I. I

P distribution singularities constitute an intrinsic characteristic of a given acoustic eld. This type of feature occurs naturally in a wavefront and is known to be resistant to disturbances in the eld [1]. In general, phase singularities, depending on the morphology of the dislocation, can be axial, screw-type, or mixed. Particularly, in this work we focused on screw dislocations, in which the transverse plane of the wavefront, normal to the propagation axis, exhibits a phase distribution which linearly increases from 0 to 2π over any circular trajectory around the principal axis. Fig. 1 shows a spatial representation of a beam with a screw dislocation, also known as a helical wave.

Because of the great similarity between a helical wavefront and vortices in a uid, pressure elds with screw dislocation are also known as acoustic vortices (AV). Indeed, under special conditions, the interaction between vortices of this type resembles that of their uid counterparts [2]. Although the existence of a wavefront with screw dislocation was rst identi ed acoustically, most of the subsequent research and applications has been reported in the optics eld [3]. In this sense, it has been demonstrated that a helical wavefront transports angular moment [4], which makes it possible to control the orientation of absorbent particles in an optical tweezer [5]. Applications to trap atoms have also been proposed [6].

In the acoustic context, A V can occur either in the linear or nonlinear regime [7], [8]. Considering that several researchers have found analogies between the structure of screw dislocations and vortices in uids and quantum mechanics, the AV has been proposed as a tool for the experimental study of their optical, uidic, and quantum counterparts. Recently the transfer of angular momentum from rotating acoustic waves to matter has been experimentally demonstrated by using several sound sources [9], [10]. Another interesting property of the A V is the storage and transmission of digitized information with the particularity that the phase coding is in space and not in time [11]. Even though the potential of use of A V has been reported, their application in acoustics has been scarce. This can be attributed, in part, to the need for complex instrumentation to generate a helical wavefront. Thus far, di erent methods for A V generation have been proposed, namely, direct generation from a specially shaped source [7], [12], the optoacoustic technique [13], mode conversion from wave plane to AV [9], or use of a phased array system [11].

Ferroelectret technology exhibits interesting properties which make it an excellent candidate to satisfy the current demand for the development of airborne ultrasonic transducers. In particular, cellular ferroelectrets open up new possibilities at the transducer design stage, to approach the trade-o among bandwidth, directivity, sensitivity, and cost. This is possible because of their high d_{33} piezoelectric coe cient; wide frequency range of operation (from 30 kHz to 2 MHz); low acoustic impedance (0.03 MRayls), which results in a good adaptation to the air; and their unprecedented mechanical exibility. Furthermore, ferroelectrets are easy to use and have a low fabrication cost [14] [16]. In this work, we propose a fast and inexpensive alternative for the creation of acoustic vortices by gluing a ferroelectret lm onto a tangential/ helical surface substrate. The high mechanical exibility of this material allows us to fabricate transducers on any developable surface. (A developable surface is any sur-

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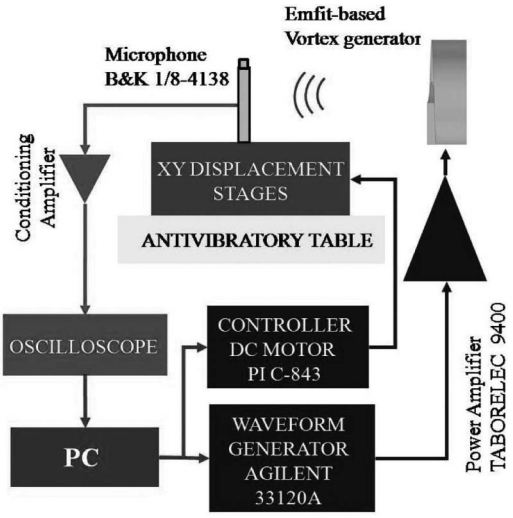

Fig. 3. Instrumentation setup.

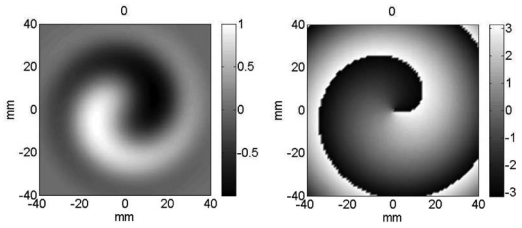

Fig. 4. Instantaneous Gaussian helical eld. Simulation results using a topological charge m = 1. Left: pressure magnitude, right: phase.

