Published in final edited form as:

IEEE Trans Ultrason Ferroelectr Freq Control. 2012 June ; 59(6): 1267–1275. doi:10.1109/TUFFC.2012.2317

Thermal-Mechanical Noise Based CMUT Characterization and Sensing

Gokce Gurun [Member, IEEE], Michael Hochman [Student Member, IEEE], Paul Hasler [Senior Member, IEEE], and F. Levent Degertekin [Senior Member, IEEE]

Abstract

When capacitive micromachined ultrasonic transducers (CMUTs) are monolithically integrated with custom-designed low-noise electronics, the output noise of the system can be dominated by the CMUT thermal-mechanical noise both in air and in immersion even for devices with low capacitance. Since the thermal-mechanical noise can be related to the electrical admittance of the CMUTs, this provides an effective means of device characterization. This approach yields a novel method to test the functionality and uniformity of CMUT arrays and the integrated electronics where a direct connection to CMUT array element terminals is not available. These measurements can be performed in air at the wafer level, suitable for batch manufacturing and testing. We demonstrate this method on the elements of an 800- μm diameter CMUT-on-CMOS array designed for intravascular imaging in the 10-20 MHz range. Noise measurements in air show the expected resonance behavior and spring softening effects. Noise measurements in immersion for the same array provide useful information on both the acoustic cross talk and radiation properties of the CMUT array elements. The good agreement between a CMUT model based on finite difference and boundary element method and the noise measurements validates the model and indicates that the output noise is indeed dominated by thermal-mechanical noise. The measurement method can be exploited to implement CMUT based passive sensors to measure immersion medium properties, or other parameters affecting the electro-mechanics of the CMUT structure.

I. Introduction

ALTHOUGH it contains valuable information about sensor and transducer systems, the thermal-mechanical (T-M) noise in ultrasonic and other mechanical transducers is mainly discussed in the context of lower limit for signal detection [1-4]. Ultrasonic transducer designs try to reduce T-M noise by minimizing losses in the system except for the unavoidable radiation losses. Electronics designs for imaging applications ultimately aim to detect signals down to T-M noise level but not much lower, because most of the cases are limited by other design parameters such as power consumption and dynamic range. Consequently the information contained in the T-M noise spectrum of ultrasonic transducers is usually ignored.

However, when the transducer is modeled as an electrical network, the power spectral density of the current noise provides information about the admittance (impedance) of the transducer [5, 6]. This provides a passive means for characterizing transducers and transducer arrays especially when no electrical port is available for direct impedance measurement. A capacitive micromachined ultrasonic transducer (CMUT) array monolithically integrated with CMOS electronics is a very relevant example where the transducer outputs are directly connected to the inputs of the pre-amplifier electronics [6]. Therefore, observing the T-M noise at the output of the electronics can be very useful for testing CMUT array performance at a wafer level, before the array packaging is completed.

Furthermore, with low internal losses, the spectral properties of the real part of the electrical impedance of the CMUT would be dominated by its radiation characteristics. This in turn can be related to the models that simulate the full spectrum of waves generated by the transducer, including evanescent waves. Evanescent waves that travel along the surface of the transducer may not be identified in the radiation pattern measurements, but they significantly affect the acoustic cross talk in imaging arrays [7]. These wave modes have been utilized for sensing and actuation purposes and passive noise measurements can provide an alternative sensing technique for these applications [8, 9]. More recently there has been a renewed interest in using diffuse noise fields for passive imaging and sensing applications, especially for underwater acoustics and geophysical applications [10]. Since T-M noise is an ideal diffuse noise source, it can be used for similar applications in the MHz range using suitable transducer arrays and electronics combinations [11-13].

Motivated by this background, in this paper we first relate the CMUT T-M noise to its electrical characteristics and determine the requirements on the electronics for T-M noise detection with high SNR. We use the T-M noise measured in air on CMUT arrays monolithically integrated with CMOS electronics to test functionality and uniformity of the intravascular imaging array elements. T-M noise measurements in water on the same array are then used to verify a finite difference model to predict CMUT array radiation and crosstalk behavior. Finally, the use of T-M noise spectrum for sensing fluid properties is predicted through calculations of evanescent wave resonances and changes in the output noise spectrum.

