Theoretical and Simulation Studies on Designing a Phase-Reversal-Based Broadband CMUT With Flat Passband and Improved Noise Rejections for SHM

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Abstract—In the past two decades, capacitive micromachined ultrasonic transducers (CMUTs) have been greatly explored for applications in structural health monitoring (SHM); however, relevant theories about their broadband sense have not been investigated systematically. Therefore, broadband CMUTs have been specifically developed from the aspects of theory and simulation in this work. Based on these theoretical developments, we propose a new design of phase-reversal-based CMUT, which has a flat passband for broadband sensing and two stopbands at both sides for improved noise rejections. First, the expressions for the evaluation of the total output current and the sensitivity of a CMUT constituted of multiple cells are deduced from the theoretical spring–mass–damping model. Then, theoretical and simulation analysis on a CMUT combined with two different cells have revealed that reversing the current phase of one of these two cells can produce significant stopbands for rejecting the low- and high-frequency noises, which are useful not only for a CMUT in coarse vacuum (low pressure) but also a CMUT in the air (atmospheric pressure). Especially, for a CMUT in a coarse vacuum, this design can effectively build a passband among the resonant frequencies of each cell instead of compensating each other to zero. Finally, the genetic algorithm is adopted to design a broadband CMUT with a given passband in air, the results of which are verified by the frequency- and time-domain simulations concurrently. Our research work may produce a theoretical way for the design of broadband CMUTs with noise rejections.

Index Terms—Broadband, capacitive micromachined ultrasonic transducers (CMUTs), noise rejection, phase reversal (PR), structural health monitoring (SHM).

I. INTRODUCTION

CAPACITIVE micromachined ultrasonic transducers (CMUTs) have been verified as feasible microelectromechanical system (MEMS) devices for applications in the medical field, e.g., ultrasound imaging [1], intravascular ultrasound [2], [3], and tumor treatment [4], [5], for their advantages of low cost, small sizes, environmental friendliness, and low impedance compared to the traditional piezoelectric transducers. In view of the great development of CMUTs in medical applications, many researchers have devoted themselves to explore the possible applications of CMUTs in other fields [6], [7], [8], [9].

The major civil infrastructures, e.g., highway bridges, railways, and pipelines, need to be continuously monitored using structural health monitoring (SHM) methods to acquire the probability of occurrence of structural damages in advance, in order to avoid accidents or unexpected losses [10]. Usually, the signals of acoustic emission (AE), which are produced by the rapid release of localized strain energy, are utilized to...
understand the occurrence of damages (e.g., crack initiation and growth) or impacts in SHM [11]. As is well known, the AE signals mostly exist in the broad frequency range of 100 kHz–1 MHz [12]. Therefore, AE sensors with high sensitivity and broadband are needed to detect the signals of interest.

The development of CMUTs in SHM is much later compared with that in the medical field. In about 2003, CMUTs were first developed with a hexagonal plate design and a spring–mass design and then fabricated in the multiuser polysilicon surface micromachining processes (MUMPs) to accommodate for the detection of AE signals [13]. The feasibility of using CMUTs to detect AE signals was preliminarily confirmed by experiments. Since then, many research studies have emerged for the detection of AE signals using CMUTs [9], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23]. In 2006, Ozevin et al. [19] had shown the potential of measuring AE signals by employing a MEMS chip, which contains multiple resonant, capacitive-type vibration transducers sensitive to different frequencies. However, the MEMS transducer was subjected to a low signal-to-noise ratio compared with the commercially available piezoelectric transducers. After that, improvements on the capacitive MEMS transducer have been done in the subsequent works. For instance, Wright [20] improved the design of the capacitive MEMS transducer to make its sensitivity closer to the conventional piezoelectric AE transducers. Saboonchi and Ozevin [21] used a well-developed micromanufacturing process, MetalMUMPs from MEMSCAP, to design capacitive MEMS AE transducers with high aspect ratio geometries. Experimental measurements for these studies confirmed the increased signal-to-noise ratios. Auerswald et al. [22] proposed a new capacitive MEMS-based AE transducer, which consists of two mechanically decoupled comb-like spring–mass–damper systems. Through the antiparallel connection of the comb electrodes, this transducer demonstrated high sensitivity in the passband and good noise rejection in the stopband. Boubiena et al. [9] presented a new design of MEMS transducer, named CMUT-R100, for SHM applications. An improved signal-to-noise ratio was measured, and the capability of detecting AE signals on a 3-mm-thick aluminum plate was verified. The capacitive MEMS transducers mentioned above are the so-called CMUT. Compared with the original design, the performance of CMUT has been greatly improved. However, it must be admitted that there is still a performance gap between CMUTs and piezoelectric AE transducers. Recently, Butaud et al. [23] developed a CMUT transducer that is sensitive over a wide range of target frequencies (80 kHz–2 MHz), which is constituted of individual circular membranes with different radii. The experiment of “pencil lead break” was carried out to characterize the broadband detection capability of this CMUT transducer for AE events. To summarize, although CMUTs have been well developed for AE detections, previous studies were carried out under well-controlled experimental conditions, where the influences of external noises did not have to be considered. In real-life practical applications, the environment may not be identical to well-controlled experimental conditions. Significant noises, which do not deliver useful information about structural health, may suppress the AE signals of damage and lead to misjudgments [10]. Therefore, it is desirable to separate AE signals from noise interferences. Besides, to the best of our knowledge, relevant theories about the design of a broadband CMUT, used for sensing stress waves in SHM, have not been scientifically investigated up until now.

In view of these research gaps, a theoretical way for the design of broadband CMUTs has been developed in this work, together with a novel design of phase-reversal (PR)-based CMUT for broadband sensing and noise rejections.

The contents of this study are arranged as follows. In Section II, the analytical expressions and the simulation model for predicting the total output current and the sensitivity of a CMUT composed of multiple cells are given in detail. In Section III, the mechanism of the PR-based CMUT for noise rejections is revealed. In Section IV, the genetic algorithm (GA) is used to optimize the design of a broadband CMUT. In Section V, this work is concluded, and the shortcomings and prospects are put forward.

