"Pipe Organ" Air-coupled Broad Bandwidth Transducer

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***Abstract*—Air-coupled transducers are used to conduct fast non-contact inspections in NDT. Normally, the bandwidth of a conventional transducer can be enhanced, but with a cost to its sensitivity. However, low sensitivity is very disadvantageous in air-coupled devices. This paper presents a methodology for improving the bandwidth of an air-coupled micro-machined ultrasonic transducer (MUT) without sensitivity loss by connecting a number of resonating pipes of various length to a cavity in the backplate. The design is inspired by the pipe organ musical instrument, where the resonant frequency (pitch) of each pipe is mainly determined by its length.**

Keywords—Air-Coupled; Broad Bandwidth; 3D Print; NDT/E; Ultrasonic Transducer; MUT

I. Introduction

Air-coupled transducers are widely used to conduct fast non-contact inspections for many materials including wood, electronic packages, aero-space carbon fiber, honeycomb structures, sandwich laminates and so on [1]. This technology can also improve the ease and the speed of non-destructive testing (NDT) [2]. The most common air-coupled transducers are piezoelectric bulk and micro-machined transducers (MUT). Many research studies [1,2,3] indicate that compared with piezoelectric devices, MUTs have a greater bandwidth and are better coupled to air, but have a lower sensitivity. Moreover, the bandwidth of a conventional piezoelectric bulk transducer can also be further enhanced by a backing layer, but with a cost to its sensitivity [1,2]. The aim is therefore to design high sensitivity devices for air-coupled NDT. This paper presents a methodology for improving the bandwidth of air-coupled MUT transducers without sensitivity loss by using a novel design of backplate.

A pipe organ produces sound by driving pressurized air into each individual pipe via the keyboard and pump system. The shape of individual pipes affects the sound produced. However, the resonant frequencies of pipes are mainly determined by the length of the pipes and the velocity of sound. The resonant frequency can be calculated by the theory of pipes [4] which states that the fundamental resonant frequency of an open pipe (both ends open) occurs when the length of pipe is equal to $\lambda/2$ and the fundamental resonant frequency of a closed pipe (one end is closed and the other end is open) occurs when the length of pipe is equal to $\lambda/4$, where λ is the wavelength of sound. The resonant frequency of open cylindrical pipes is given by equation (1), where n is a positive integer which represents the resonance node, v is the speed of sound in air, L is the length of pipe and r is radius of the pipe.

$$f_o = \frac{nv}{2(L + 1.6r)} \tag{1}$$

Figure 1(a) is a standard MUT design. Basically, this device consists of a thin diaphragm over a rigid backplate where the resonance of the membrane depends on the size of cavity and the membranes' material [3]. The new pipe organ transducer is based on this conventional design, but connects many acoustic amplifying pipes with different lengths to the backplate (as in Figure 1(b)). The design stage involves optimising each pipe's length so their resonant frequencies are very close but not equal to the membrane's resonant frequency and in so doing the overall bandwidth is increased. The pipe organ backplate can be thought of as a "musical instrument" which can play different frequencies (pitches) at the same time.

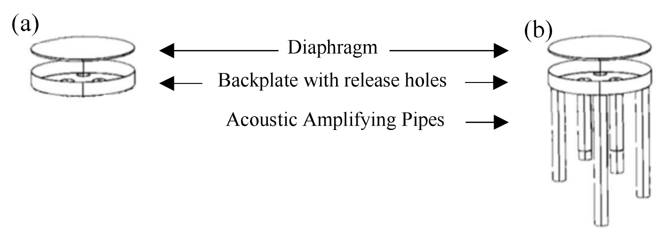


Figure 1. (a) Conventional micro-machined transducer, (b) Pipe organ transducer.

The next section describes the design and manufacture of the pipe organ transducer, including the 1D mathematical simulation, 3D finite element (FE) simulation and 3D printing of the pipe organ backplate. Section 3 describes and analyses the experimental results in order to demonstrate that the pipe organ backplate can improve the bandwidth of the MUT without sensitivity loss. Section 4 then gives conclusions for the work.

II. Methodology

A. 1D Mathematical model

The mathematical model used in this paper is a transmission line model introduced by Walker and Mulholland [5,6]. This 1D

The work was supported by the Engineering and Physical Sciences Research Council (EPSRC) under grant EP/L022125/1, and by the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. [615030].

model can simulate the transmission voltage response (TVR) and reception force response (RFR) of both a conventional transducer and the pipe organ transducer. The bandwidth and sensitivity of both transducers can then be calculated and compared. Generally speaking, the 1D mathematical model can be divided into 3 parts. First of all, the acoustic impedance of one amplifying pipe is computed. Secondly, a lumped impedance profile of the entire backplate is calculated, which includes many amplifying pipes with different lengths and an air-filled cavity. Finally, the membrane's displacement model is inserted into the backplate's model to compute the bandwidth and sensitivity of the TVR and RFR. This model runs extremely quickly and takes less than 1 second for each design.

