ACOUSTIC DRILL BEAMS: TWISTING WAVE INTENSITY BY THE SUPERPOSITION OF DETUNED VORTICES

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Palabras Clave: vortex, tweezers, holograms, Bessel beams
PACS: (Arial, tamaño 8, línea 8, mayúsculas, alineado izquierda).

ABSTRACT

We present acoustic drill beams, a novel structured sound beam exhibits a dynamic intensity distribution matching 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 control the number of drill arms, the winding period, the rotational speed, and their direction. We show that elongated drill beams are obtained using two 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 new wave structure opens new avenues for wave-matter interaction, such as contactless particle manipulation, matter processing or biomedical applications.

RESUMEN

Presentamos los haces de taladro acústico, haces de sonido estructurado que presentan una distribución de intensidad dinámica que coincide con la forma de una hélice. La distribución de intensidad gira a lo largo del eje del haz con dirección y frecuencia angular controladas, asemejándose así a la forma de una broca mecánica. Los haces de taladro acústicos surgen como la interferencia espacio-temporal de dos haces de vórtice confocales y desintonizados. Los parámetros del haz son totalmente sintonizables. La frecuencia desintonizada, el número de onda desintonizado y la carga topológica desintonizada de los haces que los componen controlan el número de brazos de perforación, el periodo de enrollamiento, la velocidad de rotación y su dirección. Demostramos que los haces de perforación alargados se obtienen utilizando dos haces de Bessel de alto orden, lo que permite obtener soluciones analíticas para un solapamiento óptimo. Mostramos resultados analíticos, numéricos y experimentales utilizando un dispositivo de bajo coste basado en dos transductores piezoeléctricos confocales de 1 MHz y hologramas acústicos impresos en 3D. Esta nueva estructura de ondas abre nuevas vías para la interacción onda-materia, como la manipulación de partículas sin contacto, el procesamiento de la materia o las aplicaciones biomédicas.

1. INTRODUCTION

The concept of the Bessel beam 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 power [1]. Since then, truncated Bessel beams have found their way into many disciplines, including optical and acoustical trapping and tweezing, precision drilling of high aspect ratio holes [2,3]. Apart from zeroth-order Bessel beams, in some cases more exotic beam shapes can be beneficial. One notable example of singular beams are vortex beams, with helical wavefronts and a dark area along the optical axis in the focal area. These exotic beams are emerging as tools for wave-matter interaction, including particle trapping and manipulation, mechanical torque transfer applications, or acoustic transceivers and underwater communications. Bessel beams with angular momentum also exhibit a central dark area but have an advantage over Laguerre-Gauss beams due to long nondiffracting region [4]. Higher-order Bessel beams can be formed by circular slits, conical lenses (axicons) [5], in addition to a spiral phase plate [6–8], or equivalently by the phase transmission masks [9–11] (holograms). Note these mechanisms have been demonstrated in acoustics, where curved surfaces can be also used [12,13]. In this work, we mix to confocal and detuned vortex beams to generate a structured beam of dynamical helical intensity [14].

In common acoustic vortex beams the *phase* is helical with the space. 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. 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.

2. MATERIALS AND METHODS

We synthesize two confocal and detuned Bessel beams of elongated focal spot and arbitrary topological charge using two concentric 3D-printed acoustic holograms. The outer beam is excited by a custom piezoelectric ring (84-mm external diameter, 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.

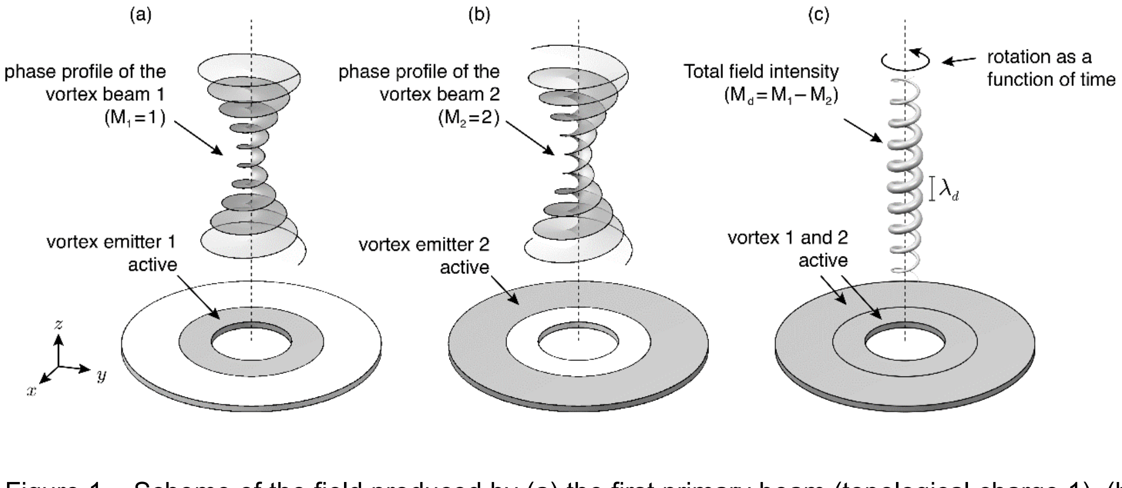

Figure 1 – Scheme of the field produced by (a) the first primary beam (topological charge 1), (b) second primary beam (topological charge 2), and (c) resulting helical intensity as the spatiotemporal interference of both detuned beams. (d) axial cross-section of the field in the case of Bessel beams. The pattern rotates as a function of time as a function of the detuning frequency.