II. THEORETICAL AND SIMULATION MODEL FOR PREDICTING THE SENSING BEHAVIORS OF A CMUT COMPOSED OF MULTIPLE CELLS

A. Theoretical Model

In SHM, CMUTs are designed to be resonant to keenly sense stress waves in an extremely narrow band [19]. Usually, integrating multiple cells together, where each of the CMUT cells is capable of resonating at different frequencies, may be an effective way to design broadband CMUTs [23]. In this work, the CMUT cell reported in [21] is referenced for designing broadband CMUTs. As shown in Fig. 1(a), a CMUT cell is composed of anchors, springs, Au layer, top electrode (served as the suspended vibrating plate together with the Au layer), the insulating layer, and bottom electrode, where the first two components play the role of supporting and fixing the suspended plate, and the latter four components together with the capacitive gap form the variable capacitor. Each spring of a CMUT cell is constructed in an L shape and is composed of two parts: one is labeled as Spring 1, extended along the y-axis, and another is labeled as Spring 2, extended along the x-axis [see Fig. 1(a)]. The suspended plate can be etched with periodic through holes to release the squeeze-film damping originated from the gas compression in the gap. Based on the classical theoretical analysis, the squeeze-film damping can be evaluated quickly. However, the accuracy cannot be guaranteed due to strong assumptions (e.g., rigid body
motion and small structural displacements) [26]. A numerical approach may be required to predict the squeeze-film damping accurately, e.g., the finite element simulation [finite element method (FEM)] or the lattice Boltzmann simulation reported in [26]. The structural parameters of a CMUT cell are represented by the definitions shown in Table I. The Au layer is deposited on the top surface of anchors, springs, and top electrodes, with an extremely narrow thickness, for electrical conductivity and wiring. For the convenience of calculation and analysis, the Au layer is assumed as fully covered (excluding through holes).

As introduced in [19], the vibrating behavior of a CMUT cell can be simplified as the spring–mass–damper model shown in Fig. 1(b), where \( m \) is the mass of the suspended plate, \( k \) is the effective spring constant of springs, \( c \) is the damping constant of the system (in this work, only the squeeze-film damping is considered), and \( t_g \) is the effective height of the gap. Along the out-of-plane direction, the displacement response of the bottom electrode and the displacement response of the suspended vibrating plate relative to the bottom electrode are, respectively, expressed as \( Z_0 \) and \( Z \), which can be expressed as functions of time \( t \) and angular frequency \( \omega \). For such a vibrating system, we can obtain the equation as

\[
m \ddot{Z} (t, \omega) + c \dot{Z} (t, \omega) + kZ (t, \omega) = -m \ddot{Z}_0 (t, \omega). \tag{1}
\]

Equation (1) implies the relation as [19]

\[
Z (t, \omega) = \frac{\omega^2}{\omega^2_0 - \omega^2 + j\omega\omega_0/Q} Z_0 (t, \omega) \tag{2}
\]

where \( Q = m\omega_0/c \) and \( \omega_0 = \sqrt{k/m} \) represent the mechanical quality factor and the resonant angular frequency of the suspended vibrating plate, respectively.

Assume the input displacement, i.e., the displacement response of the bottom electrode, as

\[
Z_0 (t, \omega) = Ae^{j\omega t} \tag{3}
\]

where the coefficient \( A \) is the amplitude.

Referring the theory in [19] and [21], the dynamic capacitor of a CMUT cell under the dc biased voltage \( V_{dc} \) can be estimated by

\[
C (t, \omega) = \varepsilon_0 S/t_g (t, \omega) \tag{4}
\]

where \( \varepsilon_0 \) is the vacuum dielectric constant and \( S \) is the area of the top electrode (the etched areas should not be included in the calculation).

Besides, \( t_g \) has the form as

\[
t_g (t, \omega) = b^2/[b - Z (t, \omega)] \tag{5}
\]

with

\[
b = a - 0.5V_{dc}^2 \varepsilon_0 S a^3/(m\omega_0^2 \varepsilon_0^2 - V_{dc}^2 \varepsilon_0^2) \tag{6}
\]

\[
a = t_1/e_i + l_0 \tag{7}
\]

where \( t_1, e_i, \) and \( l_0 \) are the thickness of the insulation layer, the relative permittivity of the insulation layer, and the height of the gap, respectively.

Thus, the dynamic output current of a CMUT cell can be expressed as

\[
i (t, \omega) = V_{dc} \frac{dC (t, \omega)}{dt} = \frac{1}{b^2 (\omega^2_0 - \omega^2 + j\omega\omega_0/Q)} Z_0 (t, \omega). \tag{8}
\]

Equation (6) can be transformed as follows:

\[
i (t, \omega) = AD (\omega) e^{j[\omega t + \varphi(\omega)]} \tag{9}
\]

where \( D(\omega) \) and \( \varphi(\omega) \), respectively, represent the current amplitude and current phase of a CMUT cell and can be written as

\[
I (\omega) = \frac{1}{b^2 (\omega^2_0 - \omega^2 + j\omega\omega_0/Q)} \tag{10}
\]

\[
D (\omega) = \text{abs}[I (\omega)] \varphi (\omega) = \tan^{-1} \left[ \text{Im}[I (\omega)]/\text{Re}[I (\omega)] \right]. \tag{11}
\]

Table I

<table>
<thead>
<tr>
<th>Structure Parameters of a CMUT Cell Used in This Work</th>
<th>Length (x-direction)( \times )width (y-direction)( \times )height (z-direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top electrode</td>
<td>( L \times W \times t_e )</td>
</tr>
<tr>
<td>Insulating layer</td>
<td>( L \times W \times t_i )</td>
</tr>
<tr>
<td>Bottom electrode</td>
<td>( L \times W \times t_e )</td>
</tr>
<tr>
<td>Through holes</td>
<td>( l \times w \times t_e )</td>
</tr>
<tr>
<td>Spring 1</td>
<td>( l_1 \times w_1 \times t_e )</td>
</tr>
<tr>
<td>Spring 2</td>
<td>( l_2 \times w_2 \times t_e )</td>
</tr>
<tr>
<td>Gap</td>
<td>( t_g ) (height)</td>
</tr>
<tr>
<td>Au</td>
<td>( t_{Au} ) (height)</td>
</tr>
</tbody>
</table>

