Fig. 4. Testing configuration for microphone.

The microphone consists of 258 series-connected 1.3 µm-thick, 100 µm x 800 µm rectangular membranes suspended over a 1 µm air gap. The area of the device is approximately 0.2 cm^2. Unfortunately, the cavity beneath the membrane could not be vacuum-sealed for this membrane geometry, which results in some additional noise and variations of the membrane response with frequency due to squeeze-film effects. With the 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 6.4×10^{-4} Angstroms/√Hz.

Collecting signal outputs at a variety of frequencies demonstrates the relatively flat frequency response that is possible with RF detection and CMUTs. Fig. 5 shows the microphone's measured output signal to noise ratio based on the equivalent acoustic pressure input from 0.1 Hz to 300 kHz. This is compared to the commonly accepted reference of 0 SPL for the human ear, which is equivalent to 94 dB SNR relative to 1 Pa. The sensitivity of the microphone is greatest at low frequencies, with a peak value of 53 dB/Pa/Hz.

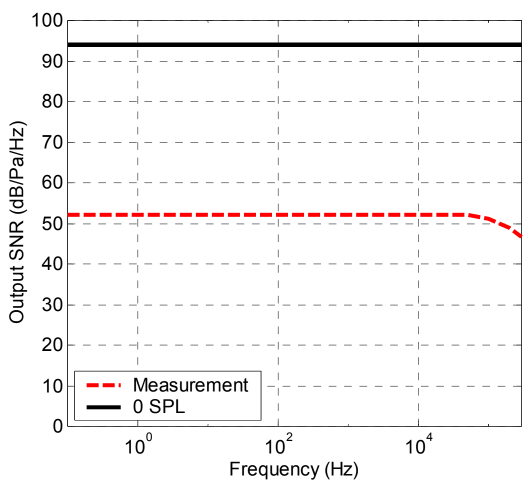

Fig. 5. Measured output SNR (dB) relative to 1 Pa equivalent input pressure, compared to reference level of 0 SPL for the human ear. The frequency ranges from 0.1 Hz to 300 kHz.

The device tested above 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 losses on the connecting microstrip transmission line. In fact, a relatively low RF frequency of 113 MHz was used in these experiments because the RF losses were prohibitively large at higher frequencies. These transmission line losses are a source of electrical noise that appears to dominate the mechanical noise of the membrane in air. Future designs using coplanar waveguide interconnects should raise the transmission line impedance, thereby reducing conductive losses. If conductive line losses are reduced sufficiently, the RF frequency may increase a few orders of magnitude, permitting detection at the mechanical noise limit. Nonetheless, the early experimental results demonstrate the sensitivity of the RF detection method and the broad frequency response attainable using RF detection.

V. Conclusion

The RF detection method discussed in this paper is a very sensitive method for detecting displacement. When combined with CMUTs, a very flat frequency response is possible when the membranes are used below their resonant frequencies. The first experimental results of a microphone using RF detection suggest that its peak sensitivity is 53 dB/Pa/Hz. Improvements to sensitivity can be obtained through higher RF frequencies used in RF detection, once the RF losses are reduced. Further optimization of transmission line structures, membrane geometry, and number of sections should improve the microphone's sensitivity, while maintaining its bandwidth.

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