SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

Earth`s Cryosphere, 2014, vol. XVIII, No. 3, pp. 92–103 http://earthcryosphere.ru/

METHODS OF PERMAFROST ZONE STUDIES

ACOUSTICS APPLICATION FOR SNOW COVER STUDY

V.P. Epifanov

Institute for Problems in Mechanics, Russian Academy of Sciences,
101 Vernadsky Av., build. 1, Moscow, 119526, Russia; evp@ipmnet.ru

Acoustic oscillations in hillside snowpacks and spectra destruction during mechanical testing of snow *in situ* have been studied. The main results have been obtained in the spurs of the Chatkal Ridge in the Dukant River Basin (western Tian Shan) and at the foot of Mount Olavsvarden (Grønfjorden) near the weather station in Barentsburg (Spitsbergen). A pulse-phase method, an acoustic emission method, acoustic mechanical sounding, stratigraphic description of snow in pits, and mechanical tests were applied to the study. Acoustic characteristics of snow, as well as its hardness, fracture toughness, structure, temperature, and density were measured. The relation between the snow acoustic compressibility and the snow grain size was found (and also with their resonant frequency and snow density in snowpack horizons). Natural oscillations at frequencies below 2 kHz have been explained by the mechanism of adhesive shear failure, and above 2 kHz, by cohesive failure. Acoustic-mechanical diagnostics of snowpack, and the possibility of numerical evaluation of the snow structure and its relation with mechanical characteristics have been discussed. Based on these data, the coefficient in the differential wave equation has been defined, which is an aggregated macroscopic characteristic of snow (the inverse problem has been solved). The method of acousto-mechanical snow stratigraphy has been developed based on sounding of snow cover with an avalanche probe, recording acoustic emission signals in the frequency range from 100 Hz to 20 kHz, and comparing them with the results of test measurements carried out in pits.

Acoustic emission, amplitude-frequency spectra, diagnostic methods, micro- and macrophysical characteristics, parameters of the state, snow cover, stratigraphy

INTRODUCTION

One of the problems related to forecasting avalanches and ensuring effective transportation in the area in question is quantitative description of the snow cover and the properties of its horizons. In modern stratigraphy of the snow cover, special signs are used [*Glaciological dictionary, 1984*], whereas solution of a wide range of practical problems requires knowledge of parameters of the state and obtaining qualitative characteristics of its physical and mechanical properties.

Quantitative evaluation of the snow characteristics may be realized with the help of acoustic methods. For example, the pulse-phase method has long been applied in the experimental mechanics of ice and snow to determine the propagation velocity of elastic waves v and to calculate the dynamic module E_{dyn}, given the density ρ_s:

$$E_{\text{dyn}} = \rho_s v^2.$$

Accumulation of deformation damage is evaluated by the defectiveness parameter Ω [*Truell et al., 1972; Epifanov, 2005*]:

$$\Omega = f(\alpha, v),$$

where v is the sound propagation velocity; and α is the attenuation factor. The relation between deformations ε and stress σ is set as

$$\varepsilon = \sigma/E_{\text{eff}},\ E_{\text{eff}} = E_{\text{dyn}} \exp\left[-\frac{\pi}{4}\Omega\right].$$

Parameter Ω is used to study the accumulation kinetics of the deformation damage and to determine identity of the samples under study [*Ishida, 1965; Epifanov, 1982; Sommerfeld, 1982*].

The acoustic emission method was applied to the study of short-term ice creep [*Zaretsky and Chumichev, 1982*] and of the degree of the snow maturity on a hillside [*Method..., 1990b*]. The possibilities of classifying the snow texture by acoustic methods were studied [*Satyawali, 2014*]. Preservation of the physical level of correctness of describing wave phenomena in the framework of the modern theory of elastic wave emission in homogeneous medium is the basis for applying acoustic methods to the study of the snow cover [*Skuchik, 1976*].

TASK SETTING

The goal of this study is to investigate the amplitude and frequency characteristics of the spectra of snow at fracture on a hillside. As a result, a parameter is found which quantitatively describes the structure and determines its relation to the macro-characteristics of snow. In addition, an express-method of acoustic stratigraphy of the snow cover (diagnostics) was developed.

The original concept is based on the fact that the process of snow fracture is accompanied by acoustic oscillations, the amplitude and frequency spectra of which are influenced by the nature of cohesion forces and the fracture scale. Snow is a porous material well absorbing the acoustic energy; its structural frame (through which sound is propagated) consists of ice grains with a radius of 0.15–0.50 mm, connected by bridge bonds. The space among the grains is filled by air with water vapor. The minimum amount of the ice frame fracture is limited by the size of the bridge bond among the grains. In the used range of frequencies from 100 Hz to 20 kHz, snow is considered homogeneous and isotropic, while the thermoelastic effect is insignificant. The dissipation effects should be taken into consideration only when the wavelength is comparable to the pore size, i.e., at the frequencies higher than 20 kHz. In the working range of frequencies, the wavelength is much larger than the size of the grains.

In order to establish the connection between the amplitude-frequency spectrum of the source and its physical macro-properties, let us turn to the theory of elastic wave emission in a solid body. We will use a single degree of freedom oscillator model to establish the connection between elastic and inertial properties of snow as a differential equation

$$\ddot{x}+\omega^2 x=0.$$

For natural frequency $\omega_0 = 2\pi f_0$ we get

$$f_0=\frac{1}{2\pi}\sqrt{\frac{D}{m}}, \qquad (1)$$

where D is the hardness of the source (oscillator); m is the attached weight. The harmonic oscillator model (1) establishes the connection between the spectrum and the physical macro properties of the source (hardness and the attached weight). This allows calculation of the spectrum by the known physical characteristics of snow (a direct problem). We will solve the reverse problem: to find the physical characteristics of snow by its spectrum.

For a spherical oscillator with a radius R and density ρ, in accordance with *M.A. Isakovich* [*1973*], hardness is equal to $D = 4\rho R^2 k$ and the attached weight is $m = 4\pi R^3\rho$. By substituting the values k and m into the equation (1), for f_0 [s^{-1}] we obtain

$$f_0=\frac{1}{2\pi}\sqrt{\frac{D}{m}}=\frac{1}{2\pi}\sqrt{\frac{4\pi R^2 k}{4\pi R^3\rho}}=\frac{1}{2\pi}\sqrt{\frac{k}{R\rho}}, \qquad (2)$$

where k is the reverse acoustic compressibility, N/m^3. In [*Skuchik, 1976*] the expression is given

$$k=4\pi^2\rho\left(f_0^2 R\right). \qquad (3)$$

In accordance with the model (equation (2)), the acoustic spectrum of the ice frame fracture is related to its structure and its physical and mechanical characteristics.

Equation (3) is a generalization of the Second Law of Motion: in the left part of the equation, the value k has dimensionality N/m^3, which in its sense corresponds to rated force (a unit vector, an ort), while in the right part there is a product of mass in a unit of volume $4\pi^2\rho$ [kg/m^3] by acceleration $f_0^2 R$ [m/s^2]. In fact, the equation (3) establishes the connection between reverse acoustic compressibility k and the grain size, their natural frequency and the snow density. In this sense, k may be considered as a parameter characterizing the structural-mechanical and the strength properties of the snow.