3. 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 2 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 detuning parameters (detuning frequency, detuning wavenumber, and the detuned topological charge) are identified as the key to tune the main features of the resulting helix.

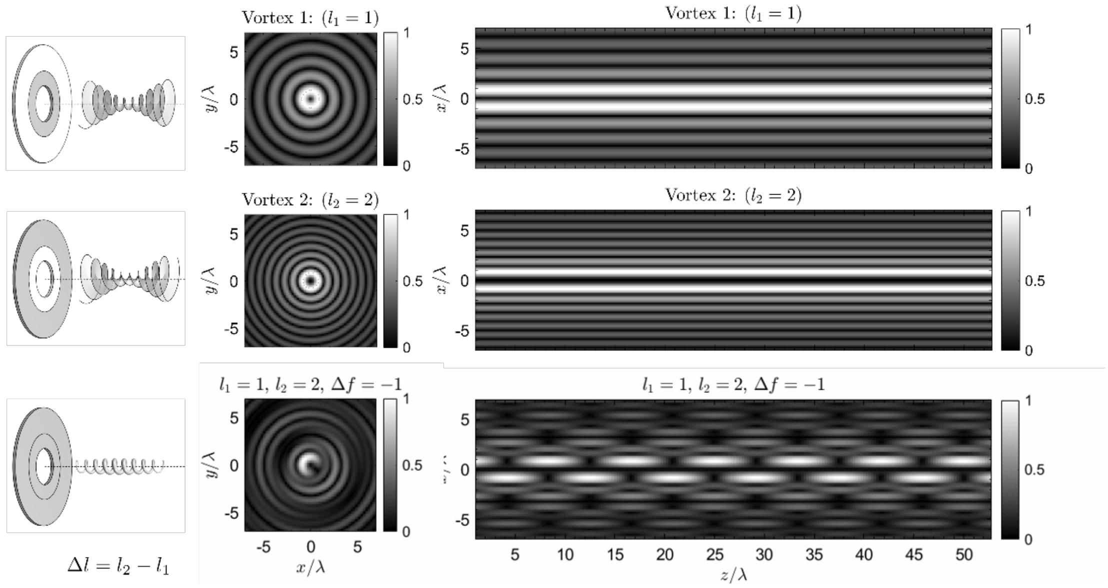

Figure 2 – (Top row) transverse and axial intensity cross section of the first primary beam in the case of Bessel beam of topological charge $l_1 = +1$, (middle row) second primary beam (topological charge $l_2 = +2$,), and (bottom row) resulting helical intensity as the spatiotemporal interference of both detuned beams. The drill winds Dl = +1 – 2 = +1 times.

A transducer is designed to generate the two confocal Bessel beams by modulating the transmitted waves using a hologram. 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 can vary the rotation speed of the drill beam. In this case, 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 Dl = +1 – (– 2) = +3 winds, as shown in Fig. 3.

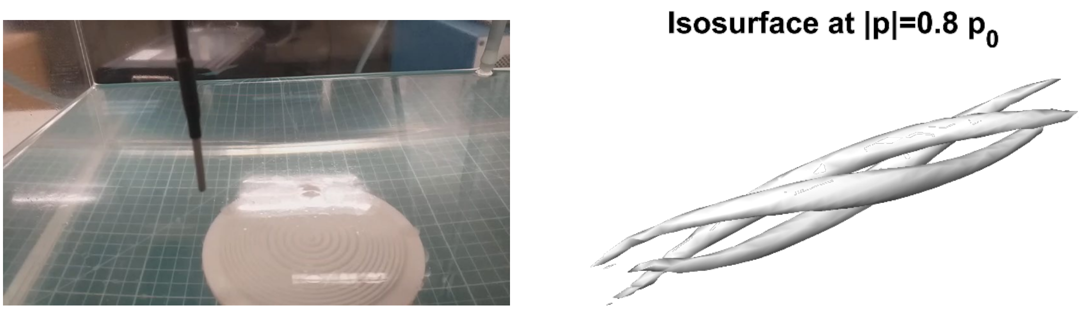

Figure 3 – (left) Frame of a video demonstrating of the transfer of acoustic radiation force at the surface of the water a drill beam. The hologram is visible at the bottom. The pattern rotates in time with controlled speed. (right) Isosurface of the magnitude of the field of the resulting drill with 3 winds.

4. 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 tuneable, their period, winding, rotation speed and direction, number of windings, 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.

ACKNOWLEDGEMENTS

This work has received funding from the Spanish Ministry of Science, Innovation and Universities (MICINN) under grants PID2019-109175GBC21 and PID2019-111436RB-C22. NJ acknowledges financial support MICINN through grant “Juan de la Cierva – Incorporación” IJC2018-037897-I and Agència Valenciana de la Innovació through grant INNVA1/2020/92.

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