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# Cloaking an acoustic sensor with single-negative materials

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ABSTRACT

In this review, a brief introduction is given to the development of acoustic superlens cloaks that allow the cloaked object to receive signals while its presence is not sensed by the surrounding, which can be regarded as "cloaking an acoustic sensor". Remarkably, the designed cloak consists of single-negative materials with parameters independent of the background medium or the sensor system, which is proven to be a magnifying superlens. This has facilitated significantly the design and fabrication of acoustic cloaks that generally require double-negative materials with customized parameters. Such innovative design has then been simplified further as a multi-layered structure comprising of two alternately arranged complementary media with homogeneous isotropic single-negative materials. Based on this, a scattering analyses method is developed for the numerical simulation of such multi-layered cloak structures, which may serve as an efficient approach for the investigation on such devices.



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## 1. Introduction

In recent years, the research of transformation optics has attracted a lot of attentions due to its application in the design of functional optical devices. The fundamental idea is based on the fact that Maxwell's equations are form-invariant under coordinate transformation. The theory proposed by Leonhardt [1] and Pendry et al. [2] and Milton et al. [3] is extended to the field of acoustics by Cummer and Schurig [4] in 2006. They proposed two-dimensional (2D) transformation acoustics theory for designing the "inaudibility cloak" to manipulate acoustic waves in a similar manner. In the recent research works, two structures have been developed to realize the cloaking effect by using the technique of transformation acoustics. One is to put the cloaked object in the "hole", and the incident wave will detour around the hidden region without any reflection [5–14]. Then a fundamental limitation arises that the cloaked object has no communication with the outside. In order to solve the problem, the scheme of "external cloaking" is then presented [15,16], in which the cloaked object is "canceled" acoustically by using complementary object and can thus share information with the surroundings. However, in order to realize the perfect cloaking effect, the complementary objects must be made of double-negative materials (DNM) with parameters highly dependent on the parameters of the object to be cloaked, which is much more difficult to design in theory or fabricate in practice when compared with the materials with single-negative parameters. Although it has been proven theoretically that simultaneous negative bulk modulus and mass density can be achieved with coexistent dipolar and mono-polar resonators, the working frequency range of the resulting DNM is much narrower than that of single-negative materials (SNM) [17]. Furthermore, the restriction on the choice of parameters of cloak structure extremely limits the potential applications in practical situations. Therefore, it is significant both physically and practically to explore the possibility of hiding an acoustic sensor by employing SNM only.

On the basis of the technique of transformation acoustics, a different scheme is proposed to cloak an acoustic sensor named as superlens cloak by using SNM materials in a double-shell structure. It is shown that the cloaked object is able to receive external signals without being sensed by surroundings, and internal signals can also transmit to outside [18]. Then the purposes of detection and communication can both be achieved, and the parameters of the acoustical cloak structure are independent of the object to be cloaked. However, one of double shells of the superlens cloak must be fabricated of inhomogeneous materials. So it also has some difficulty for the experimental fabrication and the application in engineering field. In order to solve the problem, then a multi-layered cloak model is proposed to cloak an electromagnetic sensor only by applying three kinds of homogeneous SNG instead of using inhomogeneous materials [19]. The numerical results show that the inserted sensor can receive signals from outside environment while it can be hardly detected by the surrounding for electromagnetic wave. The model may facilitate the experimental realization of the electromagnetic wave cloaks by choosing the few material parameters of the cloak, and it is also the urgent need to be addressed in acoustic field. Then, basing on the theory provided by Cummer and Schurig [4], the electromagnetic model can be extended to acoustic cloaks. However, even in acoustic field, it is still hard to find three different kinds of isotropic SNM with the parameters that can satisfy the necessary complex relationships. In order to further simplify the cloak model with SNM, a multi-layered composite structure with only a single pair of SNM is presented, and the parameters of the cloak model are also totally independent of those of the sensor and background materials [20]. In the engineering field, the cloak model with SNM may be particularly significant for acoustic measurements in which a reduction of the disturbance caused by the acoustic sensors is desired. It is possible to realize the corresponding multi-layered composite structures by using 3D printing technology.

Furthermore, multilayer scatter problems can usually be solved by Finite Element Method (FEM) easily, we still need to divide finer mesh to ensure the accuracy of calculation when there is singularity or dramatic changes in solving domain. It will undoubtedly increase the amount of computation greatly. Meanwhile, when the adjacent layers have a huge difference of materials, the acoustic field calculation by FEM will appear singular values in these small layers if the divided meshes are not enough in each layer. Although the thickness of each layer is much smaller than the wavelength of the incident wave, we still have to further split these thin layers to ensure the validity of calculation. As the