II. Thermal-Mechanical Noise of CMUT

A well-known result of thermal-mechanical noise is the Brownian motion, which is the random vibration of microscopic particles caused by the collisions with the atoms and molecules in the surrounding material. Because of the energy dissipating mechanism in the system, there has to be a fluctuation force associated with the damping term to sustain these thermal vibrations. The spectral density of that force associated with the damper in the system (i.e. mechanical resistance) is given by [1]

$$\overline{F_{T-M \text{ NOISE}}^2} = 4kTR, \quad (1)$$

where k is Boltzmann's constant (1.38×10^{-23} J/K), T is the temperature of the environment in Kelvin and R is the mechanical resistance. Note that this expression is a direct physical analog to the Johnson-Nyquist noise in the electrical systems [14], which states that the spectrum density of the thermal voltage noise of any network is proportional to the real part of the impedance of the network. Similarly, the Norton-equivalent current noise is proportional to the real part of the admittance of the network.

A simple equivalent circuit for a CMUT element [15], along with the equivalent noise force (F_{NOISE}) associated with the real part of the total complex mechanical impedance is shown in Figure 1. The terms on the mechanical side can be transferred to the electrical domain using the transformer ratio (Figure 2). In Figure 2 the noise term is represented with a Norton-equivalent current source. The equivalent CMUT electrical impedance is represented as $Z_{\text{CMUT,MEC}}/n^2$ where $Z_{\text{CMUT,MEC}}$ is the total impedance on the mechanical side that includes the radiation impedance ($Z_{\text{RAD}}S$), the membrane impedance ($Z_{\text{MEM}}S$) and any other mechanical losses. The electromechanical transformer ratio (n) of the transducer is equivalent to $V_{\text{DC}}C_0/g$ where V_{DC} is the applied dc bias voltage, C_0 is the capacitance of the CMUT and g is the gap between plates.

The spectral density of the thermal-mechanical current noise of a CMUT can be given as

$$\overline{i_{CMUT}^2} = n^2 \frac{\overline{F_{NOISE}^2}}{\text{Mag}(Z_{CMUT,MEC})^2} = n^2 4kT \frac{\text{Re}(Z_{CMUT,MEC})}{\text{Re}(Z_{CMUT,MEC})^2 + \text{Im}(Z_{CMUT,MEC})^2}, \quad (2)$$

where Mag, Re and Im denote the magnitude, real and imaginary parts of the complex impedance, respectively. Noticing that the current noise expression in (2) includes the admittance ($Y_{CMUT,MEC}$) term, the CMUT noise can simply be written as

$$\overline{i_{CMUT}^2} = n^2 4kT \text{Re}(Y_{CMUT,MEC}). \quad (3)$$

To simplify the expression one step further, the equivalent impedance of the CMUT on the electrical side ($Z_{CMUT,MEC}/n^2$) can be referred as $Z_{CMUT,ELEC}$. In that case, $n^2 \text{Re}(Y_{CMUT,MEC})$ term in (3) can be replaced by $\text{Re}(Y_{CMUT,ELEC})$ and the CMUT current noise can be rewritten as

$$\overline{i_{CMUT}^2} = 4kT \text{Re}(Y_{CMUT,ELEC}). \quad (4)$$

It is evident that the noise expression simply takes the form of the Norton-current noise associated with the real part of the admittance of the CMUT equivalent circuit.

To a first order, $Z_{CMUT,ELEC}$ can be assumed to be equivalent to a series RLC circuit. In that case, at the resonance frequency, the CMUT equivalent impedance can be assumed to be purely resistive ($R_{CMUT,ELEC}$). It follows that at resonance frequency, $Y_{CMUT,ELEC}$ in (4) becomes $1/R_{CMUT,ELEC}$ and hence CMUT current noise can be expressed as

$$\overline{i_{CMUT}^2}_{(\omega=\omega_{res})} = \frac{4kT}{R_{CMUT,ELEC}}. \quad (5)$$

Note that, the single RLC equivalent circuit assumes a device with a single resonance frequency and does not take the crosstalk effects into account. A more accurate estimation of the actual CMUT noise can be obtained by using a CMUT model such as the one discussed in Section IV and the general noise expression given in (3). However, the expression in (5) is suitable for a back-of-the-envelope calculation of the CMUT noise to be used as a design consideration for the receiver amplifier design.

