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A ROBOTIC SYSTEM FOR SPACE-TIME CHARACTERIZATION OF PARAMETRIC ACOUSTIC SOUND SOURCES

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ABSTRACT

Parametric acoustic loudspeakers use arrays of ultrasonic transducers to generate audible fields through the non-linearities of the propagation medium. Despite being commercially well consolidated, some aspects of the generated audible field still deserve further investigation, among them the spatial distribution of the radiated sound. This paper describes the acquisition of impulse responses generated by parametric loudspeaker prototypes using an automated system to scan the sound field spatially. The scanning system comprises a 6-degree-of-freedom robotic arm mounted over a linear track for increased spatial coverage. The robot positions the microphone in pre-specified locations inside two desired apertures irradiated by the sound source. First, scanning planes parallel to the source axis allows direct visualization of the sound field generated by the source. Second, the scan of a normal plane to the source axis allows future applications using near-field acoustic holography and sound field reconstruction. This work showcases the first steps in implementing such measurements for parametric acoustic loudspeakers.

Keywords: *spatial sound-field sampling, parametric acoustic loudspeakers, exponential sine-sweeps, sound source directivity, near-field acoustical holography*

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1. INTRODUCTION

Parametric Acoustic Loudspeakers (PAL) are devices that generate audible sound through ultrasonic transducers [1, 2]. They rely on the Parametric Acoustic Array (PAA) effect, in which the propagation of two ultrasonic frequencies in a medium generates a secondary field oscillating with the difference between the frequencies. This difference can be tuned to be in the audible range, allowing these devices to reproduce audio. The PAA effect happens because of non-linearity in sound propagation at ultrasonic frequencies [1, 3]. This phenomenon is cumbersome to describe from the physical point of view, and the mathematics necessary to simulate the effect are also very complex and computationally demanding. This poses a challenge to the design of PALs, which usually depend on prototyping of models and trial-and-error. Characterising the sound field radiated by these prototypes would be very valuable for their development.

One of the characteristics of the PALs is the sound field generated by them. Visualising the radiated field requires measuring the sound pressure in discrete spatial positions. Spatial discretisation can be achieved in a few ways. One option is to use an array of microphones to perform these measurements. On the one hand, they are convenient, allowing the recording of tens or hundreds of channels simultaneously. Conversely, there are a couple of shortcomings related to the quantity of microphones employed. While arrays of around a hundred microphones are possible, larger quantities are impractical. Furthermore, not only must they all be calibrated individually, but transducer mismatch errors and positioning errors often occur [4]. An alternative is to use an automated system to position the microphone sequentially in the desired positions. The microphone positioning errors are restricted to the machine's tolerances, and only one microphone is used, so there is no transducer mismatch.

Spatially scanning the sound field through sequential measurements can be done using many different types of machines. Robotic arms are composed of rotating joints positioned so that the resulting kinematic chain usually has six degrees of freedom (fewer degrees of freedom are possible but are a rarity in the market). These robots have been used extensively to reproduce array measurements [5–9] for plane wave decomposition and near-field acoustic holography (NAH) due to their flexibility, being able to place the microphone in structured grids or randomised positions. When dealing specifically with robots, the accessibility of the positions is usually solved by trial-and-error, which can be a limiting aspect for the flexibility of these pieces of equipment. The addition of a microphone holder changes the kinematic chain of the robot, which affects the accessibility of certain poses — in this case, the position and orientation of the microphone. The accessibility can be verified by performing the inverse kinematics of the robot, i.e., finding the joint configurations that place the microphone in that position with that orientation if they exist [10]. One of the downsides of the robots is that they have limited coverage, and scanning larger areas requires larger equipment. Another option is using linear Cartesian positioners [11–15]. These are composed of 2 (XY) or 3 (XYZ) linear tracks that perform the movements in their respective coordinates. These systems are usually designed and built at the place of the application. While they tend to be cheaper than robots, they are also prone to backlash and constructive errors that make their positioning errors larger. Notwithstanding, they can provide extensive spatial coverage due to the dimensions of the linear tracks.