Fig. 2. Circuit diagram of a CMUT composed of \( N \) types of resonant cells, which are sensitive to different frequencies \( f_i (i = 1, 2, 3, \ldots, N) \). The number of each type of resonant cell is \( n_i (i = 1, 2, 3, \ldots, N) \).
current responses of all cells together constitute the total output current, $i_{\text{total}}$

$$i_{\text{total}}(t, \omega) = n_1 i_1(t, \omega) + n_2 i_2(t, \omega) + \cdots + n_N i_N(t, \omega)$$  \hspace{1cm} (8)

where $i_N(t, \omega)$ is the current response of a CMUT cell that is resonating at $f_N$.

Substituting (7) into (8) and using the Euler formula, we can obtain the expression as

$$i_{\text{total}}(t, \omega) = AD_{\text{total}}(\omega) \times e^{\left[\omega t + \tan^{-1}\left(\sum_{n=1}^{N} n_l D_l(\omega) \sin \phi_l(\omega) / \sum_{m=1}^{N} n_l D_l(\omega) \cos \phi_l(\omega)\right)\right]}$$  \hspace{1cm} (9)

where

$$D_{\text{total}}(\omega) = \sqrt{\sum_{l=1}^{N} \sum_{m=1}^{N} n_l n_m D_l(\omega) D_m(\omega) \cos [\phi_l(\omega) - \phi_m(\omega)]}.$$

Usually, a transimpedance amplifier and a voltage amplifier are used to convert the time-varying current into the time-varying voltage and amplify the voltage, respectively [24]

$$v_{\text{total}}(t, \omega) = U R i_{\text{total}}(t, \omega)$$  \hspace{1cm} (10)

where $R$ is the conversion coefficient of the transimpedance amplifier in $\Omega$ and $U$ is the magnification of the voltage amplifier in V/V.

Traditionally, the sensitivity $H(\omega)$ of CMUT is defined as the ratio of the output voltage to the input speed in the unit of dB (@V/s/m)

$$H(\omega) = 20 \log_{10} \left(\frac{v_{\text{total}}(t, \omega)}{Z_0(i, \omega)}\right) = 20 \log_{10} \left(\frac{U R i_{\text{total}}(t, \omega)}{i \omega Z_0(i, \omega)}\right).$$  \hspace{1cm} (11)

Equation (11) is applicable for the small-signal model and for the cases that the total sizes of CMUTs are much smaller than the input wavelength.

### B. Finite Element Model

In this work, a commercially available FEM modeling software, COMSOL Multiphysics, is adopted to simulate the sensing behaviors of a CMUT device constituted of multiple cells, as shown in Fig. 3. In the simulation, the designed CMUT is attached on the surface of a plate constructed in the “Solid (solid)” module to receive the out-of-plane signals. The “prescribed displacement” in solid is exerted on the point source (labeled as red circle) to excite out-of-plane displacements. Absorption regions (perfectly matched layer for the frequency domain and Rayleigh damping for the time domain) are set around the plate to reduce the influence of reflected waves. The designed CMUT should be constructed in the solid module and the “Electrostatics (es)” module, where the gap should be selected as the “Moving Mesh” to analyze the change of capacitance. For the eigenfrequency study, the bottom surfaces of the anchors and the bottom electrode are set as fixed constraints to replace the plate. Meanwhile, for the transient study, the air gap should be included in the “Laminar Flow (spf)” module to simulate the squeeze-film damping induced by gas compression. Besides, the “Electrical Circuit (cir)” module is added to calculate the total output current, $i_{\text{total}}$, produced by multiple cells, where the connection of the circuit can refer to in Fig. 2. The “External I-terminal” in the cir module is adapted to couple with the “Terminal” in the es module. The average velocity of the bottom electrode is extracted as the input velocity $Z_0$. Combining the total output current and the input velocity, the sensitivity of CMUT would be calculated.

### III. MECHANISM OF THE PHASE-REVERSAL-BASED BROADBAND CMUT WITH NOISE REJECTIONS

In this section, two different CMUT cells that are capable of resonating at different frequencies (40.8 kHz for Cell 1 and 50 kHz for Cell 2) are designed through the eigenfrequency study of FEM as the analysis objects; however, conclusions may be applicable for cells that are resonating at other frequencies. Based on the assumption of rigid body motion, the resonant frequency of a CMUT cell can be estimated analytically [21]. However, the estimated resonant frequency may be inaccurate due to the assumption of rigid body motion and the influence of the spring softening effect (i.e., the reduction of the effective spring constant caused by dc biased voltage [27]). Instead of the analytical calculation of the resonant frequency, the resonant frequency calculated from the eigenfrequency study of FEM is brought into the theory shown in Section II to evaluate the sensing behavior of a CMUT cell analytically. In the analysis, the amplitudes of dc biased voltages applied to all cells are fixed at 10 V. In the calculations, $R$ and $U$ are set as 1000 $\Omega$ and 100 V/V, respectively. The amplitude of the prescribed displacement in simulation is 0.01 $\mu$m. The average out-of-plane displacement of the bottom electrode is used as the input displacement for calculating the output current analytically. The material parameters adopted are given as follows: gold (Au) as the deposition layer for wiring, with the density of 19 300 kg/m$^3$, Young’s modulus of 70 GPa, and Poisson’s ratio of 0.44; conductive polycrystalline silicon as the electrodes, with the density of 2320 kg/m$^3$, Young’s modulus of 160 GPa, and Poisson’s ratio of 0.22; and Si$_3$N$_4$ as the insulating layer, with the density of 3100 kg/m$^3$, Young’s modulus of 250 GPa, Poisson’s ratio of 0.23, and the relative permittivity of 9.7. The
The structural parameters used are given in Table II.

