On Quick Measurement of Airborne Ultrasound Pressure Fields

Zak Morgan*, Youngjun Cho† and Sriram Subramanian‡
Department of Computer Science, University College London
London, United Kingdom
*zak.morgan.17@ucl.ac.uk, †youngjun.cho@ucl.ac.uk, ‡s.subramanian@ucl.ac.uk

***Abstract*—While ultrasound has long been used in the medical field in solid and liquid mediums, it's use in air has been less thoroughly researched due to a previous lack of applications. Recently it has been used for new applications such as mid-air haptics and the levitation of small particles. These applications require accurate acoustic holograms to be generated in mid-air. In order to do so it is vital to measure accurately these pressure fields, but also quickly in order to allow for quick iteration on work, or even real-time feedback. In addition to this it is of benefit to measure the sound field without interfering with it, which microphone set ups often do due to reflections of the device used to move the microphone. This work finds these methods currently lacking, though there are techniques used in place of hydrophones in water that could be adapted to work for the in-air context such as thermography.**

***Index Terms*—mid-air haptics, sound field measurement, ultrasonic imaging**

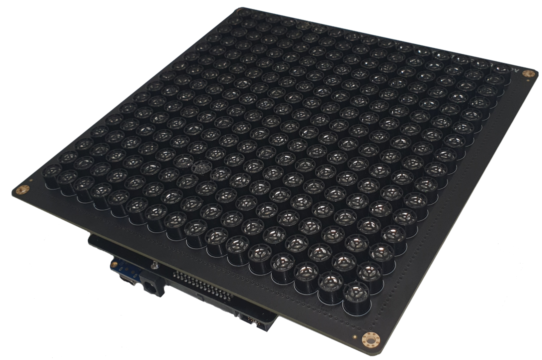

Fig. 1. Phased array of transducers, comprised of 256 40kHz ultrasound transducers in a 16x16 regular array, used for ultrasound haptics.

I. Introduction

Iwamoto et al. [1] first introduced mid-air ultrasound haptic feedback in 2008, and [2] the levitation of small particles in 2007, with [3] extending this work to allow control via a PAT (phased array of transducers) board. In order to create points of high pressure for haptics, it is needed to get constructive interference in one point in space, and deconstructive interference elsewhere. When using a PAT with a large number of transducers such as 256 in a 16 by 16 grid, as in figure 1, each transducers phase and amplitude must be controlled in order to generate the desired pressure field. While single focal points are the most trivial example to generate, it is possible to generate multiple focal points or arbitrary pressure field shapes. In these cases the actual pressures generated will differ from the simulated pressures due to artefacts from the control algorithms, transducers manufacturing tolerances or defects, noise and from imperfect control over phase and amplitude.

In order to measure these pressure fields, a standard technique is to scan a microphone (or hydrophone in water) across a 2D plane, or even a 3D volume such as in [4], taking single measurements at regular intervals in the measurement space. This is not a quick process with scan time varying with the amount of measurements taken and the size of the measurement region, but is on the order of hours. In addition to this it requires physical access to the measurement space for the microphone, and is also invasive and interferes with the sound field. This is due to the fact that any object larger than the wavelength being measured will interfere with the measurement. For this reason microphone size is important to minimise reflections and other interference, while also being small enough to be able to measure phase [14].

A set up that could be used for this type of measurement is shown in figure 2. In addition to the previous drawbacks, microphones often have a limited measurement range, in this case suffering from increased distortion over 5kPa and causing damage to the microphone at pressures over 7kPa. This is a problem as often mid-air haptics and levitation uses pressures higher than these values, causing researchers to measure with a reduced power compared to the real experiment. This is only a valid method if the mapping of power to pressure is known, as it might not be linear, and if it does not cause a phase shift. Since some PAT boards use PWM modulation to adjust amplitude, this means there can indeed be a phase shift associated with this reduction in power, and although it is predictable it is not completely accurate to predict.