This paper presents a robotic system for sound field scanning of parametric acoustic loudspeakers. The system features a six-degree-of-freedom robot mounted on a linear track to enhance spatial coverage. The proposed methodology is evaluated using an omnidirectional parametric loudspeaker (OPL) composed of 750 ultrasonic transducers arranged on a sphere [16], as well as a flat parametric array loudspeaker (PAL) with 96 transducers on a plane [17]. Results include two application examples demonstrating the system's capabilities. The first is a plane parallel to the ground and to the source axis for mapping the radiated field of these speakers. The other is for an array parallel to a parametric acoustic loudspeaker to serve as input for holographic techniques.

The structure of this paper is as follows. Section 2 presents the methodology used to measure the sound field generated by the loudspeakers, the methodology to verify the inverse kinematics of the robot, and the proposed experimental setup. Section 3 shows the measured sound fields for the OPL and the flat PAL and presents considerations regarding their differences. Section 4 concludes the discussion.

2. METHODOLOGY

2.1 Robotic system

The positioning system was comprised of the Universal Robots UR5 robot mounted over a $2.45\,\mathrm{m}$ Igus track. This allows the use of the track to improve the spatial coverage of the system while maintaining the flexibility provided by the robot.

The UR5 is a six-degree-of-freedom collaborative robot with $850\,\mathrm{mm}$ of reach. A microphone holder was designed so that the microphone could be positioned away from the robot at a variable length. The Robotics System Toolbox Support Package for Universal Robots UR Series Manipulators [18] was used to control the robot with MATLAB. In this work, communication through the Real-Time Data Exchange option of the toolbox was employed. This toolbox also allows the modification of the robot's kinematic chain to consider any tools, e.g. the microphone holder. To avoid trajectory interpolation problems, the robot was controlled directly by informing its joint configurations.

The track used is an Igus track with a Drylin D1 driver, with a length of $2.45\,\mathrm{m}$. The robot and the track were acquired as a package. However, the control of the track was initially only possible through the robot interface. The driver is commanded through Modbus TCP protocol, in which numeric messages containing instructions or requests are sent through an Ethernet connection to the driver, which replies or acts accordingly. Thus, it was possible to command the track through MATLAB through the TCP/IP port. In terms of installation, the robot's x-axis is mounted at a $45°$ angle regarding the track axis. To align both axes, a $45°$ correction of the base angles was done for all poses.

Figure 1 displays the experimental setup using the

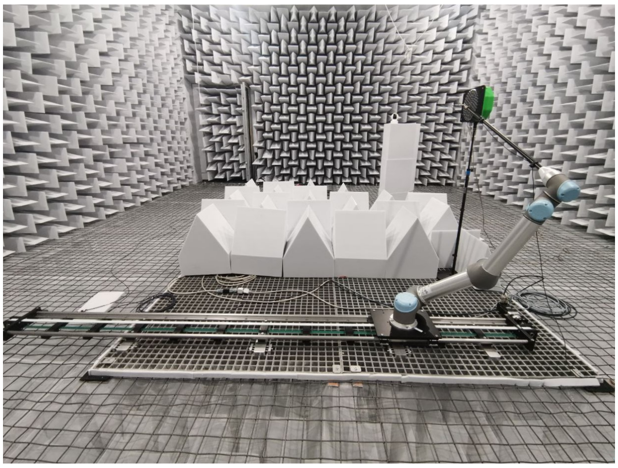
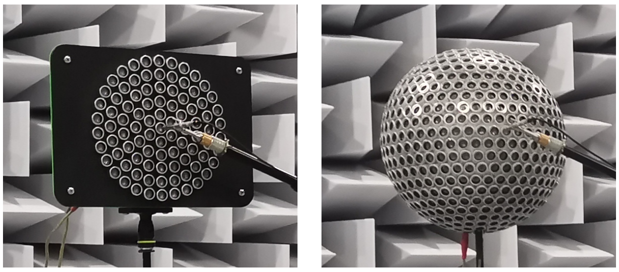


Figure 1: Measurement system composed of the robot and the track, measuring the flat PAL.

microphone holder, the UR5 robot, and the Igus track to scan the sound field generated by the flat PAL described in [17], assembled in the anechoic chamber at La Salle - Universitat Ramon Llull (Barcelona, Spain).