Fig. 5. Instantaneous Gaussian helical eld. Simulation results using a topological charge m = 3. Left: pressure magnitude, right: phase.

$$(,\phi, ,) = \quad , (,\phi,)\exp((\quad - \omega)), \tag{1}$$

where

$$p_{n,m}(r,\phi,z) = E(r,z)G_{n,m}(r,z) \quad _m(\phi) \quad _n(z) \tag{2}$$

is the pressure distribution at a plane normal to the propagation axis. The functions E, G, , and are, respectively, the envelope of the beam (usually assumed to be Gaussian), the amplitude distribution near the core of the vortex, the beam phase structure, and the Gouy s phase.

A Gaussian envelope of the beam is given by

$$(,) = \frac{}{(1 + \ ^2/ \ _R^2)^{1/2}} \exp\left(\frac{- \ ^2}{^2( )} \right) \exp\left(- \frac{^2}{2(\ ^2 + \ _R^2)} \right), \tag{3}$$

where A is a normalization constant, $z_R = kw_0^2/2$ is the Rayleigh s distance (w_0 is the width of the beam at z = 0 and k is the wavenumber), and $w(z) = w_0[1 + (z/z_R)^2]^{1/2}$ represents the width distribution of the beam throughout the propagation path.

Pressure distribution close to the core of the beam is given by

$$G_{n\,m}\ r\ z \quad \left(\frac{r\sqrt{}}{w\ z} \right)^{|m|} L_{n-|m|}^{|m|} \left(\frac{r}{w\ \ z} \right) \tag{4}$$

where $L_{n-|m|}^{|m|}$ are the Laguerre s generalized polynomials [20] of radial index n = |m|, |m| + 2, |m| + 4, ..., and topological charge m.

The helical structure of the beam phase results from the term:

$$\Phi \ (\phi) = \exp(\quad \phi), \tag{5}$$

and the Gouy s phase reads [7], [21]:

$$_n\ z \qquad\qquad i\ n \qquad \psi\ z \tag{6}$$

where $\psi(z)$ = arctan (z/z_R).

Eq. (1) enables us to synthesize a Gaussian beam corresponding to a phase singularity in the wavefront and its evolution with time at any observation plane parallel to the vortex generator transducer. This result, used frequently to model an optical helical beam, is employed in the next section to qualitatively compare the structure of the screw dislocation obtained from theoretical simulation with that measured at the observation planes. Figs. 4 and 5 show the instantaneous pressure eld of a Gaussian beam and its respective phase distribution, for two di erent topological charges, i.e., m = 1 and m = 3. Note that phase varies between π rad and π rad as we follow a circular trajectory around the core of the vortex; nding one and three discontinuities respectively.

Considering that the Gaussian beam formulation is not satisfactory to model the near eld pattern of a nite source generating a helical beam, we have also used the well-known distributed point source method [22] to numerically predict the acoustic eld produced by the fabricated prototype, as shown in Fig. 6.

IV. R : H W G

In this section, we demonstrate that gluing a ferroelectret lm on a developable surface allows us to generate a customizable acoustic radiating pattern. In particular, we show that it is possible to create an acoustic vortex using a tangential surface substrate. Empirical and theoretical simulation results are compared to evaluate the quality of the generated helical wavefront at two di erent planes of observation. We applied a sinusoidal burst of 10 cycles at a frequency of 100 kHz, using a low pulse repetition frequency to avoid the creation of a standing wave. Figs. 7 and 8 show the measured and estimated acoustic pressure elds, at 100 and 200 mm, respectively, at 4 di erent

