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A new acoustic transducer with a pressure-deformed piezoelectric diaphragm

Andrew S. Wixom[a], Michael J. Anderson[a,*], David F. Bahr[b], Dylan J. Morris[c]

[a] Department of Mechanical Engineering, University of Idaho, Moscow, ID 83844, USA
[b] School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164, USA
[c] Michelin Americas Research, Greenville, SC, USA

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ABSTRACT

A new design for wide-band acoustic transducers is described. Radial tension is applied to a thin piezoelectric diaphragm with conductive electrodes on the upper and lower surface. One side of the diaphragm is pressurized, elastically deforming the diaphragm into a slightly curved shape. The in-plane static tension is modulated by applying a time-dependent voltage across the electrodes of the piezoelectric diaphragm. The tension modulation causes transverse displacement oscillations of the diaphragm. This actuation takes place in spite of the fact that the piezoelectric diaphragm does not contain a passive elastic layer, which is necessary for actuation by flexure in planar diaphragms. A theoretical quasi-static model using hexagonal symmetry for the piezoelectric material was developed to predict the electromechanical actuation mechanism, and the mode for optimal operation in non-resonant conditions. Piezoelectric diaphragms were fabricated from PVDF film of nominal thickness 40 μm into circular diaphragms 1 cm in diameter. For the pressure-deformed transducers fabricated from PVDF film, displacement amplitudes of 9–14.5 nm/V were observed, and the maximum displacement amplitude took place at the applied tension and static pressure predicted by the model. Additional measurements with conventional flexure-type transducers containing a diaphragm consisting of a layer of PZT and a passive elastic material fabricated using MEMS processes were performed to compare with the transducers fabricated from PVDF film. The displacement amplitude per unit electric field measured for the transducers fabricated from PVDF film was comparable to those measured from conventional PZT flexure-type transducers, despite the fact that the piezoelectric coupling coefficient for PVDF was approximately 100 times smaller than that for PZT.

1. Introduction

In recent investigations, it has been found that a static-pressure deformed diaphragm has certain properties that make is potentially useful for electromechanical transduction. Amplifications in displacement amplitude of 39 dB relative to flexural excitation have been observed [1], and the means for optimal excitation through modulation in edge tension have been determined [2].

In the present work, the mechanics of a pressure-deformed diaphragm are exploited for a new transducer design. Unlike transducers that use a planar diaphragm excited by flexure, which require a passive elastic layer for excitation [3], the diaphragm for the new design is composed entirely of an elastic piezoelectric material that is slightly deformed by static pressure applied to one side. A passive elastic layer is not required for excitation.

PVDF films, albeit laminated to passive elastic support layers, have been used in curved cantilever structures for acoustic energy harvesters [4], and for acoustic transducers [5–7]. However in this work the structures operated in flexure, and a significant volume of the overall structure consisted of passive elastic support layers that could not contribute to energy conversion. Other geometries being used with PVDF for energy harvesting have noted that the performance of PVDF improves when loaded axially [8]. The choice of PVDF is noted in both these examples was partially driven by the general ease of handling and robust mechanical performance of this material.

The mechanics of actuation for a diaphragm consisting solely of a deformed piezoelectric film with negligible electrode thicknesses are different than those encountered for a diaphragm fabricated from piezoelectric and passive elastic layers. There would be no out-of-plane electromechanical actuation of a planar transducer fabricated from a polyvinylidene fluoride (PVDF) film. However, if the PVDF film is deformed from a planar shape, and tension is applied at the edges, it is plausible to expect that electromechanical actuation would occur. This is the central issue addressed in this paper – the nature of actuation of a deformed transducer fabricated from a free standing piezoelectric film, in this case PVDF.

The new design has several advantages. The first is that the transducer is not adversely affected by residual strain, which was the case for piezoelectric micromachined ultrasonic

* Corresponding author. Tel.: +1 208 669 1882; fax: +1 208 885 9031.
E-mail address: anderson@uidaho.edu (M.J. Anderson).

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transducers (pMUTs) [9–11] and an acoustic energy harvester [12] fabricated using MEMS processes. A second advantage derives from the fact that the geometry of bulk membrane stresses are ideally oriented relative to the electric field, so that actuation is optimized.

Theoretical modeling [3] predicts that residual stress in flexurally actuated piezoelectric diaphragm transducers reduces the electromechanical coupling coefficient k^2, and increases the natural frequency. Residual stresses are introduced by the MEMS fabrication process, for example as described in [9–11] with lead zirconate titanate (PZT) and AlN as the piezoelectric material. In the new design described here, the tension applied to the diaphragm is intentional, and causes the actuation mechanism to shift from flexure to in-plane membrane stress, with corresponding amplification in transverse displacement amplitude per unit actuation field.

According to Aronov [13], the electromechanical coupling coefficient of an arbitrary piezoelectric transducer will in part be determined by the relationship between strain and electric field geometries. The upper limit is the case for uniform strain in the expected direction for the corresponding electric field. This would be the case for a thin rectangular transducer, with electrodes on the top and bottom, and with uniform strain perpendicular to the thickness direction. In this case, the strain is uniform, unipolar, and everywhere perpendicular to the electric field. The electromechanical coupling coefficient k^2 for this transducer would be the same as for the bulk material, $k^2 = k_{13}^2$. A counterexample is a transducer whose diaphragm is composed of piezoelectric and passive elastic layers, clamped at the edges. In flexure, the strain magnitude in the piezoelectric layer varies across the thickness direction, and reverses polarity over the diaphragm area. If the electrodes extend over the entire diaphragm, the electric field is equal over the entire diaphragm. Because the strain reverses polarity under the electrode while the electric field does not, the electromechanical coupling coefficient k^2 for the device is significantly lower than the upper limit. To compensate, most designs limit the extent of the electrode to the center region of the diaphragm, an area in which planar strain is the same polarity as electric field.

