Improving Performance of Ultrasound Transducers with Aerogel Matching Layer for Tactile Display

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***Abstract*—Focused ultrasound is emerging as a novel technique for mid-air tactile display. A striking limitation is the low transduction of ultrasound energy due, in part, to the massive acoustic impedance mismatch between the piezoelectric transducer and air. This paper investigates the use of silica aerogel alloys as a matching layer to improve transduction efficiency in air for mid-air tactile display. Two transducers are manually machined and evaluated to proof-concept the theory proposed in this paper. Results demonstrated that the manually machined transducers produce 2-3 dBV acoustic energy in air compared to the commercially available transducer. Future work involves exploring an automated process to machine a large number of these transducers and buiding an array with the modified transducers in order to perceptually evaluate the performance for tactile display.**

***Index Terms*—mid-air tactile display, ultrasound transducer, matching layer, silica aerogel alloys**

I. INTRODUCTION

Haptics are key technologies that utilize touch to enhance the user experience in many human-computer interaction applications [1]. In particular, tactile stimulation is of high interest in the haptic research community, specially in the areas of tele-operation [2], health care [3], virtual reality [4], and entertainment [5]. Tactile displays are fundamentally based on two approaches: contact-based and contactless. Contact-based approach utilizes a wearable device (e.g. a glove or a jacket) equipped with vibration motors to provide tactile stimulation [6]. One problem with this approach is that users must wear the device in advance in order to feel tactile stimulation (challenges related to size, hygiene, usability, and quality of the haptic signal are commonly cited) [1].

The contactless approach overcomes contact-based approach challenges by transmitting tactile cues via air without wearing any device, such as air jets [7], air vortices [8], laser [9], or focused ultrasound [10]. Focused ultrasound is emerging as the most efficient contactless tactile display method because of its high spatial and temporal resolution. Focused ultrasound approach utilizes two-dimensional (phased) array of ultrasound transducers to emit acoustic waves that are superimposed to form tangible acoustic pressure at a pre-calculated location in 3D space (called the focal point) [11].

Despite the intense research and development of ultrasound-based tactile stimulation approach, several challenges remain unaddressed. First of all, the intensity of tactile stimulation seems very limited (in the range of mN of force), which is barely perceived by the human palm (this is why most ultrasound technologies display tactile sensations at the palm). Other challenges include limited workspace (ultrasound wave attenuates drastically over distance), sophisticated development, high power consumption, and high cost.

Existing ultrasound transducers, such as the MA40S4S 40 kHz Murata transducer, are widely used for midair tactile display applications but were designed to serve a completely different application, such as . These types of transducers are commonly utilized for distance measurement, obstacle detection, simple imaging applications and are commonly driven in a pulsed echo mode instead of a continuous wave mode . This driving mode creates the necessity to optimize for the input sensitivity of the transducer [12]. Regarding the mid-air ultrasound tactile display the driving mode is, generally, continuous wave mode and there is no need for input sensitivity optimization.

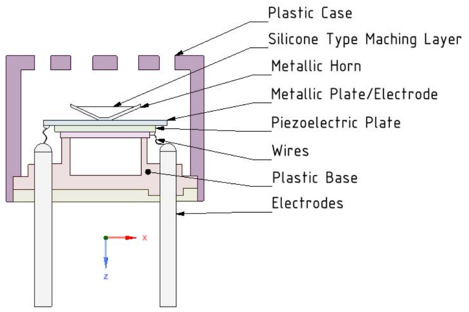

Fig. 1. MA40S4S cross section

The MA40S4S is designed by adding on top of the piezoelectric element several types of matching layers with different acoustic impedance as well as a horn structure serving as a matching layer. A layout of the different components of the transducer is shown on its cross section at Figure 1. A circular thin steel plate is placed above piezoelectric element which shifts the coupled structure to a much lower resonance frequency. Above the thin plate the Horn type layer is placed. The horn type matching structures have been described by

Fletchers and Thweites [13] as effective acoustic impedance matching structures that can reduce the impedance mismatch between air and the piezoelectric element. Finally, the last matching layer of the MA40S4S is a silicon type material which has an acoustic impedance that is closer to the air in comparison with the other matching layers but it is still several orders of magnitude higher than the acoustic impedance of the air. The material structure was captured by a scanning electron microscope and is shown on figure I and figure 3. (Flexural mode of vibration has to be described too)

