Using a Mutual Acoustic Impedance Model to Improve the Time Domain Response of PMUT Arrays

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Abstract—This paper presents an equivalent circuit model of a piezoelectric micromachined ultrasonic transducer (PMUT) array, combining an acoustic coupling model originally developed for capacitive micromachined ultrasonic transducer (CMUT) arrays and an electro-mechanical model of the individual PMUTs in the array. This model is experimentally validated with PMUT arrays of varied sizes and accurately predicts both the time response and frequency-domain bandwidth. The model also demonstrates that the transmit pulse response of PMUT arrays is strongly affected by acoustic coupling within the array.

Keywords—piezoelectric micromachined ultrasonic transducers; PMUT; cross talk; acoustic impedance; PMUT array

I. INTRODUCTION

Micromachined ultrasonic transducers (MUT) have been developed for many applications from medical ultrasonic imaging [1] to ultrasonic fingerprint sensors [2]. The wide interest in MUTs is due to their better acoustic coupling, lower fabrication cost, and better integration with integrated circuits relative to conventional ultrasound transducers [3]. Capacitive micromachined ultrasonic transducers (CMUTs) and piezoelectric micromachined ultrasonic transducers (PMUTs) are two kinds of MUTs that are widely studied. Compared to CMUTs, PMUTs do not need a high DC bias voltage and do not require a sub-micron capacitive gap, simplifying manufacture. Recently, PMUT performance has improved a lot due to the maturity of piezoelectric materials like scandium aluminum nitride (ScAlN) [4] and lead zirconate titanate (PZT) [5]. An accurate model for the dynamics of individual PMUTs was originally presented in [6]. However, both CMUTs and PMUTs are usually densely packed in arrays to achieve a high fill-factor and high acoustic performance. As a result, the coupling between each transducer in the array is significant [7] and has a significant impact on time response and bandwidth that is not considered in the single-PMUT model. In this study, we apply an acoustic coupling model originally developed through simulation of CMUT arrays [8] to an experimental study of PMUT arrays. Experimental results matched well with the model’s predictions, confirming that the model can be used to accurately predict coupling in PMUT arrays.

The PMUT arrays used in this study were fabricated via a cavity SOI process using scandium aluminum nitride (ScAlN) as the piezoelectric layer. Details of the fabrication process and device characterization can be found in [9]. An optical microscopic image of a 7x7 ScAlN PMUT array is shown in Fig. 1. The aluminum top electrode and ScAlN thin film are labeled in the figure. Each PMUT is defined by a 50 µm diameter cavity underneath the 1 µm thick ScAlN and 2.5 µm thick Si device layer; the cavities for a few representative PMUTs are marked with white dash-dot lines in the figure. The parameters of the PMUT arrays and the properties of the ScAlN thin film are shown in the Table I. The PMUTs are packed as close as possible, with a minimum spacing of 20 µm that is determined by the limits of the cavity SOI manufacturing.
The PMUT arrays are immersed in a non-conductive fluid (Fluorinert FC-70, 3M) for testing. All the PMUTs in these arrays are parallel connected and are driven together during pulse transmission.

II. EQUIVALENT CIRCUIT MODEL

A simplified equivalent circuit model of a PMUT array consisting of N PMUTs is shown schematically in Fig. 2. The impedance matrix \([Z]\) in the figure represents the acoustic impedance of the surrounding fluid as well as the coupling between PMUTs in the array. \(C_0\) is the electrical capacitance of the PMUT, \(\eta\) is the transformer ratio from the electrical domain to the mechanical domain with units of N/V, \(C_m\) is the motional capacitance, \(L_m\) is the motional inductance, \(A_m\) is the transformer ratio from the mechanical domain to the acoustic domain. The expressions of the \(C_0\), \(C_m\) and \(L_m\) are derived in [6] when the average velocity over the membrane surface is used. \(A_m\) is equal to the PMUT area \(A_{PMUT}\) in [6]; here we use the velocity at the membrane center and \(A_m = 1/3 A_{PMUT}\). The values of \(C_m\) and \(L_m\) in our model are 9x larger and 9x smaller (respectively) compared to the values in [6] due to the different velocities used. The acoustic impedance matrix can be written as

\[
Z = \begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1(n-1)} & Z_{1n} \\
Z_{21} & Z_{22} & \cdots & Z_{2(n-1)} & Z_{2n} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
Z_{n1} & Z_{n2} & \cdots & Z_{n(n-1)} & Z_{nn}
\end{bmatrix}
\]

(1)

where \(Z_{ii}\) represents the self-acoustic impedance and \(Z_{ij}(i \neq j)\) represents the mutual acoustic impedance. Expressions for the self-acoustic impedance can be found in [10] and for the mutual acoustic impedance in [11]. The mutual acoustic impedance is a function of both \(ka\) and \(k d_{ij}\), where \(a\) is the radius of the PMUT, \(k\) is the wavenumber, and \(d_{ij}\) is the distance between PMUT \(i\) and PMUT \(j\) in the array. The mutual-impedance model [11] adopted here uses simplifications and is valid for \(ka < 5.5\).