2.2 Microphone array designs

In this work, two different array designs are proposed to discretise the sound field radiated by the parametric loudspeakers and to test the proposed design methodology. After generating the measurement positions, they were reorganized to avoid large movements in short periods of time, which can lead to errors regarding the robot's safety configurations. The first array is a sound pressure level map of the irradiated region in the xy plane. A $0.2\,\mathrm{m} \times 0.8\,\mathrm{m}$ area was covered by an array with a spatial sampling of $40\,\mathrm{mm}$. The idea was that the robot could be dislocated by the track to cover a larger area. The second is an array of equidistant points measured in the plane yz $10\,\mathrm{mm}$ away from the loudspeaker to sample the sound field for the calculation of a 2D Fourier transform (also known as classical holography). With that in mind, two validation planes were also measured at a distance of $20\,\mathrm{mm}$ and $30\,\mathrm{mm}$ from the parametric source to compare with the reconstruction of the sound pressures in these positions. The planes contain a grid of 11×11 equidistant points in a $0.6\,\mathrm{m} \times 0.6\,\mathrm{m}$ square centred on the centre of the PAL. This array has a spatial resolution of $54.5\,\mathrm{mm}$.



(a) (b)

Figure 2: Parametric acoustic loudspeakers (PALs) analysed in this work: (a) flat PAL and (b) Omnidirectional parametric loudspeaker (OPL).

2.3 Experimental setup

The Exponential Sine Sweep (ESS) methodology to measure impulse responses is used in acoustics due to its robustness to noise and distortion [19–21]. The utilisation of ESSs in PALs [22] requires that the sweep goes through an Upper Side-Band Amplitude Modulation (USBAM) with a transmitted carrier component [23]. The carrier frequency should have an appropriate value, which for the omnidirectional parametric loudspeaker is of $41.4\,\mathrm{kHz}$ [24]. This means that the transducers are constantly emitting the transmitted carrier with frequency $41.4\,\mathrm{kHz}$ and whatever the frequency of the sweep signal. This, in turn, starts the PAA effect and the generation of an audible field. A side effect of transferring the sweep signal into the ultrasonic range is that the maximum frequency of the system may be too high for common audio systems, and a large sampling frequency is needed. In this work, ESSs of $1\,\mathrm{s}$ were emitted, with a fade-in ramp from $20\,\mathrm{Hz}$ to $80\,\mathrm{Hz}$ and a fade-out ramp from $12\,\mathrm{kHz}$ to $14\,\mathrm{kHz}$ [22]. Both PALs used a carrier frequency of $41.4\,\mathrm{kHz}$.

The microphone was a GRAS 46BF-1 with 1/4" of diameter, attached to the robot by the microphone holder at $1\,\mathrm{m}$ of distance from the robot wrist. The generation of the sweep and the signal acquisition from the speaker were performed using a Brüel & Kjaer LAN-XI Type 3160-A-042 module with a UA-3102-041 front-end. The generated signal was amplified up to $17\,\mathrm{V}$ peak-to-peak using an Ecler XPA3000 amplifier. A TP-Link Tapo C-212 was used for remote monitoring of the process.

Regarding the parametric sound sources analysed, the first had 96 piezoelectric transducers connected in parallel and positioned in six circular rings on a flat surface, up to $195\,\mathrm{mm}$ of diameter [17]. The other was the omnidirectional parametric loudspeaker (OPL), which has 750 transducers laid out in a spherical shape of 250 mm of diameter [16]. Figure 2 contains both parametric speakers analysed in this work.

