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FEM MODELLING AND CHARACTERIZATION OF ULTRASONIC FLEXTENSIONAL TRANSDUCERS

Abstract

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This work describes the finite element modelling and characterization of ultrasonic flextensional transducer arrays. Flexural acoustic transducers can be piezoelectrically actuated plates or capacitive devices based on the electrostatic attraction between a moving electrode and a substrate. Due to the limited miniaturization allowed by the piezoceramic fabrication process, piezoelectric flexural devices based on bulk ceramics are able to work in the low-frequency ultrasonic range. Capacitive flexural devices, instead, can take advantage of the Silicon micromachining techniques to be fabricated to reach higher frequencies.

Capacitive Micromachined Ultrasonic Transducers (CMUTs) are MEMS devices consisting of miniaturized metallized membranes, forced into flexural vibration by an electric signal during transmission, and vice versa generating a voltage signal when actuated by an incident acoustic signal. Due to their low acoustic impedance, CMUT arrays have given excellent results in ultrasound imaging applications.

The most recent frontier of ultrasound imaging is real-time volumetric imaging. 3D images have been originally obtained by means of linear phased arrays mechanically titled along the elevation plane. More complex structures like 2D arrays allow electronic beam steering and dynamic focusing in both azimuthal and elevation planes, thus achieving better performance. In order to increase the achievable frame rate, though, part of the front-end transceive and beamforming operations must be performed in probe. Therefore, 2D arrays should be small-sized and easily interfaced with the front end. Nevertheless, 2D arrays with good radiation characteristics require wide apertures with a small pitch between elements, therefore a great number of elements and many channels to wire and control individually. To overcome these issues, much attention is being focused on the design of sparse arrays, which try to achieve comparable performance by counting a lower element number.

For the design of optimized CMUT devices, accurate modeling is mandatory: the propagation of the acoustic wave produced by a source made of multiple vibrating membranes radiating into a fluid-like medium cannot be fully described by analytical models, thus CMUT devices must be simulated by Finite Elements Models (FEM). In this work, a simplified model of a wide aperture multicell CMUT device was used to develop a tool to support the design process. The model was used to investigate the design parameters variation effect on the static and dynamic performance of CMUT arrays composed of circular cells. The collapse voltage, the membrane deflection profile and the static capacitance of Reverse-Fabricated CMUT devices (RF-CMUTs) were computed by varying the membrane radius and thickness and the cavity height. Since devices fabricated by the Reverse Fabrication Process are built from top to bottom, the Silicon Nitride base can be made very thin, and the devices can be backed by arbitrarily designed backing layers. The backing material effect on the pulse-echo behavior of immersed CMUT devices was investigated, and the reverberation phenomenon reduction was observed by matching the backing material acoustic impedance to the acoustic impedance of the propagating medium.

In order to investigate the performance of a sparse CMUT array, a 3D FEM model is needed, since there is no axial symmetry in a sparse array layout. For this reason, a full model of a reverse CMUT cell was implemented, tested and experimentally validated. Due to the long simulation time required by the FE analysis of a finite transducer element, a mesh optimization study was carried out on a simpler structure, i.e. an infinite transducer. The results of this optimization process were used to mesh a CAD-imported model of a sparse array element.

The studied array element is part of a multi-chip module (MCM) comprising a CMUT array based on a density tapered Fermat's spiral and an analog front end (AFE) ASIC wafer-bonded to the transducer array by means of a Benzocyclobutene (BCB) layer. The 10-mm array is designed for broadband operation around 7 MHz in immersion operation, and is made by 256 1.0λ-wide elements consisting of 19 hexagonally tiled circular cells. The proposed model was used to perform a harmonic analysis in ANSYS, in order to compute the element factor that modulates the array radiated pressure field. The study of the array element directivity is important to assess the beam steering capabilities of the device. The beam pattern was computed by varying the mechanical boundary conditions applied to the array element, in order to investigate the effects of an acoustic isolation of the array element, achievable by performing trenches in the BCB layer or in both the BCB and the structural nitride. The results obtained for the device included in an infinitely extended structure are in good agreement with the measurement performed on the probe head prototype featuring the MCM, though some differences in the main lobe and side lobe level exist, probably due to the incorrect compensation for the hydrophone directivity applied.

The FEM model of the wide aperture multicell CMUT was used as a basis to model a flextensional array of circular membranes actuated by piezoelectric disks, housed inside the cavity and glued to the rear of the membrane. The transducer array was designed for broadband reception operation in concrete-coupled condition, in order to perform efficient acoustic emission measurements for the monitoring of concrete structures. The piezoelectric flextensional array design process was based on the computation of the device reception transfer function, obtained in concrete-coupled conditions by varying the geometrical parameters of the elastic plate, of the piezoelectric disks, of the structural layer and of the backing. The resulting device has a 200 kHz wide -6 dB reception sensitivity bandwidth around the center frequency of 112 kHz, thus is suitable for acoustic emission techniques applied to concrete structures.