III. RESULTS AND DISCUSSIONS

A. LDV measurement of time response

Time-response measurements were collected on PMUT arrays of varying size from 7x7 to 17x17 immersed in non-conducting fluid (Fluorinert FC-70, 3M Performance Materials). A function generator (DG-4102, Rigol) was used to drive each array with an 11V, 55 µs pulse. The vibration of the center PMUT in the array was recorded using a laser Doppler vibrometer (LDV, OFV 512 and OFV 2700, Polytec). The measured time response data were corrected with the refractive index of the fluid \((n = 1.303)\) and the results are shown in Figure 3. The impulse response of the center PMUT in the 7x7 and 9x9 arrays shows gradual exponential decay after the input pulse. The quality factor of these two PMUTs is \(Q \approx 5\). However, the time response measured in the 11x11 to 17x17 arrays shows a
clear step-change in amplitude at a specific time-of-arrival after the initial pulse. The time-of-arrival of this amplitude change is proportional to the half-width of the array. This correlation is plotted in Fig. 4. The data fit a line with slope ~ 634 m/s, nearly equal to the speed of sound in Fluorinert FC-70 (687 m/s). We conclude that this coupled decay motion relates to the edge wave generated from these arrays, similar to what is discussed in [12] for a single large acoustic transducer. It is important to differentiate between a long decay time of the original pulse, which effects the axial resolution, and the edge-wave’s effect on decay, which does not.

B. Results and Analysis

The impulse responses of these PMUTs were analyzed by fast Fourier transform (FFT) and the results are plotted in Fig. 5(a). A major resonance at 8–9 MHz can be found in all arrays. No spurious mode was found in the 7x7 array. However, a small spurious mode starts to appear in the 9x9 array at around 6.5 MHz. The position of this spurious mode moves closer to the main resonance as the array size increases (~7 MHz for 11x11 array, ~7.5 MHz for 13x13 array, ~8 MHz for 15x15 and 17x17 arrays). A second spurious mode also appears at 6 MHz for the 13x13 array, at 6.5 MHz for the 15x15 array and at ~7 MHz for the 17x17 array. Meanwhile, the amplitude of the main resonance increases with the increase of the array size. The amplitude is ~0.17 nm in the 7x7 array, increasing to ~0.27 nm in the 15x15 array. A null at 10-11 MHz is also observed in all the results.

The frequency responses of the center PMUTs were also measured directly via LDV in conjunction with a virtual network analyzer (E5061B, Agilent Technology) and the results are shown in Fig. 5(b). The network analyzer measurements were measured at 1V input amplitude. The network analyzer measurements agree well with the FFT of the impulse response: the position of the major resonance, the first and second spurious modes and the relative amplitudes are all consistent. Both sets of measurements also show a null at 10-11 MHz and this position is not affected by the array size.

The frequency response was also simulated using the equivalent circuit model, and the results are plotted in Fig. 5(c).
The simulated response shows slightly higher displacement amplitude and a smaller quality factor compared to the direct measured results. This is due to the boundary loss is neglected in the model but existed in the measurement. The position of the major resonance frequency, 1st spurious mode and 2nd spurious mode predicted by the model are consistent with the direct measurement. The relative amplitude change of the PMUT in different arrays of the theoretical results are also consistent with the direct measurements.

The good agreement observed between model and experiment demonstrates that mutual acoustic coupling is very significant in densely packed PMUT arrays. With the increase of the array size, the mutual acoustic impedance changes until the array is large enough that the coupling is very weak from the added neighbors in the array (as shown from the 15x15 array to the 17x17 array). At the same time, this experimentally-verified model can be used to optimize array performance (e.g. pulse transmission time and fractional bandwidth) by changing the radius of the PMUT, the pitch and number of PMUTs in the array.

IV. CONCLUSIONS

This paper presented an equivalent circuit model of PMUT arrays that can accurately predict the frequency response and time response for different array geometries and sizes. The results indicated that strong acoustic coupling exists in densely packed PMUT arrays and this coupling influences the transmit time-response of an array. The model can be applied for array parameter optimization such as PMUT radius, array pitch and number of elements of the array.

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