<table>
<thead>
<tr>
<th></th>
<th>Cell 1 (40.8 kHz)</th>
<th>Cell 2 (50 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L \times W$</td>
<td>400 $\mu$m $\times$ 400 $\mu$m</td>
<td>400 $\mu$m $\times$ 400 $\mu$m</td>
</tr>
<tr>
<td>$l \times w$</td>
<td>0 $\mu$m $\times$ 0 $\mu$m</td>
<td>0 $\mu$m $\times$ 0 $\mu$m</td>
</tr>
<tr>
<td>$t_r$</td>
<td>8.7 $\mu$m</td>
<td>8.7 $\mu$m</td>
</tr>
<tr>
<td>$t_w$</td>
<td>0.7 $\mu$m</td>
<td>0.7 $\mu$m</td>
</tr>
<tr>
<td>$t_i$</td>
<td>0.35 $\mu$m</td>
<td>0.35 $\mu$m</td>
</tr>
<tr>
<td>$t_o$</td>
<td>1.1 $\mu$m</td>
<td>1.1 $\mu$m</td>
</tr>
<tr>
<td>$t_{so}$</td>
<td>0.5 $\mu$m</td>
<td>0.5 $\mu$m</td>
</tr>
<tr>
<td>$l_1 \times w_1$</td>
<td>8 $\mu$m $\times$ 160 $\mu$m</td>
<td>8 $\mu$m $\times$ 144 $\mu$m</td>
</tr>
<tr>
<td>$l_2 \times w_2$</td>
<td>24 $\mu$m $\times$ 8 $\mu$m</td>
<td>24 $\mu$m $\times$ 8 $\mu$m</td>
</tr>
</tbody>
</table>

**Fig. 4.** Theory (symbols) and simulation (solid lines) results for Cell 1 and Cell 2 in coarse vacuum (low pressure): (a) amplitude of each output current, (b) phase of each output current, and (c) sensitivity. Frequencies are divided into three regions by two dashed lines. The graphs embedded in (a) show how the circuits are connected.

Structures of these CMUT cells are referenced as the model in [21], and the structural parameters used are given in Table II. Cell 1 and Cell 2 differ from each other by the dimensions of their springs. By adjusting the springs, the resonant frequency of the CMUT cell can be adjusted within a certain frequency range. For the frequencies out of this range, the size of CMUT cells needs to be adjusted appropriately.

Fig. 4 gives the sensing behaviors of Cell 1 and Cell 2 in coarse vacuum (low pressure), which are predicted by the frequency-domain simulations (solid lines) using COMSOL Multiphysics, together with the analytical calculations (symbols) using (7) and (11). In order to reduce the complexity of the model, save memory consumption, and shorten the calculation time, the damping ratio ($\xi$) in the Rayleigh damping is exerted on the whole cell to replace the squeeze-film damping simulated in the *spf* module. Theoretically, the value of quality factor $Q$ ($Q = 0.5/\xi$) should be infinite for (6) without considering any damping and loss (i.e., $c = 0$), which would result in an infinite peak at the resonant frequency. For the cell working in the environment of coarse vacuum (in this case, the squeeze-film damping is very small). $Q$ should have a finite large value (here, assumed as $Q = 400$ or $\xi = 0.00125$). Observing Fig. 4, it can be found that the theoretical and simulation results have shown high consistency. At resonant frequencies, the output current [see Fig. 4(a)] and the sensitivity [see Fig. 4(c)] of each CMUT cell reach maximum, while the phase of current [see Fig. 4(b)] abruptly varies by 180°. Two black dashed lines divide the frequency into three regions, which are labeled as I, II, and III. In region I (10–40.8 kHz) and region III (50–100 kHz), Cell 1 is in-phase (phase difference is 0°) with Cell 2; in region II (40.8–50 kHz, filled by gray color), Cell 1 is in antiphase (phase difference is 180°) with Cell 2. For the other regions (i.e., frequency lower than 10 kHz and higher than 100 kHz), the phenomenon of in-phase still exists, which has not been shown in this work.

Furthermore, Cell 1 ($n_1 = 1$) and Cell 2 ($n_2 = 1$) are connected together to investigate the overall sensing response of a CMUT constituted of multiple cells in a coarse vacuum, where the potentials of the top electrodes and the bottom electrodes are 10 and 0 V, respectively (here, this combination is named Combination I). As shown in the circuit diagram of Fig. 5, the output currents of Cell 1 ($i_1$) and Cell 2 ($i_2$) together constitute the total current, $i_{total}$. The phase differences [see Fig. 5(b)] between $i_1$ and $i_2$ are 0° in region I and region III, and 180° in region II, which are consistent with the results analyzed from Fig. 4(b). Simplified expressions about the amplitude of the total output current $i_{total}$ can be concluded from (9).

1. **Region I and Region III:** $D_{total}(\omega) = D_1(\omega) + D_2(\omega)$.
2. **Region II:** $D_{total}(\omega) = |D_1(\omega) - D_2(\omega)|$.

It means that the amplitude of $i_{total}$ is a linear superposition of each current in region I and region III, and a linear subtraction of each current in region II. Therefore, the amplitude of $i_{total}$ [see Fig. 5(a)] and the sensitivity [see Fig. 5(c)] of this combination are slightly higher than those of each CMUT cell in region I and region III, and are rapidly reduced in region II. When the current amplitude of Cell 1 is equal to that of Cell 2 at one frequency, the amplitude of $i_{total}$ is almost equal to zero (here, at 45 kHz). Besides, the deformations along the out-of-plane direction of each cell at 30 (in region I), 45 (in region II), and 90 kHz (in region III) are extracted from the simulation, together with the diagrams of each current flow [see Fig. 5(d)]. Because the displacements are much smaller than the total size of each cell, the deformations are excessively amplified to clearly show the range of motion of the suspended plates. It can be found that Cell 1 and Cell 2 vibrate in the same direction at 30 and 90 kHz (correspondingly, both $i_1$ and $i_2$ flow into the node) and in the opposite direction at 45 kHz (correspondingly, $i_1$ flows out the node and $i_2$ flows into the node). According to Kirchhoff’s law of current (i.e., the sum of all currents flowing into a node is equal to the sum of all currents flowing out of the node), it can be inferred from Fig. 5(d) that the amplitude of $i_{total}$ is consistent with the simplified expressions analyzed above.
Fig. 5. Simulation (solid curves) and theory (symbols) results about the sensing behaviors of a combination of one Cell 1 and one Cell 2 in a coarse vacuum (named Combination I), where the potentials of the top electrodes and the bottom electrodes are 10 and 0 V, respectively: (a) amplitude of the total output current $i_{\text{total}}$, (b) phase differences between each output current, and (c) sensitivity. Two black dashed lines divide the frequency into three regions. (d) Deformation diagrams of Cell 1 and Cell 2 at 30, 45, and 90 kHz, respectively. Circuits are embedded to show how the currents flow.

