RF Detection for Low Frequency cMUTS and its Comparison to Traditional Detection

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Abstract— **Capacitive micromachined transducers have long been used as generators and detectors of ultrasound both in air and immersion applications [1-3]. Typically, the frequency of operation has been in the MHz range. However, they can still be operated at very low frequencies, where their mechanical sensitivity is poor, but the frequency response is flat. In this paper we show that, together with the RF detection method that provides a very sensitive and broadband acoustic detection [4], [5], it is possible to operate the cMUTs at very low frequencies, which covers the microphone and sonar applications.**

Keywords— **microphone, RF Detection, Capacitive Transducers.**

I. Introduction

Capacitive microphones are made up of a diaphragm or a plurality of diaphragms that are suspended over a conductive backplate. The diaphragm is coated with a conductive electrode to create a parallel plate capacitor. The value of the capacitor is determined by the area of the electrode as well as the gap between the diaphragm and the backplate. The detection of sound with a capacitive microphone depends on the change in its capacitance when the diaphragm starts to vibrate upon receiving a sound pressure. Traditionally, the change in the capacitance is detected by measuring either the output current under a constant bias voltage or the output voltage under a constant-charge on the diaphragm electrode.

There are two significant figures that determine the sensitivity of a microphone. The first one is the open circuit output signal generated in volts per unit sound pressure impinging on the microphone in Pascals. This sensitivity figure can be decomposed into two as the product of mechanical sensitivity in angstroms per Pascal input pressure, and electrical sensitivity in volts per angstrom displacement. The research on capacitive microphones has been primarily based on optimizing these two components to maximize the open circuit output voltage per Pascal input pressure. However, this figure of sensitivity is not sufficient by itself to show the performance of a microphone because it does not include the noise generated by the microphone and the detection circuitry. Therefore, we consider the second figure of sensitivity, which is the signal-to-noise ratio (SNR) in dBs obtained per Pascal input pressure, as a more complete performance meter for a microphone. Note that, the first amplification stage is the most important electronic stage that determines the overall noise performance of the microphone, and the SNR should be measured after the preamplifier. After we introduce our approach to the microphone technology, we will be showing both calculation and measurement results in terms of SNR.

Traditionally, the trend in capacitive microphone technology has been to make the diaphragm softer, larger, and as close to the backplate as possible. The gap is filled with air to prevent the diaphragm collapsing on to the backplate due to the atmospheric pressure. This type of microphone has limitations due to squeeze film effects, air streaming resistance, nonlinearity, and durability. A fine review on capacitive microphones can be found in reference [6] as well as on other types of microphones.

II. A New Microphone Approach

Our approach to microphone technology is different from the traditional approach. Instead of making soft and large diaphragms with air backing, we build the microphone with small membranes and make them stiff enough to sustain the atmospheric pressure. Then, we can evacuate the gap and seal the membranes creating a vacuum between the membrane and the backplate [1], [2]. In this way, we eliminate the limitations of traditional microphones that are caused by air backing and soft membrane and create a more robust microphone. Furthermore, these devices have their resonance frequency in the MHz range which means a perfectly flat frequency response up to a good fraction (80%) of the resonance frequency. However, these advantages come with a disadvantage, which is the significant reduction in the mechanical sensitivity of the microphone. Note that, reduced mechanical sensitivity does not imply reduced mechanical signal-to-noise ratio. Indeed, since the mechanical losses are minimized, the mechanical noise limit of the microphone is also minimized. That means, in an ideal situation with no electronic noise contribution, the SNR obtained from a microphone with our approach would be better than the one obtained with traditional microphones. In a situation where electronic noise is dominant, this may not be possible. The main focus of our work is to increase the electrical sensitivity of the detection circuitry so that the mechanical noise of the microphone dominates the electronic noise. Then, we can detect sound pressure at the mechanical noise limit.

To compensate for the poor mechanical sensitivity we boost the electronic sensitivity by using an RF detection method which was initially introduced for capacitive micromachined ultrasonic transducers [4] [5]. In this method, the membranes are attached with a single continuous metal line as shown in Fig. 1, which is actually a transmission line periodically loaded with membrane capacitances. It has a propagation constant that is a function of the membrane capacitance, so one can imagine the modulation of the propagation constant as the membranes start to vibrate upon receiving a sound pressure. One can also imagine transmitting an RF signal with a sufficiently high frequency (for which the membranes are mechanically immune) through the line. This RF signal will experience a phase shift as a result of the electrical length of the line. Then follows the modulation in the phase of the transmitted RF signal upon receiving a sound pressure. By detecting this phase modulation it is possible to detect the incoming sound pressure as shown in Fig. 1.

