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Measuring and localizing acoustic emission events in snow prior to fracture

Ingrid Reiweger [a,*], Klemens Mayer [a,b], Kevin Steiner [a,c], Jürg Dual [c], Jürg Schweizer [a]

[a] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[b] University of Technology, Graz, Austria
[c] Institute of Mechanical Systems, ETH Zürich, Switzerland

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ABSTRACT

Acoustic emissions (AE) are transient elastic waves produced by a sudden redistribution of stress in a material caused by changes in the internal structure. In other natural, heterogeneous materials monitoring AE has proven to be a valuable tool for stability estimation and failure prediction. After studying the characteristics of ultrasonic wave propagation in snow, we measured the acoustic emission signals during snow loading experiments in a cold laboratory. Using snow columns we found that most energy of an artificial acoustic signal was transmitted at 31 kHz. Best coupling to snow was achieved by attaching the AE sensors with silicone adhesive to thin aluminium plates which were then frozen to the snow. Localizing AE events during fracture of layered snow samples showed that the AE originated within the weakest layer, i.e. the relevant layer for snow failure. For finding an indication of imminent failure, we analysed the exponent β of the cumulative size-frequency distribution ('survival curve') of event energy. At the occurrence of instabilities, the β-curve deviated from steady behaviour and exhibited distinct 'drops', indicating that the power law behaviour of the distribution was not fulfilled anymore. Studying the temporal evolution of the exponent β might therefore provide useful information about snowpack stability also in the field—provided that the AE signals are not too strongly attenuated and can be detected in time before catastrophic failure occurs.

1. Introduction

The release of a dry-snow slab avalanche is preceded by crack formation within the snowpack (e.g. McClung and Schaerer, 2006; Schweizer et al., 2003). A weak layer, often consisting of buried surface hoar, faceted or depth hoar crystals (Schweizer and Jamieson, 2001), beneath a cohesive slab is a prerequisite for dry-snow slab avalanche release. If a macroscopic crack reaches a size of 10 cm or more it may quickly propagate in the weak layer across an entire snow slope. This process is called 'crack propagation', and, if the slope is steep enough, leads to the release of a slab avalanche. The formation of the first macroscopic 'initial' crack is called 'failure initiation' and assumed to be due to the accumulation of damage, i.e. microscopic cracks within the weak layer (Schweizer et al., 2003). Cracking on a microscopic scale is expected to always happen during snow deformation, but only if not compensated by re-bonding or sintering (e.g. Reiweger et al., 2009b; Schweizer, 1999), it is expected to lead to a macroscopic instability where larger cracks form (Schweizer et al., 2003).

Since cracking within a material is accompanied by the release of elastic energy generating elastic waves (acoustic signals), recording acoustic emissions (AE) can be used for detecting cracks and crack growth (e.g. Lockner, 1993). In other quasi-brittle materials such as concrete (Ohtsu, 1996) or wood (Bucur, 2006) the AE technique is commonly used to study and predict failure processes (Johansen and Sornette, 2000). In the field of natural hazards, acoustic signals have been used to investigate earthquake occurrence (Niccolini et al., 2011) and to predict the collapse of a limestone cliff (Amitrano et al., 2005; Got et al., 2010). Girard et al. (2012) set up an acoustic sensor network in order to predict failure within rocks and permafrost. For analyzing emissions of a glacier to anticipate the break-off of a frontal lamella, Faillettaz et al. (2011) applied a method from the framework of critical phenomena. According to the theory of critical phenomena (Johansen and Sornette, 2000) an analogy between the failure of inhomogeneous or disordered materials such as snow and a phase transition exists. The material can be considered in a stable state—microscopic cracks form but do not coalesce to form a macroscopic crack that will propagate—and an unstable state—catastrophic failure highly possible.

The application of the AE technique to snow within the context of avalanche research started in the 1970s, when several field studies for detecting acoustic activity (at frequencies ranging from 3 to 100 Hz) within the natural snow cover were performed (Gubler, 1979; Sommerfeld, 1977; St. Lawrence and Bradley, 1977). The authors concluded that avalanche formation was related to an increased acoustic activity. Bradley and St. Lawrence (1975) showed the Kaiser effect in snow based on laboratory measurements.

* Corresponding author.
E-mail address: reiweger@slf.ch (I. Reiweger).

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Sommerfeld (1982) and Sommerfeld and Gubler (1983), postulated that all avalanches should be preceded by acoustic activity. St. Lawrence (1980) developed an analytical model of AE response of snow. He expressed the acoustic activity as a function of strain and stress, and succeeded to reproduce the cumulative acoustic emission curve during a slow tensile experiment at a strain rate of about 10^{-6} s^{-1} with a snow sample in the laboratory. Buser (1986), Ishida (1965), and Oura (1952) performed laboratory experiments where they measured acoustic impedance, velocity, and attenuation of snow. However, within their measurement setups they could only measure the acoustic waves travelling within the pore space and not in the ice skeleton. The frequency range studied was about 100–4000 Hz.

More recently, Scapozza et al. (2004) measured acoustic emissions in the ultrasonic range in snow during compression tests in the laboratory. They found that AE signals in snow can be measured over a wide frequency range.

A study by van Herwijnen and Schweizer (2011a,b) used geophones which had a flat frequency response from 14 to over 1000 Hz; they were looking for precursors to avalanche release. They faced difficulties identifying avalanches, not to speak of precursors, due to a lot of background noise at those low frequencies.