In fact, it is desirable that the broadband CMUT should have high sensitivity in the frequency range of interest (here, named passband) and extremely low sensitivity at other frequencies (here, named stopband). For the combination of Cell 1 and Cell 2, region II should be designed as the passband, and region I and region III should be designed as the stopbands. However, due to the linear subtraction of current amplitude in region II and the linear superposition of current amplitude at other frequencies (see Fig. 5), it may be not feasible to satisfy the requirements. The solution is to make the output current of Cell 1 ($i_1$) in-phase with that of Cell 2 ($i_2$) in region II and antiphase with that of Cell 2 ($i_2$) in region I and region III, i.e., to reverse the current phase (phase change of 180°) of Cell 1 or Cell 2.

Fig. 6 illustrates the mechanism of reversing the current phase of one CMUT cell. For the traditional case (see the left figure in Fig. 6), the potential would be lower than 0 V. The top and bottom electrodes are charged oppositely compared to those in the traditional case, thus resulting in the reversal of the current direction (i.e., the output current is phase reversed). It should be mentioned that connecting electrodes reversely could not reverse the output current because the current always flows from the high potential to the low potential in external circuits.

Based on the mechanism of PR, the potential of the top electrode of Cell 2 in Combination I is switched from +10 to −10 V (here, named Combination II). Fig. 7 shows the sensing behaviors of Combination II from the aspects of simulation (solid curves) and theory (symbols). The deformations along the out-of-plane direction of each cell and the diagrams of each current flow are also given here [see Fig. 7(d)] compared with Fig. 5(d). Switching the potential of the top electrode from +10 to −10 V would not affect the vibration behavior of the cell but would reverse its output current (here, $i_2$ is reversed). Due to the PR of Cell 2, the current phase differences are switched from 0° to 180° in region I and region III, and from 180° to 0° in region II [see Figs. 5(b) and (d) and 7(b) and (d)]. The linear superposition of output currents avoids the cancellation of amplitudes in region II, thus leading to the obvious improvement of the total output current $i_{\text{total}}$ [see Fig. 7(a)] and the sensitivity [see Fig. 7(c)]. Also, the linear subtraction of output currents maximizes the reductions in region I and region III and, thus, may be more meaningful for the rejection of noises (e.g., the rejection is about 47 dB at 100 kHz).

Although region I and region III have been constructed to form significant stopbands for the low-frequency and high-frequency noises based on the mechanism of PR, region II is not sufficient to meet the requirements of the passband.
would not be absolute at 180°. Besides, the phase differences between adjacent CMUT cells resonant frequencies would vary gently instead of rapidly. great decreased. Correspondingly, the phases around

\[ Q \]

of CMUTs around resonant frequencies (the value of air in the gap, would significantly reduce the output signals squeeze-film damping, induced by the compression of atmospheric pressure) are studied as follows. For this case, the squeeze-film damping, induced by the compression of air in the gap, would significantly reduce the output signals of CMUTs around resonant frequencies (the value of \( Q \) is greatly decreased). Correspondingly, the phases around the resonant frequencies would vary gently instead of rapidly. Besides, the phase differences between adjacent CMUT cells would not be absolute at 180° or 0°; thus, the resulting amplitude of the total output current \( i_{\text{total}} \) should have the form as

\[
D_{\text{total}}(\omega) = \sqrt{D_1^2 + D_2^2 + 2D_1D_2\cos[\phi_1(\omega) - \phi_2(\omega)]},
\]

(12)

Since the first two terms in the equation are fixed, the amplitude of \( i_{\text{total}} \) is influenced by the phase term \( \cos[\phi_1(\omega) - \phi_2(\omega)] \). The sensing behaviors of Combination I and Combination II in air are calculated based on theory (symbols) and simulation (solid lines), together with the simulated deformations along the out-of-plane direction of each cell, as shown in Fig. 8. The circuits are the same as those given in Figs. 5 (for Combination I) and 7 (for Combination II) and, thus, are not shown here. In the simulations, a large damping ratio of about 0.08 (correspondingly, \( Q = 6.25 \)) is applied on the suspended plate to take into account the effect of the squeeze-film damping. It seems that the vibration behavior of each cell that is working in air is slightly different from the cells that are working in coarse vacuum, except that the phase difference and the displacement become smaller in region II [see Fig. 8(d)]. In Fig. 8(b), the horizontal black dotted line represents the phase difference of 90°. For Combination I (see the dark blue lines and symbols), the phase differences between Cell 1 and Cell 2 [see Fig. 8(b)] vary gently from 0° to 90° in region I (\( \cos[\phi_1(\omega) - \phi_2(\omega)] \) is positive), from 90° to 128° to 90° in region II (\( \cos[\phi_1(\omega) - \phi_2(\omega)] \) is negative), and from 90° to 0° in region III (\( \cos[\phi_1(\omega) - \phi_2(\omega)] \) is positive). It means that the phase differences have positive effects on the amplitude of \( i_{\text{total}} \) in region I and region III, and have negative effects on the amplitude of \( i_{\text{total}} \) in region II [see (12)]. Therefore, the total output current \( i_{\text{total}} \) [see Fig. 8(a)] and the sensitivity [see Fig. 8(c)] of combination I are improved in region I and region III, and are worsened in region II. Especially, in region III, the lowest sensitivity is about 12 dB, which is only 12 dB lower than the peak in region II.Attributed to PR of Cell 2 (see the green lines and symbols), the phase differences of Combination II [see Fig. 8(b)] vary slightly from 180° to 90° in region I (\( \cos[\phi_1(\omega) - \phi_2(\omega)] \) is negative), from 90° to 52° to 90° in region II (\( \cos[\phi_1(\omega) - \phi_2(\omega)] \) is positive), and from 90° to 180° in region III (\( \cos[\phi_1(\omega) - \phi_2(\omega)] \) is negative). Due to the opposite effects of the phase differences, the total output current \( i_{\text{total}} \) [see Fig. 8(a)] and the sensitivity [see Fig. 8(c)] of Combination II show a more flat response in region II and a lower response in region I and region III (the lowest response is 55 dB lower than the peak) than those of Combination I. Therefore, the PR-based Combination II constructs a relatively flat passband (region II) and two significantly improved stop-bands (region I and region III) compared with the traditional combination (i.e., Combination I).
IV. DISCUSSIONS ON THE DESIGN AND PERFORMANCE OF A PHASE-REVERSAL-BASED BROADBAND CMUT WITH FLAT PASSBAND AND IMPROVED NOISE REJECTIONS

