Easy Generation of Airborne Ultrasonic Helical Wavefronts

Joao L. Ealo*, José Carlos Prieto †, Fernando Seco †
*School of Mechanical Engineering
University of Valle, Cali, COLOMBIA
Email: joao.ealo@correounivalle.edu.co
†Centre for Automation and Robotics (CAR), CSIC-UPM,
Arganda del Rey, Madrid, SPAIN

Abstract—**In this work, the feasibility to easily generate airborne ultrasonic helical wavefronts is demonstrated. We have experimentally obtained airborne ultrasonic Helical Wavefronts (HW) of great quality by gluing a ferroelectret film on a helicoid surface. A comparison between measured and theoretical results of the pressure and phase distributions of this type of wavefront is accomplished. The simple fabrication procedure, which results inexpensive and reliable, opens up a new alternative to explore the special features of wavefronts with screw-type dislocations.**

I. INTRODUCTION

In general, phase singularities can be of three types: axial, screw-type, and mixed. They occur naturally in wavefronts and are resistant to disturbances in the field [1]. Figure 1 shows a typical theoretical representation of the constant phase planes of a helical wavefront (HW), in which this paper is focused on. This type of acoustic field is also known as acoustic vortex due to its similarity with vortices in fluids. In this sense, acoustic vortices have been proposed as a versatile tool for the experimental study of their optical, fluidic, and quantum counterpart, because of their larger wavelength and the possibility to perform a direct scan of both amplitude and phase of the field. For instance, the transfer of angular momentum has been experimentally demonstrated in acoustics [2], [3] and in optics [4]. An interesting property of HW is the storage and transmission of digitized information where the phase coding is in space, not in time [5]. Even though the potential of acoustic HW has been reported, their application has been scarce which can be attributable to the need of a complex instrumentation to generate them.

Basically, three different methods have been proposed for acoustic HW generation: I) multiple source synthesis [2], [5], [6], II) optoacoustic technique [7], and III) direct generation from a special shaped source [8]. Sometimes, a slightly different category, referred to as phased array system, is considered, in which a high number of multiple sources is used. Also, a variation of the first generation method is shown in [9] where the transducers are not located in the same plane. Specifically, two couples of transducers facing each other are used to synthesize a chain of acoustic vortices. Although the use of multiples sources gives more versatility to the HW synthesis, it has a moderate to high electronic complexity and cost because the multiple transducers need to be synchronized. Regarding the optoacoustic technique, the problem of lack of efficiency in the conversion has been reported. Also, several elements are required, one of which (the absorber) is a helical surface element made of a special material. With respect to the third method, in most of the cases a helical surface substrate is required, to which an active element is attached. However, the helicoid is not required to be absorbent. In [8] (see also [6]), the generation of a helical beam in water is demonstrated using a ring of marine brass and a piezoelectric film of Polyvinylidene Fluoride (PVDF), which acts as active material, fixed to it. A similar approach is proposed in this work to easily generate airborne HW at ultrasonic frequencies using a different piezoelectreic polymer, i.e. ferroelectret film.

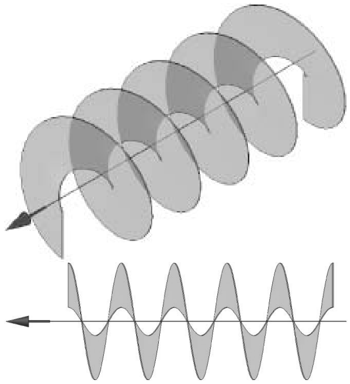

Fig. 1. Representation of the constant phase planes of a wavefront with screw dislocation (helical wavefront). The black arrow indicates the direction of propagation of the wavefront.

Ferroelectret technology is a new class of material which exhibits interesting electromechanical properties. In particular, its high d_{33} piezoelectric coefficient, wide usable frequency rang of operation (from 30 kHz up to 2 MHz), low acoustic impedance (≈ 0.03 MRayls), high mechanical flexibility and easiness of use allow us to design ultrasonic transducer versatilely for airborne applications [10], [11].

To model a HW it is possible to use the Gauss-Laguerre beams, which are solutions of the paraxial wave equation in cylindrical coordinates and exhibit many of the distinctive features of a helicoidal wave. Because of their rather simple mathematical formulation this type of beams are often used to synthesize HW. See references [12] [13]. It is important to point out that the Gaussian beam formulation is not satisfactory to model the near field of a finite source generating a HW. For comparison purposes, the Distributed Point Source Method can also be used to successfully simulate the acoustic field radiated by a helical-shaped finite source [14] [15].

