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Capacitive Micromachined Ultrasonic Transducer Based Airborne Pitch-Catch Measurement Modeling

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Capacitive Micromachined Ultrasonic Transducers (CMUTs) are attractive for airborne ultrasonic sensing due to their wide bandwidth and high sensitivity. Building on previous modeling work, this study focuses on experimental pressure measurement and validation of CMUT performances in pitch-catch configurations. An acousto-optic approach is employed to directly measure the radiated acoustic in air, providing experimental confirmation of field uniformity along the elevation and diffraction effects along the azimuth. These results validate the lumped-element modeling framework and enable accurate correlation between simulation and measurement. In addition, a detailed receiver-side noise analysis using a transimpedance amplifier model is conducted, allowing extraction of intrinsic CMUT noise floor and derivation of the Noise Equivalent Pressure (NEP). Together, these findings establish a validated methodology that links modeling, experimental pressure measurement, and noise characteristics, strengthening the basis for the use of CMUTs in airborne sensing applications.

Keywords—CMUTs, airborne ultrasonic sensing, acousto-optic measurement, noise equivalent pressure, pitch-catch time-of-flight

I. INTRODUCTION

Capacitive Micromachined Ultrasonic Transducers (CMUTs) have emerged as a promising technology for non-contact ultrasonic sensing, offering wide bandwidth, scalability, and high sensitivity [1,2]. These characteristics make them particularly suitable for operation in gaseous environments [3,4,5]. Previous studies [6,7] have successfully demonstrated the use of CMUTs to distinguish binary gas mixtures by analyzing time-of-flight (ToF) variations.

Fig. 1 shows a preliminary fabricated CMUT sensor module developed for this purpose [6], while Figure 2 illustrates the measurement principle. The emitter (TX) and receiver (RX), both mounted on a printed circuit board (PCB), are separated by a distance of 6 mm and enclosed with mechanical supports to allow a single gas medium between the transducers. When the emitter is driven by an electrical input, the resulting acoustic pressure wave propagates through the gas and is detected by the receiver, which converts the ultrasonic pressure into an electrical output. The time delay and attenuation between the source signal applied on TX and



Fig. 1. Preliminary fabricated sensor: (a) top view of the sealed module, (b) assembled with emitter and receiver, (c) transducers mounted on a PCB with zoomed-in CMUT cells.

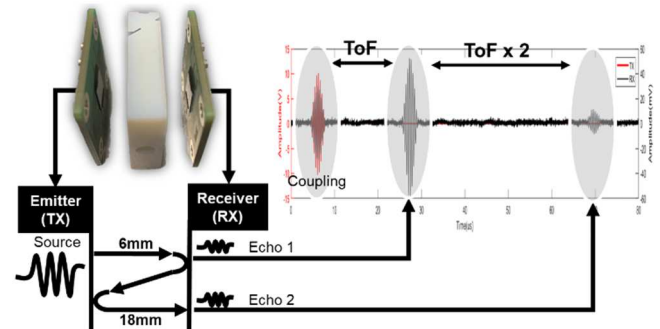


Fig. 2. Example of pitch-catch time-of-flight measurement with two echoes captured by the receiver.

the received echoes on RX provide valuable information for identifying gas valuable information for identifying gas mixtures [4,6].

The present work aims to reevaluate the complete pitch-catch, time-of-flight-based measurement chain through detailed modeling of both the emitter and the receiver, supported by experimental characterization of the radiated pressure field using an acousto-optic approach. This enables a more accurate estimation of receiver noise contributions and, ultimately, the overall performance of the sensing system.

II. TRANSDUCER MODELING

CMUTs are often analyzed using either finite element modeling (FEM) or analytical approaches involving higher-order mathematical formulations [8,9,10]. Merrien et al. [11] proposed an improved modeling method based on a lumped equivalent circuit, specifically tailored for airborne CMUTs, enabling the estimation of transducer performance when

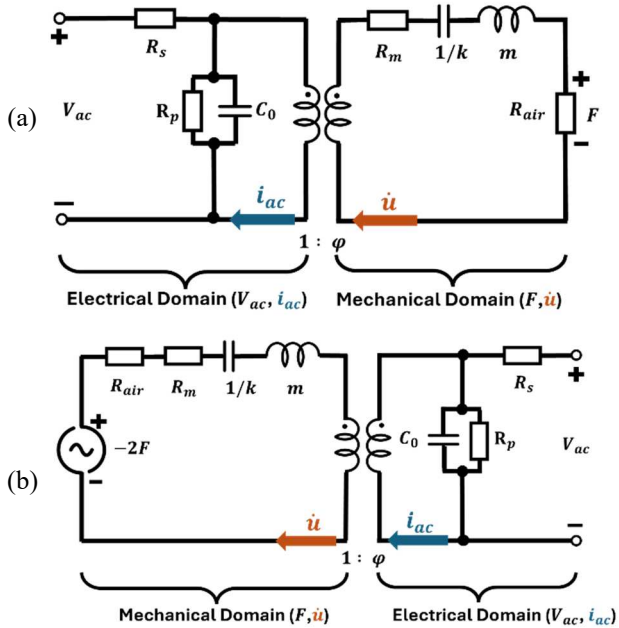


Fig. 3. Lumped equivalent circuit of CMUT: (a) emitter, (b) receiver.