Thus, the methodological solution of the task considered consists in the experimental finding of frequency f_0 of the signal of acoustic emission (AE) of fracture of the structure element of size R and density ρ and in calculation of the value k. With the wavelength greater than the snow grain radius ($\lambda >> R$), emission of elastic oscillations may be considered a quasi-adiabatic process, while snow may be considered as acoustically homogeneous.

In reality, the mechanism of snow fracture is a complicated process, and, to achieve the goal set, it is necessary to register not only natural acoustic oscillations in the snowpack and to establish compliance between the fracture spectrum and its destruction source but also to perform the tests *in situ*.

The condition of snow and its mechanical behavior are strongly dependent on its acoustic compressibility [*Truell et al., 1972; Vinogradov and Solovyeva, 1997*]. This characteristic and the sophistication of modern equipment both make it possible in principle to determine the specific features of the snowpack and to perform its acoustical-mechanical diagnostics [*Epifanov and Kuz'menko, 1986, 1988; Epifanov, 1994*].

THE INVESTIGATION METHODS

Snow fracture toughness. Compared to the previously used method [*Epifanov and Osokin, 2010*], registration of the acoustic fracture spectrum was principally new (Fig. 1). This allowed us not only to determine the maximum concentration of stress near the crack top but also to compare the amplitude-frequency characteristics of the snow fracture spectrum with the points on the deformation curve. The maximum dimensions of the snow samples were 25 × 24 × 4 cm. In the other tests for compression and bending, which were performed *in situ*, the amplitude

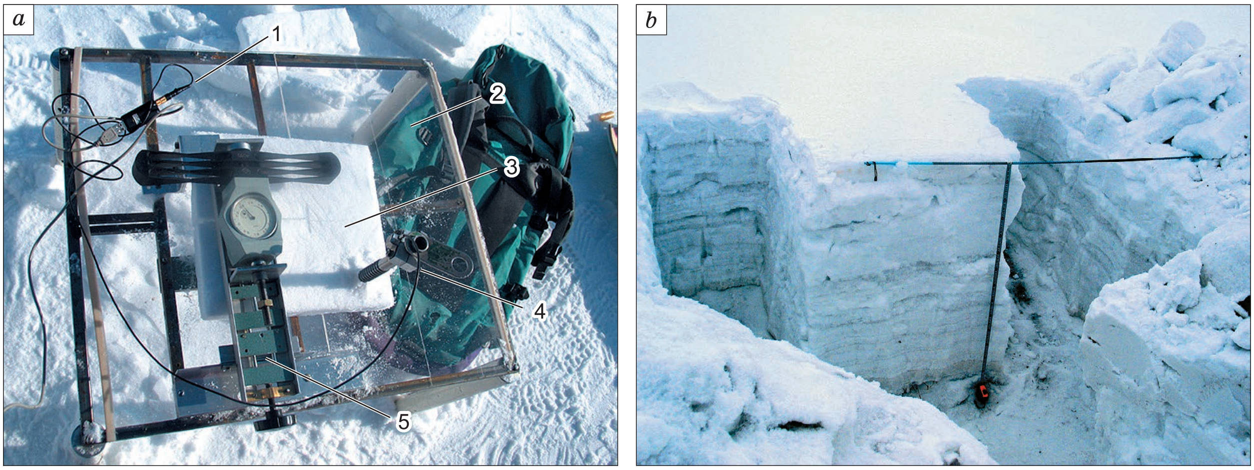

Fig. 1. A setup for testing snow for eccentric tension (*a*) and a snow pit (*b*):
1 – a prime amplifier; 2 – a portable table; 3 – a sample with a cut; 4 – an acoustic sensor; 5 – a loading device.

and frequency characteristics of the spectrum were also recorded for snow fracture [*Epifanov, 1982; Epifanov and Yuryev, 2006*].

Snow hardness. To measure snow hardness, a penetrometer was used (Fig. 2) [*Penetrometer..., 1990; Method..., 1990a*]. In this penetrometer model, all the components (a calibrated spring, a trigger, an indentor with a piezoelectrical accelerometer and a pulse voltmeter with digital indication) are placed in a single box, which is convenient for making field measurements. After pressing the trigger button, the indentor attains the set velocity, which is ensured by the calibrated spring and by the trigger. The design of the mechanism is such that from the moment of achieving the set starting velocity to penetration into the snow the indentor is in free forward motion. The starting velocity at the moment of collision with the snow surface (1.5 m/s) and the orthogonal orientation of the indentor tip in relation to the contact surface are ensured by a bearing ring. The indentor tip is made as a double-edged knife and is rigidly fixed with the accelerometer. Calibration of this measurement instrument was carried out in laboratory conditions, including the use of a piezometer and calibration of its electrical and mechanical parts [*Epifanov and Kudrya, 1985*]. Under field conditions, functionality of the penetrometer was tested on the reference material (plasticine). The measurement result was shown electronically in a digital form. To study the structure and the mechanical anisotropy of snow, a tip of another shape was used [*Penetrometer..., 2014*].

Fig. 2. A penetrometer for measuring snow hardness with a tip looking like a double-edged knife.

The acoustical-mechanical diagnostics of the snow cover. In order to avoid multiple making of pits [*Vivchar, 2010*], we developed a new method of acoustical-mechanical diagnostics, which allowed us to determine the stratigraphy of the snow cover in a greater number of single mass points in situ. Reduction of labor costs is achieved by the fact that a pit is made and the stratigraphy of the snowpack is determined only once. Then, in the immediate proximity from the pit walls, an avalanche probe is inserted vertically and the amplitude and frequency spectrum is recorded, which are generated when the tip destroys the mesostructures of the snow cover (the space frame of different-age layers, the layers' borderlines, ice bands, underlying hoarfrost, etc.). Then each horizon or mesostructure is referred to by its characteristic acoustic emission (AE), signal shape and frequency. A similar method is used to determine the stratigraphy in the other points of the snow cover, i.e., each AE signal is referred to the layer/structure determined in the tests.

A flowchart of a measuring acoustic line. The measuring acoustic line (Fig. 3) consisted of an acoustic piezosensor, rigidly fixed with an ice borer or an avalanche probe, a prime amplifier, a laptop sound card and electric cables [*Epifanov and Glazovsky, 2013*]. Signal frequency, amplitude and duration were measured. The piezoelectric sensor was connected with the input of the prime amplifier, and the necessary amplification level was set. The signal from the

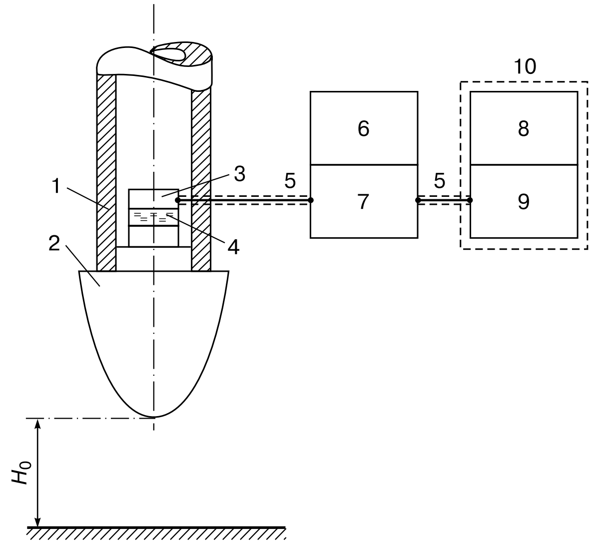

Fig. 3. A flowchart of a measuring line:

1 – an avalanche probe; 2 – a probe tip; 3 – a load; 4 – a sensor; 5 – electric cable; 6 – a monitor; 7 – a prime amplifier; 8 – a computer; 9 – an electronic memory device; 10 – a thermostat.

