Output pressure enhancement of CMUTs by using multiple Helmholtz resonance apertures

Yuan Yu Yu, Xue Wen Cao, Sio Hang Pun, Peng Un Mak✉ and Mang I Vai

Multiple Helmholtz resonance apertures are proposed to enhance the output pressure of air-coupled capacitive micromachined ultrasonic transducers (CMUTs) for non-contact ultrasound imaging applications. The methodologies of defining the design parameters of CMUTs and the resonant apertures on the membrane of CMUTs are discussed. In comparing certain configurations of resonant apertures with conventional CMUTs, simulation results show that a prospective improvement of output pressure (up to 32.1%) can be achieved.

Introduction: In the development of air-coupled ultrasound imaging applications, such as the reflection non-contact ultrasonic microscope system [1], capacitive micromachined ultrasonic transducers (CMUTs) have the intrinsic advantages of miniaturisation, easy integration with microelectronic circuits and are suitable for large array fabrication. With the advancement of CMUTs arrays, portable ultrasound imaging systems can be manufactured in the future [2].

However, the output pressure of current CMUTs is generally not as good as that of PZT and, in an early experiment of real-time imaging, the sensitivity of CMUTs about 10 dB lower than a commercial PZT [3]. Pursuing higher output pressure (to improve the signal-to-noise ratio (SNR)) of CMUTs is a popular research area.

This Letter introduces the multiple resonance apertures technique to enhance the output pressure of CMUTs. In the following, the parametric methodologies link between the CMUT and resonant apertures is discussed. Then, three-dimensional (3D) finite-element ananlysis (FEA) simulations are performed to compare the output pressure results with and without the resonant apertures. We recently conducted an initial investigation [4], but only moderate improvement was achieved.

Methodologies: To enhance the output pressure of a conventional CMUT by using the Helmholtz resonant effect, resonant apertures are introduced to the structure of the membrane as shown in Fig. 1. This Fgure shows the cross-section structure of a circular CMUT cell with the major components: a half top electrode of radius R, a membrane, a cavity, and the substrate as the bottom electrode. In this CMUT cell, the radius of the membrane is a with thickness t, and the gap height is denoted as h. To avoid a possible short circuit between the top and bottom electrodes, a thin insulator layer with thickness t_i is placed between the cavity and the bottom electrode. r and S represent the radius and area of each Helmholtz aperture, respectively. According to the principle of the Helmholtz resonator, which is an enclosure with open acoustic apertures, the overcompensation of the pressure difference across the vibrating membrane leads to the air in the apertures oscillating in and out such as an air-piston through the aperture at a certain frequency, f_h. This Helmholtz resonance frequency is given by the following equation [5]:

$$f_h = \frac{c}{2\pi}\sqrt{\frac{A}{V(1+\delta)}} \quad (1)$$

where $\delta = 0.96\sqrt{A}$, $A = nS$, δ is called the end-correction factor, n is the quantity of unified size apertures, A is the total surface of the apertures, c is the velocity of sound, and V is the volume of the cavity.

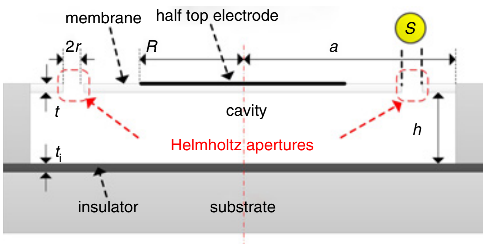

Fig. 1 *Cross-section view of CMUT cell with Helmholtz resonance apertures (red dash line indicates central axis of CMUT cell (not in scale))*

To effectively use the Helmholtz resonance enhancement effect on the output pressure of CMUTs, the resonance frequency should be driven appropriately to the fundamental frequency of the membrane f_c. From Park *et al.* [6], the fundamental frequency is determined by the geometry of the membrane via (2)

$$f_c = 0.47\frac{t}{a^2}\sqrt{\frac{Y_o}{\rho(1-\gamma^2)}} \quad (2)$$

where t is the thickness of the membrane, a is the membrane radius, ρ is the density of the membrane material, Y_o and γ are the Young's modulus and the Poisson's ratio for a material. Since the membrane is vibrated under a DC bias voltage, the spring softening effect to the fundamental frequency should be taken into account [7].

