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Technical note

Locally resonant meta-composite for sound-proof of building envelops: Analytical model and experiment

Bo Zhang [a], Yunyun Zhang [b], Wenyu Liao [c], Hongyan Ma [c,*]

[a] Department of Civil Engineering, Shenyang University, Shenyang, Liaoning, China
[b] Huayu Architectural Design Co. Ltd., Shenyang, Liaoning, China
[c] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO 65401, United States

HIGHLIGHTS

- A locally resonant meta-composite is proposed as a sound-proof building material.
- A sound transmission tube is made to evaluate the sound-proof property.
- An analytical model is developed to explain the behaviors of the sound-proof unit.
- Complete sound attenuation occurs when the effective mass density turns into negative.

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ABSTRACT

In this study, a new type of locally resonant unit is designed, analyzed and tested. Its effectiveness to be used as a sound-proof building envelop material is evaluated. Each unit consists of a hard circular plate adhered on the soft membrane that fixed in a rigid frame. This new type of locally resonant unit can easily be installed into building envelope materials, such as extruded hollow concrete, hollow wooden board and other types of light weight partition panels, to enhance their sound proof property. An analytical model is developed to describe the ability of this composite material in low-frequency sound blocking. The model provides a direct explanation for the nature of the system and an accurate method to calculate the effective mass per unit area. It is shown that the effective mass per unit area can turn to negative at certain frequency ranges, which could lead to a complete sound attenuation. In order to measure the sound transmission gap position and verify the theoretical model, experimental works are carried out. The experimental results show good agreement with the theoretical predictions.

1. Introduction

The existence of an absolute frequency gap, where the propagation of wave can be blocked in periodical composite, has drawn a lot of attention recently. This concept is originally introduced in the study of the propagation of electromagnetic wave, denoted by the "photonic band gap" [1], and subsequently extended to elastic waves [2–5]. In 2000, an experiment showed that certain three-component composites, consisting of hard spheres coated with a soft cladding and dispersed in a host medium, exhibited completely elastic wave band gaps. These spectral gaps could arise from local vibration resonances of the coated spheres, and have nothing to do with Bragg Scattering [6,7]. In addition, several other types of locally resonant materials have been developed, for example the structure with solid spheres in soft material embedded in a host matrix made of either fluid or solid material [8,9], and different models have been developed to simulate the local resonance phenomena [10–13]. These researches have shown that the locally resonant composites are promising in noise and vibration control, and even in seismic wave reflection [6].

When it comes to construction, the locally resonant composites can be used in building envelopes, such as the roof, walls and doors, to improve their sound proof property. As compared with traditional sound proof techniques, e.g. air or mineral wools filled clay blocks [14], natural fiber panels [15] and recycled cardboard panels [16], and some novel techniques, e.g. grooved panels [17] and perforated shell lattices [18], the locally resonance composites' advantages include lightweight, small volume, and high efficiency upon proper design. In this paper, a new type of locally resonant meta-composite unit is studied. Different from the locally resonant unit presented in the literature, it is very light, low cost and could

* Corresponding author.
E-mail address: mahon@mst.edu (H. Ma).

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Notation

A, B, C, D	unknown constants in Eqs. (11) and (12)
a, b	inner and outer radius of membrane
E, F	unknown constants in Eqs. (18) and (19)
m_3	the mass of medium 3
P	tension force in medium 2
u	the amplitude of the displacement of medium 1
U	the amplitude of the displacement of medium 3
s_{23}	the sum area of medium 2 and medium 3
ρ_1, ρ_2	mass per unit area of medium 1 and medium 2, respectively
ρ_e^{23}	effective mass per unit area of the medium 2 + medium 3 system
ρ_e^T	effective mass per unit area of the whole unit
ϕ_1, ϕ_2, ϕ_3	the area fractions for medium 1, 2 and 3
ω_i	angular frequency of incident wave

be easily installed into an extruded hollow concrete panel, hollow wooden board or other types of partition panels to make sound-proof building envelope materials. This new locally resonant composite has simple structure made of stretched membrane fixed in a rigid frame with periodically distributed small circular steel plates (unit weights) attached on the surface of the membrane. It's found that the composite unit shows sound transmission gaps at certain frequencies ranges. Moreover, it's proved that by varying the size of the circular steel plate adhered to the membrane and the pre-tension force in the membrane, the effective mass per unit area as a function of wave frequency can be tuned, and thus the frequency ranges where resonance occurs could be tuned to meet practical requirements.

