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General regression neural network for prediction of sound absorption coefficients of sandwich structure nonwoven absorbers

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ABSTRACT

In this paper, we propose a more general forecasting method to predict the sound absorption coefficients at six central frequencies and the average sound absorption coefficient of a sandwich structure nonwoven absorber. The kernel assumption of the proposed method is that the acoustics property of sandwich structure nonwoven absorber is determined by some easily measured structural parameters, such as thickness, area density, porosity, and pore size of each layer, if the type of the fiber used in nonwoven is given. By holding this assumption in mind, we will use general regression neural network (GRNN) as a prediction model to bridge the gap between the measured structural parameters of each absorber and its sound absorption coefficient. In experiment section, one hundred sandwich structure nonwoven absorbers are particularly designed with ten different types of meltblown polypropylene nonwoven materials and four types of hydroentangled E-glass fiber nonwoven materials firstly. Secondly, four structural parameters, i.e., thickness, area density, porosity, and pore size of each layer are instrumentally measured, which will be used as the inputs of GRNN. Thirdly, the sound absorption coefficients of each absorber are measured with SW477 impedance tube. The sound absorption coefficient at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and their average value are used as the outputs of GRNN. Finally, the prediction framework will be carried out after the desired training set selection and spread parameter optimization of GRNN. The prediction results of 20 test samples show the prediction method proposed in this paper is reliable and efficient.

1. Introduction

World Health Organization reported that among environmental factors contributing to disease in Europe, environmental noise leads to a disease burden that is only second in magnitude to that from air pollution [1,2]. Noise pollution causes or contributes to not only annoyance and sleep disturbance but also heart attacks, learning disabilities, and tinnitus [3,4]. The use of acoustical absorbing materials is one of the present effective noise control technologies in automobile, the manufacturing environment, building compartment and equipment. Acoustic absorbing materials include porous materials and resonance materials according to different sound absorption mechanisms [5]. The common porous materials can be used in noise control engineering including glass fiber felts, polyurethane foams, and mineral fiber composites. Even though those materials have excellent acoustic properties at high frequencies, their structural properties are not enough to defend against low frequency noise, expect for their possible harm to human health [6]. However, resonance absorbing materials have high absorption coefficients at low and medium frequencies [7]. It is clear that a sound absorber including only one type of acoustical absorbing material is unable to attenuate wide-frequency noise. By holding this view in mind, we will construct some sandwich structure sound absorbers.

The related theoretical researches have been kept on with the applications of fibrous materials as noise absorption elements simultaneously. In the research of sound absorbing materials, nonwovens are considered as a classical type of elastic porous materials. The theory of sound propagation in elastic porous media has been built up over approximately 60 years, since the monumental work of Zwikker and Kosten carried out in 1949 [5]. A more appropriate model was suggested by Dent, who elaborated on the theory

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of Zwikker and Kosten [8]. The propagation of sound in elastic porous materials was systemically described in Biot theory [9,10]. A review of the models of sound propagation in porous materials having a rigid frame worked out before 1980 can be found in the work by Attenborough [11,12]. More general models for the calculation of effective density was suggested by Johnson et al. [13] and Pride et al. [14]. The simplified models for the prediction of bulk modulus of porous materials were provided by Lafarge et al. [15], Johnson et al. [13] and Champoux and Allard [16]. and Allard et al. [17]. Wilson developed a model to match the middle-frequency behavior, and not to fit the asymptotic behavior at high and low frequencies [18]. A systematic comparison of the performance of the Wilson model and the Johnson et al. model was performed by Panneton and Olny [19,20].

The earliest investigation into the acoustical properties of fibrous absorbent materials was carried out in 1969, in which the relationship between characteristic impedance, propagation coefficient and frequency, flow resistance was expressed as a power law function [21]. The effect of the frame wave on the surface impedance of a layer of fibrous material, and on the transmission through a fibrous materials bonded onto a plate is studied by Allard et al. [22]. Voronina built an empirical model between acoustic parameters and structural characteristic of fibrous materials to predict values of the sound absorption coefficient [23]. A way of calculating the airflow resistivity of randomly placed parallel fibers was introduced by Tarnow [24]. In the research of Parton et al., the homogenization method was used for the analysis of acoustic wave propagation in a unidirectional fibrous material for the acoustic control of the fiber arrangement in manufacturing composites [25]. Lambert proposed some linear systems to estimate propagation characteristics of sound in fibrous porous both in fluid of the pores and in the elastic structural frame [26]. A semi-empirical prediction method for fibrous media is described in Kirby's research, which not only yielded physically reasonable predictions for the bulk properties at arbitrarily low frequencies, but also was in good agreement with measured data at higher frequencies [27]. Shoshani and Yakubov used the Dent model to calculate the noise absorption coefficients of some nonwovens and implemented the numerical method to assess the maximal absorption coefficients of nonwoven fiber webs [28–31]. An empirical model was developed by Garai and Pompoli to predict the flow resistivity, acoustic impedance and sound absorption coefficient of polyester fiber materials [32]. Honarvar used the theory of C. Zwikker and C.W. Kosten to model the noise absorption of rib knitted fabrics successfully [33]. Yang utilized an image processing method to calculate the fractal dimension of the down fiber assembly, and then set up a functional relationship between the critical fractal dimension and the maximum absorption coefficient [34]. Liu and his colleagues proposed a more general sound absorption model for double layered nonwovens by using sound propagation boundary conditions of the theory of C. Zwikker and C.W. Kosten for sound propagation through porous flexible media [35]. Experiments showed that the an empirical model of porous sound absorbing materials made of recycled foam based on Dunn and Everen model and Voronina model can provide acceptable results [36]. In Pieren's work, a theoretical model for the oblique incidence sound absorption coefficient of thin woven fabrics backed by an air cavity was presented [37]. The research of Yoon detailed a new acoustic topology optimization framework with an empirical material formulation for fibrous material [38].