In order to take faster measurements, as well as to reduce any unwanted reflections, such as from the CNC arm in the example setup in figure 2, other new measurement techniques have been developed. These can be separated into three categories, point based measurements such as the microphone set-up, plane based measurements, and finally those which reconstruct a whole volume at once using tomographic reconstruction. An example of a plane based measurement

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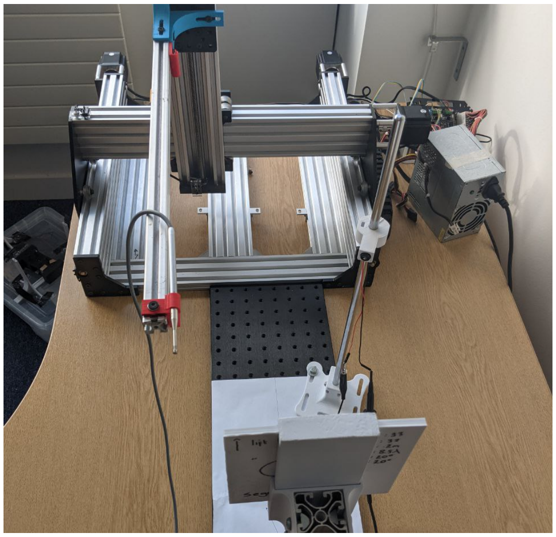

Fig. 2. A scanning microphone set up using a Bruel & Kjaer type 4138 1/8" microphone to measure a reflected sound field from a single transducer.

would be one using thermography [8], [9] or those utilising acoustically produced luminescence [10]. Finally an example of tomographic based measurements is a schlieren set-up [15], which requires imaging projections from different perspectives utilising the change in light path due to refraction from the different sound pressures in air. The multiple projections can then use a computed tomography (CT) algorithm to reconstruct the 3D pressure volume.

This short workshop paper will look at some of the currently utilised techniques in the mediums of water and air, and adapt such techniques from operating in water to work in air for assisting in the development of mid-air haptics.

Before looking at specific methods it is important to realise the differences in ultrasound when used in water and air, and also the different frequencies used for different applications.

The main difference is that for the same power, intensity (watts per meter square, or power) of ultrasound in air will be higher than that in water for the same pressure due to the lower density and speed of sound. Due to this fast ultrasound applications in water will often have pressures an order of magnitude higher than in air when the same intensity is required. Finally the frequencies used in water are often in the range of 1-20 MHz for medical applications, where as in air transducers in the frequency range of 40-80kHz are often used for example in the automotive industry for distance sensing and in PAT boards for mid-air levitation and haptics.

II. Point Measurements

Point measurements in both water and air are traditionally done using a hydrophone and microphone as described previously. The main disadvantage of these methods is that they are slow, and measurements must be synchronised if measuring a field which changes with time. Additionally, there is an upper limit to measurable pressure before there is a risk of cavitation damaging the hydrophone. In the microphone case, there is also an upper limit due to either the furthest distance the diaphragm can move, or the magnitude of vibration it can convert into an electrical signal.

Fabry-Perot sensors can also be used to take point measurements, though can take scanning measurements significantly faster. This is due to the fact that measurements are taken by interrogating the sensor with a laser beam, and laser beams can be scanned orders of magnitude quicker than a microphone. Martin et al. [18] demonstrate this taking a 9mm x 9mm scan with a sample resolution of 180x180 in 3 minutes. In addition to this it can be used in pressures exceeding that of microphones. The sensor constructed in [18] was 5cm x 3cm, and so a further disadvantage is the limited measurement area without adding additional complexity to also move the sensor, or additional cost to acquire larger sensors.

Pressure sensitive probes can also be used to take point measurements, or combined into arrays to make plane measurements. These arrays can also be scanned to produce data with a measurement step size smaller than the distance between measurement probes in the array such as in [21]. The biomimetic tactile fingertip used in [21] is ideal for measuring mid-air haptics, but does suffer from the same long scan time as the other methods in this section.

III. Plane Measurements

Plane measurements are significantly faster than point methods as they can measure a continuous plane in one measurement, also eliminating the need to synchronise between points, only needing to synchronise between planes.

There are three common techniques for these measurements, thermography, acoustically produced luminescence and via force sensors. The first two work by converting acoustic energy into light, and the most common of these methods is thermography. A material which absorbs ultrasound is placed in the sound field, which heats up in proportion to the intensity of ultrasound absorbed. This increase in heat can be measured with a thermal camera [8], or converted with a thermochromic material (which changes colour with heat) and then imaged with a normal visible wavelength camera [9]. Melde et al. [8] show however the noise equivalent pressure (NEP) for the thermography measurement is 23.6 kPa and 34.1 kPa respectively for their materials, whilst the hydrophone was 1.6 Pa, showing that this method is not nearly as accurate or sensitive.