A. Designing the Phase-Reversal-Based CMUT and the Traditional CMUT by Use of Genetic Algorithm

For a given frequency range of interest, it is necessary to balance the current amplitude and the current phase of each constituted CMUT cell to achieve a broadband CMUT with a flat passband. Usually, an optimization algorithm is needed to help find the combinations of multiple CMUT cells that satisfy the requirements. In this work, GA [28], as a self-adapting global optimization search algorithm, is adopted to seek the optimal combination. As discussed in Section III, the theoretical predictions are in good agreement with the FEM results under the condition that the resonant frequency is known. Besides, considering that the analytical expression for calculating the resonant frequency of a CMUT cell may be inaccurate due to the assumptions, a solution to the design of a broadband CMUT is proposed, by combining the theory in Section II, the GA, and FEM. The specific steps are given as follows.

1) Determine the frequency range ([f_1, f_N]) needed to be detected and the types of CMUT cells (N) needed to be used. Thus, the broadband CMUT is constituted of cells with resonant frequencies of f_i (i = 1, 2, 3, ..., N).
2) Write the program according to the theory given in Section II. Fix the parameters of CMUT cells, except for the springs. The CMUT cells with different resonant frequencies can be realized by changing the lengths of springs. Therefore, the variables to be searched are the number of each type of CMUT cells (n_i), the resonant frequency (f_i), and the quality factor (Q_i).
3) Utilize finite element simulation software to design a CMUT cell with the resonant frequency that is equal to the lower limit of the given frequency range (use the eigenfrequency study), and calculate the quality factor of this cell (use the transient study). For example, the CMUT cell with a resonant frequency of f_1 should be designed for [f_1, f_N]. As mentioned in [21], the value of Q_1 can be calculated by the half-power bandwidth method. Referencing the theory proposed by Wright [20], the quality factor (Q_i) of other CMUT cells can be estimated by the expression Q_i = Q_1 f_i / f_1 when the parameters of the suspended vibrating plate are fixed.
4) If [f_1, f_N] is too broad to adjust the springs to meet the requirements, it can be divided into multiple intervals for the convenience of design (e.g., [f_1, f_j], ..., [f_k, f_m], ..., [f_n, f_N], j ≤ k ≤ m ≤ n ≤ N). Then, repeat steps in 3) for each frequency interval.
5) Embed the program into the GA, where n_i and f_i are set as variables, i.e., the chromosomes in the algorithm.
6) Determine the objective function of optimization and the value range of variables. In this work, the variance of sensitivity in the frequency range of [f_1, f_N] is set as the objective function, and the aim is to minimize this value.
7) Add extra constraints according to the requirements. The object function and the extra constraints need to be satisfied at the same time. For example, the constraint of the amplitude difference (labeled as ΔH), between the passband and the stopbands, should be as large as possible for the PR-based CMUT.
8) Run the GA to receive the (n_i, f_i) pairs that satisfy the requirements. According to the received (n_i, f_i) pairs,
Table III
Constituted CMUT Cells Searched by GA. The Variance of the Sensitivity in the Range of 100–200 kHz for Different Designs is Calculated. The Minus Signs Indicate That the Output Currents of This Type of Cell Are Phase-Reversed

<table>
<thead>
<tr>
<th>N = 3</th>
<th>N = 6</th>
<th>N = 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>Traditional CMUT ($n_i, f_i$)</td>
<td>PR-based CMUT ($n_i, f_i$)</td>
</tr>
<tr>
<td>1</td>
<td>(1, 100 kHz)</td>
<td>(1, 100 kHz)</td>
</tr>
<tr>
<td>2</td>
<td>(2, 150 kHz)</td>
<td>(7, 150 kHz)</td>
</tr>
<tr>
<td>3</td>
<td>(1, 200 kHz)</td>
<td>(3, 200 kHz)</td>
</tr>
<tr>
<td>4</td>
<td>(4, 150 kHz)</td>
<td>(5, 150 kHz)</td>
</tr>
<tr>
<td>5</td>
<td>(3, 173.1 kHz)</td>
<td>(5, 164.7 kHz)</td>
</tr>
<tr>
<td>6</td>
<td>(2, 200 kHz)</td>
<td>(6, 200 kHz)</td>
</tr>
<tr>
<td>7</td>
<td>(3, 168.6 kHz)</td>
<td>(9, 200 kHz)</td>
</tr>
<tr>
<td>8</td>
<td>(2, 182.2 kHz)</td>
<td>(6, 167 kHz)</td>
</tr>
<tr>
<td>9</td>
<td>(2, 200 kHz)</td>
<td>(1, 200 kHz)</td>
</tr>
</tbody>
</table>

Variance (dB): 8.21, 3.32, 0.33, 0.23, 0.04, 0.04

Fig. 9. Sensitivity of the PR-based CMUT (green lines) and the traditional CMUT (blue lines) optimized by the GA, where the types of CMUT cells used are (a) N = 3, (b) N = 6, and (c) N = 9.