Table 1. Initial parameters of backplate design.

Design Parameters	μm
Height of cavity (h)	35
Diameter of pipes (d)	52
Radius of cavity/membrane (R)	300

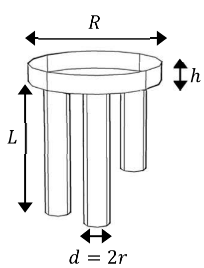


Figure 2. Parameters of the pipe organ backplate.

In order to set up the simulation, the material and the size of each component on the transducer must be considered. The initial parameters of the backplate design are given in Table 1 & Figure 2 and five thousand different designs are simulated and compared. Each design is given a random number of pipes from 10 to 100. Each pipe has the same radius but the length was randomly chosen from a linear distribution between 0.4mm and 1.4mm. The bandwidth of the TVR and RFR are generated and plotted against the number of pipes as shown in Figure 3.

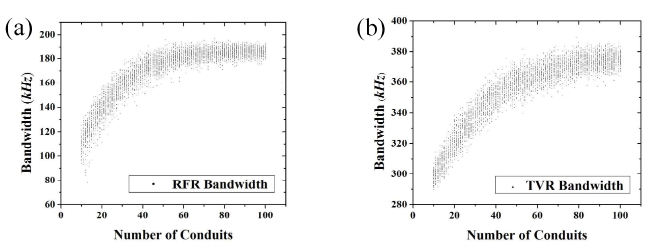


Figure 3. The bandwidth of (a) RVR and (b) TVR measured from 5000 sample devices. Plots are generated from the 1D mathematical model [5,6,8].

The 1D mathematical model indicates that the more amplifying pipes present in the device, the larger the bandwidth improvement. And if the pipe number is more than 90, the bandwidth will no longer be significantly improved.

B. 3D FEA model

Even though the 1D mathematical result suggests around 90 pipes for the backplate, in this work there are manufacturing constraints and so a study of 8 pipes emerging from the back cavity is presented. Figure 4(a) is a schematic of the pipe organ transducer which is simulated by using a commercial FE software COMSOL Multiphysics (Comsol AB, Stockholm, Sweden) to further optimize the design parameters. The transducer is located in the middle of the spherical computational region and surrounded by an air sphere. This model can calculate the resonant frequencies of the circular membrane, pipes and cavity accurately and can simulate the coupling effect between them. After considering the limitations of manufacturing and optimizing the coupling of pipes and the circular membrane, the practical parameters of the backplate are given in Table 2. Figure 4(a) indicates that the resonance frequency of the membrane is 34 kHz. Figure 4(c) (d) and (e) are the pressures inside the pipes and the cavity. When the frequency of the incident sound is 27 kHz, the shortest pipe starts to resonate. When the frequency is 36 kHz, the longest pipe reaches its resonance. When the frequency is 11 kHz, all the pipes are coupled together with the cavity and start to resonate. The pipe organ backplate has introduced the different pipes' resonances between 27 kHz and 36 kHz in order to improve the bandwidth of the membrane, and a Helmholtz resonance located at 11 kHz that will improve the overall sensitivity. Compared with the 1D mathematical model, the 3D FE model took ~2 hours for each design, but is much more realistic.

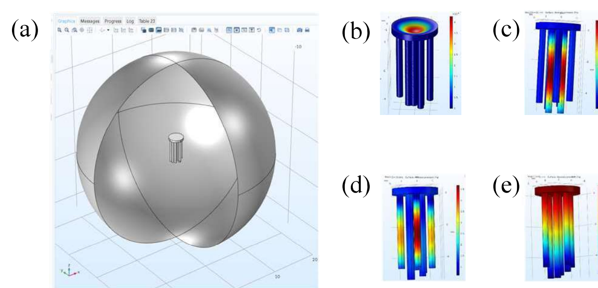


Figure 4. (a) Schematic of the COMSOL Model. (b) The circular membrane resonates at 34kHz. The pressure (resonance) in the pipes and cavity when frequency is (c) 36kHz (d) 27kHz (e) 11kHz.

Table 2. Practical parameters of the backplate design.