Conversion of this heat into emitted visible light is also possible with specific materials, called acoustically produced luminescence. These materials are first charged with energy via a source such as an ultraviolet light. Then the increase in temperature due to ultrasound absorption causes luminescence which can be measured with a standard visible light camera [10].

Of these two methods only the thermography example has currently been tested in the air domain. Due to the aforementioned difference in intensities in the different domains, Melde et al. [8] show a 5 degrees Celsius increase for a pressure of 200 kPa in water, whereas in air this temperature change would be much higher, although the pressures used in air are much smaller. For mid-air ultrasound levitation and haptics, usually an upper limit used is on the order of 10 kPa. Due to water being a good thermal conductor compared to the insulating properties of air, thermal changes in the material between measurements will dissipate much quicker in water, meaning cooling the measurement surface becomes important in the air case. Onishi et al. [11], as yet unpublished, demonstrates this effect in air but does not obtain a good accuracy for measurement with errors of 23%, compared to the 7-9% of [8].

One notable disadvantage of the luminance and thermographic techniques is that they lose all phase information, retaining only amplitude. This is common with many methods presented here, but is not an issue for applications like mid-air haptics, as only amplitude is relevant for the generated field.

The force sensing method simply uses an array of microphones, but the density is so low that it is not currently usable to measure anything but tactile vibrations [17]. When used for this purpose they are often encased in a human skin-like phantom material, to mimic the mid-air haptics interactions.

One additional method of visualisation is to use an oil or water bath, and image the surface deformation due to pressure incident on the surface. Abdouni et al. [20] created a set-up using two PAT boards, where one was used for haptics with the user, and the other was used to display the stimulus onto an oil bath and imaged using a lightbox. This method was only used for visualisation, but it is possible that pressure values could also be measured with this technique.

IV. Tomographic Reconstruction

There are many techniques that utilise light passing through the sound field to measure the pressure, for example schlieren imaging [15]. Most of these techniques require rotating the optical source or the acoustic source in order to image multiple projections to reconstruct the sound field for example via CT. The number of projections, and thus samples, is much less than a scanned microphone however so is still a time saver, but does take longer than a plane measurement method.

Holm and Persson [12] utilised light diffraction in the field to measure the pressure, while [13] utilised refraction using a heterodyne interferometer. One limitation of these methods is that if they utilise phase shift like [15] then if the phase is shifted by more than 2π the method will fail unless phase unwrapping is performed. This limits its applications in very high pressure scenarios for those methods that rely upon this assumption. A final method to be explored is refracto-vibrometry using a a scanning LDV (Laser Doppler Vibrometer), which utilises rotating the laser beam itself to obtain different line projections.

All of these optical methods are often difficult to set-up and require a large physical space and specialised equipment. The thermography on the other hand for example merely requires some foam and a piece of thermochromic vinyl. Additionally there is a computational cost to the CT algorithms needed to reconstruct the field from the projection. Therefore there is an additional time cost in addition to that used taking the physical measurements themselves.

V. Applications

While the decrease in measurement time is already extremely valuable to researchers, real-time measurements can enable the development of algorithms which use measurement information in real-time. Algorithms that control PAT boards such as IBP (iterative back-propagation) [5], GS-PAT [16] or that developed by [6] often use a simulation of the sound pressure field given an arrangement of transducers and their amplitudes and phase off-sets. This simulation could, as stated in [6], be replaced with an actual measurement to get more accurate control over these boards. This also allows AI systems to use the difference between the simulation and measurement as a loss function for optimisation.

Outside of the acoustic domain, in the optical domain, this has already been accomplished. Generally referred to as camera-in-the-loop holography [7] and is trivial due to the nature of capturing light using a standard camera sensor, where-as no similar high density array of microphones exists.

VI. Conclusion

In conclusion, while there are some challenges in bringing the techniques employed already in water to the mid-air domain, they are not significant enough to prevent the transfer of these methods. Despite this outside of these four works ([11]–[13], [17] there is not much research into the measurement of ultrasound via methods other than the classical scanning microphone method.

When phase information is not needed, these techniques offer multiple orders of magnitude speed up in measurement. In developing these measurement techniques, they will allow quicker iterative work which relies upon measurement of ultrasound holograms, as well as enabling techniques which can leverage real time measurement information as a feedback mechanism. Finally they also allow for measuring increased pressures, as the pressure levels commonly used in levitation and mid-air haptics exceed that which is able to be measured without damaging standard microphones.

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