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Citation: Proc. Mtgs. Acoust. **38**, 045008 (2019); doi: 10.1121/2.0001068

View online: https://doi.org/10.1121/2.0001068

View Table of Contents: https://asa.scitation.org/toc/pma/38/1

Published by the Acoustical Society of America

Volume 38 http://acousticalsociety.org/

2019 International Congress on Ultrasonics

Bruges, Belgium

3-6 September 2019

Physical Acoustics: PUA (2/2) Presentation 6

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Ultrasound based mid-air haptic feedback devices can produce tactile sensations at any time and position without restricting human motion. This is useful for augmented and virtual reality, feedback buttons and virtual user interfaces. The haptic feedback mechanism is caused by acoustic radiation force and streaming. Typical solutions to induce haptic feedback reported in literature use arrays made up of 'standard' single element transducers and are heavy, rigid and bulky. A novel alternative uses printed polymer transducers (PPTs), which consist of piezomembranes created using a printing process. PPTs are light, fully flexible, have a thickness < 0.25 mm and can easily be integrated in curved surfaces. However, as the piezoelectric charge coefficients of P(VDF-TrFE) are lower than those of regular PZT5A/H, higher excitation Voltages are needed to achieve the sound pressures required for haptic feedback. In this work we report on the development of flexible large-area arrays based on PPTs for mid-air haptic feedback. Simulations and experimental results of test membranes and a 300+ membrane annular array prototype are presented. Extrapolating the results of the aforementioned array, the full size array is expected to produce radiation forces an order of magnitude above the tactile threshold reported in literature.

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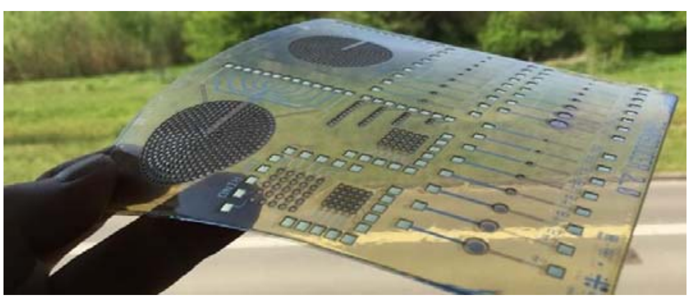
1. INTRODUCTION

Ultrasound based mid-air haptic feedback devices can produce tactile sensations at any time and position without restricting human motion. This is useful for augmented and virtual reality, feedback buttons and virtual user interfaces. The haptic feedback mechanism is caused by acoustic radiation force and streaming. Typical solutions to induce haptic feedback reported in literature use arrays made up of 'standard' single element transducers and are heavy, rigid and bulky [1,2]. A novel alternative uses printed polymer transducers (PPTs), which consist of piezomembranes created using a printing process. PPTs are light, fully flexible, have a thickness < 0.25 mm and can easily be integrated in curved surfaces. However, as the piezoelectric charge coefficients of P(VDF-TrFE) are lower than those of regular PZT5A/H, higher excitation Voltages are needed to achieve the sound pressures required for haptic feedback. In this work we report on the development of flexible large-area arrays based on PPTs aimed at mid-air haptic feedback applications.

2. SIMULATION AND EXPERIMENTAL SETUP

A. PROTOTYPE DEVICES AND MODEL DESCRIPTION

The PPTs consisted of a polyimide substrate, with a layer of P(VDF-TrFE) deposited on top using a printing process. The thickness of the piezomaterial varied, but was always below 30 µm. Metallic electrodes were used to create the element connections. The membrane edges were formed using a thick organic material. The thickness of the sheet remained below 0.25 mm. The sheet was fully flexible. The surface displacement, transfer functions, and acoustic far field response of PPTs with different geometries and materials were modeled in air. The model of the piezoelectric membrane was based on the description of Banks et al. [3]. The mechanical properties of the electrodes were neglected in the analysis since these were thin. The model was implemented in the Comsol FEM package. Numerous prototype sheets were constructed. Each prototype contained a variety of PPTs. The diameter of the PPTs ranged from 1.5 – 12 mm. Moreover, the PPTs were grouped in different configurations: single addressable membranes, linear arrays, matrix arrays (3x3 or 5x5 membranes) and annular arrays (> 300 membranes grouped in 10 rings, total array diameter 35 mm). Fig. 1a shows a typical prototype sheet and Fig. 1b displays a zoom of one of the annular arrays.

a) 

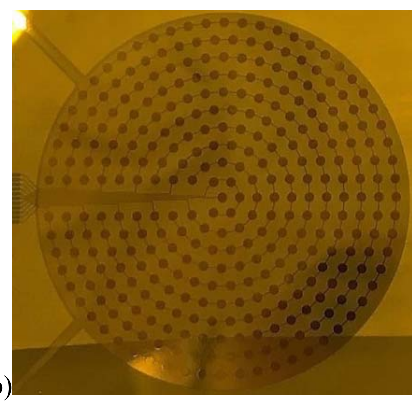
b) 

Figure 1. a) Image of a typical prototype sheet containing PPTs of various sizes and in various configurations, eg. linear, matrix and annular array configurations. b) Zoom of a PPT annular array.