To determine the dimensions of the Helmholtz aperture, the Helmholtz frequency with different sizes of the cavity is plotted in Fig. 2. In this Figure, the green surface represents the Helmholtz frequency while the red surface is the membrane fundamental frequency with consideration of the spring softening effect. The grey surface is the radius of cavity in this case. By finding the intersection of these three surfaces, the size of the Helmholtz aperture can be determined.

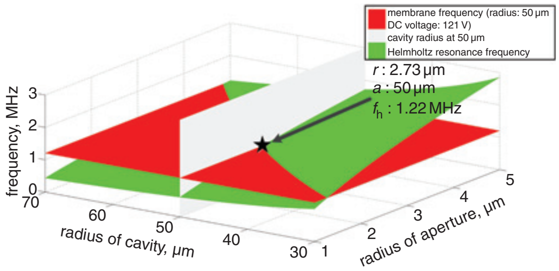

Fig. 2 *Determining dimensions of Helmholtz aperture from parameters of CMUT membrane*

In general, the Helmholtz aperture can be located at the centre of the membrane as shown in Fig. 3*a*. However, etching the aperture at the centre may reduce the average output pressure of the CMUT where the normal peak output pressure appears at the centre of the membrane. Therefore, we also propose to separate the Helmholtz aperture into four equivalent apertures equally distributed at the output portion of the membrane as shown in Fig. 3*b*.

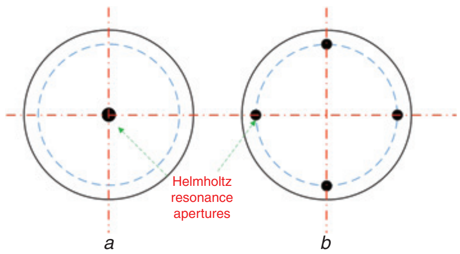

Fig. 3 *Configuration of CMUT with one (Fig. 3a) and four (Fig. 3b) Helmholtz resonance apertures (radius of apertures are: 2.73 µm for single central aperture and 1.37 µm for four apertures)*

Finite element analysis and comparison: Table 1 shows the parameters of the CMUT and Table 2 lists the parameters while using the commercial software package COMSOL Multiphysics (COMSOL Inc., Stockholm, Sweden) for performing the FEA simulation in this Letter. For effective computation, a quarter of a 3D model of the CMUT was built which is shown in Fig. 4.

Table 1: Configuration of CMUT

Parameter	Value
Membrane radius, a (µm)	50
Top electrode radius, R (µm)	25
Cavity height, h (µm)	1.0
Thickness of membrane, t (µm)	1.2
Thickness of insulator, t_i (µm)	0.2

Symmetric boundary conditions were imposed on both vertical sections. Silicon nitride was selected to be the material of the membrane based on the sacrificial layer release process. The membrane edge was fixed using a clamped boundary condition and the top electrode was added on to the membrane to supply the electric field. As shown in Fig. 1, a half-covered top electrode was attached on the top membrane because it is a concessional way for taking into account both the collapse voltage and the bandwidth [8].

Table 2: Material properties used in FEA

Parameter	Silicon nitride	Air
Young's modulus (GPa)	110	–
Poisson's ratio	0.27	–
Density (kg/m^3)	3100	1.2
Dielectric constant	5.4	1
Velocity of sound (m/s)	–	340

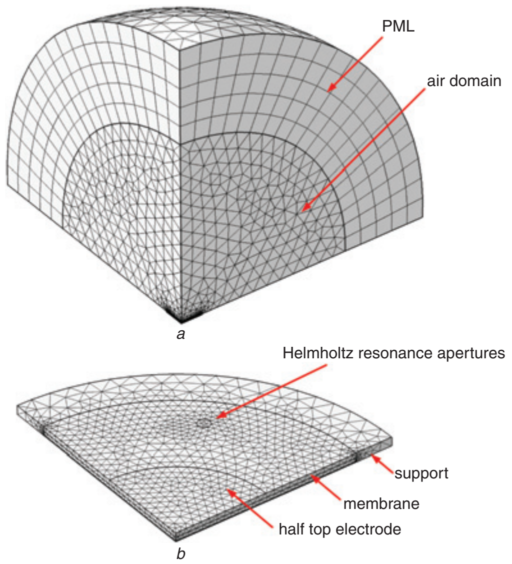

Fig. 4 *3D FEA model of CMUT cell and air domain: CMUT cell and air domain (Fig. 4a) and details of CMUT cell (Fig. 4b)*

