Rotating acoustic drills by the interference of detuned vortices

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2022 IEEE International Ultrasonics Symposium (IUS) | 978-1-6654-6657-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/IUS54386.2022.9957960

***Abstract*—We present acoustic drill beams, structured sound beams exhibiting a dynamic intensity distribution that matches the shape of a helix. The intensity distribution rotates along the beam axis with controlled direction and angular frequency, resembling in this way the shape of a mechanical drill bit. Acoustic drill beams emerge as the spatiotemporal interference of two confocal, detuned vortex beams. The beam parameters are fully tuneable. The detuned frequency, the detuned wavenumber and the detuned topological charge of the composing beams can be tuned to control the drill parameters such as the number of drill arms, the winding period, the rotational speed, and their direction. We show that elongated drill beams are obtained using two confocal high-order Bessel beams, allowing analytical solutions for optimal overlap. In addition, drill beams can also be synthesised using focused ultrasound vortices. Analytical, numerical, and experimental results are shown in the ultrasound regime using a low-cost device based on two 1-MHz confocal piezoelectric transducers and 3D printed acoustic holograms. This exotic structured wavefront opens new avenues for wave-matter interaction, such as contactless particle manipulation, matter processing or biomedical applications.**

***Index Terms*—Vortex, Tweezers, Holograms, Bessel beams.**

I. Introduction

The concept of Bessel beams was first proposed by Jim Durnin and colleagues in the late 1980s in optics. Bessel beams are invariant solutions of the wave equation, in the shape of a nondiffracting beam with an infinite number of rings that can cover an infinite distance and requiring an infinite amount of energy [1]. Since then, truncated Bessel beams have found their way into many optical disciplines, including precision drilling of high aspect ratio holes, or particle trapping and tweezing [2]. Apart from zeroth-order Bessel beams, in some cases more exotic beam shapes can be beneficial. One notable example of these singular beams are vortex beams, with helical wavefronts and a dark area along the beam axis in the focal area. In acoustics, these exotic beams are emerging as tools for wave-matter interaction, including particle trapping and manipulation, mechanical torque transfer applications, or acoustic transceivers for underwater communications.

An example of vortex beams are higher-order Bessel beams, characterized by an elongated focal spot. These Bessel beams with angular momentum also exhibit a central dark area but have an advantage over Laguerre-Gauss beams due to long nondiffracting region [3]. While zeroth-order Bessel beams can be formed by circular slits, conical lenses (axicons) [4] or diffraction gratings [5], a chiral version of these devices can be designed to generated higher order Bessel beams, for example, using Archimedean spiral phase plates [6], [7], or phase transmission masks and holograms [**?**]. These devices can be modified to control the focal spot and produce sharp focusing [8] and to simultaneously compensate the aberrations of strongly refracting layers such as skull bones [**?**]. Note vortex synthesis have also been demonstrated using a wide range of helicoidal surfaces [11]–[13].

In this work, we present acoustic drills, a new type of beam whose intensity distribution matches the shape of a helix, twisting around the beam axis [14]. In addition, the intensity distribution rotates with time along the axis of the beam with a controlled direction and angular frequency, therefore resembling the shape of a mechanical drill bit.

II. Methods

To generate the drills we first synthesize two confocal and detuned Bessel beams of elongated focal spot and arbitrary topological charge using two concentric 3D-printed acoustic holograms. Each primary beam have different frequency, axial wavenumber and topological charge. The outer beam is excited by a custom piezoelectric ring (84-mm external diameter,

This work has received funding from the Spanish Ministry of Science, Innovation and Universities (MICINN) under grants PID2019-109175GB-C21 and PID2019-111436RB-C22, Agència Valenciana de la Innovació through grants INNVA1/2022/37 and INNVA2/2022/11, and European Social Fund (project No 09.3.3- LMT-K712-17- 0016) under grant agreement with the Research Council of Lithuania (LMTLT). NJ acknowledges financial support from MICINN through grant "Juan de la Cierva – Incorporación" IJC2018-037897-I and Ramón y Cajal RYC2021-034920-I.