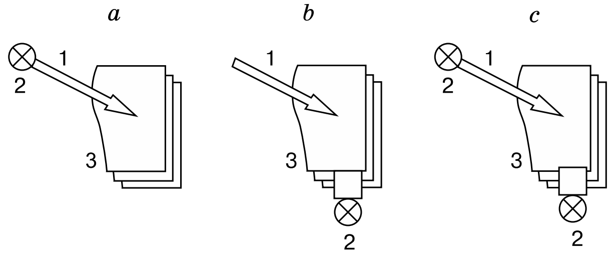

Fig. 4. Variants (*a–c*) of acoustic sensor placement:

1 – an avalanche probe; 2 – an acoustic sensor; 3 – snow cove layers.

piezosensor went to prime amplifier 7 of the PSI 202-00-001 RTF type and then it entered the input of the computer's sound card 6 (Fig. 3). The range of the measured frequencies varied from 15 Hz to 20 kHz, the amplification factor was 95 dB, and the time resolution was 10^{-6} s. As an acoustic sensor, piezoelectric transformers of the KD910 type were used. Analysis and recording of the amplitude and frequency spectrum were made using the Spectrlab software program. A standard 150 mm long avalanche probe was used, with a conic tip with a 12.7 mm diameter and with length calibration marks.

Sensor placement layouts. The choice of the layout of acoustic sensors in probing snowpack is determined by the goal of the study. Shown in Fig. 4 are the possible variations of sensor placement: *a*) a piezoacoustic accelerometer is mounted on the avalanche probe; *b*) the same acoustic sensor is embedded into one of the layers of the snowpack; *c*) the acoustic sensor is in one of the snowpack layers and on the avalanche probe, with the recorded signals synchronized, while sounding of the snowpack by the probe is performed at a fixed distance between them.

Variant *a* is reasonable to be applied when it is necessary to get a quick idea of the thickness of the snow cover, the number of same-age layers and the presence of ice bands (underlying hoarfrost). Variant *b* has the advantage that its signals are "cleared" from perturbations sometimes occurring in the probe during its friction against snow. A better signal allows the fine structure of the snow to be determined in same-age layers. Variant *c* provides a possibility of determining not only stratigraphy but also the acoustic characteristics of snow (for example, the propagation velocity of acoustic waves).

The acoustical-mechanical method of snow cover diagnostics is non-destructive methods of substance study, while the pitting method is accompanied by loss of snow cover integrity. Pitting violates the natural processes of heat- and mass transport in the snowpack. As preliminary studies have shown, it takes 2–3 minutes for the crust to form on the pitted surface, in which snow is in another stress state than in the snowpack due to thermomechanical stress.

To determine the density, structure and temperature of snow in the field conditions, traditional methods were used [*Zalikhanov et al., 2000; Kanayev, 2001*]. The methodology of determining the elastic properties of snow and ice, its hardness and fracture toughness are described in [*Epifanov and Osokin, 2009, 2010*].

RESULTS

The object of study. The methodological part of the tests was performed on the snow cover of the Moscow region; the stratigraphic observations and the studies of natural acoustic oscillations in the snow cover were performed on the western hillside of Mount Olavsvarden (Grønfjorden) near the weather station in Barentsburg (Spitsbergen). The basic pit was located at the altitude of 60 m above sea level, with its coordinates being 78°03′26″ N, 14°22′05″ E.

Stratigraphic studies normally include identification of layers, measuring their height, snow density, its temperature and structure evaluation (Table 1). The snow temperature on the surface of the pit wall was measured with an infrared thermometer of the PITON-105 type, and in the layer – with an electric thermometer of the GTH-715/PT type.

It follows from the table that the snow cover is a structure consisting of different-age layers of snow

Table 1. **Snow characteristics in a pit by layers (downwards)**

Layer number	Height, cm	Density, kg/m^3	Temperature, °C	Snow structure
1	0–11.5	327	–7.7	Deep hoarfrost, up to 3–5 mm
2	11.5–15.5	327	–7.7	Snowpack, grain 0.7–0.8 mm
3	15.5–16.0	385	–7.7	Ice bands
4	16.0–28.5	385	–10.5	Snowpack, grain 0.5–0.6 mm
5	28.5–31.5	424	–11.3	Deep hoarfrost, grain up to 2 mm
6	31.5–32.0	380	–11.3	Ice bands
7	32.0–33.5	325	–11.3	Deep hoarfrost, up to 1.5 mm
8	33.5–34.0	388	–12.5	Ice bands
9	34.0–43.5	388	–12.5	Loose snow, grain 0.8–0.9 mm
10	43.5–44.5	374	–12.5	Ice bands
11	44.5–56.0	364	–13.3	Loose snow, grain from 0.5–0.6 to 1.5 mm
12	56.0–56.5	370	–13.3	Ice bands
13	56.5–63.5	366	–13.3	Loose snow, grain 0.5–0.6 mm
14	63.5–64.0	380	–14.5	Ice bands
15	64.0–80.0	380	–15.3	Snowpack, grain from 0.5–0.6 to 1 mm
16	80.0–81.5	332	–15.3	Deep hoarfrost, up to 3 mm
17	81.5–83.5	332	–15.3	Loose snow, grain 0.6–0.7 mm
18	83.5–84,5	–	–	Ice
19	84.5–90.0	332	–15.3	Loose snow, grain 0.5–0.6 mm
20	90.0–92.0	332	–15.3	Snow has 3–4 ice horizons, grain 0.5 mm
21	92.0–95.0	256	–	Snow is pack-frozen, grain from 0.6–0.7 to 1 mm
22	95.0–97.5	–	–14.5	Snow is pack-frozen but more porous, grain up to 2 mm
23	97.5–98.5	383	–14.5	Deep hoarfrost, grain up to 3 mm
24	98.5–103.5	271	–16.0	Deep hoarfrost, grain up to 2 mm
25	103.5–104.0	327	–16.7	Ice bands
26	104.0–105.0	421	–16.7	Deep hoarfrost, grain up to 1 mm
27	105.0–112.5	251	–18.0	Snowpack, grain 0.3–0.4 mm
28	112.5–121.0	265	–16.7	Loose snow, grain 0.6–0.7 mm
29	121.0–126.0	–	–16.7	Loose snow, grain 0.3–0.4 mm
30	126.0–136.0	287	–16.7	Snowpack, grain 0.2–0.3 mm
31	136.0–141.0	–	–	Loose snow, grain 0.2 mm
32	141.0–149.5	–	–	Loose snow, grain 0.1 mm
33	149.5–154.0	–	–	Fresh snow, very loose (consisting of snowflakes with diameters up to 3 mm)

Note. A dash means that the measurements of density K or the temperature measurements were not performed in the given layer.

