System level modeling and design maps of PMUTs with residual stresses

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ABSTRACT

We report a system level approach for design of Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) with inclusion of residual tension. A multilayered circular plate model is used to derive the vibrational response of a PMUT subjected to, first a sinusoidal voltage input and second, a sinusoidal pressure load with frequencies near the first resonance of the PMUT. The model is simplified with the introduction of mode shape dependent nondimensional parameters that are found to change very little over a large range of design parameters. Introduction of these parameters leads to a tractable formulation for the forced response of the PMUT. Lumped model approach is used to derive expressions for overall performance parameters in terms of transfer functions of a PMUT acting as a transmitter, a receiver and a transceiver. These transfer functions are further used to develop parametric design maps of a PMUT with a given layer configuration (material and thickness of all layers) that enable us to easily track the effect of residual tension, vibrating area and the fundamental resonant frequency of the PMUT on the figure of merit in each of the three cases. Transition of PMUTs from plate regime to membrane regime on introduction of tensile residual stresses and corresponding difference in scaling of figure-of-merits with size have been verified experimentally. Using the design maps, we arrive at clear design inferences for a PMUT and show the difference in functional relationships between performance parameters and design parameters for plate type PMUTs and membrane type PMUTs.

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1. Introduction

Ultrasonic sensors are well known for various applications such as NDT, ultrasound imaging, and proximity sensing. Microfabrication techniques adopted from the semiconductor industry have significantly pushed the envelope of various sensor technologies including ultrasonics. These techniques make it possible to obtain an array of small ultrasonic transducers on Si wafers known as Micromachined Ultrasonic Transducers or MUTs. MUTs have not only led to improvements in conventional applications, such as 3D-ultrasound imaging, but also opened new avenues for ultrasonic sensor applications [1,2].

Based on the actuation principle, MUTs can be mainly classified as piezoelectric or capacitive type, abbreviated as PMUTs and CMMUTs, respectively. A CMUT uses electrostatic force to actuate a thin membrane suspended at sub-micron gap from the substrate. Smaller gap implies better sensitivity but it usually entails a complicated fabrication process [3,4]. A PMUT is a multilayered suspended structure whose fabrication involves deposition and patterning of various layers followed by etching out the substrate from the backside [1,5–7]. Recently, many applications of PMUTs have been identified such as gesture recognition [1], fingerprint sensing [8], intravascular imaging [9], and photoacoustic imaging [10,11] due to their low power consumption, small footprint, and CMOS integrability.

Design, fabrication, and application development of PMUTs has been an active area of research for almost two decades [1,12–14]. Most groups have relied on FEM models or analytical tools for design of PMUTs [15]. Murali et al. [12] and Akasheh et al. [16] have used analytical and FEM tools to design PMUTs with the objective of improving the electromechanical coupling coefficient and bandwidth for a given operational frequency. Structural response of prestressed circular plates have been studied earlier by Wah [17] and extended to PMUTs by Sammaoura et al. [18]. Reported plate theory based modeling studies of PMUTs are generally limited to structural response of specific PMUT designs [18,16,13,14].

Any engineering design usually demands a good grasp of various trade-offs based on a comprehensive understanding of the most important design parameters, their effect on intended per-
formance, and their intricate interdependencies. PMUTs are no exception. Although significant progress has been made in fabrication and application development of PMUT devices, a system level model that can help in design is still missing. At this stage, a design guide with key insights, tractable formulation, and complete end-to-end signal capturing can greatly help researchers and design engineers working on PMUTs.

Another important factor ignored in most of the current models is the treatment of residual stresses. The multilayer structure of a PMUT inevitably suffers from residual stresses which are highly process dependent [14,18]. A designer can either avoid the overall effect of residual stresses by adding material layers for stress compensation or consider the residual stress as a part of the design space. A PMUT can behave predominantly like a membrane or a plate depending on the relative magnitude of initial tension (residual stress integrated over the thickness) and the flexural rigidity of the PMUT. The effect of residual tension on the natural frequency of a PMUT is known (e.g., see [18,19,17,14]) but its effect on the overall performance of a PMUT is not understood yet. Although the net residual stress could be either tensile or compressive, we consider the case of net tensile stress in this paper. We have made this choice as PMUTs with significant net compressive stress are not desirable as they are likely to suffer from buckling related reliability issues in addition to sudden lowering of resonant frequency.

In this work, we aim to develop insights into design of a PMUT, along with differences in plate and membrane behaviour dominated regimes decided by the amount of residual tension, through system level modeling of the PMUT. Our approach, as depicted in Fig. 1, is to consider three possible scenarios for in-air operation of a PMUT: as a transmitter, as a receiver and as a transceiver.

For each case, we derive the end-to-end transfer functions through a simplified formulation that can directly give functional relationships between the figures of merit and various design parameters. The functional relationships are represented through parametric plots in size-tension design space along with isofrequency lines. This allows us to arrive at clear inferences about PMUT design. For example, we observe that the pressure transmitted by a PMUT is independent of its size and residual tension for a given thickness configuration, i.e., a larger low frequency PMUT will generate almost the same pressure as a smaller high frequency PMUT. In this study, we have limited the parametric analysis of PMUT performance and design variables to a case with given configuration of material layers and their respective thicknesses in order to maintain clarity in the design inferences.

2. PMUT structure and working

A PMUT is a multilayered plate structure with at least one piezoelectric layer sandwiched between two metal layers and one base structural layer (Fig. 2). The metal layers act as electrodes. This structure is also referred as a unimorph structure [20]. On the application of alternating voltage across the piezoelectric layer, the out-of-plane electric field generates in-plane stresses in the piezoelectric layer. These excess stresses are not symmetric with respect to the neutral plane of the unimorph, thus causing a net bending moment about the neutral plane (Fig. 2). Hence, flexural mode vibrations are induced when a sinusoidal input voltage is applied. The unimorph, vibrating in a flexural mode, pulsates the surrounding medium to generate an ultrasonic wave in the transmit mode. Conversely, an acoustic signal impinging on the structure induces vibrations, thus developing a potential difference across its piezoelectric layer. The best response of the PMUT, as a receiver and a transmitter is obtained when the signal matches the first resonant frequency of the PMUT.

The key steps involved in arriving at the functional relationships and the design maps for a PMUT are listed in Fig. 3.

Various parameters involved in design of a PMUT can be grouped into three categories: stack parameters, i.e., material properties and thickness of each layer; radial geometric parameters, i.e., radius of the PMUT and radius of the top electrode; and design dependent parameters, i.e., first resonant frequency. We include residual tension as a separate design parameter so that we can appreciate the effect of residual stress and resulting differences between the plate behaviour and membrane behaviour of a PMUT.

3. Structural response

The structural response of a PMUT obtained using classical plate theory is well known [18,17] and is given in brief in Appendix A for a quick reference. The structural response derivation presented in Appendix A invokes the following two important assumptions in addition to the assumptions of classical plate theory.

1. The top electrode is assumed to be uniformly spread over the PMUT. This allows us to analyze the multilayered structure using the classical plate formulation for a single layer circular plate with equivalent flexural rigidity and mass density. This assumption is reasonable when the top electrode is very thin compared to the overall structure. Our finite element analysis for a PMUT with radius \( a = 500 \text{ m} \), residual tension \( T_r = 130 \text{ N m}^{-1} \) and layer parameters as given in Table 1 shows that the first resonant frequency increase from 74.35 kHz for actual size of the top electrode \( (r_p = 0.8a) \) to 74.95 kHz if this assumption is used. This implies that assumption of the top electrode covering the PMUT introduces very small error in the solution for the first resonant frequency of a typical PMUT.
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