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Focalization of Acoustic Vortices Using Phased Array Systems.

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Abstract

Acoustic vortices (AV) are helical wavefronts that exhibit a screw-type dislocation and a phase singularity along its principal axis of propagation, at which the pressure of the field is zero. AV can be generated using various methods among which stands out the use of phased array systems because they allow us to electronically control the acoustic beam by means of the application of a given delay law to the array elements. Little research has been reported regarding the focalization of AV to obtain a higher pressure distribution. In view of this, this work presents the study of different delay laws for generating and focusing AV. The analysis of the resultant geometry and pressure distribution of the focused beams is included. We demonstrate that it is possible to increase the pressure amplitude up to 3 times with respect to a non-focalized, at the focal distance. Experimental tests were carried out using a hexagonal multitransducer of 30 elements at 40 kHz. A good agreement between simulations and experimental results was obtained.

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Keywords: Acoustic vortex; Air-coupled ultrasound; Phased-array system; helical wavefront; ultrasound

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1. Introduction

Most of the advancements in the focalization of helical wavefronts are in the field of optics. Different analytical formulations and numerical models have been proposed (Zhang, Pu, & Wang, (2008), Li, Gao, Zhang, & Zhuang, (2009), Ganic, Gan, & Gu, (2003)). Also experimental techniques, such as the use of an axicon, have proven succesful for optical vortex focalization. In acoustics, in which the phenomenon takes place at a greater dimensional scale, relevant developments are still rather scarce. However, important researches have already been reported regarding acoustic helical wavefronts generation and focalization in liquid media by using phased array systems

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(Hefner & Marston, (1999), Volke-Sepúlveda, et al., (2008), Yang et al. (2013), Courtney, et al., (2013) Demore, et al., (2011)). Using transducer arrays with many active elements opens up the possibility to precisely generate and control the helical beam structure. It also paves the way to focalize and steer the field almost at will. Recently, Baresch (2014) focused an acoustic vortex in water by using an array of 120 elements along with a focusing lens. This allowed him to manipulate small particles. In general, the need for focusing the beam is always present.

In view of this, this work explores the use of different time delay laws to focus the acoustic vortex and the effect on the phase and pressure distributions of the resultant helical beam. In particular, we compare two different focalization schemes, i.e. conical and spherical, aiming to quantify their impact on resultant characteristics of the beam, i.e beam width, focus depth, pressure and phase distributions. To do so, results are compared with the characteristics of a non-focused helical wavefront. Also, experimental measurements of focused vortex are carried out to corroborate theoretical estimations.

2. Materials and Methods

We use a hexagonal multitransducer to generate focused acoustic vortices (FAV). This is composed of 30 commercial ultrasound transducer (40 kHz) deployed in a triangular lattice. The elements are equidistantly separated 13.6 mm from each other. The larger dimension of transducer array is 80 mm. We compute the delay function necessary to generate a helical wavefront and, in addition, determinate the phase profile that focus the beam at a specific distance. By summing all these delays we obtain the spiral-like phase distributions that generates the FAV. Two different focalization delay laws are compared: spherical and conical. See figure 1. They respectively emulate the effect of spherical and conical lenses on a non-focused vortex. This effect has been analyzed using numerical simulations and experimental tests. The vortex beam is focused at the same distance in all cases, i.e. 80 mm far from the multitransducer.

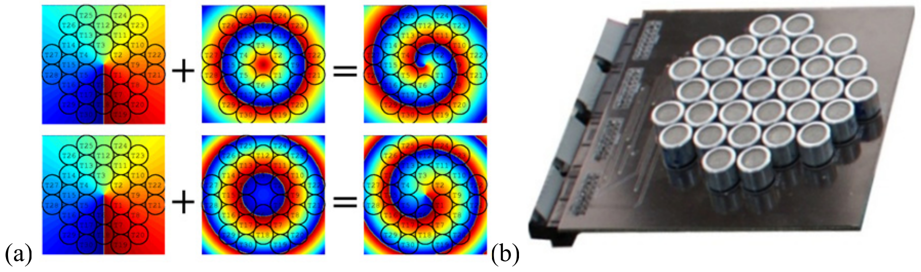


Fig. 1. Phase profiles used to focalize the acoustic vortex. (a) Up:Conical focal law. Bottom: Spherical focal law. (b) Transducer used to generate vortices.

Acoustic measurements were carried out to verify results obtained from simulations. The experimental setup is composed by a commercial phased array system (SITAU LF 32/128; DASEL SL, Madrid,Spain) and an XY linear unit (Model NSC-G eTrac Linear Stage, Newmark System, USA) used to precisely position a calibrated microphone (1/8 inch, GRAS, Denmark) with a bandwidth between 6Hz to 140kHz. This setup allows us to measure the instantaneous acoustic pressure over observation points located in azimuthal and transversal planes. Input signal is a burst with 2 pulses at 40 kHz. Special care was taken in order to avoid echoes from nearby objects.