III. Noise Characterization of CMUT Array Monolithically-Integrated with Low-Noise Amplifiers

The CMUT elements that are used in the noise measurements in this study are from a dual-ring CMUT array that is designed for forward-looking intravascular ultrasound (FL-IVUS) imaging [16]. The particular FL-IVUS array elements are designed for operation within 10 to 20-MHz frequency band with an area of $70 \mu\text{m} \times 70 \mu\text{m}$. With a simple calculation using a real radiation impedance of 1.5 MRayl for water, the value of $R_{CMUT,ELEC}$ in immersion is found as 1 M Ω and using that value in (5) suggests an expected CMUT T-M noise current of 125 fA/ Hz.

To accurately measure the CMUT noise level, the preamplifiers should be custom designed with an input current noise level that is low enough not to dominate the transducer noise. Minimizing the parasitic interconnect capacitances between the CMUT element and the

preamplifier is critical to achieve the required front-end noise levels especially for integration with FL-IVUS array elements with very small capacitances. A viable approach to minimize the parasitic interconnect capacitances is monolithic CMUT-on-CMOS integration where CMUT elements are fabricated on the same silicon substrate with the CMOS electronics. Figure 3 depicts the CMUT-on-CMOS integration scheme where the CMUT element is connected to the receiver CMOS amplifier circuitry through the bottom electrode [17].

The receiver front-end ICs were designed in 0.35- μm CMOS technology to be monolithically integrated with FL-IVUS arrays [16]. Figure 4 shows the micrograph of the device after the dual-ring FL-CMUT array is fabricated on top of the CMOS IC. The CMOS IC underneath the CMUT array contains a total of 32 receiver amplifiers dedicated to each receive CMUT element. There are four 8-to-1 multiplexers that are controlled by digital select signals. Each multiplexer takes the outputs of 8 receiver amplifiers and routes the selected receive channel to one of the output buffers.

The receive preamplifier is designed as a transimpedance amplifier (TIA) for wide-bandwidth CMUT current sensing in immersion. With minimized parasitics provided by CMUT-on-CMOS approach, the custom-designed TIA achieves a 3-M Ω gain, 20-MHz bandwidth and a 90-fA/ Hz input-referred current noise [16], which is less than the expected 125-fA/ Hz CMUT current noise level in immersion.

The same monolithically-integrated transimpedance amplifier design is also used for noise testing of CMUTs in air. For airborne applications the equivalent resistance at resonance frequency is roughly equal to the mechanical membrane losses and that is much smaller compared to the real part of the radiation impedance, which dominates the CMUT impedance in immersion. Considering (5), the smaller resistance in air applications implies that, at the corresponding resonance frequency, the noise level of the CMUT in air is higher than the noise of the CMUT in immersion. Therefore, although it is not specifically designed for air application, the TIA front-end used in this work is also low-noise enough for CMUT noise measurements in air.

It should be noted that for air coupled applications, bandwidth is not a concern because mainly the signal generated at a particular frequency, i.e. resonance frequency, is sensed. Therefore, for noise measurements in air, a charge amplifier [18] or an open-loop voltage amplifier can be more advantageous compared to a transimpedance amplifier since these amplifier topologies do not incorporate any feedback network noise.

Figure 5 shows the setup that is used to measure the noise spectrum of the CMUTs. There are additional voltages (i.e. vdd, gnd and some control lines) applied to the CMOS circuitry, which are not explicitly shown in the figure. It is important to note that no external high-voltage pulse is applied to the CMUT element. The noise measurement method only applies a static dc bias to the CMUT element and the noise spectrum is measured at the output of the receive electronics.

The noise spectrum of a CMUT element integrated with an amplifier is measured in air at the output of the receive amplifier using an Agilent 4395A Spectrum Analyzer. The CMUT element is biased at various increasing voltages (Figure 6). The measured noise at 0 V is due to the noise of the receiver electronics. As the CMUT bias is increased the coupling coefficient increases and the amount of noise associated with the CMUT increases. As shown in Figure 4, each CMUT element contains two pairs of trapezoidal membranes with slightly different sizes, which results in the two main resonance peaks in the noise measurements in air. The real part of the CMUT admittance and the CMUT noise both peak at the resonance frequency of the transducer. Therefore, noise measurements in air can

provide direct information of the resonance frequency of the CMUT. It can also be seen that as the dc bias increases the noise peaking frequency decreases due to the well-known spring softening mechanism that shifts the resonance frequency [19]. A group of small peaks also become visible in the noise data around 7.5-8 MHz range when the dc bias is applied and do not shift with bias change. These are probably due to the silicon substrate resonances generated by the CMUT vibrations.