A. *Developable Surfaces*

A developable surface is a special ruled surface that can be flattened onto a plane without distortion, i.e. "stretching", tearing or "compressing"). More strictly, there exist a transformation that maps the surface onto the plane, after which the length of any curve drawn on the surface remains the same. Such type of surfaces, which have been widely used in engineering and manufacturing processes, are known as *developable surfaces* [16]. In general, all the surfaces obtained by bending a material approximately unstretchable (i.e. paper, sheet metal, etc.) is developable. In a three-dimensional space it is possible to realize different types of developable surfaces: a. generalized cylinders whose cross-section may be any smooth curve, conical surfaces, planes (trivial surfaces) and tangent developable surfaces which can are constructed by the union of the tangent lines of a spatial curve [17]. For instance, spheres are not developable.

In this paper, a fast and inexpensive procedure to create acoustic vortices is proposed. It consists in gluing a ferroelectret film on a specially shaped substrate of developable surface, i.e. a helicoid. The unprecedented mechanical flexibility of the film enables us to fabricate transducers on any developable surface along with to its broadband piston-like, open up the possibility to custom-make special acoustic patterns [18], such as acoustic HW in air and at ultrasonic frequencies.

In section II a detailed description is presented of the HW generator transducer and the instrumentation used. In section III the generated acoustic pattern is measured and compared with simulation results. The results obtained corroborate the great potential of ferroelectret technology to fabricate developable surface transducers at ultrasonic frequencies in air. Finally, the conclusions of the work are presented.

II. MATERIALS AND METHODS

A. *Helical Wavefront Generator Fabrication*

The procedure proposed rest on two important characteristics of cellular ferroelectret technology: 1. The high mechanical flexibility of the films and 2. the piston-like response of the piezoelectret transducers regardless of the radius of curvature of the substrate. To all practical purposes a piezoelectret film resembles a piece of paper. So, the high flexibility feature allows us to create different developable surfaces by properly bending the film. In this work, we are particularly interested in a tangential developable surface: the helicoid, i.e. the minimal surface having a helix as its boundary. See figure 1.

With respect to the vibratory response of a ferroelectret film, Ealo et al. [11] experimentally demonstrated that neither its electromechanical sensitivity nor its vibratory characteristics are affected when the film is glued on a developable surface substrate. Consequently, the HW generator fabrication entails the fixation of the electromechanical film on a helicoid. Figure 2 illustrates the fabrication process of the HW generator along with a picture of the constructed prototype.

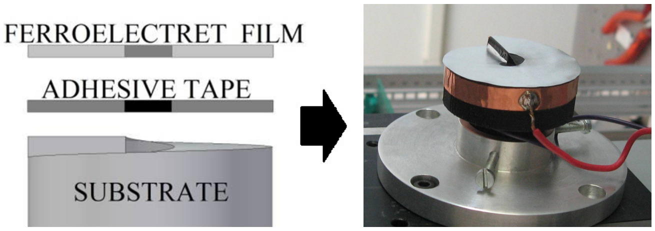

Fig. 2. Right: Prototype fabricated with ferroelectret film glued on a helical substrate using an electrically conductive adhesive tape. Dislocation p of 1λ at 100 kHz in air. Outer diameter: 40 mm. Left: Sketch of the fabrication procedure of the Helical Wavefront generator.

Regarding the transducer fabrication process, the ferroelectret film is cut to shape and size and fixed on a rigid helicoid substrate. The non-metalized side of the active film is glued to the substrate surface using an electrically conductive adhesive tape, which does not affect the electromechanical response of the film and provides a sufficiently rigid and homogeneous foundation. Because the helicoid is developable, the creation of creases is avoided. The helicoid substrate geometry determines the radiating field pattern, i.e. a helical wavefront. See figure 3.

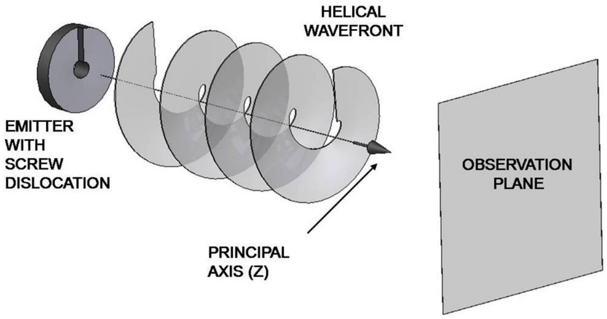

Fig. 3. Sketch of the vortex characterization setup.