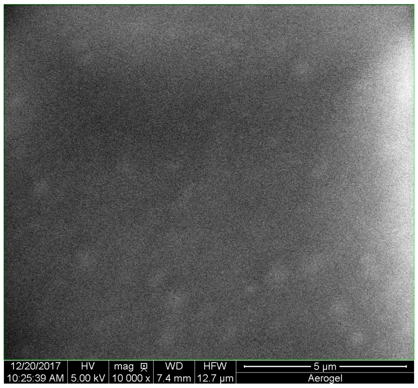

Fig. 2. Silicon structure under scanning electron microscopy

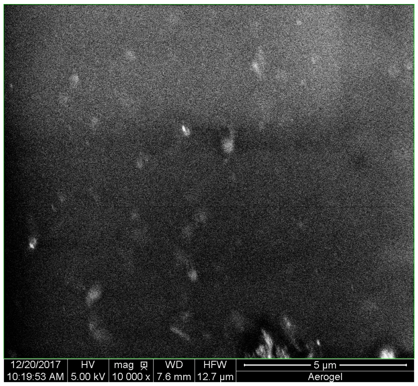

Fig. 3. Airloy structure under scanning electron microscopy

In this study, we modified the aforementioned transducer by replacing its matching layers with one very low acoustic impedance matching layer based on Polymer Cross-Linked Aerogels (X-Aerogels) which were machined by hand to fit the horn structure dimensions (figure 4). The remainder of the paper is organized as follows: Section 2 presents the related work and briefly describes the contribution of this study. The experimental setup and procedure are described in section 3. The experimental results, along with a discussion based on the results, are presented in section 4. Finally, section 5 summarizes the paper findings and provide perspectives for future work.

II. Related Work

The development of midair ultrasound tactile displays has been very intense the past few years. Early work by Dalecki et al. showed that tactile sensation was possible through ultrasound radiation using water as a coupling medium [10]. The field of mid-air ultrasound tactile display has been vastly extended since then to improve the quality of tactile rendering (improving workspace and intensity [11], temporal/spatial resolution [14] [15], and applications [16] [17]). Recently, the industry is involved in ultrasound-based tactile display manufacturing such as Ultrahaptics[1] and Emerge [2]. All the aforementioned ultrasonic systems involve transmitting ultrasound energy through air. In such applications, efficient transduction of ultrasonic energy from the piezoelectric transducer to air is a topic of considerable interest.

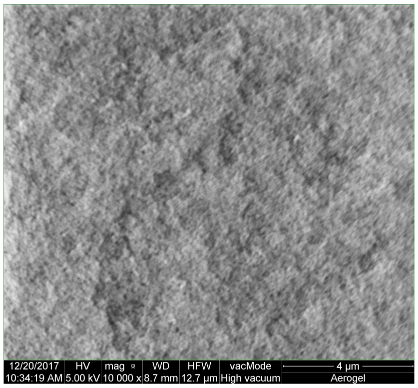

Fig. 4. Aerogel structure under scanning electron microscopy

A common strategy to maximize the total transmission power is the quarter-wavelength $\lambda/4$ thick matching layer and variations of this configuration such as $\lambda/8$ [18] and $(n{+}1)\lambda/4$ [19], stacks of $\lambda/4$ layers, half-wavelength configurations ($\lambda/2$) [20], and a stack of very thin matching layers whose total acoustic thickness is $\lambda/4$ [21]. The success of this method depends significantly on available materials with the intended characteristic acoustic impedance and thickness in order to be used as the matching layer.

Impedance matching layers for air interface applications need to have density and sound speed close to that of air while the layer must be made from a solid material. Such materials are uncommon, have limited practicality, or suffer from high absorption loss [22]. But the $\lambda/4$ matching layer strategy applies mainly to the thickness mode of vibration whereas in flexural mode the matching layer should have similar thickness but it should be attached around the area of the maximum displacement.