The observations regarding actuation and strain geometry for piezoelectric transducers have relevance to the pressure-deformed transducer fabricated from PVDF film. When operated in the membrane mode, the strain takes the form of uniform stretching. The magnitude of the strain does not vary across the thickness direction, and is unipolar with respect to an electric field supported by electrodes that cover the entire diaphragm area. Because the electrodes cover the entire diaphragm, and the entire volume of the piezoelectric material is uniformly stretched perpendicular to the electric field, it is reasonable to expect that a pressure-deformed PVDF diaphragm would be advantageous compared to a planar diaphragm composed of piezoelectric and passive elastic layers. On the other hand, it is well known that the electromechanical coupling ability of PZT material is much higher than for PVDF material. The advantages accruing from strain geometry for the deformed PVDF film transducer discussed above are then counterbalanced by the degree of coupling provided by the piezoelectric material.

Experiments were conducted with pressure-deformed transducers fabricated from PVDF film. The performance of the pressure-deformed PVDF transducers was compared to conventional pMUTS fabricated from PZT on Si using MEMS processes. In spite of the fact that the effective piezoelectric coupling coefficient for PVDF film was a factor ~100 less than the PZT, the pressure-deformed PVDF transducers exhibited transverse displacement amplitudes per unit electric field comparable to the conventional layered pMUT fabricated with PZT.

2. Theory

A short summary of the theory predicting the mechanics of an elastic diaphragm deformed into a curved shape by an applied static pressure gives several insights into the expected broad band, non-resonant performance of a transducer fabricated from a PVDF film. The static center displacement, w_S, of an simple elastic diaphragm subjected to an applied static pressure P is the sum of behavior caused by flexure, edge tension, and elastic sheet stretching, respectively [14]:

$$P = Dw_S + \gamma_o w_S + \delta w_S^3, \tag{1}$$

where

$$D = \frac{1}{12\psi}\frac{E}{1-\nu^2}\frac{t^3}{a^4}, \qquad \gamma_o = d_1\frac{\sigma t}{a^2}, \qquad \delta = d_2\frac{E}{1-\nu^2}\frac{t}{a^4}, \tag{2a–c}$$

are the bending modulus, edge tension, and sheet stiffness parameters. Furthermore, E and ν are the Young's modulus and Poisson's ratio for the elastic material; a and t are the side dimension and thickness, and d_1, d_2, and ψ are parameters accounting for the aspect ratio of the side dimensions.

Recently, the physics of actuation for a deformed, pressurized diaphragm have been analyzed [2]. In this work, it was assumed that the mechanics of deformation were caused by applied tension, stretching, and flexure. This is the case for many transducers consisting of a thin diaphragm, composed of piezoelectric and passive elastic layers, fabricated using MEMS processes. In this circumstance, the normalized center displacement amplitude $\bar{w}$ for harmonic perturbation of the edge tension at a frequency suitably below the first resonance frequency was:

$$\bar{w} = V\left|\eta_B + \eta_\gamma\frac{1}{\gamma_o}\frac{\bar{w}_S}{1+3\bar{w}_S^3}\right|, \tag{3}$$

where $\bar{w} = w/w_C$; w is the (motional) center displacement amplitude associated with modulation in edge tension, $w_C = (\gamma_o/\delta)^{1/2}$; $\bar{w}_S = w_S/w_C$ is the normalized static center displacement; η_B is the coefficient relating applied voltage amplitude V to center displacement caused by flexure; and η_γ is the coefficient relating applied voltage V to modulation in edge tension. A conclusion drawn from this analysis was that optimal excitation of such a transducer will occur at a normalized static center displacement of $\bar{w}_S = 1/\sqrt{3}$, corresponding to the application of a normalized static pressure of $\bar{P} \approx 0.77$, where $\bar{P} = P/P_C$ with $P_C = (\gamma_o{}^3/\delta)^{1/2}$.

The optimal operation of a deformed transducer can be viewed in the load/pre-strain parameter space shown in Fig. 1. This type of diagram, originating in [15], categorizes the mechanical behavior of an elastic diaphragm as a function of two parameters; the load parameter β and pre-strain parameter α. These parameters are given by:

$$\beta = \log_\varepsilon \chi, \qquad \alpha = \log_\varepsilon \varepsilon_o, \quad \text{with} \quad \varepsilon = \frac{t/a}{2(3-3\nu^2)^{1/2}},$$

$$\varepsilon_o = \sigma\frac{1-\nu}{E}, \qquad \chi = \frac{1}{2}\frac{Pa}{Et}. \tag{4–8}$$

By computing these parameters for the three PVDF transducers developed in the following section, we can show that they operate solely in the membrane regions, both linear and non-linear. Operation of a deformed transducer with $\bar{w}_S = 1/\sqrt{3}$, $\bar{P} \approx 0.77$ is shown with a dashed line in Fig. 1. The circles near the dashed line represent experimental measurements, described in Section 4. As can be seen, optimal operation parallels the boundary between linear and nonlinear membrane mechanics, slightly into the nonlinear membrane region where the elastic stretching begins to dominate the mechanical response. Experimental measurements in [2] using