Ultrasonic emissions in snow
by William Francis St Lawrence

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A detailed description of the acoustic emission monitoring system is provided and also a detailed circuit description of the signal conditioning unit.

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Date DECEMBER 21, 1972

ULTRASONIC EMISSIONS IN SNOW

by

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TABLE OF CONTENTS

List of Figures

Abstract

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INTRODUCTION

A number of different types of acoustic signals which emanate from snow subjected to mechanical loadings have been detected. These signals can be broadly classified into two groups: audible and subaudible. In terms of audible signals we can cite such examples as the squeaking which can often be heard when walking on snow on a cold day, or the sharp report which accompanies a rapidly propogating crack in the tensile region of a snow slope. Less familiar examples of audible sounds that can be detected in snow are the sound of a collapsing snow pack, and the sound of one layer of snow slipping over an adjacent layer.

The second category, subaudible noise, can be subdivided into frequency related classifications. In one instance the sound is in the audible spectrum, but is of such low intensity that it cannot be detected by the unaided ear. To date we have detected this type of signal only in snow samples subjected to deformation rates which induce a brittle response in the snow. The second type of noise is ultrasonic. This type of acoustic emission has been monitored in snow over a wide range of loadings. It is this kind of emission that will be dealt with in this thesis.

REVIEW OF RELATED LITERATURE

Until recently little attention has been given to second order effects associated with the deformation of materials. In general the production of heat, sound, and in some instances, electrons is either ignored or only briefly considered. These quantities represent irreversible energy losses associated with material deformation, and in most instances, are not critical in describing a material's rheologic character. It is possible, however, that further consideration of these loss processes may yield a better understanding of the deformation mechanism and state of stress in materials.

Acoustic signals, which emanate from some materials subjected to mechanical or thermal loads, are presently the subject of intensive investigation. The first use of acoustic emissions from stressed materials was in the late 1930's*. At that time researches in the field of rock mechanics became interested in the acoustic activity associated with rockburst phenomena in mines. Acoustic emission techniques until the 1950's were utilized exclusively by researchers in the geologic sciences. In the early 1950's researchers in other fields of material science became interested in acoustic emission technology. In the field of fracture mechanics acoustic emission techniques were used in conjunction with more standard devices to study the initiation of failure. A number of attempts have also been made to characterize various materials in terms of their acoustic response. A major breakthrough was achieved when it was determined that many materials emit stress waves at frequencies in the range from 50KHz to 1.5MHz. A

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* Although the study of seismic waves generated during earthquakes dates back 3,000 years this type of emission will not be considered here.

comprehensive survey and state of the art discussion of acoustic emission research can be found in papers by Hardy (1972) and Liptai et al. (1971). In reviewing the literature on acoustic emission technology it becomes clear that in its present state of development this science exists as an empirical form with little or no theoretical basis.

In his paper Liptai et al. (1971) considers a model of an idealized emission source in a polycrystalline material. The model is described by a single spherical grain of material sheared across its diameter, with each hemisphere vibrating at its fundamental frequency. Using this approximate analysis yields values for the expected frequency of an emission of 1MHz to 50MHz. More qualitative descriptions of the source mechanism of acoustic emissions in rock are given by Hardy (1972) and Goodman (1963). In the model they propose, a multiple source mechanism is considered which consists of: (1) the closing of microcracks, (2) relative motion between grains, and (3) twinning, splitting, shearing, and crushing within grains.

Related to the source mechanism of an acoustic event is the frequency spectra of the emission. A method for obtaining the frequency spectra of a typical acoustic event has been described by Liptai et al. (1971) but to date has not been implemented. The difficulty present in attempting to monitor, with good fidelity, an incoming acoustic event is presently limited by the resonant techniques now employed in acoustic emission monitoring systems. Since the acoustic event is of extremely low amplitude the only way to detect it is by using sensitive transducers. The required sensitivity can be achieved with present day transducers only by using them at their resonant points.

In studying the noise generated in materials under stress it has become common practice to record only the occurrence of a burst of acoustic energy. Burst type emissions are generally recorded in terms of the rate at which they take place or their accumulation with time. These quantities generally show close correlation with load or deformation parameters such as stress, stress rate, strain, or strain rate. Other acoustic parameters which have been subjected to investigation, according to Hardy (1972), are event amplitude, event energy, accumulated energy, and energy rate. Although these parameters would appear to give a good indication of the process operating in the material, this is not the case. The reason for this is many fold, but the main reason for poor characterization in terms of energy parameters is due primarily to the monitoring system.

The energy parameters described are dependent not only on basic system sensitivity and signal to noise ratio, but also on the frequency response of the monitoring system. An emission originating at some point within the specimen and being monitored at its perimeter has a wide frequency band. This has been verified by the fact that emissions have been monitored in the same material at widely varying frequencies. This wide frequency spectrum may have a bandwidth of a megahertz or more. Superimposed on the primary event signal will be specimen resonances. These resonances take the form of thickness reverberations, end to end reverberations, and spring mass phenomena. Egle and Tatro (1966) have investigated these phenomena in some detail. With these latter complications introduced and considering the frequency response of current monitoring systems, it will probably be some time before energy considerations can be properly examined. Liptai et al. (1971) have hypothesized that an ideal monitoring system should have adequate sensitivity and a flat frequency response over a bandwidth from zero to 100MHz.