Device (mm)	8 pipes	4 pipes	0 pipes
Height of cavity (h)	0.4	0.4	0.4
Diameter of pipes (d)	0.48	0.6	n/a
Radius of cavity/membrane (R)	1.5	1.5	1.5
Length of pipes (L)	5.4 5.4 5.2 5.0 4.8 4.6 4.4 4.4	5.0 4.8 4.8 4.5	n/a

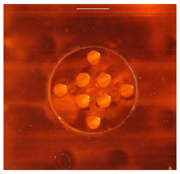
(a)  (b) 

Figure 5. (a) Plan view of the 3D printed pipe organ backplate, (b) £1 coin and 3D printed pipe organ backplate for scale.

C. *3D Printing*

After building a CAD model, an Asiga Pico Plus 27 3D printer was utilized to fabricate the pipe organ backplate (see figure 5). This is a commercial stereolithography 3D printer with 27 µm resolution in the X-Y plane and 1 μm resolution in Z plane. Instead of using commercial resins directly, the improved resins [7] we used in this project are prepared by mixing Polyethylene (glycol) Diacrylate (PEGDA) along with (2, 4, 6-trimethylbenzoyl) phenylphosphane oxide (Irgacure 819) (1% by weight) and Sudan I (0.1% by weight) vigorously in a spinner. Hua Gong et al [7] proposed that the resins formed by this improved formula will present long-term stability in water and higher printing resolution. The exposure time is set to be 2 seconds with a 10 μm build layer.

During manufacture, the actual printed size was found to always be smaller than the target size. So a correction factor was required to compensate for this. The calculation steps for the correction factor are illustrated in Figure 6. First of all, calibration pipes were printed with different lengths and diameters. Secondly, a high-resolution micrometer was used to measure the radii. The mean value between five measurements was then calculated. Finally, the correction factor was calculated from equation (2) and the data plotted in Figure 7, with an error bar to show that when the diameter is less than 0.5mm, the correction factor dramatically decreases. In other words, ~0.5mm diameter is the smallest diameter that can be fabricated with this technology. In order to connect more pipes to the cavity, the diameter of the pipes should be as small as possible. This is the reason why d= 0.48mm is chosen for this work.

$$\text{Correction factor} = \frac{Actual\ Diameters}{Target\ Diameters} \qquad (2)$$

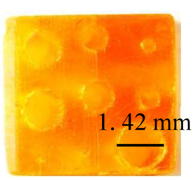
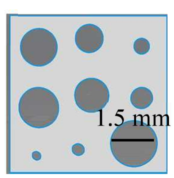
(a)  (b) 

Figure 7. (a) 3D printed calibration pipes, (b) CAD modelling calibration pipes.

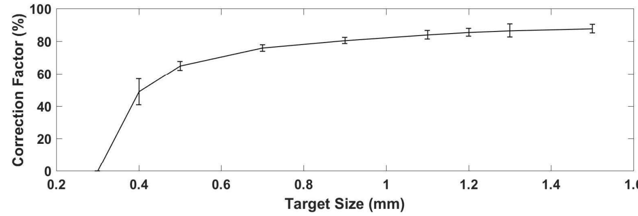
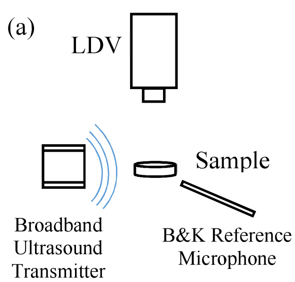


Figure 8. Correction factor against target diameter. The error bar was from five measurements.

III. Experiment and Result

A. *Experimental Set-up*

Before adding an electrical circuit to the transducer, the average displacement of the membrane was measured using a laser vibrometer to estimate the bandwidth and sensitivity. The performance of the pipe organ design and the conventional cavity-only design were then compared. The membrane was a passive Kapton diaphragm of thickness $d_m = 125$µm which was attached to the top of the 3D printed backplate with general purpose superglue. The experimental setup is illustrated in Figure 8. Initially, wideband periodic chirps covering frequencies from 5 kHz to 50 kHz were generated by a signal generator, and passed through a voltage amplifier, to a broadband ultrasound transmitter (Ultra Sound Advice Loudspeaker). The transmitter was enough far away from the sample to ensure that there were no near field effects. A 1/8 inch reference microphone (Brüel and Kjær, Type 4138) was used to measure the reference sound pressure around the sample. An amplitude correction algorithm was utilized to compensate for the transmitter's output variance. The front face displacement of the sample was obtained by using a Polytec PSV-300 scanning laser vibrometer (LDV) (Polytec, Inc., Waldbronn,Germany).

