Acoustic cloaking in three dimensions using a feasible metamaterial approach

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ABSTRACT

A unified theory model is developed for a three-dimensional anisotropic acoustic cloak based on the sound speed matching and boundary impedance matching. A crucial parameter \( \delta \), which denotes the material properties, is involved in this multilayered acoustic cloak model. Based on the effective medium approximation theory, each layer in the multilayered acoustic cloak could be constructed using the homogeneous isotropic materials. The different values of the parameter \( \delta \) are discussed to investigate the invisible effects of the multilayered acoustic cloak. By analyzing the invisible effect of the acoustic cloak, it is found that the incident sound wave can pass through the acoustic cloak smoothly with the less backscattering TS using an appropriate \( \delta \) value. More importantly, it is seen that the essential requirement for the infinite mass density in Cummer’s acoustic cloak can be circumvented in the present multilayered acoustic cloak model. This paper can offer a practical guidance to design and construct the acoustic cloak using the multilayered structures which are composed by the existing materials in natural world.

KEY WORDS: metamaterial, acoustic cloak, multilayered, scattering acoustic field

INTRODUCTION

Recently, there is an increasing interest in the possibility of the electromagnetic (EM) cloaks, which could hide the objects from the electromagnetic illumination. By using the coordinate transformation, a cylinder electromagnetic cloak composed by metamaterials was formulated for the electromagnetic field (Schurig, Mock, 2006). Both the theory model and the related experiment results showed that this cylinder electromagnetic cloak could indeed be obtained. Meanwhile, the three-dimensional spherical cloaks are also proposed based on the invariance of the Maxwell’s equations (Pendry, Schurig, 2006). Following the related concepts and methodologies for electromagnetic cloaks, many researchers have also devoted their time and efforts to the acoustic cloak study. An ideal cylinder acoustic cloak was proposed by comparing the electromagnetic field and the acoustic field (Cummer, Schurig, 2007). Later, an ideal three-dimensional acoustic cloak shell was developed through acoustic scattering theory, indicating that the acoustic cloak requires an anisotropic mass density (Cummer, Popa, 2008). Therefore, the acoustic cloak should be composed of anisotropic materials, but the anisotropic materials are difficult to realize due to the limited natural resources. Thus, one possible approach for this issue is to use the multilayered shell structure with isotropic materials to replace the anisotropic materials. Based on the effective medium approximation theory, the parameters of the multilayered acoustic cloak structure were investigated and the low reflection and wavefront-bending phenomenon could be found from the obtained acoustic pressure fields (Cheng, Liu, 2009). The invisible effects for the near-field and the far-field scattering patterns are described distinctly, indicating that the plane wave could be deflected smoothly around the object shielded by the acoustic cloak and the scattering could be reduced in almost all directions. Besides, the acoustic cloak with multilayered structures has great potentials in practical engineering applications.

And, because of the singular problem, the infinite mass density, which would be difficult to obtain in nature, is required for the inner acoustic cloak structure. Thus, it is of some importance to remove the singularities which are required for ideal cloaks. For instance, the density or sound speed, which is just related to the radius for the ideal acoustic cloak, is taken as an appropriate constant value for the imperfect acoustic cloak (Torrent, Sánchez-Dehesa, 2011). Based on this, it is possible to obtain the required materials in nature, but the acoustic cloak would not perform perfectly as the ideal acoustic cloak. In addition, by using the match of the sound speed and acoustic impedance, several models for the imperfect acoustic cloak are studied, which avoid singularity in the acoustic cloak, indicating that sound speed matching for the acoustic cloak may be more important than the impedance matching for the imperfect acoustic cloak (Jo, Oh, 2014). Therefore, other various imperfect acoustic cloaks could be generated based on the balance between the sound speed and the impedance, and the visible effect of the acoustic cloak could be improved with the increment of the thickness ratio between the high mass density and the light mass density.

In this paper, the acoustic cloak pressure field is derived based on acoustic scattering theory using the partial series method expression (Li, Wang, 2018).

THEORY