All meshes except PML were smaller than 1/6 of wavelength of operating frequency

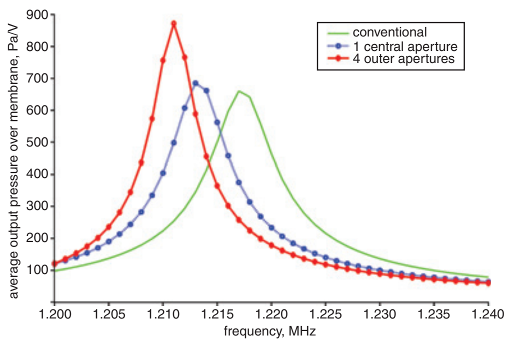

Fig. 5 *Average output pressure over membrane: comparison between CMUTs with Helmholtz resonance apertures and conventional CMUT*

In the simulation, the *emi* and the *acpr* modules were used to construct the CMUT cell and these represented the air domain medium, respectively. '*boundary load*' and '*normal acceleration*' were added on the boundary interface between *emi* and *acpr* to couple them during the multiphysics simulation. For simulating the semi-infinite air domain of the model and minimising the influence of omnidirectional wave reflection, a semi-spherical perfected matching layer (PML) is used to encircle the outside of the air domain. Considering the air flows through the apertures when the membrane vibrates, the squeeze-film gas damping was taken into consideration [9] and was added at the boundaries of the apertures and the bottom of the membrane.

The CMUT model was biased using a constant 121 V DC voltage which equals 80% of the theoretical pull-in voltage, and is driven by a 1 V harmonic AC voltage. First, the simulation of the conventional CMUT was performed. Then, CMUT cells with a centred Helmholtz aperture (Fig. 3*a*) and four distributed apertures (Fig. 3*b*) were simulated. The simulation results are plotted in Fig. 5. From the results, the output pressure of the CMUT with four evenly distributed Helmholtz resonance apertures near the perimeter is better than that of the conventional one. Compared with the conventional CMUT, the improvement of average output pressure with four apertures is up to 32.1%.

Conclusion: An effective method of improving the average output pressure of CMUTs is proposed. This method, based on the principle of the Helmholtz resonance effect, uses Helmholtz apertures on the membrane to enhance the output pressure of the CMUT. Using this method, the dimensions of the Helmholtz aperture should be chosen so that the Helmholtz resonant frequency coincides with the membrane fundamental frequency. It should be noted that the spring softening effect to the membrane fundamental frequency in operation should be considered. From the simulation results, it is manifest that Helmholtz resonance theory can improve the output pressure of CMUTs. The centred single aperture can promote the output pressure; however, removing the centre of the membrane is not desirable as it reduces the average displacement of the membrane. In this Letter, multiple Helmholtz resonance apertures give better performance, and as a result the CMUT can improve the SNR of the received signal and eventually enhance image quality. In future, investigations of the other configurations of apertures will be performed. This will enable the optimal configuration of apertures to be studied for a better performance of CMUTs.

Acknowledgments: This work was supported by the Science and Technology Development Fund of Macau (FDCT) under 024/2009/A1, 087/2012/A3, 047/2013/A2; the Research Committee of the University of Macau under grants MYRG076(Y1-L2)-FST12-MPU, MYRG079(Y1-L2)-FST12-VMI, MYRG103(Y1-L3)-FST13-VMI, MRG014/MPU/2014/FST, MYRG2014-00010-AMSV.

Submitted: *30 June 2015* E-first: *19 August 2015*
doi: 10.1049/el.2015.1871
One or more of the Figures in this Letter are available in colour online.

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