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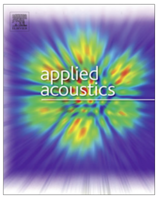

Experimental measurements of acoustical properties of snow and inverse characterization of its geometrical parameters

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ABSTRACT

Snow is a sound absorbing porous sintered material composed of solid matrix of ice skeleton with air (+water vapour) saturated pores. Investigation of snow acoustic properties is useful to understand the interaction between snow structure and sound waves, which can be further used to devise non-destructive way for exploring physical (non-acoustic) properties of snow. The present paper discusses the experimental measurements of various acoustical properties of snow such as acoustic absorption coefficient, surface impedance and transmission losses across different snow samples, followed by inverse characterization of different geometrical parameters of snow. The snow samples were extracted from a natural snowpack and transported to a nearby controlled environmental facility at Patsio, located in the Great Himalayan range of India. An impedance tube system (ITS), working in the frequency range 63–6300 Hz, was used for acoustic measurements of these snow samples. The acoustic behaviour of snow was observed strongly dependent upon the incident acoustic frequency; for frequencies smaller than 1 kHz, the average acoustic absorption coefficient was found below than 0.4, however, for the frequencies more than 1 kHz it was found to be 0.85. The average acoustic transmission loss was observed from 1.45 dB cm^{-1} to 3.77 dB cm^{-1} for the entire frequency range. The real and imaginary components of normalized surface impedance of snow samples varied from 0.02 to 7.77 and −6.05 to 5.69, respectively. Further, the measured acoustic properties of snow were used for inverse characterization of non-acoustic geometrical parameters such as porosity, flow resistivity, tortuosity, viscous and thermal characteristic lengths using the equivalent fluid model proposed by Johnson, Champoux and Allard (JCA). Acoustically derived porosity and flow resistivity were also compared with experimentally measured values and good agreement was observed between them.

1. Introduction

Snow is composed of tiny ice crystals joined together in a complex skeleton resulting into a sound absorbing porous structure with porosity varying from 40% to 95%. Snowpack grows as a layered structure of varying physical properties during successive snowfall events. An acoustic property of snow depends on the porosity, grain size, grain shape, and three dimensional distributions of pore spaces [1]. The multi-path propagation of acoustic waves within the open micro-structure of snow is quite complex phenomenon, and it poses several challenges to understand snow–acoustic interaction. The acoustic properties of snow such as reflection coefficient, impedance and transmission losses across a snowpack are quite essential to understand the propagation of acoustic waves. Initial measurements of acoustic properties were reported by Oura [2] in low density snow using an external sound field. Subsequently, Ishida [1] estimated frequency dependent normal acoustic absorption coefficients of snow through multiple layers using real and imaginary parts of acoustic impedances. Using a rigid frame model, Buser [3], determined the acoustic impedance values of snow corresponding to different densities and frequencies. Johnson [4], for the first time attempted to use Biot [5] theory of acoustic wave propagation in snow and included the coupled interaction of ice skeleton and pore space in his analysis. He assumed snow as an elastic frame of ice saturated with a compressible viscous fluid and confirmed the presence of two dilatational waves and a shear wave in snow as predicted by Biot's theory. However, he could not validate all analytical results due to the lack of experimental measurements. Later, laboratory experiments were conducted by Marco et al. [6] on artificially compressed snow, to find out the correlation between acoustic

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impedance and snow density with an aim to develop acoustic method for non-destructive snow density estimation. Further, a comprehensive idea about acoustic properties and their relation with physical properties would certainly be helpful to understand snow–acoustic interaction and also for the development of methodology for non-invasive in-situ probing of the snow properties [4].

Moreover, apart from sound wave propagation, there are various other physical processes which are directly related to structural properties of snow such as tortuosity, flow resistivity, pore-sizes and their distribution. These properties, also known as mass transport properties of snow are pertinent to a wide range of snow–air exchange processes which have influence on heat transfer, snow metamorphism, evolution of snow structure in seasonal and polar snowpack, composition of the air trapped in snow with implications to climatology [7–10]. Connectedness of the pore spaces or the tortuosity of snow has been shown to be a powerful concept to describe diffusion in snow and in porous media in general [11,12]. Tortuosity of snow varies with the type of snow, its microstructure and degree of metamorphism. Snowpack permeability has an important role in governing the melt water percolation through different snow layers [13], and also, is a sensitive parameter for snowmelt runoff models [14] for hydrological applications. The movement of melt water through the complex snow-structure plays vital role in changing the mechanical properties of the snowpack [15] and hence wet-snow stability. Thus, the understanding of geometrical properties of snow has wide applications and useful in various physical processes occurring in snow science. Previous researchers had also attempted to deduce geometrical properties such as porosity, tortuosity, flow resistivity and characteristics length of snow non-invasively from acoustic measurements both in laboratory and in-situ [16–20]. However, there exists a limited work on snow tortuosity mainly by some of the authors [16,17,20–25]. Tortuosity values for snow were deduced by most of these researchers either by the inverse methods using acoustic sounding, gas diffusion experiments or analysis of microstructure images of snow. Recently, X-ray micro-computed tomography (μ-CT) images of snow were used for modelling the sound absorption behaviour and determination of various geometrical properties [25,26], but such measurements are computationally intensive and limited to very small snow samples.