To investigate the array functionality and uniformity, noise data is collected in air for all of the 32 CMUT-TIA pairs on the chip shown in Figure 4. The elements are scanned using the on-chip multiplexers. For this measurement CMUT elements are biased at 80 V. Figure 7 plots four of those measurements. Each noise measurement is acquired by 32 averages. The average resonance frequencies in air are measured as 13.6 MHz and 15.5 MHz for the two peaks across the 32 elements. The standard deviation of the resonance frequency values is found to be less than 0.9% of the mean for both of the peaks.

These results demonstrate that noise measurements in air can be used to easily verify the proper functionality of the monolithically integrated receive circuitry and the CMUT array. This is important because this noise-based method can be used for wafer level testing of the monolithically-integrated devices before any packaging or immersion effort. Without such a method it would be very challenging to test the integrated device. Once one of the CMUT electrodes is directly connected to the receive amplifier, measuring the impedance of the CMUT elements using a network analyzer for characterization is not an option because that type of measurement would require access to both of the electrodes. One should also note that the noise-based characterization method uses receive amplifiers already existing in the catheter for the imaging application; therefore it doesn't require any additional power consumption or chip area.

When the CMUT current is sensed with an amplifier with finite input impedance, the amplifier input impedance forms a current divider network with the CMUT impedance and the impedance of the total capacitances at the input. This slightly reduces the measured peak noise magnitude in air. However, it does not change the measured peak frequency. On the other hand, for operation in immersion, the equivalent CMUT impedance is typically much higher compared to the amplifier input impedance. Therefore, it can be claimed that in immersion almost all of the current generated by the CMUT flows through the amplifier and is sensed.

It should also be mentioned that although the noise-dominated system discussed in this study is based on CMUT-on-CMOS integration, for a larger CMUT transducer with a higher CMUT current noise level (i.e. a 1D linear array element), the noise performance requirement of the front-end electronics can be relaxed. In that case, a wirebonded or a cable-connected receive amplifier might also be low-noise enough to enable the measurement of the CMUT noise.

IV. CMUT Model Verification in Fluid Using T-M Noise

Understanding of CMUT array behavior in immersion is very critical in designing and implementing CMUT based ultrasound imaging and sensing systems. For this purpose, a model was created to predict the CMUT impedance and hence corresponding noise spectrum in immersion. The CMUT impedance includes mechanical (i.e. stiffness, mass, viscoelastic damping), electrical (i.e. spring softening), and radiation (i.e. self-impedance, fluid crosstalk) effects. A simplified analytical approach based on the finite difference approximation techniques described elsewhere was implemented [20, 21]. These references contain a more detailed description of the utilized modeling techniques. A brief summary of the approach is outlined here. Full details regarding the development and implementation of

the specific model used in this paper including effects of CMUT array geometry such as element pitch and membrane dimensions can be found in [22].

The membrane stiffness was approximated using thin-plate equations solved via a finite difference (FD) scheme. The mesh defined for this finite difference approach was also utilized to create a Boundary Element Matrix (BEM), which related the dynamic nodal displacement to the fluid radiation effects. This BEM was derived from the Green's function for a baffled point source in a semi-infinite fluid medium. The BEM is a fully-populated stiffness matrix describing how the displacement of every node in the array mesh translates to a pressure field that affects the behavior of every other node in the mesh. Electrostatic forces on the membranes were approximated with a first-order Taylor expansion, constraining the validity of the model to small-signal analyses. All of the mechanical, electrical, and radiation effects present in the CMUT array were combined into a global stiffness matrix, which could be solved using simple matrix operations. It should be noted that the model used for this paper did not employ the multiscale, lumped element, equivalent electro-acoustic circuit approach described by Meynier et al. [21]. Rather, it left the nodal mesh intact, and simultaneously solved the full system of equations for the entire array.

