Ultrasonics 80 (2017) 66–71

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Short communication

A flat acoustic lens to generate a Bessel-like beam

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ARTICLE INFO

Article history:
Received 7 March 2017
Received in revised form 7 May 2017
Accepted 7 May 2017
Available online 9 May 2017

Keywords:
Acoustic lens
Bessel beam
Schlieren imaging technique
Periodical structure

ABSTRACT

We report a flat acoustic lens with a periodical structure to transform a divergent beam into a Bessel-like beam. Using the Schlieren imaging technique, the propagation process of acoustic wave in the periodical structure was experimentally observed. The pressure distribution in the main lobe is in good agreement with the Bessel function and the positions of the side lobes are close to the peak of the Bessel function. To observe the directivity of the beam, simulations were performed using the finite-element method. The simulation results indicated that the transmitted acoustic intensity at the central axis was several times greater with the lens than without it. The applicability of the lens for detecting the location of an acoustic source was also investigated.

1. Introduction

Bessel beams have been the subject of much research interest over the past two decades [1–5] owing to their interesting propagation properties (e.g., nondiffracting and self-healing properties). A Bessel beam maintain a narrow beam width as it propagates, it does not diffract and spread out. Moreover, the beam can reconstruct itself behind obstacles further down the beam axis.

Bessel beams were first proposed by Durnin et al. in 1988 as propagation-invariant solutions to the Helmholtz equation. Specifically, the radial transverse pressure profile was described theoretically in terms of the Bessel functions [6]. Ding and Lu subsequently calculated the second harmonic component in the Bessel beam and found that it is almost nondiffracting in the radial direction [7]. Ding and Lu further derived an approximate analysis for the propagation of Bessel beams with a finite aperture [8]. In recent years, the propagation characteristics of acoustic Bessel beams have been widely studied. In particular, the arbitrary scatterings of Bessel beams by rigid spheres [9,10], rigid spheroids [11,12], and compressible soft fluid spheres [13] have been investigated. Moreover, a negative axial radiation force was discovered in the Bessel beam [14]. Accordingly, Bessel beams have been used to trap microparticles without any contact between the transducer and objects [15]. The nondiffraction characteristics of Bessel beams have also been widely investigated for applications in ultrasonic medical imaging and Doppler velocity estimation [16].

Different methods have been investigated to generate acoustic Bessel beams. For example, Hsu et al. fabricated a piezoelectric transducer to generate a Bessel beam. The transducer element had a spatially nonuniform electric field and was driven by a time-varying uniform field [17]. The conventional method to generate acoustic Bessel beam is to use a phased array, which generally requires complex systems and an external power supply [5,18]. Although the axicon has been widely used in optics to generate Bessel beams, it has barely been investigated in acoustics because it makes fabrication of the lens difficult [15] and makes the system too complex [5]. Therefore, a more effective, convenient and feasible means to generate acoustic Bessel beams is highly desired.

In this paper, we propose an acoustic lens to generate a Bessel-like beam. The lens is made of a periodical structure. We discuss the mechanism of the generation of the Bessel-like beam using the lens and present experiment observations of the propagation process of acoustic wave in the lens using the Schlieren imaging method. Results from numerical simulations are also provided to determine the pressure variation of the main lobe. Finally, we assess the practical use of the lens for locating the sound source.

2. Experimental

The lens to generate the Bessel-like beam was made of a 1D periodical structure with two elements: glass (density: 2203 kg m^{-3}, Young's modulus: 73.1 GPa, Poisson's ratio: 0.23)

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http://dx.doi.org/10.1016/j.ultras.2017.05.005

and water (density: 998 kg m^{-3}; sound speed: 1482 m s^{-1}). In our previous paper, we identified the backward propagation of acoustic waves in this structure [19]. A schematic diagram of the backward propagation in the glass plate is shown in Fig. 1(a). The acoustic waves propagate from the upper side of the glass plate with a certain angle of incidence. After the waves pass through the glass plate, the transmitted wave is shifted backward. This behavior is ascribed to the negative group velocity in the plate. In the plate, Lamb waves are formed by the reflection and interference of the incident waves from liquid. The acoustic energy propagates with the group velocity along the plate. The accumulation of the acoustic energy in the plate induces the plate radiates acoustic energy into liquid. Thus, the shift of the leaky wave is dependent on the group velocity. When the group velocity is negative (at frequency of 2.76 MHz), the leaky wave moves backward.

In this study, we focused backward-shifted waves in the plate with different angles of incidence. The calculated results, which are presented in Fig. 1(b), reveal that the backward shift linearly increases with increasing angles of incidence for angles below 8°; the backward shift increases nonlinearly with increasing angle of incidence above 8°. The formation of the Bessel beam with the axicon and with the 1D periodical structure is illustrated in Fig. 1(c) and (d), respectively. It is evident from Fig. 1(d) that the formation of the Bessel beam depends on the backward shift of the wave in the periodical structure, and that the backward-shifted wave does not contribute appreciably to the formation of the Bessel beam at angles of incidence greater than 8°. Thus, the pass and stop bands of the periodical structure were carefully adjusted such that waves with angles of incidence greater than 8° were reflected, because the incident wave was in the stop band of the periodical structure. Our lens was made of six layers of the water/glass structure. The thickness of the water and glass layers were 1 and 1.1 mm, respectively.