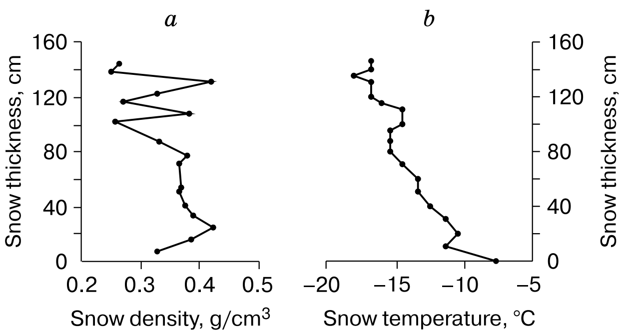

Fig. 5. Dependence of density (*a*) and temperature (*b*) on snow depth in a basic pit.

with different structure, density, thickness, temperature, and with specific features like ice bands. Stratification of snow density and temperature by its thickness is shown in Fig. 5.

Traditional stratigraphic description of a snow cross section in a pit was supplemented by the results of the field measurements of the acoustic and strength characteristics of snow, which were performed also *in situ*.

The characteristics of snow in a homogeneous layer with $T_s = -14.5$ °C are the following:

– Density 366 kg/m^3;
– Grain diameter 0.6 mm;
– Poisson ratio 0.26;

– Shear modulus 728 MPa;
– Dynamic elasticity modulus 2.2 GPa;
– 3D elasticity modulus 1.53 GPa;
– Relaxation time 330–377 s;
– Shear toughness of snow 240–270 GPa;
– Fracture toughness 29 kPa·m$^{1/2}$.

The natural resonance frequencies were determined by spectrograms, which were recorded when testing homogeneous layers of the snow cover with an avalanche probe to the depth reaching 1 m.

For example, for the one-age layer of medium granularity firn with the grain diameter $\bar{D}$=0,6 mm, density ρ_s = 366 kg/m^3 with the snow temperature T_s = −14.5 °C the following data were obtained. The plane wave velocity v_p = (2470 ± 7) m/s, and the shear wave velocity v_s = (1410 ± 9) m/s. The relaxation time, the shear toughness of snow, and the fracture toughness were calculated by the results of creep tests with eccentric tension. Reverse acoustic compressibility of snow was calculated by equation (3), with the value of f_0 obtained in the test measurements of fracture spectrum of this type of snow.

Dependencies of the dynamic modulus on the density and hardness of snow on shear stress are shown in Fig. 6 and 7, respectively. There is no doubt that as the snow density increases, its structure and microscopic properties change. It is likely that the non-linear nature of the dependencies of the dynamic modulus on snow density is caused by reduction in the acoustic compressibility of snow as its density increases.

Two things should be pointed out: the absence of a directly proportional dependence of the dynamic modulus on density (Fig. 6) and different values of snow hardness with practically equal snow density (Fig. 7). The possible reason for that is formation of anisotropic structures in the direction of the slope, which is confirmed by lower (~60 %) snow hardness across the hillside [*Epifanov and Osokin, 2009*]. In fact, snow with the same density may have different hardness and structure. The revealed experimental fact does not allow snow density to be considered as a value explicitly characterizing its mechanical and structural properties.

Snow fracture spectra. The known effect of snow crunching when walking is shown in Fig. 8, *a* as dark narrow pulses corresponding to each step of the experimenter, while two bright pulses of a greater amplitude result from an impact with a 3 kg indentor. It is to be pointed out that the known mechanism of breaking inter-crystalline cohesion bonds and subsequent crushing of ice crystals as the snow is compressed, which generates the crunching sound, seems to be similar during the indentor impact. The closely spaced frequencies of the generated oscillations point to that. Different shapes of the pulses and their amplitudes were used to recognize the emission sources of the acoustic oscillations.

The pulse shape is related to the scale of snow fracture and the duration of contact, while the signal amplitude is determined only by the energy of contact, and the frequency of pulse filling is caused by destruction of the snow grains. The physical process occurring in a homogeneous horizon consists of elastic shear of grains, formation of the sliding planes inside single grains, destruction of bridges among grains, their disconnection, and sliding. In fact, two processes are observed: destruction of snow grains and their sliding. Destruction of snow grains generates high-frequency oscillations (17 kHz), while grain sliding causes oscillations, the frequency of which is less by at least one order of magnitude, and its energy is less by nearly two orders of magnitude. High-frequency oscillations overlap the envelope of the impact pulse (Fig. 8, *c*). It is to be noted that high-frequency signals may only be detected only given enough signal amplification.

Thus, the experiment confirms the possibility of establishing a connection between the acoustic emission (AE) characteristics and the scale of snow fracture.

Snow sample fracture spectra. Snow bars clamped at one end with the cross section of ~10 cm^2 were tested for bending. The complicated field of

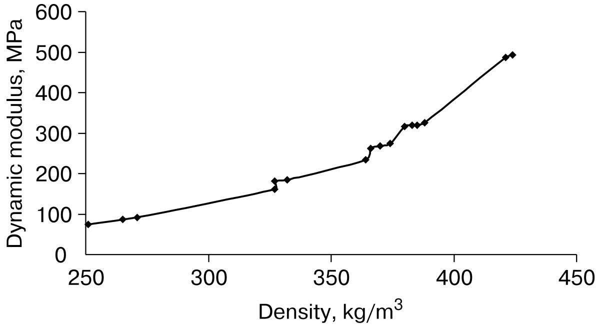

Fig. 6. Dependence of a dynamic snow modulus on snow density in a one-age layer.

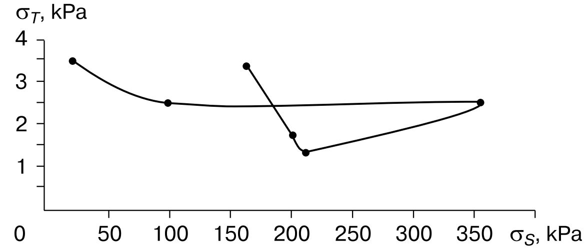

Fig. 7. Dependence of snow hardness (σ_T) on shear stress (σ_S).