A. Modeling the Dual-Ring Array Receive Element

As derived earlier in Section II, the input current noise is directly proportional to the real part of the CMUT admittance. Thus, the analytical model was used to first calculate this admittance, which contained both the mechanical and radiation effects. This was accomplished by creating a model that simplified the experimental receive element as a linear array of 8x4 membranes (with symmetry), as shown in Figure 8. The model represented a small section of the dual-ring array, about 5 elements, and assumed that crosstalk effects from membranes not included in the model could be neglected. The rest of the array was modeled as a rigid surface. As shown in Figure 4, the device used in the experiments utilized elements that contained 4 trapezoidal membranes of 2 different sizes. Theoretically, the trapezoidal shape could have been incorporated into the FD/BEM model. To simplify the geometry, the model utilized the average dimensions of each membrane and assumed that they were rectangular in shape. The membranes were 2- μm thick, had $34\text{ }\mu\text{m} \times 36.75\text{ }\mu\text{m}$ and $34\text{ }\mu\text{m} \times 31.5\text{ }\mu\text{m}$ lateral dimensions, for the large and small ones respectively, and the element pitch was 40 μm in both X and Y directions.

The same dc bias was applied to all membranes, and the membranes illustrated in red were actuated with a uniform, 1Pa harmonic pressure over their entire surface. All other membranes in the array were left inactive (but biased) with 0-V ac input simulating a short circuit electrical boundary condition and were only present to account for cross-talk effects. A frequency sweep in the band of interest (1-30 MHz) was performed. A lumped element value for the total mechanical impedance of the element including both mechanical and radiation effects was obtained by dividing the total force on the active element by the average velocity over that same element. The transformer ratio, n , was calculated using the total electrode area and average gap under those electrodes. With these two values, (3) could then be solved for the estimated current noise of a CMUT element within the array.

B. Experimental Validation of Dual-Ring CMUT Array Simulation

For experimental noise measurements in immersion the same setup shown in Figure 5 is used. In this case the integrated array needed to be coated in parylene and placed in a water tank. System noise is measured at various CMUT bias voltages (Figure 9) [6, 16]. As mentioned earlier, when there is no dc bias, noise is only due to front-end electronics. The plot clearly indicates that CMUT T-M noise dominates the output noise for 95-V dc bias, which is close to the collapse voltage of the larger membrane.

The corresponding CMUT current noise spectrums are calculated using the FD/BEM model at 70-V and 95-V bias voltages. For comparison with the amplifier output noise measurements shown in Figure 9, the model-predicted CMUT current-noise values are multiplied by the transfer function of the amplifier (3-M Ω gain and 20-MHz bandwidth) to refer the values to the amplifier output. Furthermore, since the model does not include the effect of electronics noise, the noise power at 0-V bias case is removed from the biased CMUT noise measurements for more accurate comparison. Figure 10 shows the measured and predicted current noise spectrums.

The relative shape and magnitudes of the simulated graphs match very well with experimental results in spite of the significant simplifications made to the model. The two separate graphs in Figure 10 clearly shows the spring softening effect, which reduces the frequency of the two dominant peaks in the 5-10 MHz range corresponding to the resonances of the two different sized individual membranes in water. Increasing the voltage increases the separation between the resonance frequencies, which is also observed in experiments. The larger disagreement for 95-V bias case at low frequencies is probably due to large stiffness variations in CMUT behavior when the larger membrane is close to its collapse voltage. The rectangular approximation to trapezoidal membrane shape would have a significant effect in determining the collapse voltage. Both graphs also contain three distinct regions of interest. The first one occurs between 5 and 10 MHz (at 95-V bias) and corresponds to a region of large amplitude, sharp peaks. The second region is located between 10 and 20 MHz and is a much broader band, smoothed peak. The final region occurs beyond 20 MHz and displays a series of notches in the frequency response. All three regions were accurately predicted by the model.

There are sharp, large magnitude peaks in the simulated frequency response that are not visible in the experimental results. This may be the result of several factors. The model assumes perfect geometrical uniformity and pitch for the membranes in the linear array with rigid boundaries resulting in sharp transitions in device behavior. That would not be the case in the real device with trapezoidal membranes and circular structure, which results in a varying pitch. Furthermore, it is expected that these peaks may not show up in experiments because noise measurements require averaging to eliminate extraneous noise from the data. During this process, very sharp features tend to get averaged out because small shifts due to temperature and charging over time will result in their large magnitudes being damped out as they are averaged with many low-magnitude data points.

However, in spite of these discrepancies, there is a clear agreement between the simulation and experimental results. Thus, we conclude that the CMUT noise measurement comparisons provide another means to verify the accuracy and usefulness of the analytical model in addition to the impedance measurements presented in [21]. Furthermore, these results simultaneously validate that the measured noise spectrum in Figure 9 is indeed dominated by CMUT T-M noise, which is directly proportional to the real part of the CMUT admittance.