The solid substrate geometry was fabricated with a rapid prototyping machine using Acrylonitrile Butadiene Styrene-ABS polymer. A computer numerical control milling machine can also be used to obtain the helicoid surface.

To fabricate our HW generator prototype we have used the electromechanical film Emfit^{TM}, type HS-03-20BRAL1 (Emfit Ltd., Vaajakoski, Finland). Nominal thickness of the film is ≈ 70 μm and one of its sides is coated with vaporized aluminum, which acts as the upper electrode.

B. *Helical Wavefront Generator*

The prototype substrate exhibits a helicoid surface which correspond to a screw dislocation of a pitch $p = 3.45$ mm. See figure 2. In this work we have measured the acoustic field generated by a burst excitation signal of ten cycles at 100 kHz. A low pulse repetition frequency was used to avoid the creation of a standing wave field. The resultant HW exhibits a topological charge $m = p/\lambda = -1$ where λ is the acoustic wavelength. At frequencies greater than 150 kHz the velocity profile of the film becomes uneven due to the random nonuniformities of the electromechanical properties of the film. However, at frequencies of up to 100 kHz, the vibratory pattern of the Emfit film resembles a piston-like response. Consequently, a quasi ideal HW was expected at this frequency [11].

C. Instrumentation Setup

The experimental apparatus used in this work basically consists of 3 parts: the excitation equipments, the measurement devices and the controlled XY linear units. To produce the acoustic signals we have employed an arbitrary waveform generator (Model U2531A. Agilent,CA) connected to a PC. A high-speed high voltage amplifier allows us to apply up to 300 Vpp from DC to 5 MHz (Model WMA-300, Falco Systems, Amsterdam, Netherlands). With regard to the measurement of the acoustic field, the linear units enabled us to sample the instantaneous pressure distribution of the wavefront at the observation points arranged in a square grid. Linear steps of 1.65 mm were used in both horizontal and vertical directions. The acoustic measurements were carried out using a calibrated microphone (1/8 in. Type 40BF, G.R.A.S, Holte, Denmark), which has a frequency range from 10 Hz to 140 kHz. Specifically, the helical beam was measured at a distance of 200 mm far from the transducer.

III. RESULTS

In this section we demonstrate that fixing a ferroelectret film on a helicoid surface allows us to generate a helicoidal acoustic radiating pattern. In particular, a comparison between empirical and theoretical simulation results is accomplished to ponder the quality of the generated helical HW in the farfield of the transducer. In Figure 4 we show the measured and estimated instantaneous acoustic pressure fields at 200 mm respectively. Experimental results greatly agree with the theoretical estimation obtained using a synthesized Gaussian beam of topological charge $m = -1$, which corroborates the feasibility of using the proposed procedure to produce a HW. The screw dislocation singularity is clearly appreciated because the phase changes from $-\pi$ rad to π rad as we move around the core describing a circle. That is, the phase linearly increases from $-\pi$ to π as the principal axis is encircled counterclockwise.

Figures 5 illustrates the stationary absolute value of the pressure distribution at 200 mm from the HW generator. The simulation results were obtained using the Distributed Point Source Method. As it was expected, the acoustic pressure fields, measured and modeled, resemble a doughnut and the pressure at the core is zero with phase undetermined. This behavior is also observed in the near field of the tranducer. The effect of the attenuation with frequency was not included in the theoretical simulations.

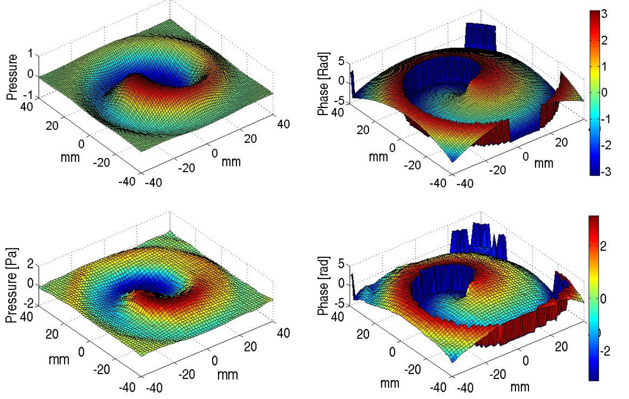

Fig. 4. Normalized instantaneous pressure amplitude and phase at an observation plane located 200 mm far from the transducer. Topological charge $m = -1$. Bottom: Measured helical wavefront. Top: Synthesized Gaussian beam. See reference [13]