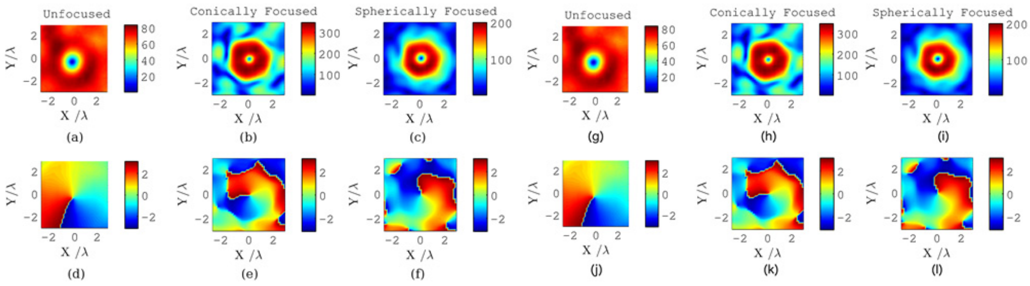
Considering that radiation from a single array element can be modeled as $A/R\ \exp\{i\,(k\,R\ -\omega\,t)\}$ where R is the distance from the source to the receiver and A is a constant of amplitude, it is possible to obtain an approximation of the resulting sound field from the whole multitransducer as:

$$P_m(r,\phi,z,t) = \sum_{n=1}^{N} \frac{A_0(\phi)}{R_{mn}}\, exp(-i\,\omega\,t)\ exp(i\,kR_{mn})\, exp(i\,\phi_0) \qquad (1)$$

where ϕ_0 is the phase shift applied to each element and R_{mn} is the distance between an element n of the array and an observation point m.

3. Results

Pressure distribution FAV of topological charge m=1 at the focalization plane was estimated and experimentally verified. Figure 2 shows a comparison between simulations and experimentation results. A very good agreement between them was obtained. Also it shows that no significant changes are observed between the phase distributions of the focused vortices. Both resultant phase distributions (conical and spherical) have a clear hexagonal structure at the focalization plane, which vanishes as we move away from the focal plane. In this case, an almost rounded shape is observed at a plane located 3 wavelengths further.



EXPERIMENTAL RESULTS SIMULATION RESULTS

Fig. 1. Pressure (upper row) and phase (lower row) distributions of a FAV at a transvers focalization plane locate at a distance of 80 cm from multitransducer. Three different focalization delay laws were use i.e. no focalization, conical and spherical. Left: Experimental results. Right: Simulation results.

Fig. 3a shows the experimental lateral pattern of the FAV generated. A significant reduction (68% and 81% for conically and spherically focused beams respectively at $-3\ dB$) in the beam width is obtained when a focalization function is applied, which results in an amplitude increment of up to 3.7 times with respect to an unfocused vortex.

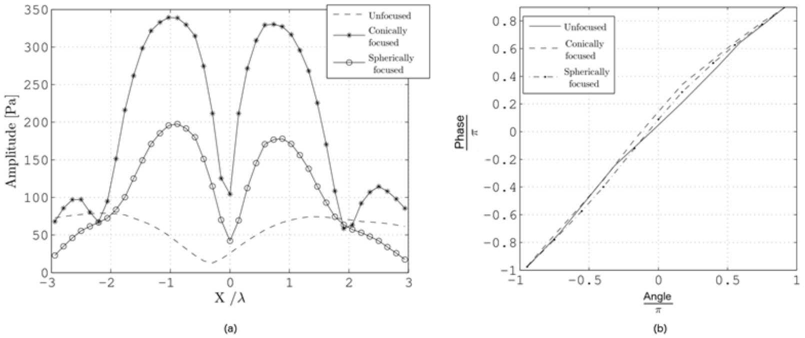


Fig. 3. (a) Experimental lateral pattern obtained from an unfocused vortex, a conically FAV and a spherically FAV). (b) Phase distribution of conically FAV along three circular paths with center at the singularity.

Fig. 3b shows the behavior of the phase along a circular path around the core of the vortex. Phase is almost linear for an unfocused vortex and quite similar for FAV. However, the greater the radius of the trajectory the more irregular the phase behavior becomes. In this particular focalization plane, this is clearly observed along circular trajectories with radius greater than 1.4 wavelengths for conically FAV and 1.7 wavelengths for spherically FAV. Finally, dependence between focus distance, beamwidth and focus depth is summarized in Fig.4. The closer the focus distance the lower the beam width and focus depth.

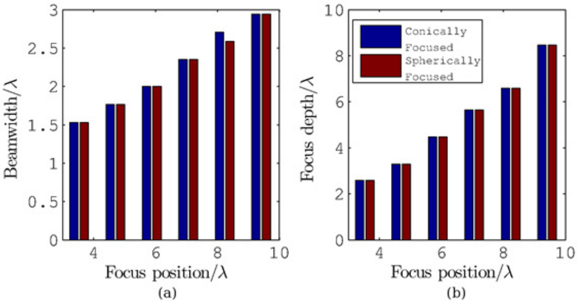


Fig. 4. Variation of the beamwidth (a) and focus depth (b) for different focal distances.

4. Conclusion

Using a proper focal law can advantageously modify vortex structure. A reduction of up to 80 % in the vortex width along with an important increase in the pressure amplitude are possible using a focalization law, without a significant distortion in the phase distribution. Further research is required to quantify the changes (due to focalization) in vortices of higher topological charge. Also, the influence of the multitransducer parameters should be included. The variation of the capacity of the FAV to transfer angular momentum and its use in air-coupled applications is a matter of further study.

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