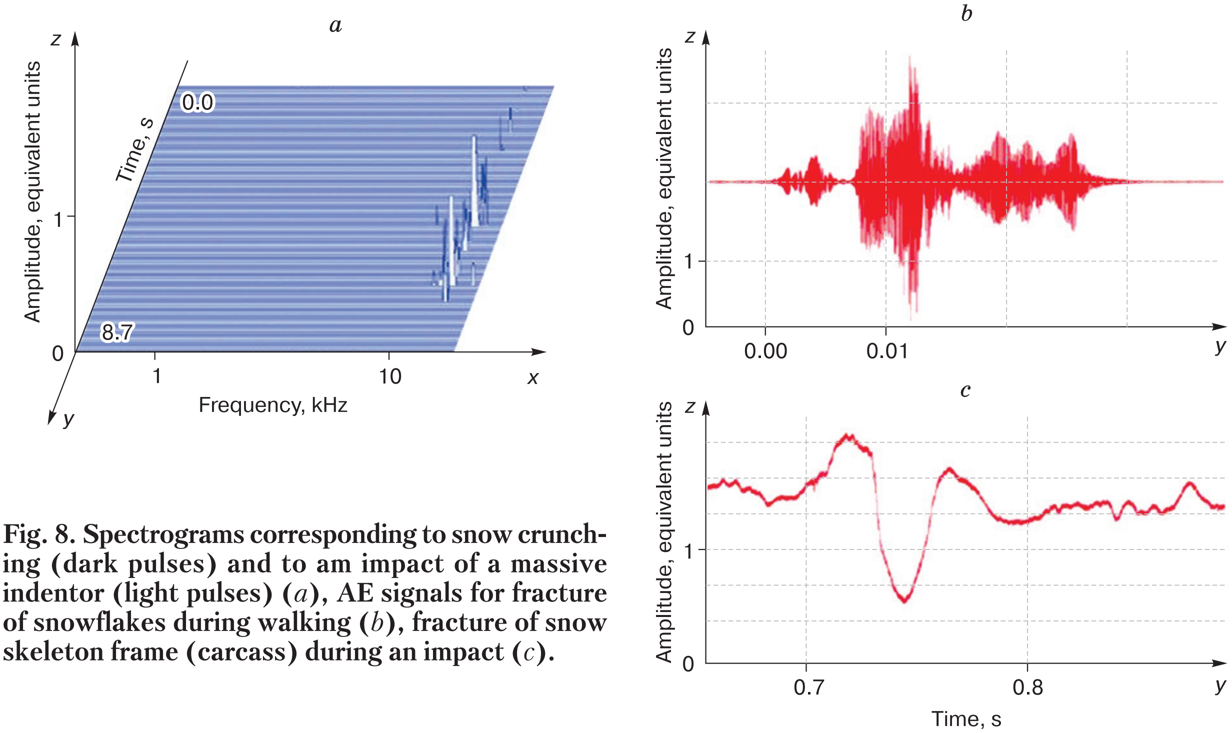

Fig. 8. Spectrograms corresponding to snow crunching (dark pulses) and to am impact of a massive indentor (light pulses) (*a*), AE signals for fracture of snowflakes during walking (*b*), fracture of snow skeleton frame (carcass) during an impact (*c*).

stresses at bending and correspondingly the complicated mechanism of crack formation are illustrated in the fracture spectrogram (Fig. 9, *a*). The high amplification factor (–70 dB) and the short length of the acoustic path allow a greater part of the fracture spectrum to be observed in the spectrogram, especially its high-frequency components.

Shown in Fig. 9, *b* is the spectrogram of the fracture of a snow bar with the cross section of ~1250 cm^2 (dimensions 70 × 50 × 25 cm) in the tests for fracture toughness. Compared to the previous experiment, the amplification factor was reduced by 15 dB; therefore the high-frequency amplitude is registered only partly in the spectrogram. The observed shear of the acoustic amplitude to the area of low frequencies (compared to Fig. 9, *a*) is caused by an increase in the fracture amount by two orders of magnitude and by a high acoustic absorption factor. In this case, brittle fracture in the area of the main crack generation is localized in a small volume/scale, has low amplitudes of oscillations and is not reflected on the spectrogram when low amplification is used.

Thus, the scale of fracture, all other conditions being equal, correlates with the acoustic amplitude parameters, which allows quantification of the scale of fracture by using acoustic spectra.

Natural elastic oscillations in the snow cover. Shown in Fig. 10 are the spectrograms of natural acoustic oscillations in the snow cover of Mount Olavsvarden. Recording was performed with the amplification factor of –87 dB, with the acoustic sensor placed in a dense layer No. 21 of the snow cover (Table 1).

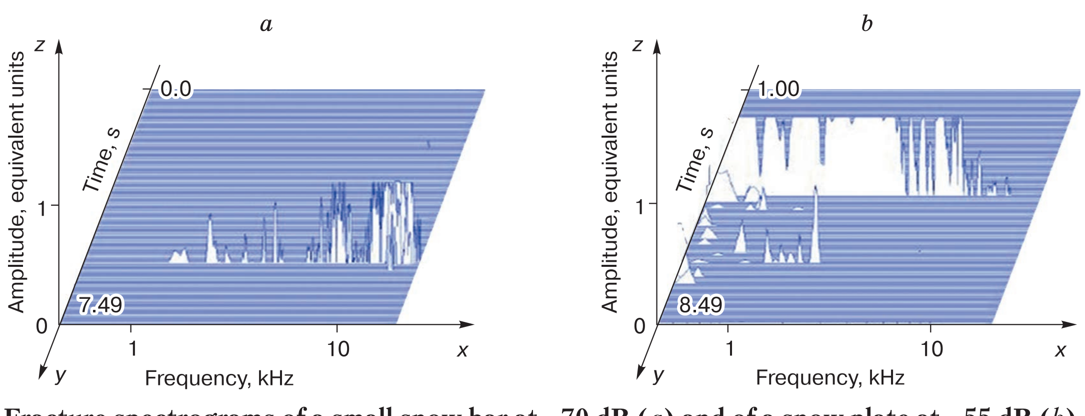

Fig. 9. Fracture spectrograms of a small snow bar at –70 dB (*a*) and of a snow plate at –55 dB (*b*).

In accordance with the spectrogram, natural oscillations in snow are observed only in the low-frequency amplitude (less than 2 kHz), the acoustic "path" at the frequency of 13 kHz behaves like a resonance harmonica, which is excited by them in the acoustic waveguide. To be sure, the sources of natural oscillations of snow are remote from the source, and their sizes essentially exceed the sizes of the snow grains. This is confirmed by the low frequency of the natural oscillations of snow, their small amplitude (the model of a harmonic oscillator, equation (1)), as well as by comparing the spectra observed with the test spectrum. It is likely that the observed natural elastic oscillations in the snow cover are caused by the local shear of the layers in relation to each other or in the contact with the underlying surface. The result obtained does not contradict the laminar structure of the snow cover, in accordance with which its natural spectrum of acoustic oscillations should be broad-band with its maxima located at the frequencies corresponding to the scope of the fractured structures. The direct proof of that was obtained in the experiments.

Sounding same-age layers of the snow cover. To investigate the response of the mesostructure in the one-age layers of the snow cover, an acoustic sensor was placed in the layer under study. This layer was probed with an avalanche probe, which was oriented in parallel with the day surface. The acoustic spectra caused by the fracture of the snow mesostructures in the one-age layer are shown in Fig. 11.

As noted above, each maximum in the broadband spectrum in a medium with a complicated structure hierarchy may be connected with the scale of the structure being fractured. For example, the high-frequency component of the spectrum (~17 kHz) corresponds to the fracture of the snow grains (cohesive fracture). A pulse with the filling frequency ranging from 1 to 3 kHz is caused by the fracture of larger structural formations.