operating as either a transmitter or a receiver. Recent work [12] refined this approach by incorporating experimental data as model inputs, improving the accuracy of CMUT characterization in air. In this representation, the device converts an electrical voltage into a radiated acoustic force in transmission mode (Fig. 3a), and conversely, converts an acoustic pressure input into an electrical output in reception mode (Fig. 3b).

During transmission, a predefined electrical signal drives the CMUT membrane into vibration, displacing air particles and generating an acoustic field. This electro-mechanical coupling can be effectively represented using a lumped equivalent circuit model, which captures the dynamics of airborne CMUT emitters.

During reception, the CMUT acts as a pressure sensor, converting the incident acoustic pressure wave impinging on the membrane into an electrical signal. Owing to the inherently low electrical output levels, pre-amplification is required. In this work, a transimpedance amplifier (TIA), FEMTO HCA-100M-50K-C, is employed to convert the current induced on the CMUT electrodes into a measurable voltage. Modeling the transducer together with its front-end preamplifier allows the evaluation of both sensitivity and noise characteristics of the receiver.

III. MEASUREMENT WITH ACOUSTO-OPTIC INTERACTIONS

Measuring broadband acoustic pressure in air remains challenging, particularly at very low amplitudes, where highly sensitive devices are required to extract pressure information from measurement noise and bandwidth limitations. Moreover, pressure measurement is essential for validating both emitter and receiver models, since pressure serves as both their output and input. To address this, an acousto-optic interaction method is introduced. This approach monitors variations in optical path length (OPL) induced by acoustic in air and converts them into pressure values [13,14]. Fig. 4 shows the simplified measurement setup. A laser beam passes

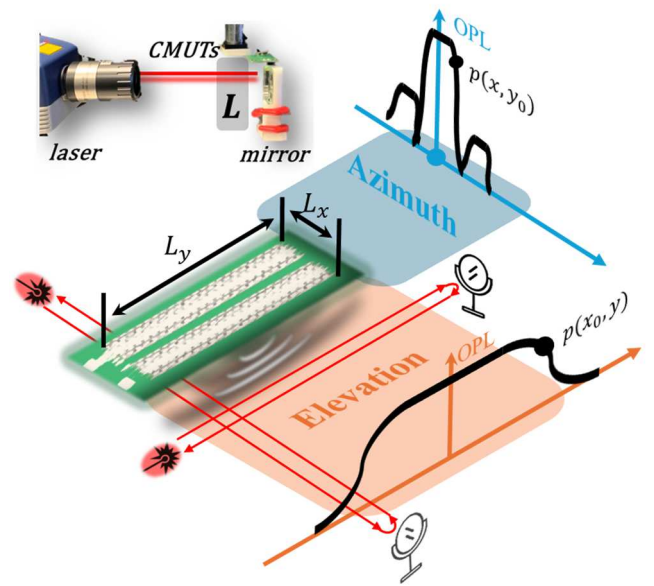


Fig. 4. Optical topography setup for airborne transducer characterization.

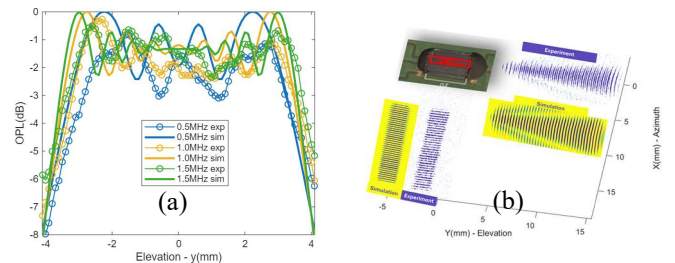


Fig. 5. Optical topography results: (a) OPL along elevation for different frequencies (experiment vs. simulation), (b) OPL map at 1 MHz (experiment vs. simulation).