So far, it is not clear whether AE emissions in a weak layer under loading can be detected and whether these data include precursory information. The goal of this study was therefore to initially assess some basic properties of ultrasonic wave propagation in snow, and then to measure and localize the acoustic emission in snow during load-controlled laboratory experiments. We used the theory of critical phenomena to link the cracking processes observed in snow at the microscale to catastrophic failure of the whole snow sample. Our long-term goal is to exploit acoustic emissions in the framework of critical phenomena to distinguish between unstable and stable snowpacks. This would allow developing an early warning system for snow avalanches.

2. Methods

In the following, we describe the methods used for studying some of the basic acoustic properties with snow columns and to perform the loading experiments as well as the corresponding analysis methods. First we will introduce the acoustic measurement system.

2.1. Acoustic measurement system

We measured acoustic emissions (AE) and acoustic reference signals with a six channel acoustic measurement system from Physical Acoustics. The system consisted of wide band piezoelectric AE transducers (20–1000 kHz), preamplifiers (with 40 dB gain), band pass filters, digitizers, a personal computer, and the recording and analysis software AEwin. The recording devices (three 18 bit 5 MSample PCI2 A/D cards) allowed for real time waveform acquisition and feature extraction. Fig. 1 shows a basic block diagram of the AE system. The threshold was set to 28 dB. Definitions of common AE parameters and expressions such as threshold, count, amplitude, and energy can be found in Grosse and Ohtsu (2008).

2.2. Snow samples

To determine the propagation characteristics of ultrasonic signals within snow, we performed wave propagation experiments where an acoustic reference signal was sent through a snow column. The reference signal was recorded before and after travelling through the column. The free standing snow columns had a diameter of 145 mm and heights ranging from 300 to 700 mm. The snow densities ranged from 270 to 310 kg m^{-3}; the snow was characterized as rounded grains of average size 0.5 mm and medium hardness (hand hardness index 3; Fierz et al., 2009). The snow columns were prepared by sieving new snow produced by a snow machine (Schleef et al., 2014) into a plastic tube and letting it sinter for three days at −5 °C.

For the localization and loading experiments we used samples consisting of three snow layers, where the middle layer was the 'weak layer'. All samples were rectangular samples with a length of 120 mm, a width of 90 mm, and a thickness of 70 mm (35 mm top layer, 5 mm weak layer, 30 mm bottom layer). The top and bottom layers of the layered samples had a density of 260 kg m^{-3}; grain type was rounded grains, the average grain size was 0.5 mm, and hand hardness index was 3. The weak layer consisted of depth hoar crystals of 1–1.5 mm in size and was soft (hand hardness index 2; Fierz et al., 2009). For validation of the AE source localization experiments, we also performed loading experiments with uniform snow samples of dimension 120 mm × 90 mm × 50 mm. The density of the uniform samples was 200 kg m^{-3}, grain type was rounded grains, average grain size was 0.5 mm, and the snow hardness was medium (hand hardness index: 3).The production of rectangular samples, either uniform or layered, in the laboratory is described in Reiweger et al. (2010) and Reiweger et al. (2009a).

2.3. Signal propagation in snow columns

All signal propagation experiments were performed in a cold laboratory at a constant temperature of −5 °C. A free-standing snow column was used in order to avoid measuring signals which had travelled through a confining container. The experimental setup is shown in Fig. 2.

As an acoustic reference signal we used a pencil lead fracture (PLF; e.g. Grosse and Ohtsu, 2008; Higo and Inaba, 1991). The PLF signal is an impulsive signal with a flat frequency distribution, ranging approximately from 1 to 600 kHz. The PLF was applied at an aluminium plate onto which the snow column was frozen and the initial PLF signal was measured by the

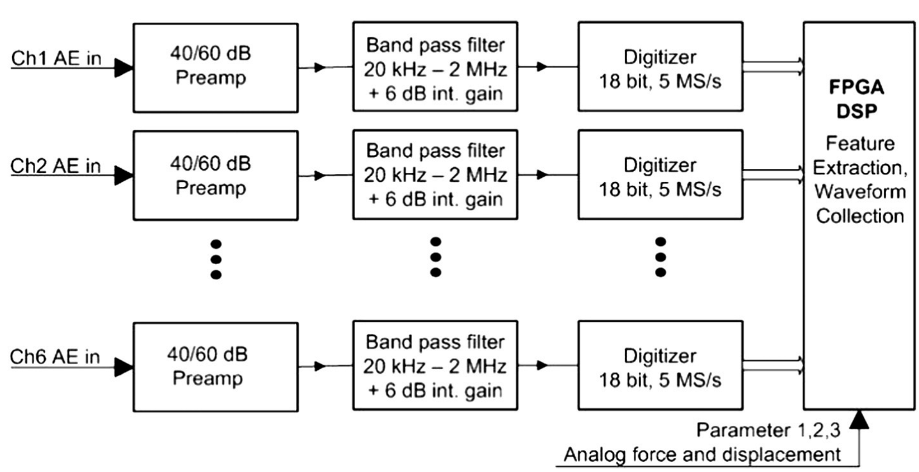

Fig. 1. Basic block diagram description of the six channel AE measurement system. The abbreviations denote Ch: channel, FPGA: field programmable gate array, and DSP: digital signal processor.