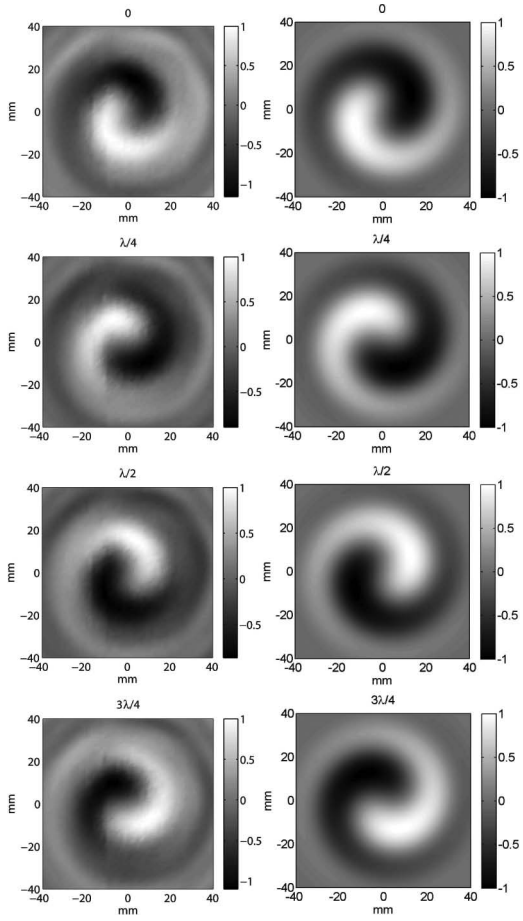

Fig. 8. Normalized instantaneous pressure amplitude at an observation plane located 200mm from the transducer. Four di erent instants within a period of oscillation τ are shown (0, τ/4, τ/2, 3τ/4). Topological charge m = 1, left: measured acoustic vortex ( ). Right: synthesized Gaussian beam (w_0 = 13 mm, z = 200 mm).

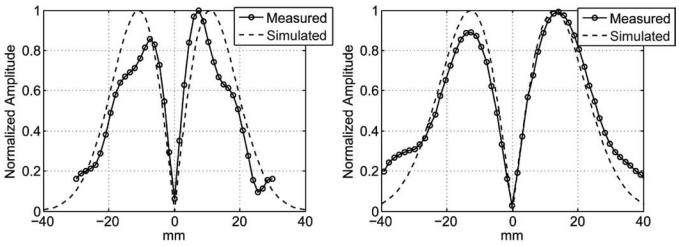

Fig. 9. Comparison between the envelope of a Gaussian beam and that of the acoustic vortex generated with the ferroelectret-based transducer. Left: at the observation plane (X,Y, 100 mm), i.e., in the near eld of the vortex generator; right: at the observation plane (X,Y, 200 mm).

Experimental results obtained were in excellent agreement with theoretical estimations which indicates that it is possible to generate high-quality helical wavefronts easily and reliably. This paves the way for the potential use of acoustic vortices in engineering applications without using a complicated setup to produce them. Considering that the sensitivity of the ferroelectret lms is moderate (around 15 to 20 dB lower than that of resonant piezoceramics and PVDF-based transducers), the excitation voltage and

Fig. 10. Normalized magnitude (top panel) and phase (low pane) of a helical wavefront at an observation plane located at a distance of 100 mm from the transducer. Maximum pressure obtained: 1.37 Pa. Frequency = 100 kHz. Topological charge m = 1. Left: measured acoustic vortex, right: simulated using the distributed point source model method.

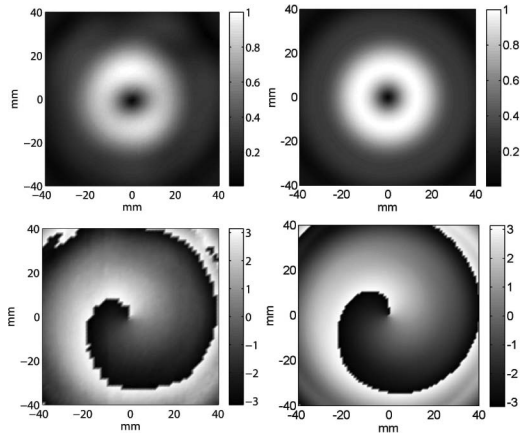

Fig. 11. Normalized magnitude (top panel) and phase (low pane) of a helical wavefront at an observation plane located at a distance of 200 mm from the transducer. Maximum pressure obtained: 0.98 Pa, frequency = 100 kHz. Topological charge m = 1. Left: Measured acoustic vortex ( ), right: simulated using the distributed point source model method.

the size of the vortex generator must be properly chosen to obtain the desired acoustic output. However, its wide frequency range of operation, from 20 kHz to several hundreds of kilohertz, which allows us to create vortices of di erent topological charge using the same transducer, and its ease of use make the ferroelectret technology an excellent candidate for ultrasonic vortex generation. Further research is required to quantify the e ect of the variations in the piston-like response of the lm at frequencies beyond 150 kHz on the generated acoustic vortices.

It is important to point out that the ultrasonic vortex can also be achieved using a ferroelectret-based multi-transducer along a phased-array system. In this manner, the phase singularity is created not by using a helical surface but electronically. An easy procedure to fabricate ferroelectret-based multi-transducers has recently been demonstrated [23].

Fig. 12. Time variation of the acoustic pressure of 51 di erent points deployed on a line that transversely crosses the helical wavefront measured at (X, Y, 200 mm). The spacing of the observation points was 1.6 mm. Left: time responses arranged vertically, right: top view of the pressure distribution.

Fig. 13. Time evolution of the ultrasonic vortex. Plotted dots correspond to the points with constant phase measured on a grid covering the plane (X, Y, 200 mm). The spacing between the elements of the grid is 1.6 mm.

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