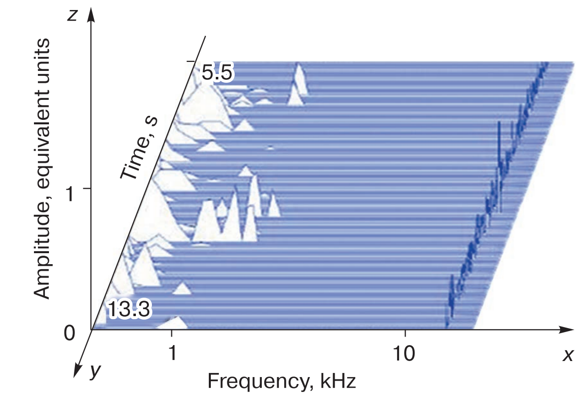

Fig. 10. Natural acoustic spectra of oscillations in snow cover in the range of frequencies from 100 Hz to 20 kHz.

In the general case, such consistency of the response is related to the increase of the added weight for example, when one layer slides along the underlying surface (adhesive fracture). In the case in question, snow packing in front of the probe tip is not excluded, as well as sporadic fracture of the packed mass. This assumption is confirmed by the discontinuous intermediate signals and by the decreased rate of their filling frequency. It seems that the use of tips of various shapes will allow making respective corrections in determining the mechanism for this frequency component of the spectrum [*Penetrometer, 2014*].

In analyzing the recorded signals, the *Spectrlab* software program allows changing not only the presentation of the recording (logarithmic or linear) but also the amplification factor, setting the scale convenient for the solution of the specific task (in the cases under study the data on the spectrum amplitude are shown in a linear scale).

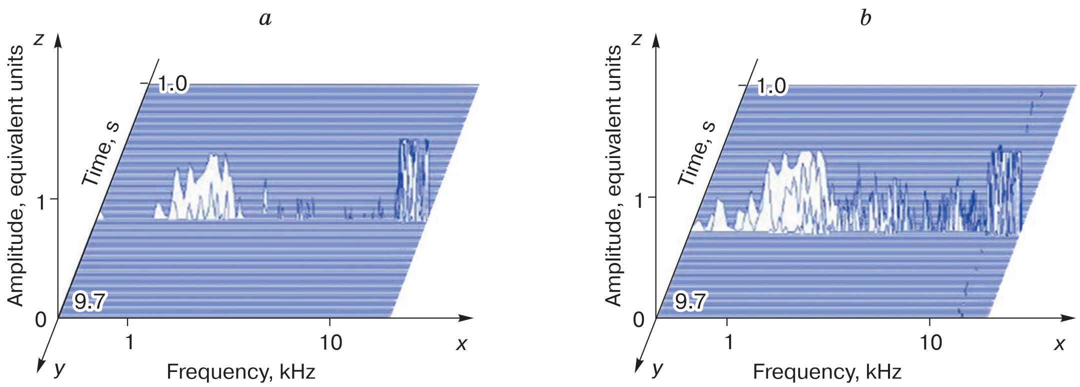

Fig. 11. Typical spectrograms of deep sounding (up to 1 m) of one-age layers of snow cover with an avalanche probe.

The amplification factor is –67 dB (*a*), –73 dB (*b*).

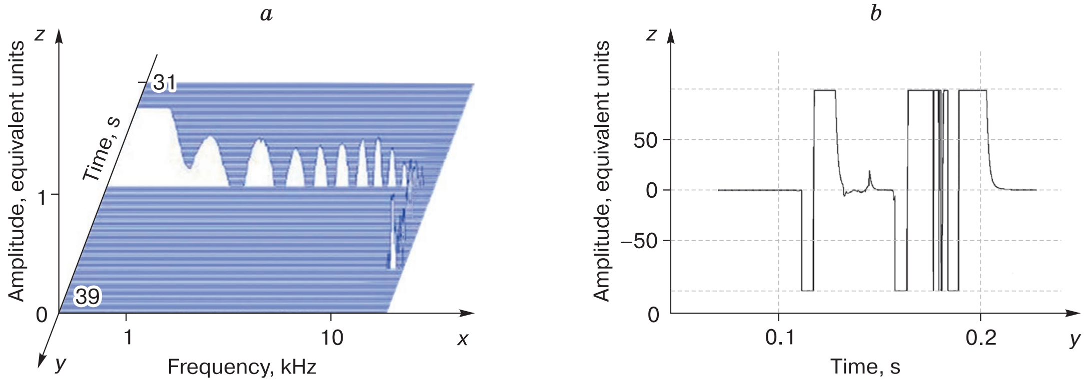

Fig. 12. AE spectrogram, recorded during penetration of an avalanche probe through different-age layers of snow cover, in frequency–amplitude–time coordinates (a) and dependence of signal amplitude (snow resistance to probe tip penetration) on time (b).

Response of different-age layers. In the vicinity of the control pit, about 130 measurements were made (in parallel with and orthogonally to the layer surfaces). The typical spectra of the fracture of different-age layers of snow probed with an avalanche probe downwards are shown in Fig. 12. The spectrogram (Fig. 12, *a*) was obtained in vertical motion of the avalanche probe in the snowpack from the day surface to the underlying surface, with the probe going through the entire snowpack (137 cm) during 1 second. The response contains two groups of acoustic emission signals. The first group of signals (12 of them were identified) were observed in a narrow time interval and differ from each other by the filling frequency and by the shape of the envelope. The second group signals (5 signals) are spaced in time, have close filling frequencies but different amplitudes and shapes. For greater visibility, the second group signals (snow response to the penetration of the avalanche probe) are shown in Fig. 12, *b* in another system of coordinates (dependence of the signal amplitude on time).

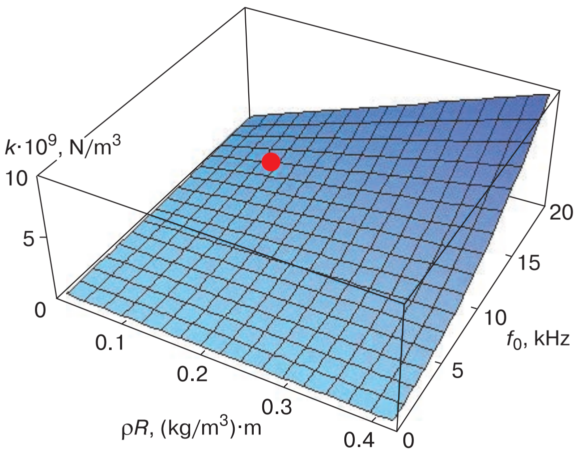

Fig. 13. Dependence of reverse acoustic capacitance (k·10^9, N/m^3) on frequency (f_0, kHz) and a product of multiplication of density (ρ, kg/m^3) by grain radius (R, m).