Fig. 10. Theory (lines) and simulation (symbols) results of (a) total output current $i_{total}$ and (b) sensitivity of the PR-based CMUT and the traditional CMUT designed in Table I (N = 6).

Design corresponding CMUT cells by finite element simulation.

9) Verify the effect of the designed broadband CMUT by FEM, and then, manufacture and test the broadband CMUT, experimentally.

Then, according to the above steps, the ($n_i, f_i$) pairs of the broadband CMUT are searched for sensing in the given frequency range of 100–200 kHz. Assume that the amplitude of dc biased voltage is 10 V for each type of CMUT cell. Fig. 9 shows the sensitivity of the designed broadband CMUT, including the PR-based CMUT and the traditional CMUT (i.e., the phase is not reversed), where the types of CMUT cells used are adopted as N = 3, 6, and 9. The specific ($n_i, f_i$) pairs of the constituted CMUT cells are shown in Table III, where the minus signs indicate that the output currents of this type of cell are phase-reversed. By observing Fig. 9, it can be found that a more flat passband (see the gray region) in the 100–200-kHz frequency range would be formed with an increase in the types of used CMUT cells (N). The variances of the sensitivity in the range of 100–200 kHz also show that increasing N can significantly improve the smoothness of the passband. Compared with the traditional CMUT (blue lines), the PR-based CMUT (green lines) has the stopbands (lower than 100 kHz and higher than 200 kHz) with much lower sensitivities, which are favorable for the rejection of low- and high-frequency noises. Besides, it should be mentioned that PR-based CMUT can realize a relatively flat passband using just three types of CMUT cells [see Fig. 9(a)]. The sensitivity could be improved by increasing the number of each type of CMUT cells ($n_i$) and increasing the dc biased voltages applied on the CMUT cells.

Furthermore, the frequency-domain simulation has been carried out to verify the total output current $i_{total}$ [see Fig. 10(a)] and the sensitivity [see Fig. 10(b)] of the PR-based CMUT.
and the traditional CMUT designed in Table III \((N = 6)\). COMSOL Multiphysics is used to design cells satisfying the \((n_i, f_i)\) pairs shown in Table III. A high degree of consistency has been shown between the theory (lines) and the simulation (symbols) results, which verifies the theoretical feasibility of the proposed steps. Although \(i_{\text{total}}\) fluctuates in the passband (see the gray region), the fluctuations are within an acceptable range. Achieving a completely flat passband is almost impossible. By expanding the search range of \(n_i\) \((i = 1, 2, 3, \ldots, N)\) and increasing the types of CMUT cells used \((N)\), the passband and stopbands could be further improved.

### B. Influence of Some Parameters on the Phase-Reversal-Based CMUT

In Section IV-A, the PR-based CMUT with a flat passband for broadband sense and two stopbands at both sides for improved noise rejections is designed for the given frequency range of \([100 \text{ kHz}, 200 \text{ kHz}]\). Fixing the types of CMUT cells used as \(N = 6\) and the quality factor as \(Q = 6.25\), the given frequency range \([f_1, f_N]\) is set at lower or higher frequencies, with the bandwidth \((f_N - f_1)\) kept as 100 kHz, to illustrate that the PR-based CMUT can be designed for arbitrary frequencies of interest. Since the searched \((n_i, f_i)\) pairs are different for different given frequency range of \([f_1, f_N]\), the average sensitivity of the passband may be significantly different. To compare easily, the maximal sensitivities are unified to 0 dB for all cases, as shown in Fig. 11. It was found from Fig. 11 that the PR-based CMUT can be designed by use of GA, no matter the given frequency range moves to frequencies lower than or higher than \([100 \text{ kHz}, 200 \text{ kHz}]\).

Besides, with the given frequency range moving to higher frequencies, the PR-based CMUT can be designed with a flatter passband. In view of the relation that \(Q = f_0/(f_{\text{low}} - f_{\text{high}})\), where \(f_0, f_{\text{low}},\) and \(f_{\text{high}}\) are the resonant frequency of the cell, the lower limit of \(-3\text{-dB} \) band, and the higher limit of \(-3\text{-dB} \) band, respectively (here, \(-3\text{-dB} \) band refers to the frequency band corresponding to a maximum reduction of 3 dB in sensitivity relative to the peak amplitude), the CMUT cell with a lower resonant frequency should have a smaller \(-3\text{-dB} \) bandwidth when the value of \(Q\) is fixed. Therefore, the passband at lower frequencies may be more difficult to be flat enough (e.g., see the black line in Fig. 11). There are two possible solutions to improve the flatness of the passband at low frequencies, i.e., one is increasing the types of CMUT cells used \((N)\), and another is decreasing the quality factors \((Q)\) of CMUT cells resonating at low frequencies.

The performance of the designed PR-based CMUT, when the bandwidth \((f_N - f_1)\) of the given frequency range \([f_1, f_N]\) is decreased or increased, is shown in Fig. 12. As concluded
from Fig. 9, when the bandwidth of the given frequency range is constant, the more types of CMUT cell are used, the flatter the passband of the designed PR-based CMUT would be. For different bandwidths of the given frequency range, sufficient number of the types of CMUT cell is used to ensure that the performance of the designed PR-based CMUT is close to the optimal solution ($N = 6$ for [100 kHz, 150 kHz], $N = 9$ for [100 kHz, 200 kHz], $N = 15$ for [100 kHz, 300 kHz], $N = 18$ for [100 kHz, 400 kHz], and $N = 21$ for [100 kHz, 500 kHz]). The maximal sensitivities are also unified to 0 dB. Observing Fig. 12, it can be found that the PR-based CMUT can be designed to have a flat passband and two perfect stopbands at both sides when the bandwidth is increased from 50 to 400 kHz.