C. Exploring the Noise Current Spectrum in Immersion

With the validated model, some insight into CMUT crosstalk can be gained with a closer investigation of the simulation results. For example, at the first region of interest (5 MHz to 10 MHz), a high degree of crosstalk is observed as all membranes in the array are being excited with different phases and amplitudes, including the inactive (not actuated) membranes. This explains the presence of large peaks and notches in the frequency spectrum. Depending on the frequency, crosstalk will either increase or decrease the noise current seen by the TIA. Many of the features in this region are very sharp because the array displacement distribution is constantly shifting between completely different resonance

modes. Note that the two main peaks near 6 MHz and 9.5 MHz in Figure 9 correspond precisely with the center frequencies that would occur if the two membranes geometries that exist in the active element were isolated in immersion. This is clearly shown in Figure 11, which shows the normalized average particle velocity for the small and large isolated membranes. It should also be noted that the two largest magnitude peaks occur because a periodic wave is being set up in a direction that is specific to a particular inter-membrane spacing. Figure 12 shows the real part of the displacement field in response to 1-Pa harmonic pressure applied to the red membranes in Figure 8. At 6.1 MHz for example, as shown in Figure 12-a, the largest peak in the noise spectrum is created because a crosstalk resonance is occurring along the second row of membranes. This row corresponds to a unique membrane pitch. Similarly at 9.7 MHz, a crosstalk resonance activates the membranes in the inner ring of the array as shown in Figure 12-b. As described in detail elsewhere, these resonances are due to dispersive surface waves on the CMUT arrays with propagation speeds below the speed of sound in the immersion fluid [7]. These resonances have been shown to be good candidates for fluid sensing applications [8].

The next region from 10 MHz to 20 MHz, as demonstrated in Figure 12-c, represents the main radiation band of the transducer array. The array still exhibits crosstalk effects, but in general the effects are much more localized when compared to the previous region. This is due to the fact that no significant resonance is excited by the surface waves that cause standing waves over the array. In a typical pulse-echo measurement, this part of the spectrum dominates the received spectrum.

The final region, which occurs at approximately 20 MHz and beyond, displays a series of notches. At these frequencies, a periodic standing wave is being set up in a direction that is specific to a particular inter-membrane spacing, similar to the waves that were created at certain frequencies in the high-crosstalk region. For example, at 20 MHz, the first notch is caused by a crosstalk wave that is occurring along the second row of membranes (see Figure 12-d). In this case, however, the wave is supported by an antisymmetric mode shape in the associated membranes. This vibration profile results in low electromechanical coupling due to the symmetric CMUT electrode shape, resulting in a null (rather than a peak, as before) in the noise spectrum.

D. Noise Measurements for Passive Fluid Sensing

Since the T-M noise spectrum essentially provides the electrical impedance information for the CMUT, it can be used for passive sensing of fluid properties as in other similar sensors [8]. To explore this possibility, we performed simulations on the model geometry shown in Figure 8 for different fluid properties. In the simulations, all 2- μm thick membranes were assumed to have equal lateral dimensions of 35 $\mu\text{m} \times 35 \mu\text{m}$, pitch of 40 μm , were biased at 60 V, and the noise current was calculated using the method described earlier. Figure 13 shows a typical set of results when the speed of sound in the fluid (in this case water) is changed $\pm 5\%$ to 1425 m/s and 1575 m/s. The significant changes in the various parts of the noise spectrum suggest that this approach can be used for sensing purposes. The location of the sharp peaks due to surface wave resonances change significantly, as well as new resonances are occurring at specific higher frequencies (22.5 MHz in this case), enabling single frequency amplitude measurements to detect changes in fluid properties. These measurements can be performed by filtering the output noise in a narrow frequency band. Alternatively, the overall shape of the spectrum, including the broadband radiation region, may be used to obtain information on several parameters. These noise based measurements can be performed without disturbing the fluid medium and can provide a low power sensing technique due to their passive nature. We note that the particular device simulated here is just for feasibility demonstration. Different membrane and array geometries should be

explored to identify and selectively excite optimized surface wave modes for fluid sensing applications.

