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A row–column addressed micromachined ultrasonic transducer array for surface scanning applications

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ABSTRACT

Row–column addressed arrays for ultrasonic non-destructive testing (NDT) applications are analyzed and demonstrated in this paper. Simulation and experimental results of a row–column addressed 32 by 32 capacitive micromachined ultrasonic transducer (CMUT) array are presented. The CMUT array, which was designed for medical imaging applications, has a center frequency of 5.3 MHz. The CMUT array was used to perform C-scans on test objects with holes that have diameters of 1.0 mm and 0.5 mm. The array transducer has an aperture size of 4.8 mm by 4.8 mm, and it was used to scan an area of 4.0 mm by 4.0 mm. Compared to an N by N fully addressed 2-D array, a row–column addressed array of the same number of elements requires fewer (N instead of N^2) pairs of interconnection and supporting electronic components such as pulsers and amplifiers. Even though the resulting field of view is limit by the aperture size, row–column addressed arrays and the row–column addressing scheme can be an alternative option of 2-D arrays for NDT applications.

1. Introduction

The objective of this paper is to propose an alternative 2-D array structure and control scheme, namely the row–column addressed array and the row–column addressing scheme, for non-destructive testing (NDT) applications. A capacitive micromachined ultrasonic transducer (CMUT) 2-D array was used to demonstrate the surface scanning ability of the row–column addressing scheme. The 32 by 32 CMUT array [1], with a center frequency of 5.3 MHz, was originally designed for medical imaging applications, more specifically for external ultrasound applications such as abdominal imaging. In this paper, the row–column addressed CMUT array is used to detect holes on a flat surface.

Ultrasonic arrays are widely used to steer and focus sound beams in NDT applications. Many NDT applications use 1-D arrays to improve the scan flexibility and reduce the need of transducer movement [2]. For example, a 1-D array was used to inspect objects with complex geometry in an immersion setup [3], where the time delay of each element was adjusted according to the surface geometry. In two other examples, 64-element 1-D arrays were employed to increase the inspection speed of surfaces on aircraft [4,5]; in both designs, the arrays were immersed in a fluid-filled probe, and C-scans were performed with the probe moving in one direction. It was concluded in [4] that the scan speed was limited by the time it took to maintain good contact between the probe and the scanned surface. For these examples, employing 2-D arrays can be beneficial because 2-D arrays reduce the frequency of transducer movement and further enhance the scan flexibility by providing an addition dimension where the sound beam can be steered and focused. However, the adoption of 2-D arrays for NDT has been slow [1].

The main obstacle faced by 2-D arrays, which scan volumes or surfaces, is the complexity of the imaging, or scanning, systems. For a system using a fully-populated N by N array, the best performance and flexibility can be achieved if each element in the array can be controlled individually. However, such a transducer requires the number of elements, as well as the number of connections to the array, to increase quadratically as the size of the array goes up. For example, a modestly sized 32 by 32 array requires over 1000 array controller channels, resulting in a complex design and making the control difficult. As a result, different 2-D array configurations and driving strategies have been proposed [2]. For instance, the Mills cross configuration (elements arranged in the shape of a cross) and the circular array (elements arranged in a circle) were investigated and compared with the fully-populated array by Mondal et al. [6]. It was concluded that given the same number of elements, circular arrays outperformed fully-populated

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arrays in terms of beam directivity, and cross arrays in terms of side lobes. A 64-element segmented annular array was compared with a 68-element square array of similar size in [7] through simulation. It was found that the segmented annular array produced grating lobes that were on average 20 dB lower. Other NDT 2-D array examples include a 64-element ring array designed for far-field NDT imaging applications [8] and a sparse array, designed using conformal map theory, with an element count of 97 [9].

Thus far, the approach to adopt 2-D arrays for NDT systems has been reducing the number of active elements. However, the number of interconnects can still be reduced without sacrificing the element count, if multiple elements share the same connection in such a way that each element can still be addressed; it can be achieved using row–columned addressed 2-D arrays. Row–column addressed arrays were first proposed by Morton and Lockwood [10], who called the configuration a cross-electrode array. In 2009, a 256 by 256 row–column addressed 2-D array that was made from a 1-3 PZT composite was reported by Seo and Yen for rectilinear imaging [11]. More recently, CMUT Top Orthogonal to Bottom Electrode (TOBE) arrays, which is another name for row–column addressed arrays, were proposed for photoacoustic imaging [12]. Thus far, row–column addressed arrays have not received much attention in NDT research. Therefore, the goals of this paper are (1) to investigate the use of row–column addressed arrays as a practical and efficient solution for NDT, especially on surface scanning applications, and identify the limitations of these arrays; (2) to demonstrate surface scanning using a row–column addressed capacitive micromachined ultrasonic transducer (CMUT) array.

