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A numerical scheme for investigating the effect of bimodal structure on acoustic behavior of polylactide foams

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ABSTRACT

In order to understand the acoustic behavior of porous membranes, there is a need to further investigate the link between microstructure and macroscopic properties of such materials. This study presents the sound absorption properties of a novel bimodal foam structure made of polylactide (PLA) with an interconnected network of pores and micropores of very different characteristic sizes, fabricated utilizing the blend of PLA and polyethylene glycol (PEG) water soluble polymer. Fabricated foams are bio-based and have the advantage of resolving the environmental concerns raised by petrochemical based sound absorbers. The purpose of this study is to develop bio-based open cell structures as a practical solution to today's needs for noise control resolutions. Acoustic performance of the bimodal PLA foams is studied by measuring the normal incident absorption coefficient and the effect of bimodal structure is investigated in terms of acoustic properties (i.e., sound absorption) and non-acoustic properties associated to the Johnson–Champoux–Allard model (i.e., porosity, airflow resistivity, tortuosity, ...). Inverse method based on JCA model and impedance tube measurements for normal incident absorption coefficient was applied to estimate tortuosity and characteristic lengths. Results of inverse method are in good agreement with direct measurements of normal incident absorption coefficient. While tortuosity increases by increasing the polymer weight percent, it remains constant as the secondary porous structure extends in the porous medium. As the bimodal structure extends through the foam, both thermal and viscous characteristic lengths increase for different foam categories.

1. Introduction

Design of foams for noise and vibration damping purposes is a multi-dimensional engineering task which includes material selection, structural morphology, pore geometry, pore interface, etc. which requires in-depth understanding of acoustic and wave propagation phenomena. Due to the complicated microscopic structure of open cell foams, investigating the relation between foam morphology and acoustic properties is rather intricate and still an open problem in the field. Present study reports the practical experience of design, fabrication and modeling of bio-based polymeric foams to be used as sound absorbers in sectors such as automotive, aerospace and building industries.

To address the environmental issues constitute with petroleum based, nonrecyclable polymeric foams currently used for acoustic applications, PLA was chosen to fabricate open cell structures. PLA is a bio-based polymer made from renewable resources such as sugar cane and corn starch with properties that lie between those of polystyrene (PS) and polyethylene terephthalate (PET) [1], and as a bio-based alternative it is expected to replace these commodity polymers.

Open cell foams are extensively used for sound absorption purposes in different sectors. An example of sound absorber foams is polyurethane (PU) open cell foams used in automobiles as a part of headliner for noise control. These foams are cross linked and will be landfilled after their end of life. To establish the state of the art in acoustic performance of sound absorbers, acoustic absorption of the polyurethane foam currently employed in automobile industry is also compared with the bio-based foams fabricated through this study. Besides being environmentally friendly, any successful design of porous structures must be able to compete with the existing sound absorbers such as the introduced PU foam.

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To achieve this goal, porous structures were designed and fabricated by particulate leaching which is a relatively new method for open cell foaming. This method involves the addition of an inhomogeneous domain into the polymer matrix at the beginning. Solid particles, such as sodium chloride and potassium chloride crystals, are introduced into the polymer matrix at the beginning of the process.

When exploring the propagation of sound wave in a porous media, two phases must be considered, the solid skeleton and the saturating fluid. For most open cell foams due to the heterogeneity of the structure, a characteristic microscopic size can be defined and a single porosity is assumed. In the case of the foams under consideration in the present study, two interconnected networks of pores with very different characteristic sizes can be recognized in the structure and hence these foams have bimodal structure [2]. To fabricate this bimodal structure, PEG powder which is a bio-based water soluble polymer was added to the main polymer as well. The solid particles and water soluble polymer will later be dissolved out of the matrix resulting in a porous cellular network throughout the entire polymer matrix [3]. This technology has commonly been used in the production of highly porous bioscaffolds [4]. Recent research has tried to apply the particulate leaching technique to non-continuous batch foaming processes. The incorporation of this technique into the rotational foam molding process has also been investigated in the literature [5,6].

By this technique the larger cells are formed by salt particles and the secondary porous structure in the cell walls is created by water soluble polymer. The advantage of such bimodal structure is that while the large cell structure allows the sound wave to enter the porous medium, the micro pores increases the damping effect of the overall frame. In other words, water soluble polymer forms additional micro voids in the foam matrix resulting in a bimodal foam structure. This structure can also be described as a fractured material with a porous frame or as a porous medium with a microporous skeleton [7].