V. Conclusion

The T-M noise of the CMUTs, even small elements with capacitances in the sub-pF level, can be measured using low-noise CMOS integrated electronics. This noise spectrum can be directly related to the real part of the admittance of the CMUT using well known theorems. When performed in air, T-M noise measurements provide a novel way for testing functionality of CMUT array elements as well as the monolithically integrated electronics. As CMUTs behave as lightly damped resonators in air, distinct resonance peaks in the T-M noise spectrum and their frequency shift with dc bias provide accurate information on the CMUT characteristics. In immersion, the T-M noise spectrum contains information that is not readily available in a typical pulse-echo response. This is because the T-M noise spectrum reveals the effect of both evanescent acoustic waves trapped over the array and bulk acoustic waves radiated away from the array on the admittance of the CMUT elements. Consequently, once the CMUT is well characterized, the T-M noise spectrum can be used to measure certain characteristics of the immersion fluid, providing an alternative to impedance-based active CMUT fluid sensors.

Acknowledgments

The authors want to thank Jaime Zahorian, Toby Xu and Sarp Satir for their help with device fabrication and noise testing. This work was financially supported by Award Number R01EB010070 from the National Institute of Biomedical Imaging and Bioengineering, and Award Number R01HL082811 from the National Heart, Lung and Blood Institute.

References

1. Gabrielson TB, Center U, Warminster PA. Mechanical-thermal noise in micromachined acoustic and vibrationsensors. *IEEE transactions on Electron Devices*. 1993; 40:903–909.
2. Walters DA, Cleveland JP, Thomson NH, Hansma PK, Wendman MA, Gurley G, Elings V. Short cantilevers for atomic force microscopy. *Review of Scientific Instruments*. 1996; 67:3583–3590.
3. Thompson SC, LoPresti JL, Ring EM, Nepomuceno HG, Beard JJ, Ballard WJ, Carlson EV. Noise in miniature microphones. *Journal of the Acoustical Society of America*. Feb.2002 111:861–866. [PubMed: 11863188]
4. Oakley CG. Calculation of ultrasonic transducer signal-to-noise ratios using the KLM model. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*. 1997; 44:1018–1026.
5. Loyau V, Feuillard G. Relationship between electrical impedance of a transducer and its electroacoustic behavior: Measurement without primary source. *Journal of Applied Physics*. 2006; 100:034909–034909-7.
6. Gurun G, Zahorian J, Hasler P, Degertekin L. Thermal mechanical noise based characterization of CMUTs using monolithically integrated low noise receiver electronics. *Ultrasonics Symposium (IUS), 2010 IEEE*. 2010:567–570.
7. Eccardt PC, Lohfink A, Garssen H. G. v. Analysis of crosstalk between fluid coupled cmut membranes. *Ultrasonics Symposium, 2005 IEEE*. 2005:593–596.
8. Thranhardt M, Eccardt PC, Mooshofer H, Hauptmann P, Degertekin L. A resonant CMUT sensor for fluid applications. *Sensors, 2009 IEEE*. 2009:878–883.
9. McLean J, Degertekin FL. Directional Scholte wave generation and detection using interdigital capacitive micromachined ultrasonic transducers. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*. 2004; 51:756–764.
10. Sabra KG, Gerstoft P, Roux P, Kuperman WA, Fehler MC. Extracting time-domain Green's function estimates from ambient seismic noise. *Geophysical Research Letters*. Feb.2005 32

