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Acoustic metamaterials for sound mitigation

Métamatériaux acoustiques pour l'isolation sonique

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ABSTRACT

We provide theoretical and numerical analyses of the behavior of a plate-type acoustic metamaterial considered in an air-borne sound environment in view of sound mitigation application. Two configurations of plate are studied, a spring-mass one and a pillar system-based one. The acoustic performances of the considered systems are investigated with different approaches and show that a high sound transmission loss (STL) up to 82 dB is reached with a metamaterial plate with a thickness of 0.5 mm. The physical understanding of the acoustic behavior of the metamaterial partition is discussed based on both air-borne and structure-borne approaches. Confrontation between the STL, the band structure, the displacement fields and the effective mass density of the plate metamaterial is made to have a complete physical understanding of the different mechanisms involved.

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RÉSUMÉ

Dans ce travail, nous présentons des études théoriques et numériques sur le comportement physique de métamatériaux acoustiques en plaque dans un environnement sonique dans le but de développer des systèmes pour l'isolation acoustique. Deux configurations sont analysées, une à base d'un système masse-ressort et une à base d'un système à piliers. Les performances acoustiques des systèmes en question ont été étudiées suivant différentes approches et ont montré l'obtention d'une perte en transmission (STL) allant jusqu'à 82 dB pour un métamatériau en plaque ayant une épaisseur de 0.5 mm. L'interprétation physique des performances acoustiques de ces métamatériaux est analysée à la base des deux approches sonique et vibratoire considérées dans ce travail. Une confrontation entre les résultats des pertes en transmission, la structure de bande, les champs de déplacement et la densité de masse effective du métamatériau est réalisée afin de comprendre les mécanismes physiques mis en jeu.

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1. Introduction

For many decades, we have been witnessing an increasing demand for suppressing undesirable air noise for human comfort as well as mechanical vibrations in solid structures such as buildings, planes, and machinery in general. In fact, noise reduction is one of the key issues for enhancing the quality of life. A better night rest results in more productivity during the day, lower noise levels preserve the human ear for a longer time, and less annoyance by acoustic noise results in a better well-being in general. These issues are even more important nowadays due to the overwhelming presence of road and air traffic noise. As a matter of fact, people exposed to repetitive long periods of high level sound noise can cause health issues such as stress, sleep disorder, and even mental health problems. It is the case, for example, of industrial manufacturers working near noisy machines, aircraft passengers setting close the plane engines, or people leaving in dwelling places near heavy traffic flow roads, railway lines or airports. A higher noise level can even cause deafness in some cases. The danger of noise is not less than the one of mechanical vibration for the human body where health problems can also occur in the case of long-period direct contact with vibrating systems such as jackhammers. The low-frequency mechanical vibrations present also a real and challenging issue that the industry faces, which causes the deterioration of machines and increases significantly the maintenance coasts. In general, the combination of vibration intensity with its duration characterizes the risk in all these application fields for both acoustic and elastic noise/vibration.

Nowadays, a large research community is using the best of their scientific knowledge and means to take up the challenge of controlling acoustic and elastic waves to face all technological requirements. Sound mitigation and structure vibrations damping are important topics in acoustical and mechanical engineering. We are witnessing the development of new engineered materials and technologies to achieve high-performance mitigation for both sound and mechanical vibrations for a wide range of applications. In fact, material insulators such as foams, concrete walls, fibrous materials and rubbers are often used to increase noise absorption, sound transmission loss, and/or vibration damping. They can be found for example in buildings, especially dwelling places located near noisy environment like airports or highways. In addition, industrial manufacturers often use these specific materials to create soundproof enclosures for machinery and noisy equipment pieces as well as to reduce mechanical vibrations to avoid factor weakening. In the aerospace field, for instance, there is an increasing demand for the development of sound insulators, vibration dampers, and new technologies for aircrafts and spacecraft. In a plane, for example, continuous noises in the cabin are mostly generated by the engines (jet noise), the air flowing around (boundary layer noise), and the air-conditioning system, along with other sounds coming from the airplane control mechanism such as landing gear operation, hydraulic pumps, etc. For many decades, great efforts were undertaken to design and construct light-weight and cost-effective noise and vibration proofs for aerospace industry, and it is been commonly agreed that engineered panels based on foams are the most effective technological solutions used for this matter, although noise isolation for the frequency range below 500 Hz remains very weak.

In concrete terms, the concept of using a thick single homogeneous solid plate as a barrier to reduce undesirable acoustic noise and mechanical vibrations at the sonic level is limited by the mass density law. In fact, the plate has to be thicker to mitigate sound at the lower frequencies, and the problem of sound mitigation becomes even more challenging when seeking for lightweight and non-bulky solution systems. A well-known and used appropriate solution is viscoelastic materials where the elastic energy of mechanical vibrations is converted into heat by internal frictions and dissipated. Rubbers is the most used viscoelastic materials in industry and many works have been devoted to study the sound transmission loss through systems made of rubber. Porous materials and foams are also used to achieve the same goal, and are generally made of glass and polyester fibers [1]. Moreover, more complex technological designs of sound proofs have been developed such as the so-called double or sandwich panels, which are made of two thin plates "sandwiching" either a viscoelastic material [2] or a solid periodic structure [3] (Fig. a–b). They can then provide high internal damping to reduce resonant vibrations better than a single metallic plate. Sandwich panels are one of the most studied systems for sound insulation and vibration reduction, which are meant to be used especially in aircrafts and ships as they can offer high stiffness properties and low weight. Despite their multiple advantages, sandwich panels often display limited sound transmission loss because of the coincidence frequency region which can be much larger compared to single plates [4].

Another technological solution proposed for noise reduction is the micro-perforated plate (MPP) [5–8]. Well-designed holes in the panel can reduce the surface wave velocity in the vibrating structure, which can decrease the structural noise radiation into the air. Several works have dealt with MPPs or micro-perforated shells to study their sound-absorption and radiation performances for the single-layer configuration [5,6], and even multi-layer ones [7,8]. A sound transmission loss (STL) of almost 62 dB was reached based on these configurations. Although these technological solutions can increase the STL performances, multilayer panel structures are needed, which increases the total thickness and weight of the whole system.

In 2000, Liu et al. [9] proposed an unprecedented structure based on a new physical concept to open the possibility of breaking the mass density law. The system is known as acoustic metamaterial (AM) or locally resonant sonic crystal (LRSC), and gives the possibility to open acoustic band gaps at sonic frequency range using a reduced-size system. This kind of structure initiates a promising way to develop new designs of panels based on AM to achieve very high sound transmission loss while keeping the desired panel thickness. In general, AM are made of periodic distribution of low-frequency resonators basically made of a rigid core coated by a very soft material, usually a soft polymer, and arranged in a stiff hosting matrix. A wave propagating inside the system excites the low-frequency resonant modes occurring inside the AM. Due to the low stiffness of the polymer, the resonant modes can occur at wavelengths in the stiff hosting media much larger by some orders

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