2. Materials and experiments

The structure of the locally resonant unit is shown in Fig. 1(a). It consists of a holding plate, a membrane sheet and a unit weight. The holding plate is made of polyvinyl chloride and has holes with the radius of 17.5 mm, in which the polyurethane membrane is fixed. A unit weight is a circular steel plate with the radius of 7 mm. Each unit weight is attached at the center of the membrane in a hole. A pre-tension force of 5 N/m is applied in the membrane. The mass per unit area of membrane is 0.8 kg/m^2. The mass of a steel plate unit weight is 2 g. Note that perforated steel plates were used in experiments, as shown in Fig. 1(b), but they can achieve the same sound proof properties upon having the same weight as solid steel plates.

In experimental tests, the locally resonant units were installed into small hollow thin polyvinyl chloride partition, as shown in Fig. 1(b). Sonic proof tests were conducted using a sound transmission tube, as shown in Fig. 2. The partition was fabricated in the tube first, and then the sound source was mounted at one end of the tube. Two microphones were installed on the two sides of the partition within a short distance, which were used to measure the sonic amplitudes before and after passing through the partition. A signal generator, Model SR830 supplied by Stanford Research Systems, was employed to provide the sound source. The amplitude of sound wave after passing through the sample to that of the incident one is defined as the amplitude transmission ratio and used to characterize the sound proof property of the sound-proof material.

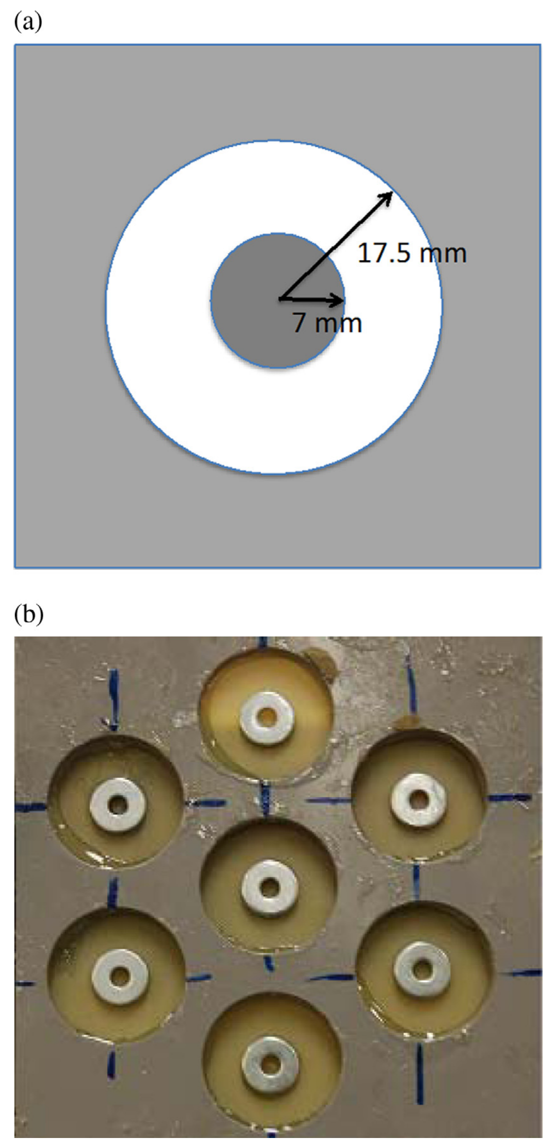

Fig. 1. The structure of a specimen for sound proof experiment: (a) unit illustration; (b) sample.

3. Experimental results and theoretical analysis

3.1. Experimental results

The amplitude transmission ratio of the locally resonant units fabricated polyvinyl chloride partition, as a function of wave frequency, is shown in Fig. 3. As a reference, the amplitude transmission ratio of a polyvinyl chloride partition without holes and the locally resonant units is also plotted in the figure for comparison. It can be seen that the reference partition shows only one dip on the curve, at the frequency of 295 Hz. However, the locally resonant units fabricated partition shows three additional dips, at the frequencies of 135 Hz, 225 Hz and 365 Hz, respectively. The additional dips have clearly demonstrated the effect of local resonance. Another important information given by Fig. 3 is that the locally resonant unites help to reduce the amplitude transmission ratio of the partition significantly. In other words, the locally