11. Weaver RL, Lobkis OI. Ultrasonics without a source: Thermal fluctuation correlations at MHz frequencies. *Physical Review Letters*. Sep.2001 87
12. Weaver R, Lobkis O. On the emergence of the Green's function in the correlations of a diffuse field: pulse-echo using thermal phonons. *Ultrasonics*. May.2002 40:435–439. [PubMed: 12159980]
13. Lani S, Satir S, Gurun G, Sabra KG, Levent Degertekin F. High frequency ultrasonic imaging using thermal mechanical noise recorded on capacitive micromachined transducer arrays. *Applied Physics Letters*. Nov.2011 99
14. Nyquist H. Thermal agitation of electric charge in conductors. *Physical Review*. 1928; 32:110–113.
15. Wygant I, Jamal N, Lee H, Nikoozadeh A, Oralkan O, Karaman M, Khuri-Yakub B. An integrated circuit with transmit beamforming flip-chip bonded to a 2-D CMUT array for 3-D ultrasound imaging. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*. 2009; 56:2145–2156.
16. Gurun G, Hasler P, Degertekin FL. Front-end receiver electronics for high-frequency monolithic CMUT-on-CMOS imaging arrays. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*. 2011; 58:1658–1668.
17. Hochman M, Zahorian J, Satir S, Gurun G, Xu T, Karaman M, Hasler P, Degertekin FL. CMUT-on-CMOS for forward-looking IVUS: Improved fabrication and real-time imaging. *Ultrasonics Symposium (IUS), 2010 IEEE*. 2010:555–558.
18. Sheng-Yu P, Qureshi MS, Hasler PE, Basu A, Degertekin FL. A Charge-Based Low-Power High-SNR Capacitive Sensing Interface Circuit. *Circuits and Systems I: Regular Papers, IEEE Transactions on*. 2008; 55:1863–1872.
19. Senturia, SD. *Microsystem Design*. Springer; 2001. Chapter 6.
20. Certon D, Teston F, Patat F. A finite difference model For cMUT devices. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*. 2005; 52:2199–2210.
21. Cyril M, Franck T, Dominique C. A multiscale model for array of capacitive micromachined ultrasonic transducers. *J. Acoust. Soc. Am*. 2010; 128:2549–2561. [PubMed: 21110553]
22. Hochman, M. M.S. Thesis. Georgia Institute of Technology; 2011. Investigation of acoustic crosstalk effect in CMUT arrays.

Figure 1.

Equivalent circuit model for the CMUT element in receive mode. The thermal-mechanical noise is represented with a force term on the mechanical side. Units of Z_{RAD} and Z_{MEM} is in rayls and S is the area of the transducer. On the electrical side spring softening capacitance is omitted.

Figure 2. Simplified Norton equivalent circuit of CMUT where all the elements on the mechanical side are referred to the electrical domain.

Figure 3.

Illustration of the monolithic CMUT-on-CMOS integration scheme. Receive amplifier is connected to the bottom electrode. In actual implementation there is an oxide passivation layer between the CMUT bottom electrode and the CMOS ASIC, which is not demonstrated on this figure.

Figure 4. Micrograph of the dual-ring CMUT-on-CMOS array used for noise measurements, demonstrating the presence of two slightly different-sized membranes in each element. CMUT array has a diameter of $800\ \mu\text{m}$ and consists of two rings of elements. The 32 CMUT elements on the outer ring are used for receive operation and the 24 elements in the inner ring are used for transmit operation. The inset depicts a single element.

Figure 5. Illustration of the experimental setup used to measure the output voltage noise of a CMUT element integrated with the receiver electronics.

Figure 6.

Measured noise of a monolithically-integrated system in air with CMUT biased at 0 V, 60 V and 90 V. As CMUT bias is increased the resonance peak shifts to lower frequencies due to spring softening effect.

Figure 7. Measured noise of 4 CMUT elements monolithically-integrated with their dedicated TIAs.

Figure 8.

Model geometry used for simulating noise of a dual-ring array element in water. All elements have same static bias. Red membranes have uniform, harmonic pressure wave applied to their surface. Dashed line denotes symmetry axis.

Figure 9.

Measured output noise of the monolithically-integrated TIA and CMUT in immersion (this figure is reproduced from [16]). For 0-V bias, the noise is only due to the front-end electronics. As the dc bias is increased, the CMUT noise starts to dominate the system noise.

Figure 10.

Simulated and measured output noise spectra of a 4-membrane CMUT element in immersion at 70 V and 95 V. Since the simulated noise values do not include the noise contribution of the amplifier, the measured amplifier noise power for 0-V dc bias case is subtracted from the biased measurements for comparison.

Figure 11.

Simulated normalized average velocity of large and small membranes in the dual-ring array when single membranes on rigid baffle are simulated in water. The two peaks at 6-MHz and 9.5-MHz correspond to fluid-loaded membrane resonances. The dc bias is set to 95 V, which is closer to the collapse voltage of the larger membrane.

Figure 12.

Simulated displacement of membranes in a dual-ring array in immersion for single-element actuation (95-V bias) - a) at 6.1 MHz, b) at 9.7 MHz, c) at 15 MHz, and d) at 20.5 MHz. Green plane denotes symmetry.

Figure 13.

The effects of increasing or decreasing the speed of sound of the fluid medium by 5% on the real part of the admittance (noise current) spectrum.