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On the sound insulation of acoustic metasurface using a sub-structuring approach

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ABSTRACT

The feasibility of using an acoustic metasurface (AMS) with acoustic stop-band property to realize sound insulation with ventilation function is investigated. An efficient numerical approach is proposed to evaluate its sound insulation performance. The AMS is excited by a reverberant sound source and the standardized sound reduction index (SRI) is numerically investigated. To facilitate the modeling, the coupling between the AMS and the adjacent acoustic fields is formulated using a sub-structuring approach. A modal based formulation is applied to both the source and receiving room, enabling an efficient calculation in the frequency range from 125 Hz to 2000 Hz. The sound pressures and the velocities at the interface are matched by using a transfer function relation based on "patches". For illustration purposes, numerical examples are investigated using the proposed approach. The unit cell constituting the AMS is constructed in the shape of a thin acoustic chamber with tailored inner structures, whose stop-band property is numerically analyzed and experimentally demonstrated. The AMS is shown to provide effective sound insulation of over 30 dB in the stop-band frequencies from 600 to 1600 Hz. It is also shown that the proposed approach has the potential to be applied to a broad range of AMS studies and optimization problems.

1. Introduction

Sound insulating structures are widely used in various engineering and architectural applications. Structures such as a heavy wall can achieve high sound insulation. However, when ventilation or heat conduction is needed, introducing an opening can significantly deteriorate the overall sound insulation performance. The sound insulation property of a structure is usually adversely dominated by the poor performance of the opening, making it difficult to conciliate noise reduction and ventilation at the same time. Previous studies have considered the use of porous material [1] and partially open double glazing [2] to treat the opening. Although the sound reduction can be improved, the final structure required is usually very bulky.

In recent years, acoustic metamaterials (AMM) received much attention and appeared to open up a new direction for designing acoustic devices, exemplified by research in the field of sonic crystals [3], AMM with negative effective mass [4], negative effective bulk modulus [5] and double-negative AMM [6]. The existing AMMs are often realized either by resonant

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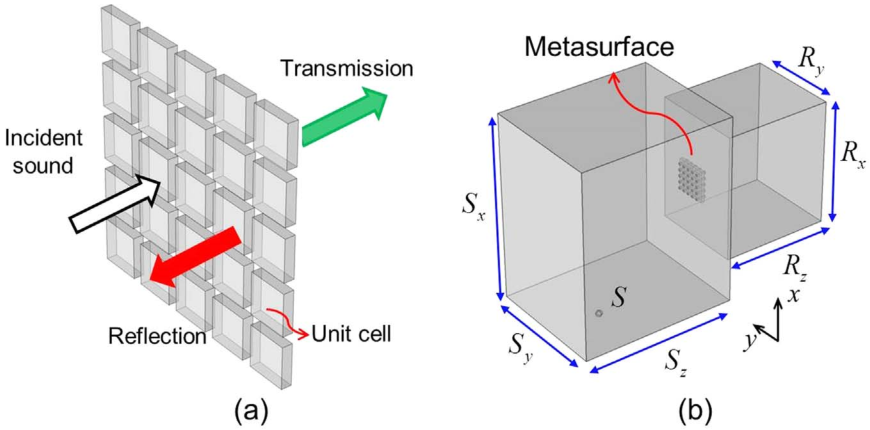

Fig. 1. (a) AMS constructed of structured unit cells for controlling and manipulating sound waves; (b) AMS connecting a sound source field and a receiving room.

systems such as Helmholtz resonators (or elastic membranes with attached mass), or by periodic lattices based on the Bragg scattering. Several researchers have demonstrated the existence of acoustic stop-bands in acoustic ducts lined with periodic scatters [5–7]. The forming of the acoustic stop-band is related to both the individual property of the scatterer and the periodicity. However, the acoustic duct systems presented in these studies are very bulky, which hampers their applicability in real-world applications.

The use of AMM for practical noise control is more desirable with compact size and broadband performance. With an emphasis on the sub-wavelength property, the realization of acoustic metasurface (AMS) may overcome some of these limitations. As illustrated in Fig. 1(a), an AMS is constructed by stacking structured unit cells in a periodic pattern such as a planar array, aiming to realize a certain acoustic function such as high reflection, high absorption or negative refraction. Recent studies reported the design of AMS based on Helmholtz resonators, locally resonant absorbers and artificial Mie resonances [8–10]. The objective of the present study is to use the concept of AMS to realize a surface for broadband sound insulation while allowing for air ventilation. To this end, the unit cell is constructed in the shape of a thin air chamber with apertures on the front and rear surfaces (see Fig. 9 below). The structure inside the air chamber is tailored by adding partitions, ideally forming an acoustic stop-band, to prevent noise transmission. The proposed structure is applicable to those working environments where noise mitigation, ventilation and heat conduction are simultaneously required. Typical examples are ventilation windows with high noise insulation, sound enclosures for engine and machinery equipment, etc.

Most of the existing analyses on AMS carried out to date were focusing on the dispersion curves based on eigen-state properties [8,9]. As an equivalent acoustic medium, the effective material properties of the AMS can be deducted from the analyses based on small-scale samples under normal incidence condition. However, when using AMS in real applications, its acoustic response is not only determined by its eigen properties, but also by the characteristics of the coupled acoustic fields. For example, the size, arrangement of the AMS, and most importantly, the sound incidence pattern can all affect the results, which makes the so-called "*in-situ* performance" significantly different from the *theory* [11]. As our target is to design AMS for sound insulation, a representative configuration in Fig. 1(b) is considered, where the AMS is connecting a sound source room and a receiving room. Such a configuration is described in ISO 10140 [12] for guiding a standardized sound reduction index (SRI) measurement, provided that certain acoustic conditions for the two rooms are satisfied. Since the two rooms are three-dimensional (3D), and the acoustic excitation and radiation are not limited to a particular angle, the resultant acoustic performance is inherently different from the normal incidence case. This study addresses the SRI prediction based on the standardized configuration as illustrated in Fig. 1(b).

Numerical models are useful tools to understand the physical phenomena and tune the acoustic performance. Finite element method (FEM) has been applied to model AMS composed of both acoustical (e.g. Helmholtz resonator) and structural (e.g. membrane with/without attached mass) elements [8–10]. Eigen-state analyses and effective material parameter retrieval based on small scale samples have been demonstrated. However, it is definitely challenging to extend those FEM models for predicting the SRI, mainly hampered by the extremely heavy computational cost. The FEM requires a convergence criterion of at least six to eight nodes per wavelength. To predict the SRI at 2000 Hz, for example, the element size should be smaller than 0.03 m (wavelength in air is 0.18 m), which means that millions of elements are needed to mesh a 3D room with side length in the meter range. This greatly restricts the applicability of FEM for such kind of problems.

To evaluate the acoustic performance of the AMS and tackle the numerical difficulties, this study presents a sub-structuring approach with hybrid theoretical-numerical techniques to evaluate the SRI under laboratory test setting. The sub-structuring approach first characterizes the acoustic properties of the two rooms separately, and then couples the AMS to solve the overall response. The simple room geometry allows analytical treatment to expedite the calculation, whilst the complex AMS can still be modeled by detailed methods without encumbering the total calculation process. Similar hybrid modeling has been demonstrated [13], with the continuity condition at the interface being written in a modal integration