3. RESULTS AND DISCUSSIONS

3.1 Sound field Mappings

Fig. 3 displays the SPL mappings in the irradiated region of the flat PAL [17] at 500 Hz, 1000 Hz,5000 Hz, and 10 000 Hz for both the audible and ultrasonic ranges. While very little difference can be noticed between the 500 Hz and the 1000 Hz audible fields close to the source, the increase of SPL at distances farther than 1 m from the source indicate the formation of a beam with the increase of the frequency. At 5000 Hz and 10 000 Hz, the formation of a concrete beam can be seen. Moreover, focal areas of energy in the immediate vicinity of the PAL and around 24 cm from the irradiated region can be noticed. Another remark is that the shapes of the audible sound fields for the two lower frequencies displayed follow the shape of their respective ultrasonic radiations. The formation of a proper beam in frequencies above 5000 Hz is in good agreement with the established theory of PALs, which says that triggering the PAA effect is easier the higher the frequency. Looking at the ultrasonic mappings, the levels seem to decrease with the frequency. This is explained by the energy transfer from the ultrasonic range to the audible range [1] and also by the behaviour of these transducers. They have a reduction in SPL until 49 kHz, where it starts to rise again due to a second resonance peak [23]. Although both phenomena of focusing and linear transmission of sound can be seen for this PAL, its contours are not as well defined as the ones displayed by Zhong *et al.* [13]. This is likely due to the spacing between these transducers, their dimensions, and their influence on their interactions. The transducers employed in the flat PAL and the OPL are larger than the ones used in Ref. [13] focusing PAL and do not allow for more compact configurations.

Fig. 4 displays the SPL mappings in the irradiated region of the OPL [16, 22] for both the audible and ultrasonic ranges. It corresponds to what has been shown in [22] regarding the generation of higher levels at lower frequencies. Moreover, once again, a reduction in the ultrasonic SPLs indicates that the energy is being transferred to the audible frequencies. However, there's no "beaming" of the sound because the transducers are not aligned, and instead, many directions of irradiation are achieved [22]. Comparing the two loudspeakers, it is visible that the curved disposition of the transducers in the OPL generates an omnidirectional irradiation as opposed to the flat PAL, which tends to either concentrate the energy in a region or form a beam of sound.

3.2 Near-field parallel mappings

Fig. 5 displays the SPL mappings in a parallel plane 10 mm from the flat PAL [17] and the OPL [16] in the audible range. At 500 Hz and 1000 Hz, the radiation in the plane of the flat PAL is more intense than at 5000 Hz and 10 000 Hz, which corroborates with the SPL map from Fig. 3. It can be said that for the two lower frequencies, the energy stays mostly in the near-field and on the focusing region of the speaker, while for the higher frequencies, it flows along the beam, and so the SPLs in the near-field region are lower. Furthermore, it is evident that the radiation from the flat PAL does not happen symmetrically, even if the transducers are symmetrically distributed. This may be due to differences in each transducer that show up when they are all fed the same signal simultaneously. Regarding the OPL, it can be seen that the levels at the centre of the array are higher. This is because, in this position, the microphone is facing a transducer directly and at the closest possible distance. As positions stray from the centre, the transducers point to other directions, and their influence is less impactful due to their directivity. Notwithstanding, it can be noted that the irradiation is not very directive and is almost omnidirectional, as expected for this loudspeaker. Moreover, it can be stated that the OPL generates more SPL than the flat PAL at that distance.