Several materials are assessed for their potential to act as a matching layer. These layers include thin sheets of material that are formed from polyaimide Aerogels [23] and filtration membranes that have been characterized previously with plate/transmission methods [24]. The absorption loss, characteristic impedance and other relevant parameters have been previously determined for these filter membranes [22]. For the polyaimide Aerogels, only material properties such as density and Youngs modulus are available. Acoustic properties

[1] www.ultrahaptics.com

[2] www.emergenow.io

such as impedance and sound speed must be derived from the material properties for the Aerogel materials.

Silica Aerogels have exceptional thermal properties which revolutionized the thermal and insulation applications but more recently the acoustic properties are also been under investigation from the scientific community. Aerogels offer several unique features that enable it to function as a matching layer. The most notable characteristic is its extremely low static density which is directly related to the very high porosity of the structure shown in figure 4, making it much closer to that of air compared to other types of elastic solid and thus giving a relatively low acoustic impedance. Acoustic impedance matching materials for coupling 200 kHz ultrasonic signals from air to materials with similar acoustic properties to that of water, flesh, rubber and plastics are examined in [25]. Results demonstrated that a single impedance matching later consisting of these new aerogel materials will recover nearly half of the loss in the incident-to-transmitted ultrasound intensity.

Material requirements to produce impedance matching layers for air-coupled piezoelectric transducers are investigated in [22]. In particular, variation of the attenuation coefficient with frequency has been measured for several materials where best properties were observed in polythersulfone and nylon membranes. Guild et al. [26] examined the use of Aerogel as a soft acoustic metamaterial for airborne sound. Other studies focused on utilizing Aerogels as a matching layer for air-coupled piezoelectric transducers for the frequency range 0.3-5 MHz. This frequency range is of special interest for applications related to material characterization, nondestructive testing, and surface analysis, but not suitable for mid-air tactile display due to extreme attenuation.

III. AEROGEL ALLOYS AS MATCHING LAYER

A. Theoretical Background

The work described here investigates acoustic impedance matching materials for coupling pressure waves in the region of 40 kHz from piezoelectric transducers in flexural mode of vibration to air, for the application in mid-air tactile display. The 40 kHz band is selected primarily due to the availability of high power transducers, associated electronics, and common use in mid-air tactile display applications.

Silica Aerogels seem to be the ideal material to serve as a matching layer for an air coupled ultrasonic transducer. This is partially true since Silica Aerogels brittleness makes them practically unusable especially to serve matching layers when attached to a highly vibrating surface such as the piezoelectric transducers [27]. Recent advances in material science have proposed Aerogel alloys types such as the cross coupled Aerogels which are Aerogels coupled with polymers or other cross linking agents to improve either their thermal properties or their structural properties. Polyamide/Polymer Aerogels are the type of cross coupled Aerogels which have a higher density than the Aerogels (about 2 to 10 times) but they are about 100 times more robust. These types of Aerogel Alloys are machinable, robust and can easily adhere on vibrating surfaces such as a piezoelectric transducer [28].

There are three main theories which can determine the optimal matching layer for an air-coupled transducer namely the Chebychev, Desilets and Souquet theories [29], defined by equations 1, 2, 3 respectively.

$$Z_m^{Ch} = \sqrt{Z_t Z_a} \tag{1}$$

$$Z_m^{Des} = \sqrt[3]{Z_t Z_a^2} \tag{2}$$

$$Z_m^{Souq} = \sqrt[3]{2 Z_t Z_a^2} \tag{3}$$

Where Z_m is the matching layer acoustic impedance and Z_t,Z_a are the acoustic impedances of the transducer and air respectively. The acoustic impedance of air is about 400 Rayl and the acoustic impedance of the piezoelectric transducer is about 35 MRayl. Feeding these values to equations 1, 2 and 3 yields an acoustic impedance of about 0.11 MRayl, 0.017 MRayl and 0.021 MRayl respectively. The three different theories producing somehow different results for the optimal acoustic impedance of the matching layer but, nevertheless, it is clear that the matching layer material has to have an acoustic impedance several orders of magnitude less than the corresponding acoustic impedance of the piezoelectric transducer. The characteristic acoustic impedance of the Airloy X103L Aerogel Alloy is $Z = \rho c =$ 0.044 MRayl which lies within the range proposed by the three aforementioned theories.