Investigation about the tortuosity and porosity of other porous materials and their relationship is also subject of interest for various researchers [19,27–30]. They reported that there exists an inverse relation between the porosity and tortuosity. Ref. [19] used a high frequency pulse method to deduce porosity and tortuosity of large grain porous materials. For cancellous bone, Attenborough et al. [27] observed anisotropy in tortuosity and decrease in mean tortuosity with increase in porosity. In addition, Shin et al. [31], deduced information about soil frame elasticity as well as pore characteristics by the optimized fitting of Laser Doppler Vibrometer (LDV) and microphone data. Their method uses acoustic to seismic coupling, is non-invasive and can be performed in situ.

Unlike other porous materials, studies on the acoustical properties of snow are relatively rare in the literature and hence, there is a need to improve snow acoustics understanding. Objectives of this paper are (i) experimental measurement of acoustic properties for different snow samples (natural and sieved) for a relatively wide frequency range and (ii) characterization of geometrical properties (non-acoustic) of snow based on acoustic data. Experiments were conducted in a controlled environmental facility installed in the vicinity of the field site in Great Himalayan range of India (Patsio, 3800 m asl) using an impedance tube system for frequencies ranging from 63 Hz to 6.3 kHz with spectral resolution of 2 Hz. Further, the impedance tube data was used for inverse characterization of various geometrical properties of snow with reference to the Johnson, Champoux and Allard (JCA) model [32]. The inverse characterization is based on the optimization problem in which the physical properties are adjusted in the prediction model [34]. The physical parameters such as flow resistivity, tortuosity, porosity, viscous and thermal characteristics lengths are estimated and some of these parameters are compared with the experimental values obtained by direct methods.

2. Methodology and experimentation

Acoustic properties of snow were measured by using an impedance tube system based on transfer function method. Impedance tube has been widely used and a popular method for characterization of acoustical properties of various porous materials for both laboratory and industrial applications [33–39]. Unlike standing wave ratio (SWR) method, this method provides measurement of acoustical properties for a wide frequency range very fast and at higher spectral resolution. However, in snow, most of the earlier studies report measurements made at selected frequencies employing SWR method [6,1,3,4]. Therefore, we believe that application of impedance tube is suitable to measure acoustical characteristics of snow at higher spectral resolution in laboratory condition, provided a proper care is taken during sample preparation or extraction. Further, using the impedance tube data geometrical properties (non-acoustic) of the snow were deduced by the inverse characterization method. A brief theory about transfer function method, inverse characterization method and experimental procedures are discussed in this section.

2.1. Transfer function method

The transfer function method was proposed by Chung and Blaser [40] for estimation of acoustic properties of a porous material. This method uses a broadband stationary random signal as an excitation source placed at one end of the impedance tube. The acoustic material is placed on the other end of the long tube and a plane wave hits at normal incidence to the material. The incident and reflected signals are recorded by two fixed microphones mounted on the wall of tubes at some known positions. The sound pressure field at any of the microphone location is the sum of the incident and reflected wave from the material under investigation. The transfer function between the two microphones is measured for the calculation of reflection coefficient. The complex reflection coefficient (R) is expressed by Eq. (1):

$$R = [(H_{12} - H_i)/(H_r - H_{12})]e^{j2kl} \tag{1}$$

where H_{12} is the acoustic transfer function deduced from the pressures at two microphone positions 1 and 2, H_i is the acoustic transfer function associated with the incident wave component evaluated at above microphone positions, H_r is acoustic transfer function associated with reflected wave component evaluated at two microphone positions, k is wave propagation constant ($2\pi/\lambda$, λ is acoustic wavelength), l is distance between first microphone to the test sample and s is the spacing between two microphones (1 and 2). Using Eq. (1), the acoustic absorption coefficient (α) can be determined as represented by Eq. (2):

$$\alpha = 1 - |(H_{12} - H_i)/(H_r - H_{12})|^2 \tag{2}$$

Moreover, the complex acoustic impedance (Z) of the sample could be measured using Eq. (3):