4. CONCLUSIONS

This work described the implementation of a robotics-based system that combined the flexibility of a six-degree-of-freedom robot with the length of a linear track to be used in parametric loudspeaker characterisation. The sound fields of a flat PAL and a spherical PAL were scanned in two different planes. One was parallel to the ground, which allowed for a view of the irradiation through an extensive area around the radiation axis. The other was a plane perpendicular to the radiation axis and in the near-field of the sources, allowing for an assessment of the near-field irradiation of the flat PAL and the OPL. The OPL behaves as expected based on its modelling, with an omnidirectional irradiation. The flat PAL tested

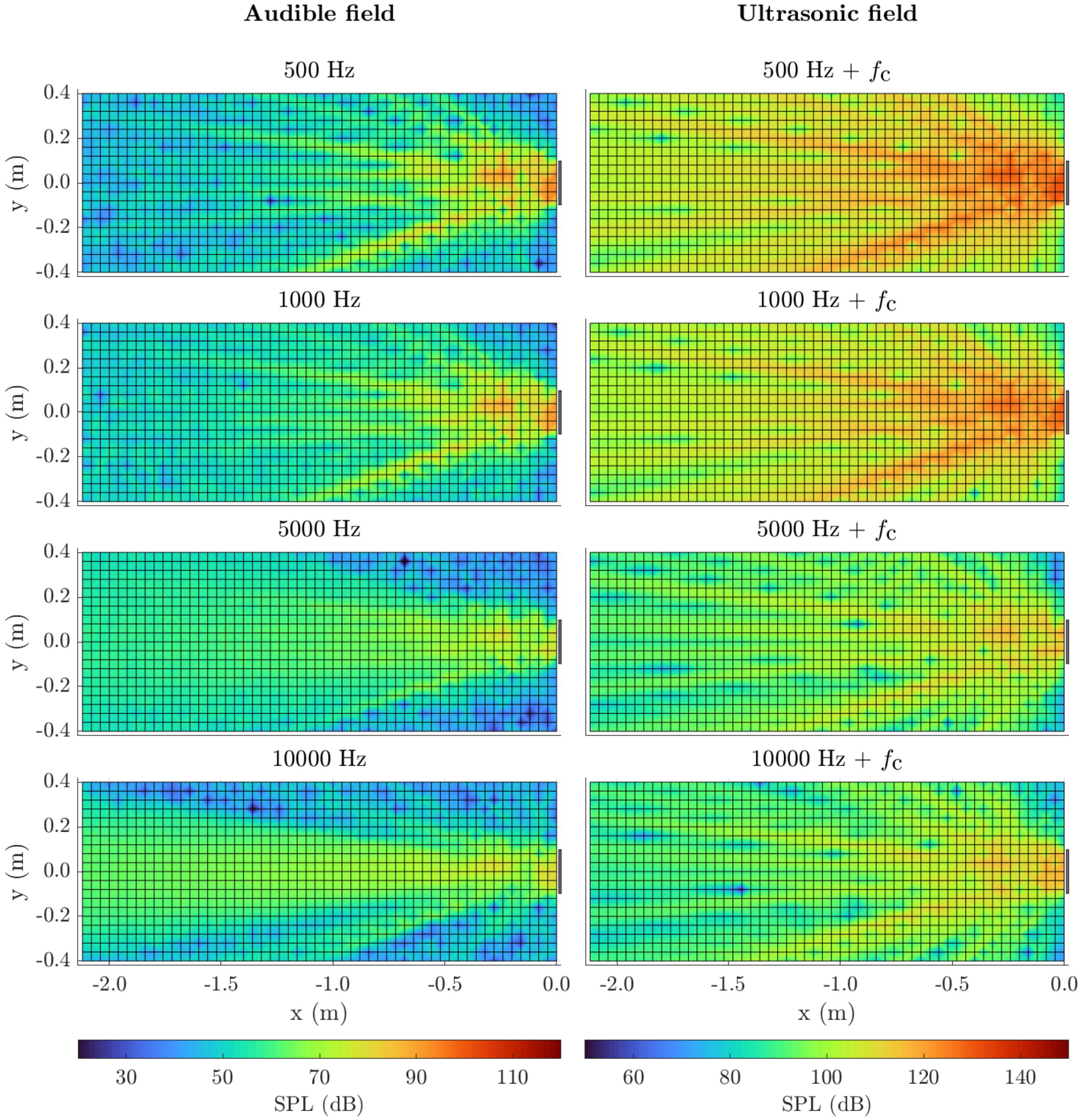


Figure 3: SPLs irradiated by the flat PAL in the audible and ultrasonic fields. $f_c = 41\,400$ Hz.