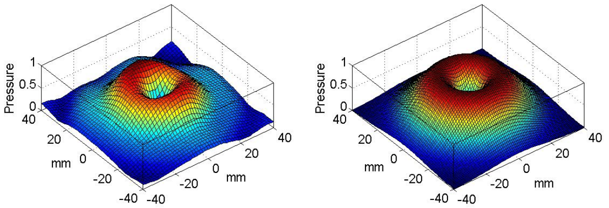

Fig. 5. Normalized magnitude of a helical wavefront at an observation plane located at a distance of 200 mm from the transducer. Maximum pressure obtained: 0.98 Pa. Frequency = 100 kHz. Topological charge $m = -1$. Left: Measured acoustic vortex. Right: Simulated using the Distributed Point Source Model Method.

The shape of the envelope of the obtained HW is also of great interest for characterization purposes. Figure 6-left compares the envelope of the synthesized Gaussian beam with that of the measured HW at the observation plane. A good agreement is appreciated which allows us to conclude that a Gaussian envelope approximation is possible in the farfield of the HW generator.

Finally, figure 6-right shows the time variation of the pressure at along a straight line that crosses the principal axis of the transducer and is located in the observation plane. The low pressure level at the principal axis is clearly appreciated.

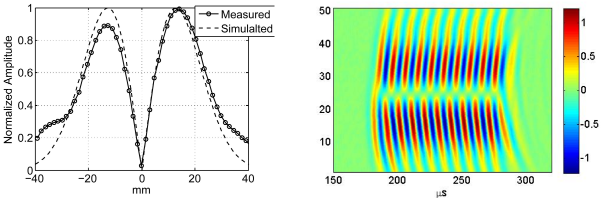

Fig. 6. Left:Comparison between the envelope of a Gaussian beam and that of the acoustic vortex generated with the ferroelectret-based transducer. Right:Top view of the time variation of the acoustic pressure on a line that transversely crosses the helical wavefront measured. The spacing of the observation points was 1.6 mm. Observation plane located in the farfield.

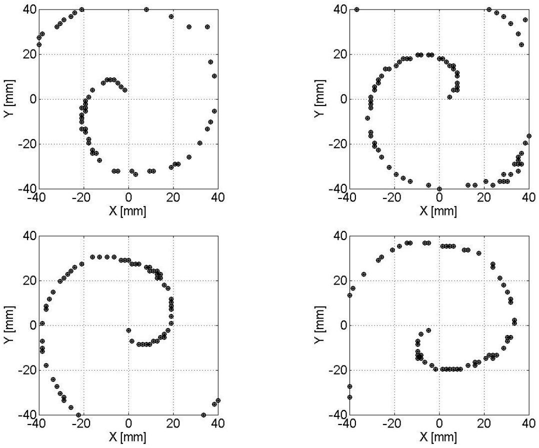

Fig. 7. Time evolution of the helical wavefront. Plotted dots correspond to the points with constant phase measured, at four different instants within a period of oscillation, on a grid covering the observation plane located at 20 from the vortex generator. Topological charge m =-1. Frequency 100 kHz. The spacing between the elements of the measurement grid is 1.6 mm.

Also a phase shift of π between any two observation points located on each side of the center is observed. Furthermore, figure 7 illustrates the points of constant phase (wavefront) measured on the observation plane, at four different instants of time within a complete oscillation, i.e. as the measured wavefront crosses the plane. The spiral deployment of the points observed also allows us to conclude that the generated field greatly emulates the theoretical characteristics of an ideal HW.

IV. CONCLUSIONS

The fairly good agreement between the experimental results and theoretical simulation indicates that it is possible to produce high quality HW easily using the proposed procedure. This expands the possibilities of HW in engineering applications without using a complicated experimental apparatus. Cellular ferroelectrets exhibits an unprecedented versatility to design acoustic transducers. Their wide usable frequency range of operation of cellular ferroelectrets, from 20 kHz to several hundreds of kHz, enables us to create HW of different topological charge using the same transducer. Also, its easiness of use makes them an excellent candidate for airborne ultrasonic HW generation. It is important to point out that the HW can also be generated using a ferroelectret-based multitransducer along with a phased array system so that the phase singularity is created not by using a specially shaped surface but electronically [19]. More complex geometries for HW generation are possible. Current research is being conducted using a developable surface that combines an inner cone and a helical surface.

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