Furthermore, considering the issues of MEMS microfabrication techniques (e.g., residual stress in suspended thin films), the resonant frequency of the microfabricated CMUT cell may deviate from the predicted value mainly due to the differences in structures. The influence of shifts in the resonant frequencies of constituted cells on the PR-based CMUT is discussed in this part, where the designed PR-based CMUT with $N = 6$ (as shown in Table III) is selected as the research object. Assume that the shift in the resonant frequency of each constituted cell is $\Delta f$ ($\Delta f$ may be different for different types of cells), the value of which is randomly selected in a given interval. After the shift of resonant frequencies, the analytical values about the variance of the passband and the maximal sensitivity difference (as shown in Section IV-A, labeled as $\Delta H$) between the passband and the stopbands in the frequency range of 20–280 kHz (the frequency range shown in Fig. 9), for the PR-based CMUT, may fall within new numerical intervals. In order to test the change of the variance (left figures) and $\Delta H$ (right figures), 100 000 groups of random $\Delta f$ are adopted, and the numbers of times falling in different numerical intervals are counted, as shown in the histograms of Fig. 13. As the random range of $\Delta f$ gradually expands, i.e., from $[-1 \text{ kHz}, 1 \text{ kHz}]$ to $[-5 \text{ kHz, 5 kHz}]$, the variance of the passband, for the PR-based CMUT may appear in a larger value range [see Fig. 13(a), (c), (e), (g), and (i)], while $\Delta H$ may appear in a smaller or larger value range [see Fig. 13(b), (d), (f), (h), and (j)]. This means that the larger the possible value range of $\Delta f$, the greater the possibility that the passband and the stopbands would deviate from the predicted results. As shown in Table III, the predicted variance of the passband for the designed PR-based CMUT with $N = 6$ is about 0.23, which is within the interval of [0.2, 0.3]. For $\Delta f \in [-1 \text{ kHz, 1 kHz}]$ and $\Delta f \in [-2 \text{ kHz, 2 kHz}]$, most of the incidents have the variance of the passband around 0.3 (the value does not deviate from 0.23 significantly). Therefore, when the shift in the resonant frequency caused by the microfabrication is less than 2 kHz, the passband and the stopbands of the manufactured PR-based CMUT may meet the expectations.

C. Comparing the Phase-Reversal-Based CMUT With the Traditional CMUT Using Transient Simulations

The transient simulations are also included to test the passband and the stopbands of the designed PR-based CMUT with $N = 6$ (see Table III). Results of the traditional CMUT with $N = 6$ are also given for comparison. The five peak...
wave signal with a center frequency of 150 kHz is selected as the excitation signal [see Fig. 14(a)], the spectrum of which covers the whole passband (100–200 kHz). Besides, low- and high-frequency random noises are added to the five-peak wave signal to verify the performance of noise rejection [see Fig. 14(e)]. Both the traditional CMUT and the PR-based CMUT are used to receive these signals. It can be seen that the traditional CMUT [see Fig. 14(b)] and the PR-based CMUT [see Fig. 14(c)] could both capture signals with the profiles of spectra approximate to that of the input five peak wave [see Fig. 14(d)], which shows their properties of the flat passband. Observing Fig. 14(d) carefully, a little difference, which is originated from the fluctuations of currents for different frequencies [see Fig. 10(a)], is shown between the FFT profiles of the input signal (solid line) and the output signals (dotted lines). Since the energy of the input five peak wave signal is mainly concentrated near the center frequency (gradually decreasing away from the center frequency), the difference is most significant near the center frequency (here, around 150 kHz). To reduce this difference, the variables considered in GA should be adjusted to further optimize the passband. From the point of noise rejection, the PR-based CMUT could reduce the influence of the low- and high-frequency noises perfectly [see Fig. 14(h)] and output the needed current signal with waveforms highly preserved [see Fig. 14(g)]. However, the current signal of the traditional CMUT is almost undetectable due to noise [see Fig. 14(f)]. The maximal reduction of the PR-based CMUT ($N = 6$), for the frequency larger than 200 kHz, is about 53 dB, while that of the traditional CMUT ($N = 6$), for the same frequency range, is only about 6 dB. 

V. CONCLUSION AND PERSPECTIVES

Based on the spring–mass–damper model, expressions of the total output current and the sensitivity of CMUTs constituted of multiple cells have been given in this work. Taking the simplest combination of two CMUT cells (i.e., $N = 2$) as an example, it is found that reversing the current phase of one of the cells could form a low-frequency and a high-frequency stopband for noise rejections, which is not only useful for the CMUT in coarse vacuum (low pressure) but also for the CMUT in air damping (atmospheric pressure). The theoretical and simulation results are in good agreement. Combining the GA and the mechanism of PR, a PR-based broadband CMUT is designed with a flat passband in the range of 100–200 kHz and two improved stopbands on both sides. Both frequency- and time-domain simulations show perfect performance for sensing stress waves of interest with highly preserved waveforms, while rejecting the interferences of low- and high-frequency noises. Changing the frequency position and the bandwidth of the given frequency range, it was found that the PR-based CMUT can be designed to accommodate an arbitrary frequency requirement of the passband, accompanied by two perfect stopbands at both sides of the passband. The discussions on the random shifts in the resonant frequencies of constituted cells have revealed that the passband and the stopbands of the manufactured PR-based CMUT may meet the expectations when the shift in the resonant frequency caused by the microfabrication is within a certain frequency range (for the designed PR-based CMUT with $N = 6$, about $\pm 2$ kHz, 2 kHz). However, the proposed steps are time-consuming, and the large-signal model of CMUTs is not considered in this work. The large-signal model of CMUTs is planned to be implemented in our future studies. Besides, although the feasibility of designing this PR-based broadband CMUT, in theory, is confirmed by the simulation, experimental tests are still necessary; thus, the next step of our team is to manufacture and test such CMUTs, experimentally.

REFERENCES

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