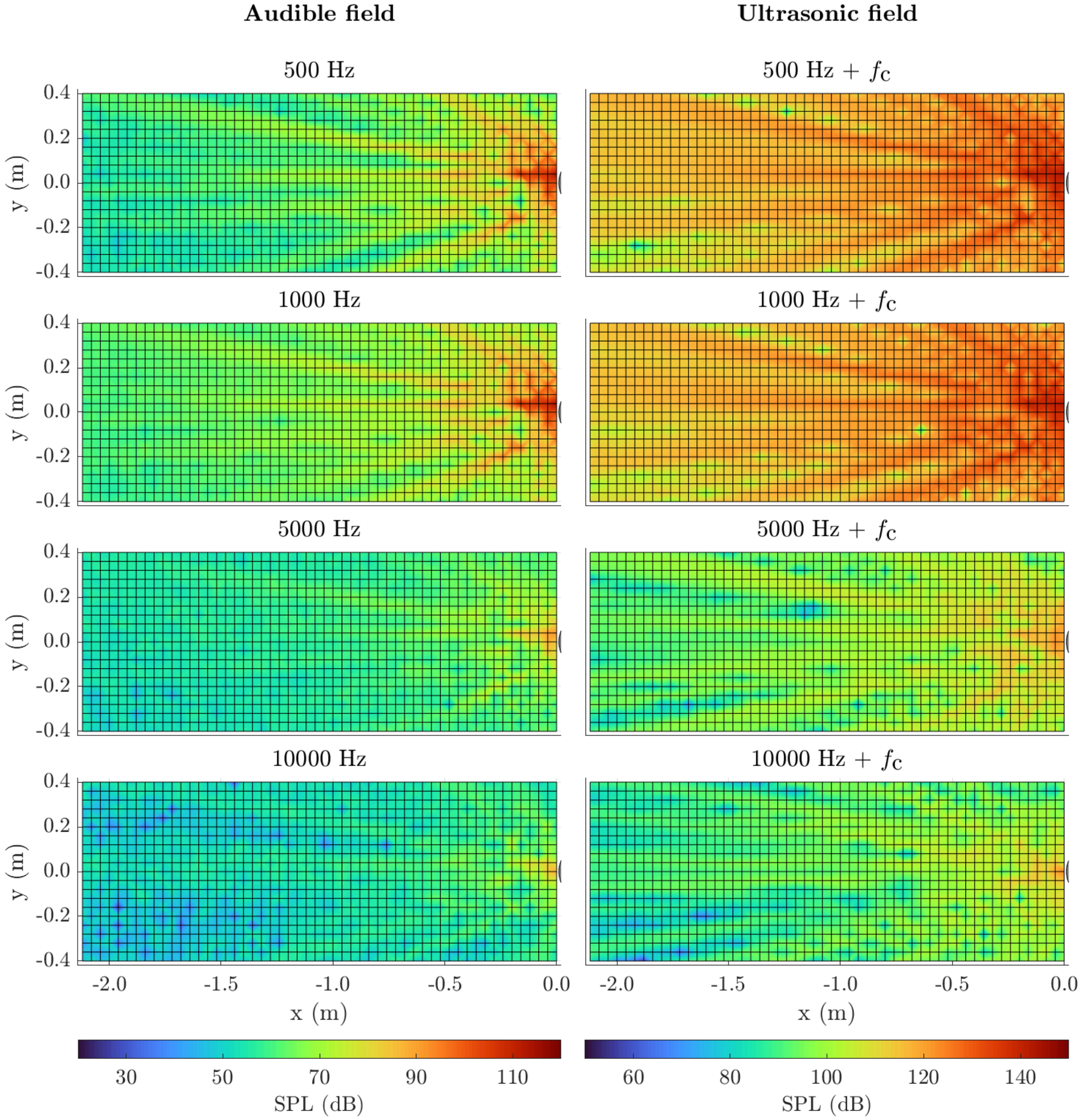


Figure 4: SPLs irradiated by the OPL in the audible and ultrasonic fields. $f_c = 41\,400$ Hz.

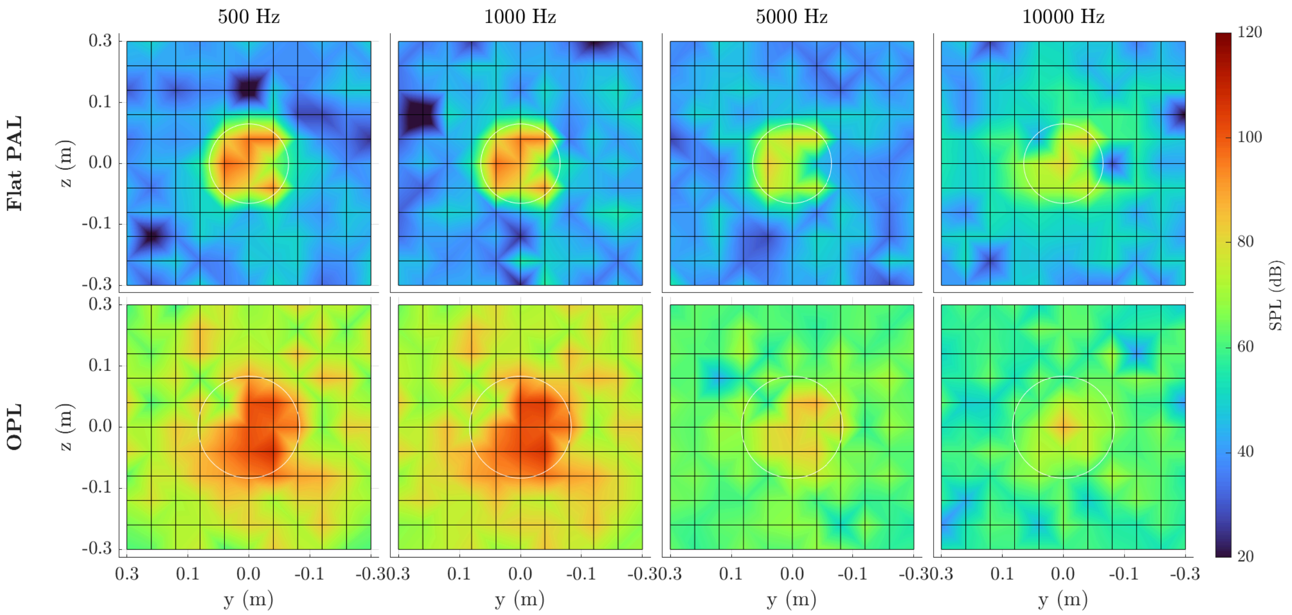


Figure 5: SPLs irradiated by the flat PAL (top) and the OPL (bottom) at a plane perpendicular to the incidence at 10 mm.

presented a focusing behaviour in lower frequencies, with the formation of a proper beam happening with an increase in frequency. In any case, the transfer of energy from the ultrasonic range to the audible range can be observed in the mappings, and in the flat PAL case, a very strong correlation between the audible field and the ultrasonic field can be seen. From the signal processing perspective, future work involves using regularized plane-wave expansion techniques for sound field analysis. In a more general sense, both NAH and spatial mapping can be employed in the future to further study different transducers and different prototypes.

5. ACKNOWLEDGMENTS

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