Applied Acoustics 139 (2018) 69–74

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical note

Hybrid sound-absorbing foam materials with nanostructured grit-impregnated pores

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ARTICLE INFO

Keywords:
Sound protection
Sound absorbent
Passive absorber
Absorption ratio
Low-frequency absorption
Transmission loss
Foam
Porous material
Nanopowder
Nanosilica
Nanomagnetite
Nanopores
Nanoporous material

ABSTRACT

A new approach to the design of sound-absorbing materials was experimentally investigated. Improved acoustic properties were obtained in a wider frequency range through the impregnation of nanoporous grit into foam pores. Using this approach, the range of efficiency of these materials was extended from high frequencies of 2.0–6.3 kHz to a lower band of 0.5–1.6 kHz. The absorption ratio was increased by 60–100%, and the transmission loss was increased by 20–22 dB.

1. Introduction

Noise is one of the most commonly encountered environmental impacts due to urbanization and industrialization. In Korea, noise-related complaints account for more than 35% of all environment-related complaints. This problem is ubiquitous, regardless of occupation, age, and residence region [1]. Sound suppression is highly desirable for modern industry, especially for advanced applications like aviation, space, and the automotive industry, where weight is also relevant.

Materials with a high sound absorption ratio are usually porous [2], so their application solves problems of both sound suppression and weight. Theoretical and experimental considerations of porous materials for noise control started around the 1940s [3] or perhaps even three decades earlier [4]. Nevertheless, the theory of sound suppression by porous materials is still under development, and the correct choice of porous materials is still being investigated, especially for comparatively new area of nanoporous ones.

Porous sound-absorbing materials can be classified as cellular, fibrous, or granular materials based on their microscopic configurations [5]. A variety of concepts have been suggested to improve acoustic protection features, especially for lower frequencies. The approaches can be classified as organic foams, inorganic foams (metal, ceramic, and aerogel), layered structures, and passive/active control [5]. The foams are used most often in industry because they provide quality at a reasonable cost, but they are effective in only a narrow band of high frequencies (a few kHz) [6].

With the rapid development of nanotechnology, there have been many attempts to mix nano- and microsized materials such as nanoclay, carbon nanotubes, and nanosilica with polymers to create foam materials [7–12] with modified strength, elastic, dynamical and vibrational properties. But the acoustic parameters (absorption ratio and

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https://doi.org/10.1016/j.apacoust.2018.04.024
Received 17 December 2017; Received in revised form 19 March 2018; Accepted 17 April 2018

transmission loss) of such materials could not be fundamentally enhanced thus far [13].

Therefore, the main idea of this research is to impregnate the pores of conventional foam with nanoporous grit to obtain the composite sound-absorbing material.

Aerogel is a commercial material based on silica with extremely small pores. Due to its nanoporous structure, it could also serve as a good sound-protection material [14]. Unfortunately, the application of aerogel is expensive due to the complicated production process. However, it is less-known that the nanoporous material can be prepared from fine silica powder Aerosil [15,16] or Tarkosil [17]. They are similar to aerogel, have 10–30-nm open pores, but can be created by just drying a highly concentrated suspension of silica nanoparticles in water and other liquids [18].

Nanopowder is a new kind of continuum material [19] that could be a good absorber of sound, which was shown by hot-wire measurements [20–23]. The group velocity of acoustic wave propagation in nanopowders is 5–6 times lower than that in air. A series of harmonics is generated when a monochromatic wave passes through such nanopowders, which supports the idea of strongly nonlinear interaction and consequently strong sound energy dissipation. Moreover, such media have Knudsen numbers in the transitional range separating the flow of the continuum from the flow of free-molecular media. This fact is also important for considering nanoporous materials for use in sound absorption. This point of view was supported in a previous study [24]. Thus, a hybrid material with nanostructured grit could be promising.

This paper focuses on an approach to extend the range of the acoustic absorption frequency and the noise protection quality of conventional foam materials combined with nanoporous grit. Silica and magnetite nanopowders were used as precursors. The nanoporous grit was prepared by drying in a highly concentrated nanosilica liquid suspension in ambient conditions, milling the obtained green body, and sieving it to obtain about 0.5-mm grit particles. Another material is the foam with 0.2-mm open pores filled with similar grit, but the grit is formed directly in the pores of the foam after the desiccation of a nanosilica or nanomagnetite suspension that is impregnated into the foam.