Visualization of the acoustic fields was conducted using the Schlieren method, which is based on the acousto-optic effect. A schematic diagram of the experimental setup is shown in Fig. 2 (the experimental details are described in our previous paper [19]). In this experiment, a line-focused transducer (2.76 MHz) is

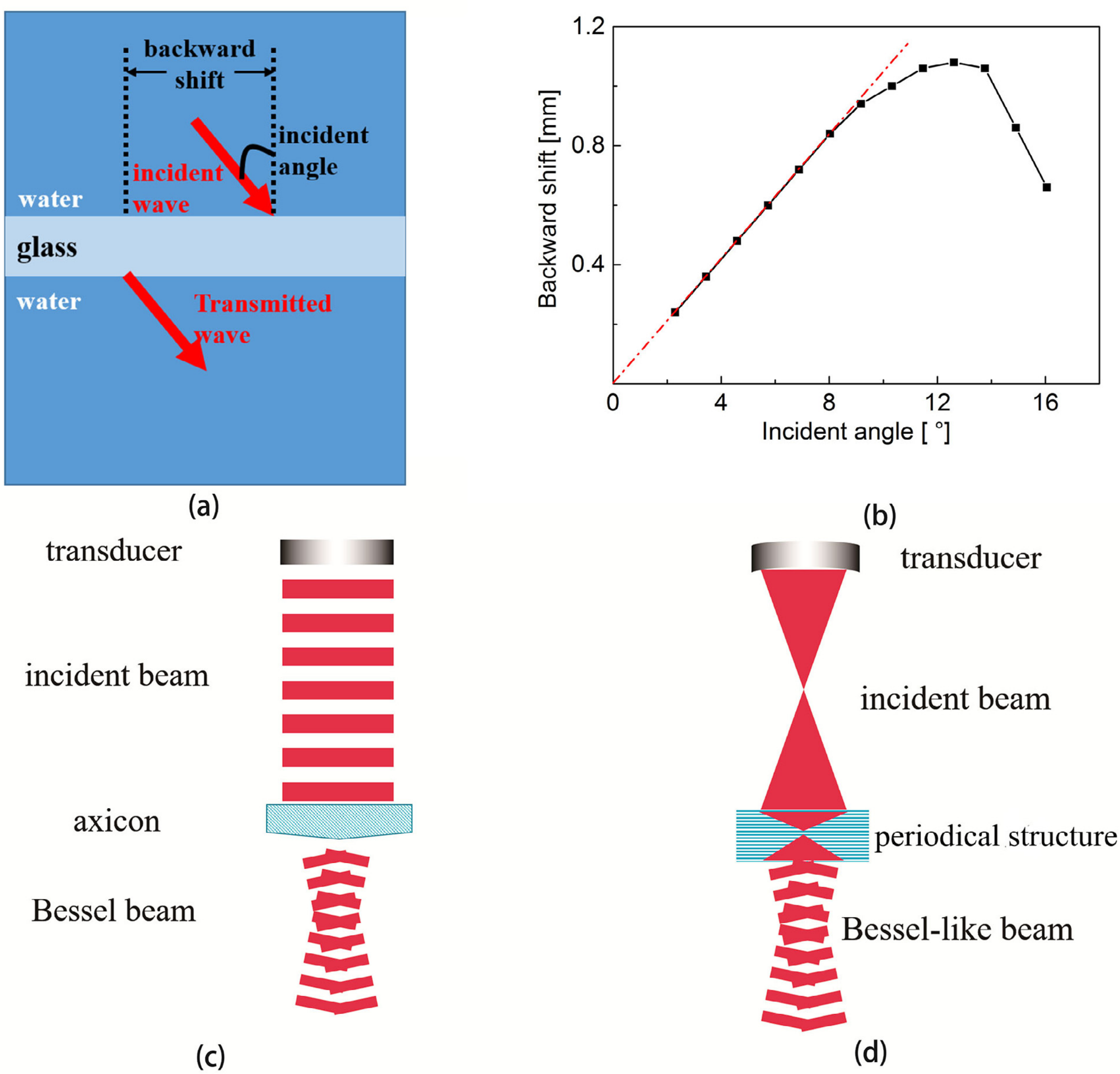

Fig. 1. Formation of the Bessel beam with a glass plate. (a) Schematic diagram of wave propagation through the glass. (b) Backward shift at different angles of incidence. (c) Bessel beam formation with an axicon. (d) Bessel-like beam formation with a periodical structure lens.