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Steering elastic SH waves in an anomalous way by metasurface

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A B S T R A C T

Metasurface, which does not exist in nature, has exhibited exotic essence on the manipulation of both electromagnetic and acoustic waves. In this paper, the concept of metasurface is extended to the field of elastic SH waves, and the anomalous refractions of SH waves across the designed elastic SH wave metasurfaces (SHWMs) are demonstrated numerically. Firstly, a SHWM is designed with supercells, each supercell is composed of four subunits. It is demonstrated that this configuration has the ability of deflecting the vertical and oblique incident waves in an arbitrary desired direction. Then, a unique SHWM with supercell composed of only two subunits is designed. Numerical simulation shows its ability of splitting the vertical and oblique incident waves into two tunable transmitted wave beams, respectively. In the process of steering SH waves, it is also found that two kinds of leakages of transmitted waves across the designed SHWM will occur in some particular situations, which will affect the desired transmitted wave. The mechanisms of the leakages, which are different from that of the common high-order diffraction mentioned in existing literatures, are revealed. The current study can offer theoretical guidance not only for designing devices of directional ultrasonic detection and splitting SH waves but also for steering other kinds of classical waves.

1. Introduction

Engineered artificial metamaterials, originally designed in the field of electromagnetic (EM) waves, have drawn much attention of researchers, as metamaterials can provide properties unavailable in natural materials for EM waves, such as negative refraction [1], polarization manipulation [2], cloaking [3] and inverse Doppler [4]. The successes have boosted a great amount of efforts to develop their acoustic and elastic analogues, i.e., acoustic metamaterials [5,6] and elastic metamaterials [7,8], respectively. However, metamaterials in three-dimensional form have the limitations of high attenuation of waves and are difficult to be manufactured. Recently, a kind of ultrathin metamaterial named metasurface with phase discontinuities is proposed to break these restrictions in the field of EM waves. Such a designed metasurface with sub-wavelength thickness can easily control the trajectory of EM waves by supporting the proposed generalized Snell's law of reflection and refraction (GSL) [9]. Inspired by these EM metasurfaces, researchers have developed their analogous sub-wavelength acoustic ultrathin devices, which have common forms of labyrinthine [10], space-coiling [11,12] and resonance [13] based on phase discontinuities.

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Unfortunately, the extension of the metasurface design to elastic waves in solids has not been drawn much attention other than some studies on elastic waveguides with metamaterial inserts [14–16], although big progress has been achieved in the fields of both optics and acoustics. With the inherent properties of different wave types and mode conversions, the elastic wave has a richer physical meaning, compared to the EM wave and acoustic wave. Only several studies are recently related to this topic. Some researchers [17,18] proposed the concept of structured interface and discussed the influence of structured interface on filtering and focusing elastic waves. Maznev and Gusev [19] showed that surface wave, i.e., Love wave, can propagate in the metasurface formed by grooves on the surface. Boutin et al. [20] proposed the concept of elastodynamic metasurface and brought the experimental evidences of its efficiency and capacity to depolarize mechanical waves in homogeneous media. However, the researchers in the field of mechanics just noticed the concept of metasurface and did not take the advantage of phase discontinuities to steer the propagations of elastic waves in solids. Very recently, we just found that Zhu and Semperlotti [21] investigated the anomalous refraction of Lamb waves in thin-walled structural elements based on phase shift implemented by the use of geometric tapers and Liu et al. [22] designed source illusion devices to manipulate flexural waves using zigzag structure metasurface.

In nondestructive evaluation (NDE) technique, metamaterials [23–25] and phononic structures [26–28], which are designed in three-dimensional form, have the disadvantage of high attenuation of waves and are difficult to be manufactured. They have been utilized to focus, filter and negatively deflect wave by modulating based on multi-materials or single-material approach. However, these studies did not take the advantage of phase discontinuities to steer the propagation of elastic wave in solids. Among various kinds of elastic waves, SH wave is a typical wave, which exhibits in two different forms: body wave [29–31] and guided wave. In the current study, the researches mainly focus on steering SH wave in the form of body wave, which can be used in NDE technique [32,33]. The concept of ultrathin SH wave metasurface (SHWM) is proposed by extending the concept of acoustic metasurface to compensate this deficiency of metamaterials and phononic structures. The designed SHWM supercells in the form of periodic structures can be composed of different numbers of subunits. For EM and acoustic metasurfaces, the number of subunits in one supercell is usually chosen as four or more than four. In the present study, the SHWM with the ordinary supercell composed of four subunits and a unique SHWM with the supercell composed of two subunits are designed to steer the elastic SH waves.

Subsequently, in the process of steering SH waves, two kinds of leakages of transmitted waves across the designed SHWM, which will affect the desired transmitted wave, are found and discussed in details. The elastic wave leakage emerges to play a key role in the described physics and relevant issues have also received attentions of researchers in recent years [34–36]. Therefore, the elastic wave leakage across the designed SHWM is an important issue in the application of SHWM in NDE technique. In steering EM wave [37,38] and acoustic wave [39,40] by metasurfaces, the wave leakages also occurred, which were interpreted by high-order diffraction in the existing studies. However, the mechanisms of the wave leakages discussed in the present study differ from that of the common high-order diffraction. The rest of the paper is organized as follows. Section 2 presents the design method of SHWM. In Section 3, two types of SHWMs are designed and used to steer vertical and oblique incident SH waves. The leakages of transmitted waves appearing in the process of steering SH waves are discussed in Section 4. The further discussion and prospect are presented in Section 5. Finally, the conclusions are provided in Section 6.

2. Design of SHWM

The designed SHWM, bonded between the host structure and excitation device, is a thin plate with a thickness less than half of the wavelength of the incident wave, as shown in Fig. 1(a). In the present study, the incident wave is considered as plane SH wave because the dimensions of the host structure and excitation device are much larger than the wavelength of the incident wave. The polarization direction of the incident SH wave in the form of Gauss beam is perpendicular to the x-y plane of Cartesian coordinate system, the propagation direction is opposite to the x-axis.

The partially enlarged Fig. 1(a) in the x-y plane is shown in Fig. 1(b). It can be observed that the SHWM consist of periodic arrays of supercells, which has N ($N > 1$) subunits, in the direction of the y-axis. The numbers of the subunits are marked as $1, 2 \cdots N-1, N$ successively. The first and the Nth subunits are only composed of plate 1 and plate 2, respectively. The other subunits consist of both plate 1 and plate 2. The widths of the supercell, subunit and groove are denoted as L, l and w_0 ($w_0 = l/6$), respectively, the SHWM has a thickness h, as shown in Fig. 1(b).

When a scalar wave propagates in a thin plate with thickness h, which is less than one wavelength, the phase change of transmitted wave can be expressed as

$$\phi = 2 \cdot \pi \cdot h/\lambda \tag{1}$$

where λ is the wavelength. For the designed SHWM, because the propagating wavelengths of SH waves in the two kinds of plates are different, the phase of the transmitted wave across the first subunit differs from that of the transmitted wave across the other subunits of the supercell. It just shows the prospect of altering the phase of the transmitted wave in longitudinal space. The amount of phase shift of the jth subunit compared with the first subunit of the supercell can be expressed as

$$d\phi = 2 \cdot \pi \cdot \left[h^{(j-1)} \Big/ \lambda_2 - h^{(j-1)} \Big/ \lambda_1 \right], \quad (j = 2, 3 \cdots N) \tag{2}$$