First group signals. Signals of different filling frequency are formed at the initial moment of the impact of the probe tip against the ice crust of the snow cover. At this moment, the crust becomes the source of acoustic waves (longitudinal, shear and flexural waves). These acoustic waves are practically not propagated to the upper layer of fresh snow, as their density is low, therefore nearly all the acoustic energy is directed downwards. However, not all of the acoustic energy reaches the underlying surface, then some part of it is reflected upwards, and such reflection occurs from each inhomogeneity. As a result, the acoustic sensor records a number of signals, the quantity of which, given correct tuning of the device, will be equal to the number of the ice bands plus two or three more (depending on the depth and structure of the snow cover) signals from the flexural wave. (In the case in question, 12 reflections were obtained, with only 9 of them connected with reflection of the longitudinal wave). The longitudinal wave penetrates the depth of the snowpack within several thousandths of a second. In fact, the first group of signals contains complete information about the structure of the snow cover, primarily about the presence of ice bands in it and the boundary lines. Using this spectrogram, the structure of the vertical cross section of the snowpack can be understood. In practice, it is not difficult to determine the depth of the snow cover without using an avalanche probe with length marks and, even more so, without making a pit but using the ice band as an emitter's membrane (the acoustic wave source) and the measuring acoustic line [*Epifanov and Glazovsky, 2013*].

The second group of signals. Dependence of the signal amplitude on the observation time (Fig. 8, *b*) characterizes the shape of the mesostructures (their contact fracture), i.e., the way snow resistance changes when the probe tip penetrates the borderlines of different-age layers and inhomogeneities of the ice band type. In effect, the sequence of these signals and their parameters reflect the structure of the snow cover in the vertical cross section. In other words, here the parameters of the acoustic signal characterize the geometry and the physico-mathematical and tensile properties of inhomogeneities (interlayer boundaries and ice bands), while the fine structure of the spectrum characterizes the properties of the snow skeleton frame of the same-age layer (snow density, grain size and elastic modulus). A fragment of such a spectrum was observed previously during impact interaction between a hard indentometer having a piezoelectric accelerometer and ice [*Epifanov, 1985*].

When the snow mesostructures are destroyed (inter-layer borders, snow skeleton frame, ice bands, etc.), natural acoustic oscillations are emitted, the parameters of which are determined by the physical-mechanical characteristics of these structures (as emission sources). Thus, acoustic pulses of different amplitudes but of close frequencies are spread in time in such a way that they reflect in the first approximation the depth of one-age layers and the work spent on their fracture (Fig. 8, *b*). As each structure is fractured, certain acoustic energy is emitted, to which a certain amplitude, frequency, and duration of an acoustic pulse correspond. Comparison of these acoustic characteristics with the data of stratigraphic studies by the method of traditional pit-making is quite acceptable, as the acoustic characteristics are determined from the basic physical laws. The data of stratigraphic measurements in pits quantitatively agree with the acoustic spectrogram calculations.

For example, as the probe tip penetrates a same-age layer of snow, elastic perturbations of lesser amplitude overlap the envelope of each pulse, compared to the main AE signal, and having a greater filling frequency f_0 (modulation of the main signal). These characteristics of the high-frequency component of the spectrum contain information not only on the fracture energy of the ice particles but also on their granulometric composition [*Epifanov, 1990; Penetrometer ..., 1990*].

DISCUSSION

We recorded natural acoustic oscillations in the snow cover only in the low-frequency range (less than 2 kHz), as practically a continuous spectrum was registered in the snow samples in the working range of frequencies. Conditionally maxima were identified at the frequencies less than 500 Hz and higher than 2 kHz. The absence of the high-frequency spectrum component in the snow cover is related to greater sound absorption and a remote position of the source of emission of acoustic oscillations from the receiver.

One can assume that emission sources of acoustic oscillations with different physical-mechanical characteristics correspond to the identified spectrum areas. It is most likely that the ratio of snow hardness to added mass (equation (1)) for sources with frequencies under 500 Hz is less compared to that for sources with frequencies higher than 2 kHz. It seems that a smaller ratio (low hardness and a large added mass) corresponds to the adhesion type of fracture (at the stage of growth of the main crack). Such a type of fracture occurs, for example, during shear of different-age layers in relation to each other [*Epifanov and Osokin, 2009*]. Oppositely, sources with frequencies higher than 2 kHz (greater hardness and a small added weight) are likely to be the characteristic of the cohesive type of fracture. Such a type occurs in an ice space frame, for example, in local fractures in a one-age layer. Indirect proofs of that are visual observation of local fractures in snow (homogeneous snow) and the presence of respective acoustic spectra. This agrees with the theoretical assumptions that small local fractures are accompanied by emission of acoustic oscillations in the high-frequency part of the spectrum, while larger fractures correspond to the low-frequency part of the spectrum [*Epifanov, 1985*]. The high sensitivity of the spectral characteristics to the scope of fracture and to the type of cohesion in the snow makes the acoustic methods convenient for investigation of the snow cover structure.

The results of the stratigraphic studies of the snow cover obtained in the pit during indentation with an avalanche probe and during mechanical tests of snow in one-age (homogeneous) layers were considered in the framework of the theory of propagation of acoustic waves in snow. As a result, the method of acoustic-mechanical diagnostics was developed. Reverse acoustic compressibility k was found to serve as a "bridge" between the micro- and macro-characteristics of snow. This physical value is considered as a parameter which establishes connection between the snow structure and its macroscopic characteristics: density, the size of the snow grains and natural resonance frequency. The method of acoustic-mechanical diagnostics allows the toolkit for the object under study to be expanded. In addition, this method allows measurements to be made nondestructuvely, i.e. without violating the quazi-equilibrium state in the snow cover.

The relevance of the problem of establishing connection between the micro- and macro-characteristics of snow is necessitated by the need for quantitating its state. The non-linear character of the dependence of a dynamic modulus on snow density shows that such connection is multi-parametric for its nature (Fig. 6). As shown in the studies conducted, the reverse value of acoustic compressibility k in the integral form characterizes the structural-mechanical and strength properties of snow (equation (3)) and, as shown in the studies performed, considers the impact of not only the density and size of snow grains but also of the time factor (resonance frequency or fracture rate).

Shown in Fig. 13 is the "theoretical" dependence of the reverse acoustic compressibility k on the frequency and the product of multiplication of the size of snow grains by its density. For layer 23 of hoarfrost (Table 1) with the density 256 kg/m^3, the grain radius $1.2 \cdot 10^{-3}$ and f ~ 15 kHz, the value of $k = 39.44 \times \times 366 \cdot 0.0003 \cdot 15000^2$ Pa/m = 0,97 GPa/m was calculated. The value k calculated by the experimental values is shown by a red dot in Fig. 13.

Such representation of the physical-mechanical characteristics of a one-age layer in principle allows transition from verbal description of the structural characteristics, density and elasticity of snow to their representation as a parameter.

Reverse acoustic compressibility k may be presented as a dimensionless parameter. For this, k should be divided by the ice shear modulus $G = 2.91 \cdot 10^9$ Pa and multiplied by the Burgers vector $b = 4.52 \cdot 10^{-10}$ m [*Frost and Ashbey, 1989*]. We will obtain the dimensionless parameter $k = 1.5 \cdot 10^{-9}$. The given example demonstrates the possibility of establishing a tie between the micro-characteristics of the snow structure and presenting the state of snow in a convenient form. However, this requires validation of the agreement between the experiment and simulation models for equal products ρR with different values ρ and R. As corresponding models are developed, such studies are planned to be conducted as models are developed used for description of sound generation during fracture of the snow skeleton frame, and for improvement of the field methods of measuring the physical-mechanical characteristics of snow.