B. Experimental Setup and Procedure

In order to validate the theoretical efficiency of the Aerogel alloy matching layer acting over a commercially available ultrasound transducer we modify the Murata MS40S4S ultrasound transducer by replacing its matching layers with the Airloy-X103L Aerogel Alloy (Figure 4) matching layer. The new matching layer has the same dimensions as the original transducer's matching layer (Figure 5). We measure the frequency response and the acoustic beam directivity of the regular and the modified transducers and compare the results.

Fig. 5. Left: Modified transducer, Right: original transducer

The experimental setup (Figure 6) is composed of the transducer base (Figure 7), a signal generator, an oscilloscope and a laptop. The transducer is placed on its base across the receiver about 8 cm apart and is driven by the signal generator with a sinusoidal signal of variable frequency from 30 kHz to 60 kHz which is the region of resonance of the commercial transducer. The oscilloscope acquires the signal through a Fast Fourier Transform. The laptop controls and records the data acquired by the oscilloscope for each different transducer. Because the matching layers were machined by hand some discrepancies between samples are expected. For this reason, measurements in this experiment are taken with two different modified transducers in order to have more consistent results. Finally, because the purpose of the study is to compare only the performance of the different matching layers, other factors such as the transducers protective cap which acts as a passive speaker and the bonding between the transducer and the matching layer had to keep the same or eliminated. For this reason, the cap of the transducer was stripped completely off and all the transducers disassembled and assembled again with the same adhesive for both the commercial and the modified transducers. In total, three transducers were used as samples in this study: two modified transducers with Airloy X103L as a matching layer and one commercial unmodified transducer. The frequency response was measured in dBV which is given by equation 4

$$L_V = 20\log_{10}\frac{V}{V_0},\ V_0 = 1Volts \tag{4}$$

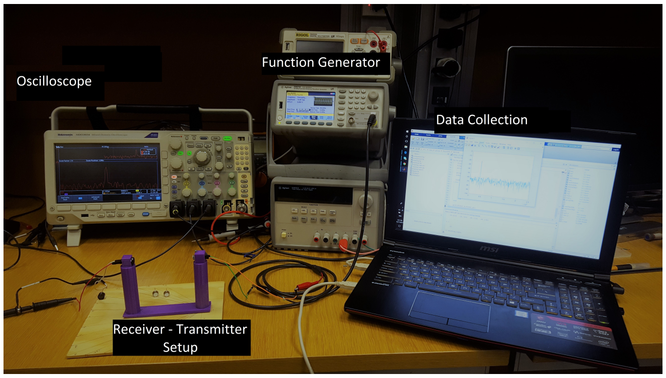

Fig. 6. The experimental Setup

In order to measure the directivity of each sample, the same setup was used in a slightly different fashion. The transducer base was designed to rotate manually around the receiver at 7.5 degrees steps in a fixed distance of 8 cm away from the receiver. A MATLAB script was used to control the procedure and record the peak transducer response at each 7.5 degrees angle step. The measured beam directivity range was from -60 degrees to +60 degrees.

IV. RESULTS

The frequency response for all of the transducers and the average of the two modified transducers is shown in Figure 8. As for the original transducer, its peak frequency has slight shifted from 40kHz to 41.8kHz as expected after the cap removal and reassembling it. One of the modified transducers yielded around 6dBV more intensity compared to the commercial transducer. Also its peak frequency has shifted close to 42.5kHz. Finally the second modified transducer yielded about 1.8dBV more intensity than is commercial counterpart at a shifted frequency of of 45.5kHz. The average power for the modified transducers is around 3dBV more than the commercial counterpart.