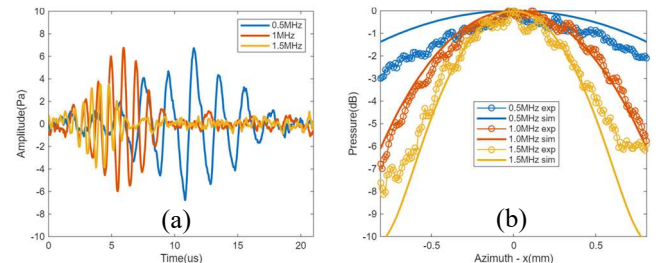


Fig. 6. Results at 0.5 MHz, 1 MHz and 1.5 MHz: (a) time-domain pressure at center of azimuth, (b) azimuth profile scan (experiment vs. simulation).

through the acoustic field, where the optical path length depends on the refractive index of air, which varies with pressure [15]. An optical mirror is placed near the edge of the acoustic field so that the beam is reflected back into the laser system, allowing the OPL variation to be calculated. The transducer is positioned parallel to the laser beam, such that the emitted pressure field is directed perpendicular to the optical path.

The CMUT element pair under test forms a rectangular aperture of elevation $L_y=8.012$ mm and azimuth $L_x=1.694$ mm. Diffraction is primarily governed by the shorter azimuth dimension, especially in the 0.5–5.0 MHz frequency range at a fixed distance of 6 mm, which corresponds to its near-field zone [16].

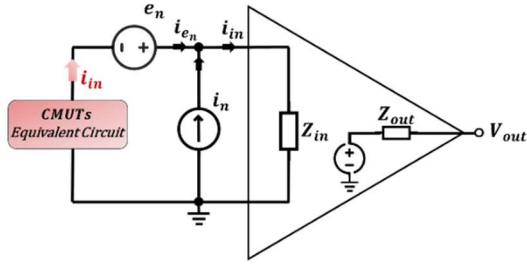


Fig. 7. Equivalent noise circuit model of a CMUT connected to a transimpedance amplifier.

A scan along the elevation is first performed using a positioning motor that moves the transducer relative to the laser beam. Figure 5a shows that the OPL distribution along the elevation remains nearly uniform across different frequencies. However, the length of the -3 dB OPL varies slightly with frequency, and this variation should be considered by introducing an equivalent elevation, L_{eq} , instead of using the fixed physical elevation distance, L_y , when deriving pressure. Figure 5b presents a two-dimensional OPL map at 1 MHz, where diffraction effects along the azimuth are clearly visible and consistent with simulations. Assuming uniform pressure distribution along the elevation, the average pressure p_x can be deduced from OPL variations as expressed in (1) [14].

$$p_x = \Delta OPL / (2\mu L_{eq}) \quad (1)$$

Where μ is the piezo-optic coefficient of air, and the factor of two accounts for the double laser pass after reflection.

Figure 6a shows the translated time-domain pressure signals at two different frequencies. A reduction in amplitude at the higher frequency is observed, which is mainly attributed to the strong attenuation of ultrasound in air, despite the relatively lower signal loss due to diffraction. A profile scan of the OPL along the azimuth direction was performed in the same way as for the elevation, and Figure 6b compares the experimental results with simulations generated using the FIELD II toolbox in MATLAB [17,18].

Once the pressure has been determined, it becomes possible to validate both the emitter and receiver models by fitting the average pressure into the previously presented lumped two-port equivalent network. This also provides a means of justifying the transducer sensitivity. For the emitter, measurements at shorter distances are required, together with attenuation compensation, in order to accurately represent the true emitted pressure and validate emission sensitivity. For the receiver, the experimentally measured pressure can be used as the model input to derive the corresponding output voltage or current, thereby validating the sensitivity at reception. However, these further steps to refine the model are beyond the scope of this work. The present study aims primarily to demonstrate the feasibility of validating CMUT simulation models with experimental pressure measurements, with particular emphasis on receiver sensitivity.

IV. RECEIVER NOISE ANALYSIS

The CMUT receiver can be modeled either as a voltage source or as a current source, depending on the load impedance. Amplifiers can thus be configured with high or low input impedance by adding appropriate passive