This paper is organized as follows. The CMUT array and the operation of row–column addressed arrays are described in Section 2. The modeling of row–column arrays is presented in Section 3. Experiments and results are described and analyzed in Section 4. Finally, Section 5 discusses the potential of the row–column addressing scheme for NDT applications. While row–column addressed arrays can be implemented in piezoelectric technology [10,11], CMUTs are used in this work because large-area high-density arrays can be more easily manufactured using the CMUT technology; however, the analysis presented is applicable to any row–column addressed arrays.

2. Row–column addressed CMUT arrays

CMUTs, electrostatic transducers that are fabricated using micromachining techniques, have garnered a lot of research interest in the past two decades [13,14]. The operation of a CMUT is based on the vibration of a membrane. A voltage pulse applied across the CMUT electrodes causes the membrane to vibrate and generates sound pulses, while incoming sound waves displace the membrane and change the capacitance of the device, which can be detected as an output current. Because CMUTs are manufactured using micro-fabrication techniques, array elements with size in the order of micrometers can be realized.

The CMUT array used in the experiment section was fabricated with a fusion bonding process that was reported in [15]. The fabrication process was similar to [16] except that silicon-on-insulator (SOI) wafers were not required. Silicon nitride, chosen as the membrane material, was deposited on two silicon wafers using low-pressure chemical vapor deposition (LPCVD). After the CMUT cavities were etched on the bottom wafer, the two wafers were bonded in a vacuum. Aluminum and polysilicon were used as the materials for the top and bottom electrodes, respectively. A detailed description of the fabrication process of the 2-D CMUT array can be found in [17]. Fig. 1 shows an image of the array. The image is a view of multiple array elements, with each element consisting of 30 CMUT cells. The squares in the image are bonding pads. The bonding pads of adjacent columns or rows are located on opposite sides of the array. The characterization of the CMUT array was presented in [1]. The CMUTs have a center frequency of 5.9 MHz and a 6 dB bandwidth of 110% in immersion. The array consists of 32 columns and 32 rows, with a pitch of 150 μm in both directions. The array aperture is 4.8 mm by 4.8 mm.

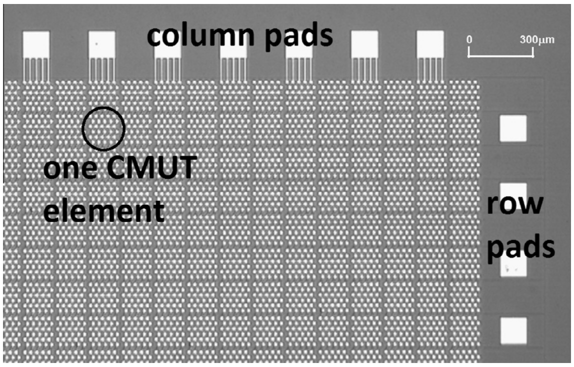

Fig. 1. Micrograph showing a section of the CMUT array.

There are different ways to control a row–column addressed array transducer. The row–column addressing scheme, which was described in [1,10], uses the entire array for both transmit and receive operations. It delivers maximum acoustic energy, because the entire array is used, and is straightforward to implement because the operation is based on 1-D arrays. In [11], a subset of rows and columns were used for either transmit or receive beamforming. The elements always focus at the center, and beam steering is achieved by shifting the activated elements. This rectilinear imaging approach has the advantage that the signals received are highly uniformed, but it is only feasible for arrays of high element count (>100 in each direction) because the number of pixels in the resulting image cannot exceed the number of element in the array. A new addressing scheme that involves retroactive transmit focusing was proposed in [18]. This new approach provides an identical resolution as fully-addressed 2-D arrays in one direction (lateral in [18]), but the resolution in another direction is the same as the row–column addressing scheme. The new scheme requires selectively disabling certain rows and columns, thus it can only be implemented with CMUTs. In order for the discussion to be applicable also to piezoceramic transducers, and to keep the size of the array managable, the row–column addressing scheme is presented in this paper.

The operation of the row–column addressing scheme was explained in [1,10,11] and it is further illustrated in Fig. 2. All the elements in the same column are connected through the top electrodes, and the bottom electrodes are connected in rows. If electrical pulses are applied to the columns when all the rows are connected to a constant bias voltage, the array becomes a 1-D array that generates a vertical line of focus, as shown in Fig. 2(a). On the other hand, if all the columns are connected together and each row is addressed individually, a rotated 1-D array that generates a horizontal focal line, as shown in Fig. 2(b), is produced. Instead of transmitting, the rotated array is in receiving mode; however, due to the principle of reciprocity, the effects on the beam profile can be considered the same regardless of whether the aperture is transmitting or receiving. As a result, if a row–column addressed array is configured such that a 1-D array is used to transmit and a rotated 1-D array is used to receive, the response is the convolution of two, vertical and horizontal, focal lines, resulting in a focal spot. Changing the location of the focal spot can then be achieved by adjusting the focal line locations of both the transmitting and the receiving operations. In summary, the row–column addressing scheme involves transmit beam-forming on one direction, for