Tomography scans illustrate a relatively homogeneous 3D filling of the specimens with grit. An original test setup and algorithms were used to predict the absorption ratio and transmission loss. The approach's validity and efficiency are discussed, along with the possibility of increasing the efficiency in the mid- and low-frequency ranges by developing an active control strategy. The strategy consists of the distribution and localization of nanoporous objects in a porous material.

2. Experimental

2.1. Materials

Off-the-shelf urethane and polyethylene terephthalate foams with open porosity were used as a matrix, which have been studied previously for their acoustic absorbing properties [25,26]. These materials are widely employed for noise protection, such as in transport vehicles. We mostly used foams with average pore size of about 200 μm. The pore volume fraction was 0.85. Test specimens were cut from large blocks using a pneumatic cutter. Each specimen was cut with a diameter of 30 or 45 mm, and the thickness varied in the range of 8–40 mm. This first sound-absorbing material was used as a reference for comparison.

The nanopowders were produced by an original gas-phase technique [17]. This technique is based on a method of high-temperature vaporization of a solid raw material by a 1.4-MeV focused electron beam. The beam power density can reach 5 MW/cm^2, which is sufficient for the vaporization of any substance. The vaporization was followed by cooling of the vapor and condensation in air, resulting in micro- and nanoparticles with the necessary properties. The nanopowders were silica (SiO_2, Tarkosil®) with a specific surface area of 55–110 m^2/g and magnetite (Fe_3O_4) with a specific surface area of 70 m^2/g. These values were determined by a standard BET analysis with a nitrogen-helium mixture (Sorbi-M, Meta). The values correspond to average primary particle sizes of 25–50 nm for silica and 17 nm for magnetite. The silica nanopowders were X-ray amorphous, and the magnetite nanopowders had cubic structure (card number 75-1610, space group Fd3m, a = 8394 Å), which was determined using an HZG-4 diffractometer with cobalt irradiation.

The nanoparticles' size and shape were also analyzed using a transmission electron microscope (TEM, JEOL-2010). The TEM-images are shown in Fig. 1(a) and (b). The figures show that the silica and magnetite powders consist of spherical nanoparticles. The sizes of particles are not the same due to some size distribution, what is typical of nanosize powders.

Nanoporous silica grit was prepared by an established method [18]. A 20 wt% water suspension of nanopowder with a specific surface area of 55 m^2/g was dried in ambient conditions for two weeks. Large, shapeless, solid green bodies formed in the vessel (the term "bodies" comes from ceramic engineering and means weakly bound ceramic material). The green bodies were easily crushed and sieved to obtain 0.5-mm powder particles. The same procedure was used to prepare nanoporous magnetite grit powder. Both powders were used only in combination with other more rigid specimens. Data obtained using established procedures [18] indicate that these green bodies have open porosity, the pore volume fraction is 0.45–0.52 of the whole grit

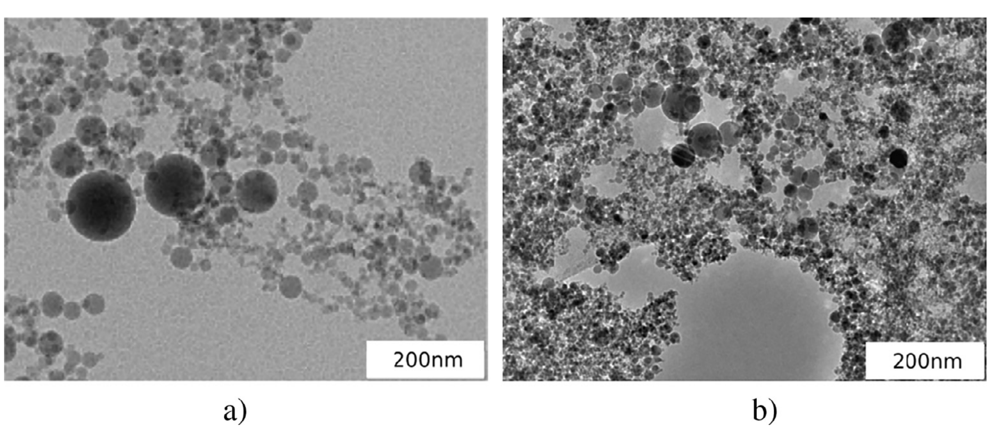

Fig. 1. TEM images of initial nanopowders. (a) Nanosilica (SiO_2) with a specific surface area of 55 m^2/g, (b) nanomagnetite (Fe_3O_4) with a specific surface area of 70 m^2/g.