(a) 

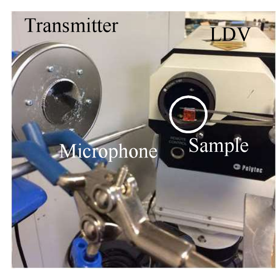
(b) 

Figure 6. (a) Simplified schematic of the experimental setup (b) Photo of experimental setup.

B. *Experiment and Simulation Result*

In this section, the frequency response of a device with no pipes (customer built standard device), is compared with a 4 pipes device and an 8 pipes device in terms of bandwidth, central frequency and sensitivity. The design parameters are those given in Table 2, and the simulation and experimental results are shown in Figure 9(a) and (b) respectively. The Comsol model does not include any loss factors, and the fluctuations in the simulation result arise from the resonances of different pipes or the cavity. In the simulation result, the Helmholtz resonance is located at 11 kHz and this enhances the overall sensitivity of the transducer. The multiple pipes' resonances vary from 30 kHz to 37 kHz, which are close to the membrane's resonance frequency. Compared with the 4 pipes device, there are more fluctuations in the 8 pipes device at ~31 kHz. So the bandwidth of the 8 pipes device should be larger than the 4 pipes device. Figure 9 (b) is the average displacement of the three devices, a noise floor is defined as 6dB below peak gain of each individual device to calculate the bandwidth of displacement. The central frequency and sensitivity are also evaluated and shown in Table 3.

Table 3. Bandwidth, central frequency and sensitivity comparison with respect to no pipe, 4 pipes and 8 pipes device.

	Bandwidth	Central Frequency	Sensitivity
No pipe device	3.8%	33.5 kHz	-103dB
4 pipes device	7.2%	34.2 kHz	-97.9dB
8 pipes device	9.6%	36.2 kHz	-102.8dB

The results in Table 3 and Figure 9 indicate that the respective bandwidths of the pipe organ devices are much larger than the device with no pipes. The central frequency shift is due to manufacturing tolerance. When attaching the Kapton membrane with super glue, some of the super glue may enter the cavity which makes the cavity smaller (or larger) than the designed size. However, the frequency shift is less than 8%. There is no sensitivity loss because the pipe organ backplate improves the bandwidth by amplifying the frequencies instead of damping the resonance. Both the device with no pipes and the 8 pipes device have the same gain. The sensitivity of the 4 pipes device is slightly larger than the other two devices because the resonant frequency of the circular membrane overlaps with one of the pipes' resonances.

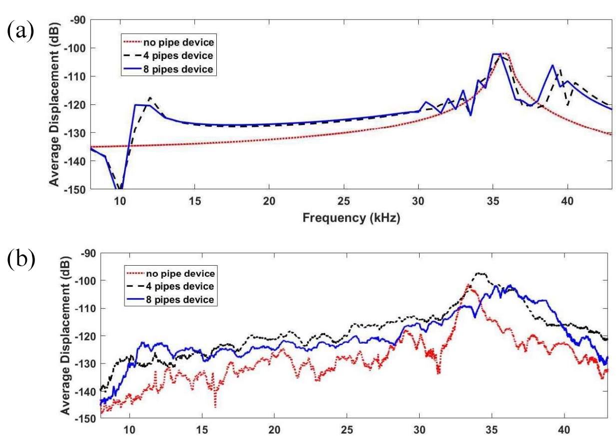


Figure 9. Average displacement against frequency in (a) simulation and (b) experiment.

IV. CONCLUSION

This paper presents a pipe organ inspired backplate which can replace the conventional backplate to increase the bandwidth of an air-coupled micro-machined transducer without sensitivity loss. The 1D mathematical model proves that more resonant pipes leads to larger bandwidth improvement. The FEA (Comsol Multiphysics) simulation was used to locate the membrane's and pipes' resonant frequencies more accurately and also simulated the coupling effects between the membrane, pipes and cavity. An 8 pipe backplate was built with an improved resin formula and a commercial stereolithography 3D printer. In the experiment, the -6dB bandwidth of average displacement improvement was found to be up to 9.6% (2.5 times larger than the customer-build conventional device).

The future work on this project includes changing the passive Kapton membrane to an active piezoelectric PVDF membrane, optimizing the lengths of the pipes to further increase the bandwidth, increasing the number of pipes by improving the materials and/or developing a smart backplate design to fit more pipes, and increasing the central frequency to over 60 kHz for use with air-coupled ultrasound NDT applications.

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