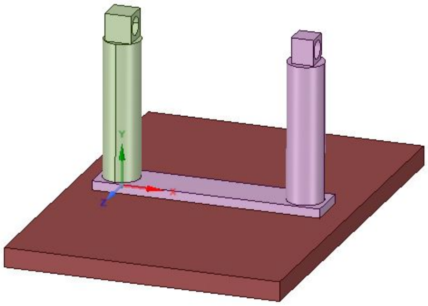

Fig. 7. The 3D design of the transducer-mic base

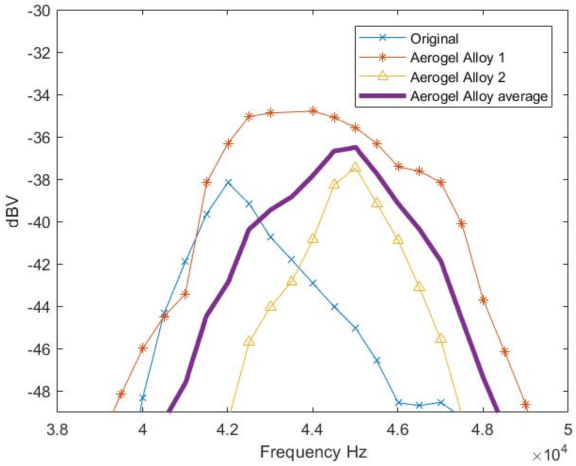

Fig. 8. Transduction intensity frequency response

The directivity of each transducer, normalized with respect to the minimum dBV measurement, is presented on Figure 9. It is notable that the beam directivity angle of the full width half maximum of the modified transducers is similar to the regular transducer's but the modified transducers still perform better within the measured range.

Furthermore, there is asymmetry for all the different transducers which is probably due to the fact that the matching layers where bonded to the piezoelectric element by hand and they were not accurately placed in order to produce the same directivity pattern. Nevertheless, Figure 9 clearly shows that the peak directivity occurs close to 350^o for all the modified transducers which is about 10^o off than the design peak directivity.

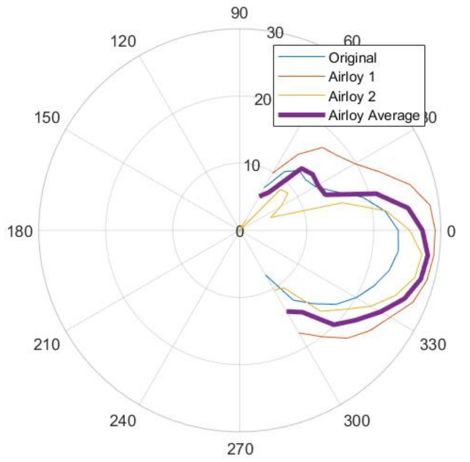

Fig. 9. Directivity response

V. DISCUSSION

The experimental results clearly validate the theoretical efficiency of the proposed aerogel alloys matching layers over the commercial ones. However this result is marginal since in average the intensity was improved about 3dBV and there are also big discrepancies in the response curve of the two different Aerogel alloy maching layers. These discrepancies are due to the fact that the matching layers were machined by hand. The second major observation has to do with the impedance matching between the transducer and the air. The acoustic impedance for the single matching layer was theoretically found to be between 0.021 MRayl and 0.11 MRayl. The use of a cross coupled Aerogel Alloy with an acoustic impedance of 0.044 MRayl serves well as a matching layer between the transducer and the air. This modification increases the sound intensity of a commercial transducer in comparison to its prior matching layer to air.

The directivity that was measured at the peak frequency response for all the transducers is showing a somehow narrow beam width (about 40^o) at the full width half max. This is clearly a disadvantage since in midair tactile display applications the total force is obtained by the superposition of the different contributions of the transducers operating on the phased array. A narrow beam width could reduce the working space significantly. The peak response directivity is observed to be 10^o off from the desired design directivity of a commercial transducer and the reason for this is that the matching layers were bonded manually to all the transducers. Finally, an asymmetry is observed through all the transducers in their directivity patterns. This asymmetry probably has to do again with the manual bonding and the manual machining of the matching layers also when it comes to the transducers with the modified matching layers.

VI. CONCLUSION

In this paper we demonstrate that by modifying the matching layer of a commercial transducer, which is common in mid-air ultrasound tactile display applications, a more efficient energy transfer from the piezoelectric element to the air can be achieved. The use of Aerogel alloys as matching layers can reduce even more the acoustic impedance mismatch between the air and the transducer and, thus, transfer more energy. However, machining and bonding manually the matching layer to the piezoelectric element causes slight inconsistency in behavior in terms of beam directivity and peak resonance frequency when compared against the design specifications. This could be avoided if an automated method is used to produce and bond these matching layers to the piezoelectric transducer. Therefore, the future of this project is to create an automated process to machine the matching layer and build a 2D array of ultrasound array with the modified transducers. A usability study to compare the perceptual differences between the commercial and modified transducers array.

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