The purpose of this study is the practical investigation of the effect of micropores on sound absorption of PLA foams and highlight the parameters affected by the micro pore structure. With this objective Johnson–Champoux–Allard model was applied to the PLA foam samples to simulate the acoustic absorption and investigate the effect of the bimodal structure on acoustic properties of open cell foams. In Section 2 the Johnson–Champoux–Allard model is explained. The porous medium is assumed to have a rigid motionless structure saturated by a compressible Newtonian fluid. Considering the low elasticity of the fabricated PLA foams this assumption is expected to accurately simulate the acoustic behavior of foams under study. Results section presents the characterization of the foams under study determined through direct measurements to be the base for analytical simulation. In theoretical prediction of acoustic properties, the JCA model is applied to the bimodal PLA foams and the relation between macroscopic and microscopic properties is discussed.

2. Modeling the acoustic performance of PLA open cell foams

In order to optimize the acoustic performance of porous medium, the relation between different structure properties and acoustic behavior must be studied. Theoretical prediction of the acoustic properties of porous materials is a difficult task due to the complicated cell structure of these materials. Three approaches have been suggested in the literature to link microstructural properties of porous structures to macroscopic acoustic and physical properties: empirical methods based on the direct analysis of the microstructure and measurement of acoustic performance [8–12], analytical models of propagation of wave inside the microstructure using scaling laws [13–17], and numerical homogenization derived in a representative unit cell [14,18–21]. Two microphone impedance tube was used to measure normal incident absorption coefficient. The two microphone impedance tube is explained in Section 3.3. Porosity and airflow resistivity of foams are measured directly as well. Inverse method based on optimization problem to adjust properties in the model to reproduce sound absorption coefficient measurements was applied to eight groups of PLA foams to determine tortuosity and characteristic lengths. The sample is assumed to be homogeneous, symmetric, isotropic and acoustically rigid therefore behaving as an equivalent fluid.

In this paper an equivalent fluid model based on the Johnson–Champoux–Allard model is used to simulate the propagation of acoustic wave in a porous medium. The model assumes the frame to be motionless and not exposed to deformation, therefore the inertia of the frame is not taken into account. Since the frame of the majority of porous materials can be approximated as acoustically rigid over a wide range of frequencies when excited by acoustic waves, the porous material can then be replaced on the macroscopic scale by an equivalent fluid of effective density $\tilde{\rho}(\omega)$ and effective bulk modulus $\widetilde{K}(\omega)$ that occupies a proportion ϕ of the volume of the porous material. In the equivalent fluid model developed by Johnson–Champoux–Allard [22] employed in this work, the values of these two quantities are determined by five macroscopic quantities of the porous medium, which are: the airflow resistivity σ (N s/m^4); porosity ϕ (%); dynamic tortuosity α_∞; and viscous and thermal characteristic lengths Λ (μm) and Λ' (μm). Since these parameters make it possible to predict the material's acoustic performance, identification and measurement of these parameters is very important.

The porosity represents the percentage of interconnected void space with respect to the bulk volume. Airflow resistivity σ is ruled by the geometry and interconnection of the open cells ($\sigma = \eta/K_0$ where η and K_0 are the dynamic viscosity of the saturating fluid and the permeability, respectively). Dynamic tortuosity α_∞, as identified by Johnson et al. [23], describes the complexity of the path followed by the acoustical wave inside the skeleton network. In other words, the way the open pores are oriented and interconnected determines the tortuosity of the material. As the path followed by the acoustic wave inside a porous material becomes more complex, tortuosity increases which yields better sound absorption in the porous material [22]. The characteristic lengths Λ and Λ' represent the average macroscopic dimensions of the pores with respect to the viscous and thermal losses, respectively. The thermal characteristic length Λ' reflects the pores of larger size, where thermal transferring surface is significant. By contrast, the viscous characteristic length Λ reflects the importance of airflow in the pores and thus represents the smaller pores due to the high air particle velocity at these locations. In other words, Λ' stands for the average radius of the largest pores, while Λ represents the average radius of the smallest pores. The ratio Λ'/Λ is always higher or equal to 1 [22]. Based on the work of Johnson et al., it can be shown that Λ' is generally larger than Λ if the flow is considered laminar [23].

It is certain that cellular structure of any porous material (i.e., cell morphology, cell wall thickness, pore size, etc.) affects the macrostructure of the material. Therefore, the five macroscopic properties outlined by the Johnson–Allard model, which are all responsible for the acoustic performance of a given material, are linked to the inner microstructure of the porous network. As sound propagates through a porous material, acoustical energy is dissipated by frictional effects at the cell walls, heat transfer through the skeleton, and the conversion of acoustical energy into internal energy [22]. The microstructure of a fabricated porous membrane is determined by the processing parameters during its fabrication. Therefore, to optimize material's sound absorption effectiveness,