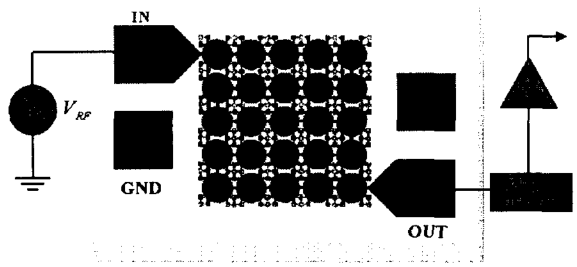

Fig. 1. A New Approach to capacitive microphones.

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 the membranes, and the frequency of the RF signal. It is evident that, using an RF frequency as high as the RF losses allow, is the way to boost the electrical sensitivity.

The modulation of the phase of the transmitted RF signal is usually narrow band which can be viewed as a residual amplitude modulation and detected by mixing the modulated signal with a reference RF signal. By assuming a conversion loss of 1 for the mixer we can write the expression for the current out of the mixer as follows:

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

In this equation, N is the number of membranes, C_0 is the capacitance of a single membrane, x_0 is the gap height, Δx is the vibration amplitude of the membrane, V_{RF} is the RF voltage, and ω_{RF} is the RF frequency. Using a traditional detection method with a constant bias-voltage the same current would be:

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

Comparing Eqs. 1 and 2 reveals a good similarity in the expressions, and two major differences. The DC voltage and the sound frequency in the traditional output current are replaced with the RF voltage and the RF frequency in the RF detection output. The DC voltage is limited by the collapse voltage which is typically an order of magnitude larger than the RF voltage we can apply to the microphone. On the other hand, the RF frequency we can use can be in the GHz range which brings about five orders of magnitude gain in terms of the output current. This is how the electrical sensitivity is boosted. Looking at Eq. 1 reveals another advantage of the RF detection. The output does not have a dependence on the frequency of the incoming sound which means practically an infinite detection bandwidth. When combined with the flat mechanical response of the membranes, the RF detection provides us a very broadband and sensitive microphone technology.

The output of the RF detection should also be compared to a traditional detection under a constant charge regime for completeness. However, because of the loading effect of the electrical port to the mechanical port, the mechanical frequency response of the membranes become distorted. We cannot obtain a simple expression for the output which we can compare to the RF detection, although numerical solutions are possible which will be shown in the following section. Although the constant charge regime works better than constant voltage regime in terms of bandwidth, it does not make a significant difference in the SNR of the microphone.

III. Signal-to-Noise Ratio Calculations

The SNR calculations are based on very simple models. The one used for traditional detection method is shown in Fig. 2. The input impedance of the amplifier determines whether it is a constant-voltage or a constant-charge regime. For both regimes a suitable and low-noise commercial amplifier is selected to determine the SNR at the output in terms of the membrane displacement. The membrane displacement as a function of the incoming sound frequency is calculated by solving the differential equations for the mechanical model of the membrane. For the constant-charge regime the loading effect of the electrical port is also taken into account. Combining them gives the output SNR of the microphone with its preamplifier with respect to a Pascal input pressure.

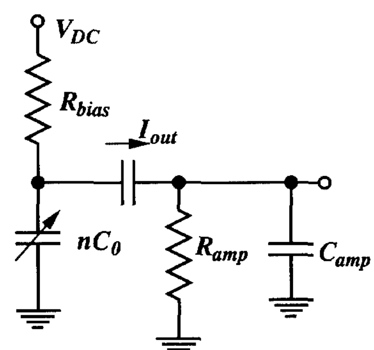

Fig. 2. Traditional detection circuitry.

For calculating the output of the RF detection, the detection circuitry in Fig. 1 is used where the amplifier is the same as the ones used in traditional detection methods. 3, 4 and 5 show the output signal, and noise levels of the constant-voltage, constant-charge and RF detection methods, respectively. V_{DC} is chosen to be 90% of the collapse voltage, whereas ω_{RF} and V_{RF} are chosen to be $2\pi \times 5$GHz, and 2V respectively. The reason for the choice of V_{RF} and ω_{RF} is the availability of commercial CMOS RF sources.

6 compares the output SNR obtained from the three detection methods with the 0 SPL level. The 0 SPL cor-

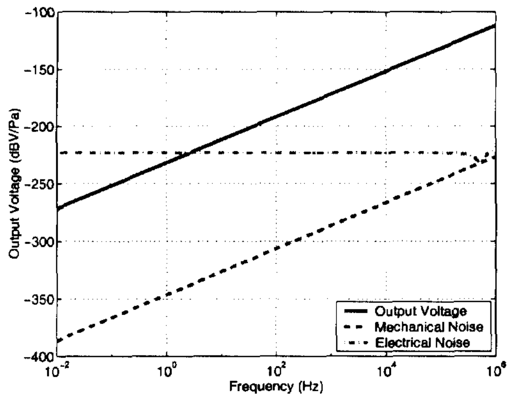

Fig. 3. Output signal and noise levels of a 1 mm^2 device under constant-voltage regime.