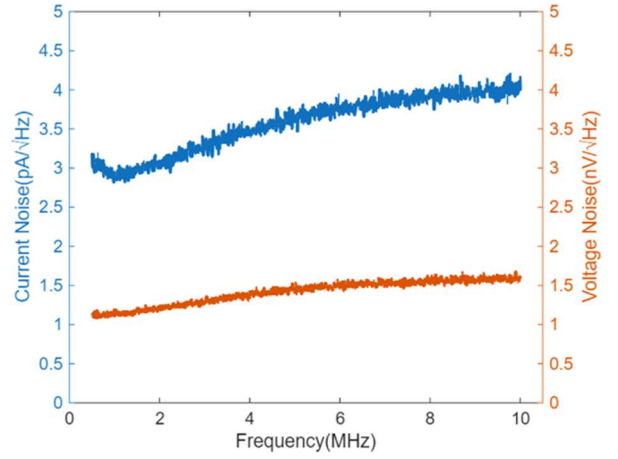


Fig. 8. Measured TIA intrinsic noise with unloaded input

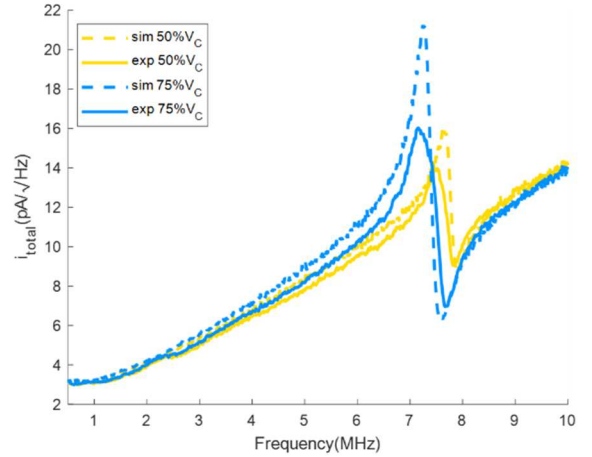


Fig. 9. Measured total noise expressed as current noise at the TIA input, consisting of CMUT noise and intrinsic TIA noise, for two different bias voltages, with comparison between simulation and experiment.

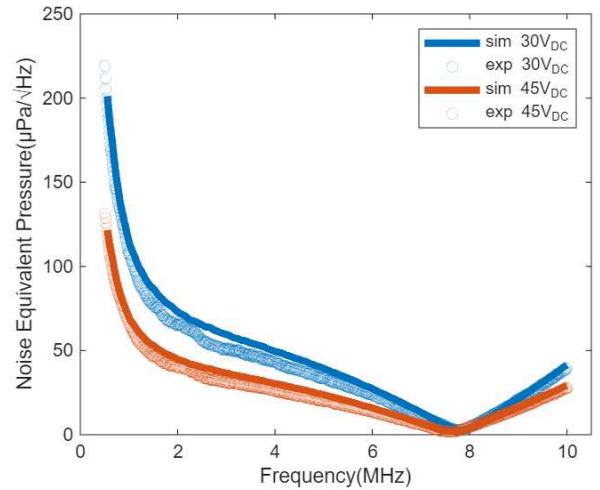


Fig. 10. Derived noise equivalent pressure of the CMUT receiver for two different bias voltages, with comparison between simulation and experiment.

components. In this study, the CMUT receiver is connected to a transimpedance amplifier with a low input impedance ($50 \Omega \parallel 5 \text{ pF}$). Under this configuration, the CMUT behaves as a current source, and the TIA converts the generated current into a measurable voltage. This amplification stage is essential for signal readout with an oscilloscope; however, it must be

carefully handled, as it also amplifies the intrinsic noise of the CMUT together with its internal perturbations, which can be quantified over a frequency range using dedicated noise measurement equipment.

The CMUT contributes both pressure-induced noise and thermal noise, which appear as current noise at the output when the TIA is connected. The intrinsic noise of the TIA itself can be represented by an equivalent model (Fig. 7) consisting of a voltage source e_n and a current source i_n [19]. The current noise contribution dominates when the input is open, whereas the voltage noise contribution dominates under short-circuit conditions.

Figure 8 shows the intrinsic TIA noise with an unloaded input, whereas Fig. 9 presents the combined noise when the CMUT is connected—corresponding to the sum of the CMUT noise and the intrinsic TIA noise at the TIA input (before amplification). By subtracting the intrinsic TIA contribution, the remaining current noise reflects the intrinsic noise of the CMUT arising from pressure. Applying the previously presented lumped-element model in reverse, this CMUT noise can be expressed as a Noise Equivalent Pressure (NEP), which serves as a direct figure of merit for evaluating receiver performance (Fig. 10).

CONCLUSION

This work presented a comprehensive study of airborne CMUTs through combined modeling and experimental validation. A lumped-element approach was applied to describe both emitter and receiver behavior, while acousto-optic measurements provided direct access to the radiated pressure field. The results confirmed uniformity along the elevation dimension and diffraction along the azimuth, in agreement with simulations, thereby validating the accuracy of the CMUT model and its sensitivity. Receiver noise analysis, performed using a TIA model, enabled extraction of the CMUT's intrinsic noise contribution and the derivation of its noise equivalent pressure. Together, these results establish a validated complementary framework for analyzing CMUT pitch-catch systems in air and improve the predictability of their behavior.

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