CONCLUSION

Natural amplitude-frequency spectra have been investigated in the range of frequencies from 100 Hz to 20 kHz in the snow cover on a hillside and spectra of snow fracture were tested in situ (for fracture toughness, bending, and impact). Elastic characteristics of snow, its hardness, fracture toughness and kinetics of snow fracture in different-age layers have been identified, with their stratigraphic description provided. Correlation between the shape and characteristics of acoustic emission signals obtained in acoustic-mechanical probing of snow cover, with mechanical properties, the structure of snow in one-age layers, their thickness and quantity, as well as in the presence of ice bands, has been determined. A method of acoustic-mechanical stratigraphy of snow has been developed, based on sounding of snowpack with an avalanche probe, registration of acoustic emission signals in the range of frequencies from 100 Hz to 20 kHz, and comparison of their shape and characteristics with the results of stratigraphic description and of the tests performed in a pit were performed. A reverse problem has been solved: in a differential equation of a harmonic oscillator

$$\ddot{x} + \omega^2 x = 0, \quad \omega^2 = k/m$$

factor k has been determined by the experimental data, which relates the macro- and microscopic characteristics of snow (the grain size, density and natural frequency of the shifting element of the fractured snow structure) and which is the averaged macro-physical characteristic of snow.

It has been experimentally shown that the parameters of acoustic emission signals obtained in probing are determined by different mechanical and stress properties of snow, thickness of its layers and of ice bands. The investigation results agree with the previously obtained data for the purposes of avalanche forecasting for hillsides [*Method..., 1990b*]. It has also been shown that the boundaries of layers, ice bands, and different snow density in the layers may be identified by their response to sounding. The results of the acoustic-mechanical tests of snow agree with the theoretical model and may be applied to identification of natural acoustic emission spectra and of the spectra excited in snowpack sounding.

The studies performed have shown the perspectives of the acoustic stratigraphy method for investigation of snow cover both for quantitation of the traditionally measured snow characteristics in a pit and for evaluation of their spatial and temporal changes in large areas of their natural location.

The study was conducted with the financial support of the Russian Foundation for Basic Research (projects 14-01-00282, 14-05-00469).

References

Epifanov, V.P., 1982. Polycrystal ice fracture. Dokl. AN SSSR, vol. 267 (6), 1364–1367.

Epifanov, V.P., 1985. Ice fracture during impacts. Dokl. AN SSSR, vol. 284, 3, 599–603.

Epifanov, V.P., 1990. Impact of a moving mass of snow on structures. Izv. RAN, Solid Body Mechanics, Issue 3, 176–182.

Epifanov, V.P., 1994. Snow fracture micromechanics, Intern. Symp. on Snow and Related Manifestations: Snow and Avalanche Study Establishment, Manali (HP), India, p. 102–105.

Epifanov, V.P., 2005. Mechanics and hardness of fresh-water ice. Materialy Glyaciol. Issled., 98, 56–64.

Epifanov, V.P., Glazovsky, A.F., 2013. Investigating glaciers on the basis of acoustic measurements. Led i Sneg, 3 (123), 12–19.

Epifanov, V.P., Kudrya, V.P., 1985. Method of evaluating mechanical properties of viscoelastic materials during their impact with an indentor. Zavod lab., vol. 51, 64–66.

Epifanov, V.P., Kuz'menko, V.P., 1986. Mechanics of Snow Fracture. Izv. AN SSSR. Mekhanika Tverdogo Tela, 4, 191–197.

Epifanov, V.P., Kuz'menko, V.P., 1988. Acoustic emission methods applied to avalanche-formation studies. J. Glaciol., 34, No. 117, 232–235.

Epifanov, V.P., Osokin, N.I., 2009. Plastic flow and snow cover fracture on mountain slopes of Spitsbergen Island. Kriosfera Zemli XIII (2), 82–93.

Epifanov, V.P., Osokin, N.I., 2010. Study of structural properties of snow on mountain slopes of Spitsbergen archipelago. Kriosfera Zemli XIV (1), 81–91.

Epifanov, V.P., Yuryev, R.V., 2006. Fracture and dynamic toughness of ice. Dokl. RAN, vol. 406, No. 2, 187–191.

Frost, G.J., Ashbey, M.F., 1989. Maps of Deformation Mechanisms, Translation from English: L.M. Bernshtein. Mettalurgiya, Chelyabinsk, 329 pp.

Glaciological dictionary, 1984 / Edited by V.M. Kotlyakov. Gidrometyeoizdat, Leningrad, 528 pp.

Isakovich, M.A., 1973. General Acoustics. Nauka, Moscow, 496 pp.

Ishida, T., 1965. Acoustic properties of snow/ Contribution from the Inst. of Low Temperature Sci. A20:23-63, 1965, 03-30. URL: http://hdl.handle.net/2115/20232 (submittal date: 12.01.2014).

Kanayev, L.A., 2001. A Guide on Snow Avalanche Observations and Methods of Avalanche Management. SANIGMI, Tashkent, 168 pp.

Method of calibrating piezoelectric accelerometers: inventor's certificate 1569730 of USSR. Kl. G 01 P 21/00 / Epifanov, V.P.; published on 07.06.1990a, bulletin 21.

Method of forecasting avalanche hazard: inventor's certificate 1608600 of USSR. Kl. G 01 V/00 / Epifanov, V.P.; Kuz'menko, V.P.; published on 23.11.1990b, bulletin 43.

Penetrometer: inventor's certificate 1539583 of USSR. Kl. G 01 N 3/48 / Epifanov, V.P.; published on 30.01.1990, bulletin 4.

Penetrometer: patent 2508448 of RF of invention / Epifanov, V.P.; Kazakov, N.A.; published on 27.02.2014, bulletin 6.

Satyawali, P.K., 2014. Multi-sensor couplers and waveguides for efficient detection of acoustic emission behavior of snow/ Cold Regions Sci. and Technol., Accep. date: 11 Jan. 2014. doi:org/10.1016/j.coldregions.2014.01.003.

Skuchik, E., 1976. Foundations of Acoustics, vol. 1. Mir, Moscow, 520 pp.

Sommerfeld, R.A., 1982. A review of snow acoustics. Rev. Geophys. and Space Phys., 20, No. 1, 62–66.

Truell, R., Elbaum, Ch., Cheek, B., 1972. An Ultrasound Method in Solid Body Physics. Mir, Moscow, 308 pp.

Vinogradov, S.D., Solovyeva, M.S., 1997. Emission of elastic waves in fractured medium (3-D simulation). Fizika Zemli, 9, 3–10.

Vivchar, A.N., 2010. Snow cover and the position of the orographic snow line in the valley of the River Mzymta (Western Caucasus) under conditions of modern climatic changes. Kriosfera Zemli XIV (4), 80–88.

Zalikhanov, M.Ch., Losev, K.S., Epifanov, V.P., 2000. A Guide on Avalanche Works, 2000. RD 52.37.613-2000. Gidrometyeoizdat, St. Petersburg, 134 pp.

Zaretsky, Yu.K., Chumichev, B.D., 1982. Short-term Creep of Ice. Nauka, Novosibirsk, 116 pp.

Received March 4, 2014