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Optimization of low frequency sound absorption by cell size control and multiscale poroacoustics modeling

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ABSTRACT

Sound absorption of a polyurethane (PU) foam was predicted for various geometries to fabricate the optimum microstructure of a sound absorbing foam. Multiscale numerical analysis for sound absorption was carried out by solving flow problems in representative unit cell (RUC) and the pressure acoustics equation using Johnson-Champoux-Allard (JCA) model. From the numerical analysis, theoretical optimum cell diameter for low frequency sound absorption was evaluated in the vicinity of 400 μm under the condition of 2 cm-80 K (thickness of 2 cm and density of 80 kg/m^3) foam. An ultrasonic foaming method was employed to modulate microcellular structure of PU foam. Mechanical activation was only employed to manipulate the internal structure of PU foam without any other treatment. A mean cell diameter of PU foam was gradually decreased with increase in the amplitude of ultrasonic waves. It was empirically found that the reduction of mean cell diameter induced by the ultrasonic wave enhances acoustic damping efficiency in low frequency ranges. Moreover, further analyses were performed with several acoustic evaluation factors; root mean square (RMS) values, noise reduction coefficients (NRC), and 1/3 octave band spectrograms.

1. Introduction

There are many issues to improve the driving conditions for better quality of life. Among them, noise pollution is a critical problem in daily life [1–4]. In order to solve this problem, many sound proof materials and systems have been developed over a long period of time. There are two kinds of sound proof materials: sound absorption materials and sound insulation materials. Sound insulation materials are generally massive materials having a high surface density [5–7]. These materials having high transmission loss are capable of reflecting the sound energy to the incident direction. Unlike the sound insulation materials, sound absorption materials are much lighter materials with porosity higher than 90% [8–12]. Porous sound absorption materials have two sound damping functions; structural damping in a fluid domain (air) and material

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damping in a solid domain (*i.e.*, polymeric part) [12,13]. For the structural damping, acoustic wave propagation in porous media mainly dissipates as viscous friction on interconnected pores and thermal heat exchange on solid-fluid boundary, due to complex microscale porous structures [14–16]. Theoretical models reflect these two mechanisms as complex effective density ($\rho(\omega)$) and effective bulk modulus ($K(\omega)$), and these mechanisms will be discussed in Numerical simulation section. In the aspect of the material damping, a transferred acoustic wave from the air to the solid diminishes by molecular friction in vibration modes [17,18]. According to these mechanisms, the energy of offensive noise transforms into heat loss.

For the sound absorption, porous polymeric foams are used in buildings, automobiles, and aircraft [19–21]. Polyurethane (PU) foams are the most frequently employed polymeric foams because of its light weight, low cost, and good processability in industrial areas. In the fabrication process of PU foams, Reactant A (composed of polyol, foaming agent, catalyst, surfactants and *etc.*) and Reactant B (composed of isocyanates) are mixed at high speed, and then the mixture is inserted into a mould to manufacture a desirable shape [22–25]. Two chemical reactions occur simultaneously; a gelling reaction and a blowing reaction. From the gelling reaction, covalent chemical bonds are generated with –OH groups in polyol and –NCO groups in isocyanate, yielding urethane linkages. The blowing reactions are classified into chemical and physical blowing reactions. In the former reaction, the chemical foaming agent (*e.g.*, water) reacts with the isocyanate functional groups (–NCO), and then carbon dioxide gas yields the nuclei when they contain sufficient energy. The generated nuclei are grown up into bubbles with microsize diameter. In the process of physical blowing, the physical blowing agent dissolved in polyol (*e.g.*, HFC, Cyclopentane) acts as a nucleus after forming a cluster by triggering phase change of the dissolved gases under heating or pressure drop process.

Damping of the low frequency noise has attracted considerable attentions for many industrial applications, since general sound absorbing materials do not show good performance in low frequencies [26–30]. Moreover, there were only two solutions for the improvement of low frequency sound damping: an increase of overall mass density [31,32] or a utilization of thickness of foams [33]. However, these solutions have limitations for industrial applications. So, the microstructure manipulation is considered as the best strategy to enhance or optimize the acoustic damping properties without changing other intrinsic properties.

Several groups have studied the manipulation of the microstructures to improve thermal and mechanical properties. Lee et al. [9], Verdejo et al. [32], Zhai et al. [34], and Wee et al. [35] have fabricated composite foams with nanoparticles to promote heterogeneous nucleation. If nanoparticles were suspended in a polymeric matrix during a foaming reaction, critical energy needed for generation of bubbles would be decreased on the surface of the particles due to lower surface tension [34]. The other methodology for the manipulation of a cellular structure is an ultrasonic foaming method [22,25,36,37]. Irradiation period, timing, and magnitude are most significant processing conditions. Wang et al. [38], Zhai et al. [39], and Gandhi et al. [40] reported the relation between exposure time and the cell size distribution with respect to power of an ultrasonic wave. Torres-Sanchez et al. [41–43] investigated the effect of ultrasonication on porosity of foam by carrying out a simulation of the acoustic environment.

Various theoretical analysis methods have been performed to model and predict the sound absorption performance of the porous materials [13,44–51]. Among them, a multiscale modeling using finite element method [13,46,47,52–54] was reported recently to consider not only macroscopic parameters but also microstructural parameters. For microscale simulation, a representative unit cell (RUC) is made by considering a real geometry of the sample. Poroacoustics parameters for macroscale simulation (*e.g.*, flow resistivity) are obtained by solving two flow problems based on the RUC. Sound absorption coefficient is calculated by an analytical or numerical method with such theoretical models as Diphasic models (*e.g.*, Biot's theory [18]) and Motionless skeleton models (*e.g.*, Johnson-Champoux-Allard model [15,16]). So the attribution of a microcellular structure can be evaluated theoretically and compared with measured data, resulting in the high reliability of the current research.

In this study, we theoretically demonstrated effects of the cell size on sound absorption properties from a multiscale numerical analysis using a finite element method. From the theoretical results, the optimum cell diameter of 80 K density and 2 cm thick PU foam was estimated. The 80 K density and 2 cm thickness are specific conditions applied for sound absorbing foams in automobile industries. We generated polyurethane foams with the cell size in the vicinity of the optimum value. And the cell size was manipulated by irradiation of the ultrasonic waves to the resin mixture during the foaming process. It is noted that enhancement of low frequency sound damping could be governed by the mechanical excitation which can increase the bubble nucleation rate. Acoustic absorption coefficients were measured experimentally by employing the B&K impedance tube and additional characterizations, *e.g.*, root mean square (RMS) analysis, noise reduction coefficient (NRC), and 1/3 octave band spectrogram, were conducted.

2. Materials and methods

2.1. Materials

NIXOL SA-120 (Reactant A, KPX Chemical, Republic of Korea) is composed of polyether polyol (~94 wt%), water (~2.3 wt%), surfactants, and catalysts. SUPRASEC® 2527 (Reactant B, Huntsman Holland BV, Netherlands) is an isocyanate-based compound of diphenylmethane 4,4'-diisocyanate (MDI, ~50 wt%) and isocyanic acid (~20 wt%), and other additives. AKO-HM207K (Akochem, Republic of Korea) was used as a releasing agent of PU foams.