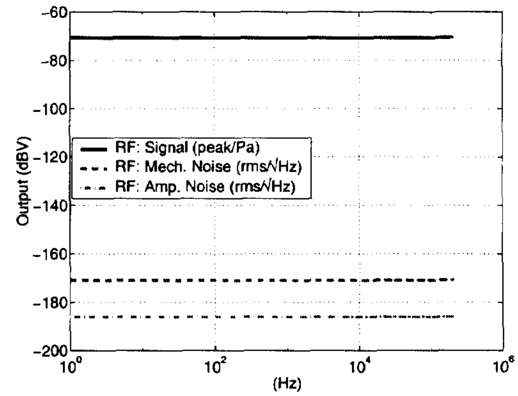

Fig. 5. Output signal and noise levels of a 1 mm^2 device with RF detection.

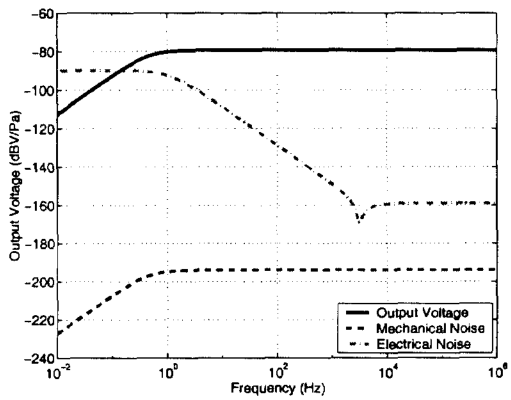

Fig. 4. Output signal and noise levels of a 1 mm^2 device under constant-charge regime.

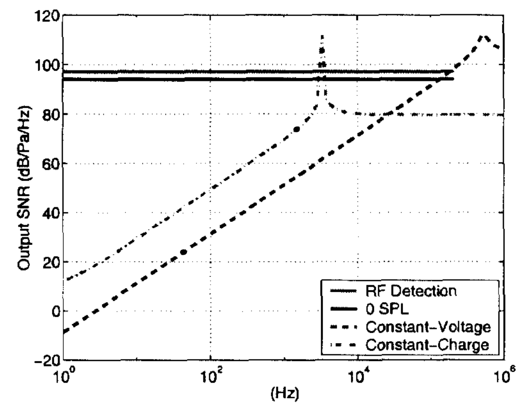

Fig. 6. Output SNR of a 1 mm^2 device.

responds to 94 dB SNR/Pa. This much of SNR implies a minimum detectable sound pressure of 20 μPa which is the minimum detectable sound pressure of the human ear. That is why 0 SPL is used as a reference point for microphones.

We see that in terms of both bandwidth and SNR our approach to the microphone technology is promising very good results. Even with a 1 mm^2 area, a microphone as sensitive as a human ear seems possible. These results will turn out to be over-estimated because of the losses and other noise sources that we ignored. However, it still provides a good comparison among the detection methods. When we increase the size of the microphone, the output SNR improves even more (Fig. 7) allowing us do detect sound levels as low as 2 μPa.

IV. Measurement Results

We fabricated our first batch of devices to operate as microphones. These devices were designed to operate as ultrasonic transducers and were converted to microphones. That is, they are not optimized in terms of geometry and electrical properties for the microphone application. However, they should suffice to demonstrate the basic properties of our microphone approach. In the experiment setup shown in Fig. 8 we apply a low frequency signal to vibrate the membranes electrostatically. Through a bias-T we send the RF signal and measure the phase modulation due to membrane vibrations. We calculate the vibration amplitude generated by the electrostatic excitation and then the pressure input needed to generate the vibration amplitude. Then, we correct the output SNR we measured to determine the SNR per Pascal input. Although not a very accurate way, it should be enough to make initial tests.

The frequency response of the microphone with an area of 0.3 cm^2 is plotted in Fig. 9. The response is quite flat, up to 3kHz, after which the output starts to roll off. The reason for this roll-off is clearly the squeeze film effect and the streaming air resistance, because this first batch of devices were not sealed. The solution to this is to seal the membranes, which will be done in the next batch of devices.