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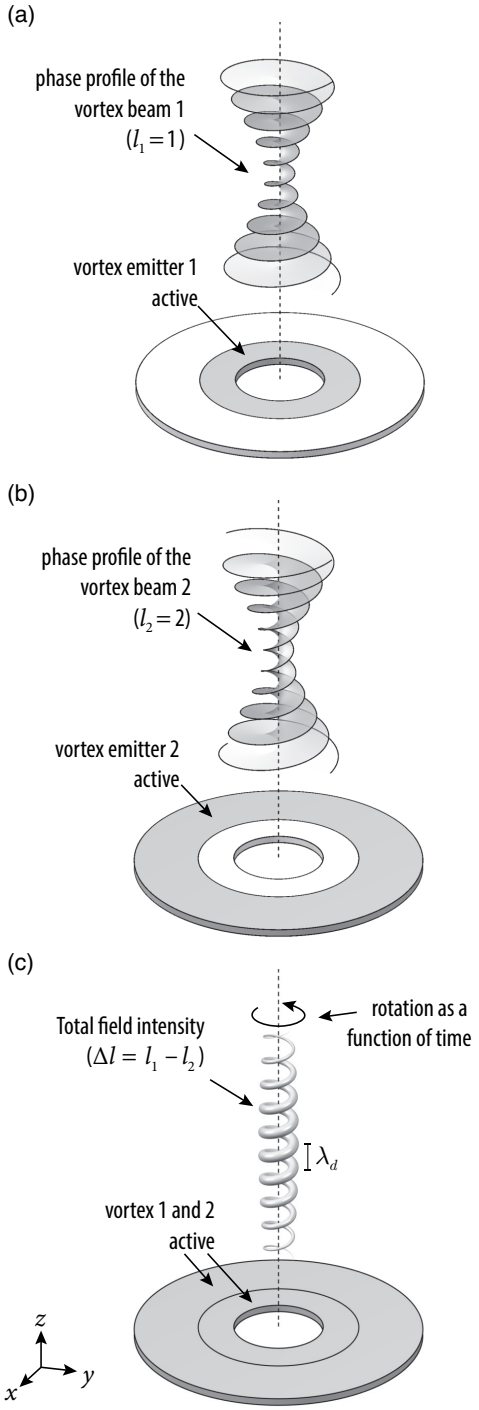


Fig. 1. Scheme of the field produced by (a) the first primary beam (topological charge $l_1 = 1$), (b) second primary beam (topological charge $l_2 = 2$), and (c) resulting helical intensity as the spatiotemporal interference of both detuned beams, showing a total of $\Delta l = l_2 - l_1 = 1$ wind.

50-mm internal diameter) and a concentric unfocused circular transducer (50-mm aperture). Each transducer is excited with a separate AWG and RF amplifier, with a sinusoidal pulsed burst whose central frequency is around 1.1 MHz. The frequency was slightly detuned, to about several Hertz. Field measurements were taken in water, k-space pseudoespectral simulations were performed, and the acoustic field was calculated using the Rayleigh-Sommerfeld integral. Camera measurements were taken at the surface of the water to show acoustic radiation force effects at the interface.

III. Results

Elongated drill beams are obtained by mixing two high-order Bessel beams, conforming a helical structure of intensity distribution rotating with a controlled angular frequency. Figure 1 show an example for the superposition of two ideal Bessel beams of topological charges $l_1 = +1$ and $l_2 = +2$, and a detuning frequency of 1 Hz. An acoustic drill of one-arm winding emerges as the spatiotemporal interference of the two confocal and detuned vortex beams. The resulting drill beam exhibits a number of winds that is proportional to the detuned topological charge

$$\Delta l = l_2 - l_1. \tag{1}$$

In fact, the detuning parameters (detuning frequency, detuning wavenumber, and the detuned topological charge) has been identified as the key to tune the main features of the resulting helix. In a last experiment, we use $l_1 = +1$ for the first primary beam and $l_2 = -2$ for the second primary beam, therefore, the resulting drill beam exhibits $\Delta l = +1-(-2) = +3$ winds. Hydrophone measurements were projected to conform the 3-dimensional intensity distribution. The helical structure agrees with theory, and the drill is formed all over the elongated focal spot of the primary beams, up to 30 mm in this case. Finally, the resulting acoustic radiation force pushes the boundary of the water, and it becomes visible the transversal profile of the helix on the surface of the water tank. By changing the detuning frequency, we validate that the rotation speed of the drill beam can be controlled according to theory.

IV. Conclusions

In this work we present acoustic drills, a new type of beam whose intensity distribution matches the shape of a helix, twisting around the beam axis. The intensity distribution of these dynamic beams rotates with time along the axis of the beam with a controlled direction and angular frequency, therefore resembling the shape of a mechanical drill bit. Analytical constraints for optimal beam overlapping were obtained. We show how the parameters of the helical beam are fully tunable, their period, winding, rotation speed and direction, number of winds, and we link these parameters to the geometrical and detuning parameters of the primary vortex beams. This new wave structure opens novel avenues for wave-matter interaction, such as contactless particle manipulation, matter processing or biomedical applications.

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