B. VIBROMETER SETUP

A waveform generator (33250A, Agilent Technologies, Loveland Colorado, USA) generated linear chirp signals (-6 dB bandwidths 10 - 200 kHz, 100 ms in length, various center frequencies and amplitudes), which were 100x amplified (Voltage gain) by a power amplifier (7500, Krohn-Hite Corporation, Brockton, MA, USA) and routed to one or more PPTs. A laser scanning vibrometer system was used to measure the out-of-plane surface displacement of the PPT/group of PPTs. The sheet containing the PPTs was mounted in an XYZ scanner system (A3200 Npaq, Aerotech Inc., Pittsburg PA, USA), and moved with a step size of 0.1 mm. The vibrometer was a modular vibrometer (OFV-5000, Polytec GmbH, Waldbronn, Germany) and used an OFV-552-1 differential fiber laser interferometer. An OFV-MR lens was used to focus the laser beam (spot diameter ~50 µm). The analog output of the vibrometer was proportional to the measured velocity using either a VD-09 Digital

Velocity Decoder or a DD-900 Digital Wide Range Decoder and digitized using a digitizer (MI.3025, Spectrum Instrumentation, Grosshansdorf, Germany) at a 1 MHz sample frequency.

3. RESULTS AND DISCUSSION

Table I shows the fundamental mode resonance frequencies in air as a function of the membrane diameter obtained using modeling and measurements. The modeled and measured resonance frequencies showed good agreement and followed a 1/diameter^2 relation. The difference between the model and experimental results increased for larger membrane diameters, which was likely caused by unexpected variations in the geometry and material properties of the membranes (notably the edges).

Table 1. Fundamental resonance frequencies for various membrane diameters obtained using simulations and measurements.

Membrane diameter [mm]	Modeled resonance [kHz]	Measured resonance [kHz]
2	30	30
4	7.4	7.7
6	3.2	3.7
12	0.78	1.2

Laser vibrometer measurements of the out-of-plane peak displacement of a 2 mm membrane at its fundamental mode resonance frequency of 29.5 kHz showed that the peak displacement followed a linear relation as a function of the excitation Voltage up to 1000 V_{pp}. The peak out-of-plane membrane displacement was 1.6 µm at 1000 V_{pp}. The measurement distortion was low with a 2nd harmonic level <-45 dB compared to the fundamental. The integrity of the PPT stayed intact even after several hours of continued measurements at Voltages up to 1500 V_{pp}.

Fig. 2 shows a snapshot of the measured out-of-plane displacement in nm for the annular array shown in Fig. 1b. All membranes were excited at the fundamental resonance of 66 kHz.

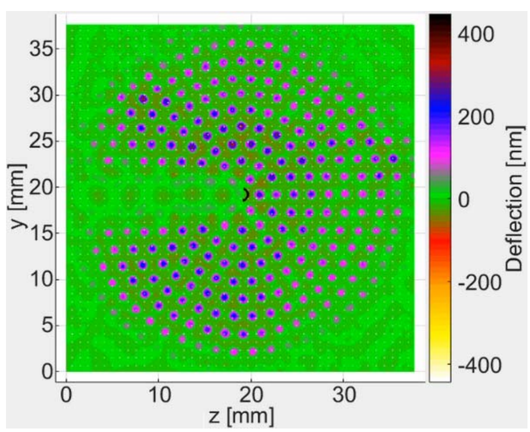


Figure 2. Snapshot of the out-of-plane displacement in nm recorded of the annular array (see Fig. 1b) membranes near their 66 kHz resonance frequency. All elements were excited with a 100 V chirp.

Fig. 2 shows that the inter-element phase differences were limited. The membrane peak displacement occurred first in the center and then moved radially outwards. There was some variation in the peak out-of-plane surface displacement, which will be quantified in Fig. 4. The outer ring of membranes showed significantly lower out-of-plane surface displacement. These membranes were not electrically connected and the displacement was caused by acoustic crosstalk. Said crosstalk was caused by the large opening angle of the PPTs and by an A_0 Lamb wave propagating in the sheet itself. Fig. 3a shows a histogram of the fundamental membrane resonance distribution of the annular array shown in Fig. 1b. Fig. 3b shows a map of the fundamental mode resonance frequencies of the membranes.