We can then calculate the output SNR per Pascal pressure input which is plotted in Fig. 10. We see that we are still about 30 dB away from 0 SPL. The main reason for this is the RF frequency we use. Because of the RF mismatches and losses in the microphone and the measurement set-up, the optimum operation frequency of this microphone turns out to be 170 MHz. Recall that we intend to go as high as 5 GHz in RF frequency which is about 30 times of what we

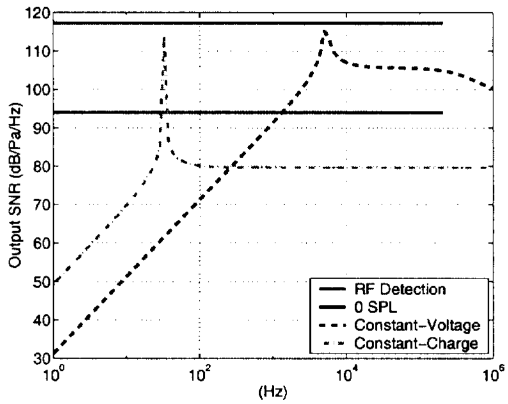

Fig. 7. Output SNR of a 1 cm^2 device.

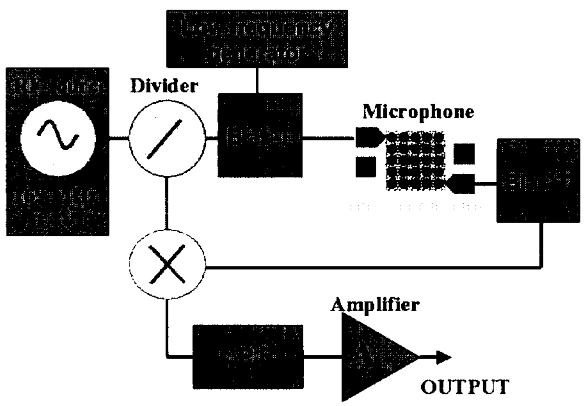

Fig. 8. Measurement set-up.

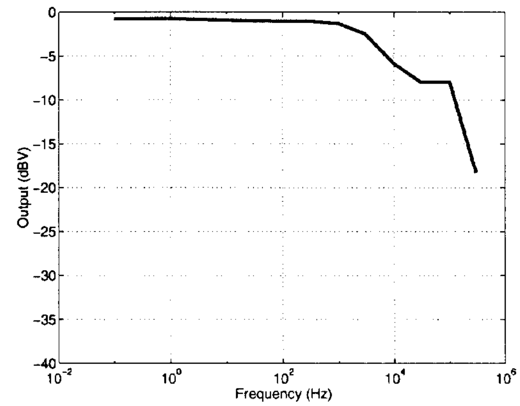

Fig. 9. Frequency response of the microphone.

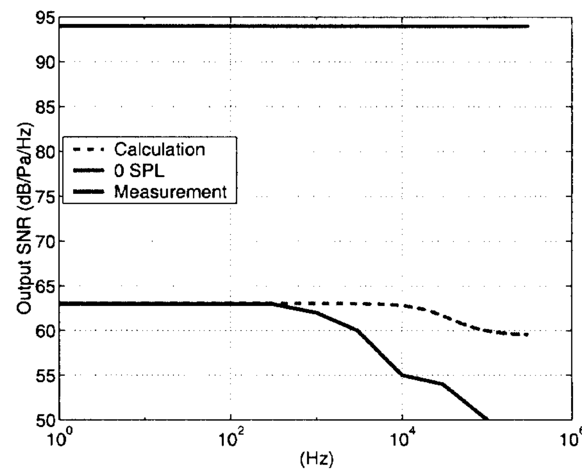

Fig. 10. Measured SNR of the microphone compared to 0 SPL.

used in these experiments. Then, we will gain another 30 dBs which will bring us to 0 SPL. The actual amplifier we used is not as good as the one we want to use. If we put actual values for the RF frequency and amplifier parameters, we get an output SNR that is quite close to what we measure, which is also included in Fig. 10.

Conclusion

We bring a new approach to microphone technology. We adopt capacitive micromachined ultrasonic transducers together with the RF detection method to the microphone application. The calculation results, and comparisons with the traditional microphones promise a very good improvement over the existing technology. The plots in this paper also show the possibility of microphones that are as sensitive as the human ear with a wider bandwidth.

The results of the first test runs did not come out as good as the calculations, because the mismatches and losses did not allow us to use higher RF frequencies. We got our SNR 30 dB below 0 SPL which is actually consistent with what the calculations tell for the RF frequency we actually used. Therefore, for this initial tests, the results are encouraging because we know how to deal with the problems.

Acknowledgments

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