The sound absorption properties of thermally bonded nonwovens made of composing fibers and production parameters was researched by Lee and Joo [39]. Manufactured by the premix, lamination, preheating, and molded techniques, the porous laminated composite material used in Yang's research exhibited very high sound absorption coefficient in the frequency range of 500–2000 Hz with a relatively thin and light structure [6]. How to determine the psychoacoustic parameters that affect subjective sensation of fabric sound at given sound pressures was researched initially by Cho's team [40]. A comparison between acoustic sound absorption coefficient and transmission loss index of absorption panel using natural organic multi-layer coir fiber as the filler with and without perforated panels were studied in Zulkifli's experiments [41]. Four types of nonwoven samples made of polyester fibers of various cross-section, i.e., circle, hollow, flat, and triangle, had been prepared to exam the effect of the variation in the cross-sections on the acoustical properties [42]. In Cho's research, the characteristic fast Fourier transform spectra of weft knitted fabrics was analyzed to investigate the relationship between sound parameters and the mechanical properties of the weft knits, and to determine the effects of fiber type and stitch type on the frictional sound and mechanical properties [43,44]. Tasacn and his colleagues pointed out fiber denier, fiber cross sectional shape, fabric total surface area and density had great impact on the acoustical behavior of traditional thermal-bonded highloft and vertically lapped nonwoven fabrics [45,46]. In Jiang's work, a carbonized and activated cotton nonwoven with three surface layers (glassfiber, cotton and ACF cotton) were evaluated in terms of their acoustic properties for sound absorption and sound insulation [47–49]. The effects of porosity, fiber size and treatment parameters on airflow resistivity and normal incidence sound absorption coefficient of compressed three-layer nonwoven composites had been studied in Yilmaz's research [50,51]. Kucuk and Korkmaz investigated the effect of physical parameters on sound absorption properties of natural fiber mixed nonwoven composites [52].

In the case of acoustic sound absorbent from recycled fibers, it should be noted the work of Lee and Changwhan, where the acoustic absorption coefficients for different mixtures of recycled polyester fibers were obtained with the aim of replacing conventional materials used for sound insulation [53]. The work of Lou and his cooperators explored the functional sound absorption composites made from blends of polyester and polypropylene nonwoven selvage and analyzed the influence of the thickness and density in the sound absorption coefficient [54]. Maderuelo-Sanz and his colleagues used the material waste, coming from the fibers of fluff (a textile residue from grounded end life tires) to manufacture sound absorber products [55]. Acoustic absorption evaluation of high modulus puncture resistance composites made by glass fabric and Kevlar fabric reinforced recycled nonwovens was presented in Li and her cooperators' work [56]. In Seddeq's work, the sound absorption properties for recycled fibrous materials including natural fibers, synthetic fibers and agricultural lignocellulose fibers were investigated [57,58].

The successful development and application of artificial neural network in industrial data forecasting provide a reliable reference for the similar project in acoustic research field. Gardner proposed a neural network model to predict the acoustical properties of polyurethane foam [59]. A similar work was also carried out by Lin and his cooperators, in which artificial neural network algorithm was employed to estimate the sound absorption coefficients of perforated wooden panels with various setting combinations including perforation percentage, backing material and thickness [60].

One significant point can be concluded from the above summary is that some theoretical and empirical models have been built about fibrous materials used as sound absorber. But the foremost limitation of them is the generalization ability. Most of the built models are suitable only for some certain kinds of fibers and specific structures of the fibrous absorbers. Maybe, the main problem for the existing theoretical and empirical formula for sound absorption coefficient computation is that the included structural properties and physical–chemical parameters cannot