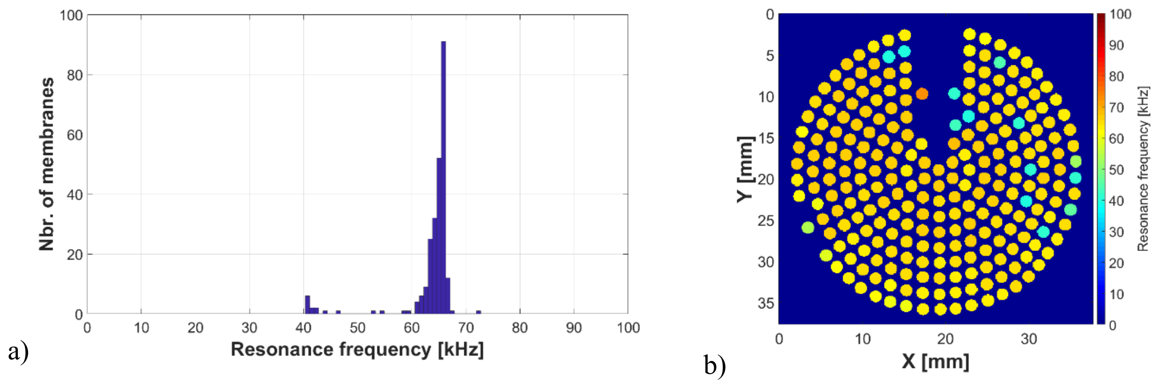


Figure 3. a) Histogram detailing the nbr. of membranes vs. the resonance frequency. b) Schematic plot showing the resonance frequency for each working annular array membrane shown in Fig. 1b.

The histogram of Fig. 3a shows the narrow resonance frequency distribution of the functioning membranes in the annular array. Some outliers are visible. The schematic of Fig. 3b indicates that there is no clear grouping of the outliers. Fig. 4a displays a histogram detailing the out-of-plane peak displacement distribution of the membranes in the annular array shown in Fig. 1b. Fig. 4b shows a map of the out-of-plane peak displacement for each working membrane.

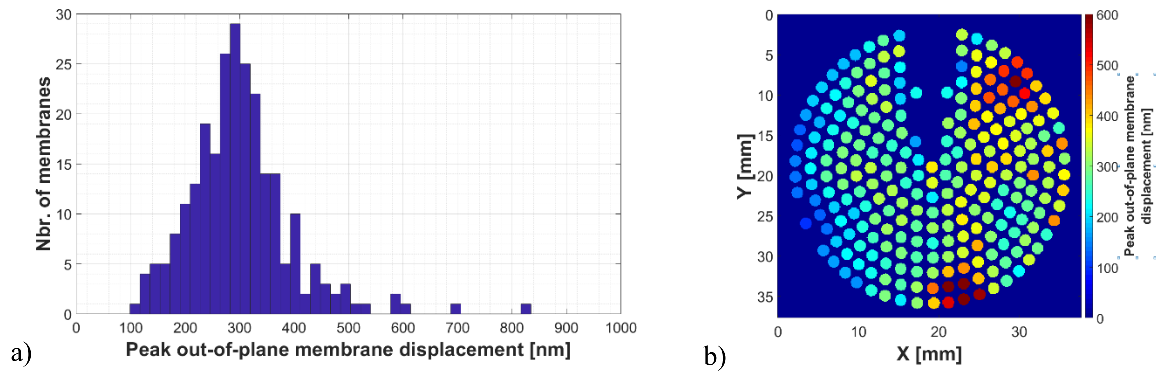


Figure 4. a) Histogram detailing the nbr. of membranes vs the out-of-plane peak displacement. b) Plot showing the out-of-plane peak displacement for each working annular array membrane (see Fig. 1b).

Fig. 4a shows that the out-of-plane peak displacement of the membranes ranged from 145 to 439 nm with a mean of 242 nm. Fig. 4b indicates that the variation of the out-of-plane peak displacement was approximately random, except for a region at (22 mm, 35 mm) and a region at (30 mm, 9 mm). The cause was localized delamination, leading these regions containing multiple membranes to also vibrate as a whole at a lower frequency. Said low frequency vibration mode had a larger amplitude than the fundamental membrane mode.

Based on the results of the previous sections a full size PPT based array (annular, 30x30 cm^2 area, 32 elements – 17 full rings, 15 ring-parts) was designed. Each element consisted of many PPTs (radius 0.88 mm, resonance frequency 40 kHz in air, fill grade 50%) connected in parallel. The focal distance was set to 30 cm and the excitation Voltage was 500 V. The peak out-of-plane membrane displacement of a PPT resonating at 40 kHz was calculated at 2.5 nm/V. An equivalent piston-like mean displacement of 0.42 nm/V was calculated for the full array. Taking into account diffraction (using eq. 34 of [4]) and the sound attenuation, a peak pressure of 152 dB re. 20 µPa was calculated. Using the equations derived by Nowicki et al. [5] a 0.88 m/s acoustic streaming peak velocity was calculated producing a peak force of 0.29 mN at focus (tactile receptor radius 1 cm). Moreover, an acoustic radiation force of 2.7 mN was calculated using eq (1) of [1]. This was 1 order of magnitude higher than the tactile radiation force threshold of 0.3 mN reported in literature [6].

4. CONCLUSION

Encouraging results of single PPTs and PPT arrays were presented. Based on this the performance of a full size array prototype was calculated, which showed that haptic feedback using PPTs appears feasible and realistic. This paves the way for free space haptic feedback based on ultrasound, where deformable and flexible ultrasound emitters are integrated seamlessly in other objects, such as car dashboards.

ACKNOWLEDGMENTS

This work has been supported by the EU-funded H2020 ECSEL project SILENSE (ID 737487).

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