Monitoring the occurrence of acoustic emissions in terms of event rate, total number of events, and event location is presently yielding the most meaningful data in applied acoustic emission research. The principles, which guide this data collection, are described by Tatro (1971). In this type of investigation it is of consequence to record only that an acoustic disturbance is taking place and the time of its occurrence.

In the field of snow and ice physics little information on acoustic emissions has been presented in the literature. Gold (1960) has considered the audible cracking associated with samples of polycrystalline ice subjected to various states of stress. In his experiments Gold found that the acoustic activity detected was associated with the formation of visible cracks in the ice. He determined that in uniaxial compression a stress of 10^4 gm cm^{-2} produced little acoustic activity. When the stress was increased to 1.52 x 10^4 gm cm^{-2}, the amount of acoustic activity was appreciable during primary creep. For ice subjected to stresses of 1.6 x 10^4 gm cm^{-2}, the acoustic activity was found to increase with time over the duration of the experiment. In a more recent paper Gold (1966) expanded the scope of his original work to include temperature considerations in the cracking activity of ice.

In terms of field research, two papers reporting acoustic phenomena in ice have been published. Neave and Savage (1970) working on the Athabaska Glacier attempted to determine if slip faulting takes place at depth within a glacier. Using techniques along the lines of classical seismic investigations they found that no evidence of slip faulting could be detected. They did find that ice quakes originating from extensional faults near the surface could be detected. The transducers used in this study were geophones distributed in a three dimensional array. In a recent paper Milne (1972) has investigated tension cracking in sea ice as a source of underice noise. Using remote instrument packages placed on the sea floor, Milne was able to correlate underice noise and thermal cracking at the ice-air interface. He shows that under certain conditions where thermally induced cracks can exist that the underice noise rises in intensity exponentially with an increase of the thermal stress.

In a short note St. Lawrence et al. (1972), using low frequency techniques, determined that snow subjected to certain rates of deformation emitted low frequency burst emissions. It was determined that at rates of deformation which produced brittle failure in snow a definite and reproducible pattern of emissions is observed. The results reported are obtained at one temperature and for one density of snow. In discussing the source mechanism of these emissions it is proposed that the breaking of intercrystalline bonds is the most likely mechanism. This conclusion is based on information presented by Kinosita (1966).

In reviewing the literature it is apparent that acoustic emission technology has not yet developed to its full potential. It is also apparent that although this science is still in its infancy, it represents a powerful technique when applied to many problems in material science. In the following pages possible applications in snow mechanics will be discussed.

EMISSION CHARACTERISTICS AND POSSIBLE SOURCES

To investigate the nature of ultrasonic emissions in snow, consideration must be given to the possible source of the acoustic event and to the system used for detecting it. Consideration of the acoustic emission monitoring system, and in particular the transducer, is important since information obtained in terms of frequency content, amplitude, and duration of an acoustic event in general reflect system characteristics. The source disturbances probably bear little resemblance to the signal that is recorded. In defining ultrasonic emissions we are indicating that the transducer used is most sensitive to excitation in the ultrasonic region of the frequency spectrum.

Since the energy release associated with a burst emission is small (an estimate in the neighborhood of 10^{-13} Joules has been suggested by Liptai et al. (1971)), it is customary to monitor the transducer used to detect the acoustic signal in the vicinity of one of its resonance points. This method makes it possible to detect small amplitude signals, but provides little information about the form of the exciting signal. Using this technique limits the information obtained to establishing that a transient disturbance has taken place and that the disturbance has sufficient energy in the region of the transducers resonant frequency to excite the transducer to resonance. A definite advantage in working in the ultrasonic region of the frequency spectrum is that for frequencies above 30 KHz interference from extraneous noise is minimal.

Figure 1 is intended to illustrate the frequency dependence of the emission signal to the characteristics of the transducer. Figure 1a represents the calibration curve of the transducer over a frequency range from 30 KHz to 112 KHz. Note in this figure that the transducer shows a primary resonance peak at 55 KHz with a sensitivity at this frequency of -105 decibels (referenced to one volt per microbar).

A harmonic of this resonance point can also be observed at 110 KHz with the sensitivity at this point being reduced by 18 decibels. Figure 1b represents a frequency analysis of an acoustic emission that was obtained with this transducer. Note that in general the wave analysis reflects the characteristics of the transducer with the exception of the amplitude at the 110 KHz point. This amplitude variance indicates that the acoustic signal has a higher energy component at the 110 KHz frequency. It should be noted that all other system components exhibited a flat frequency response over the frequency range in question.

As indicated it is difficult to describe in any detail or with any precision the form of the acoustic emission as it originates. The fact that acoustic signals are detected in snow indicates that when snow is subjected to mechanical loadings a non-conservative energy conversion takes place with part of this energy being dissipated in the form of noise.

It is probably correct to assume that acoustic energy represents only a small portion of the total energy dissipated. From oscilloscope and magnetic tape records we can establish that the emission of sound from snow occurs in burst of noise rather than continuously. These bursts take place at intermittent intervals depending on the particular loading applied.

To identify the sources of acoustic emissions in snow, we will

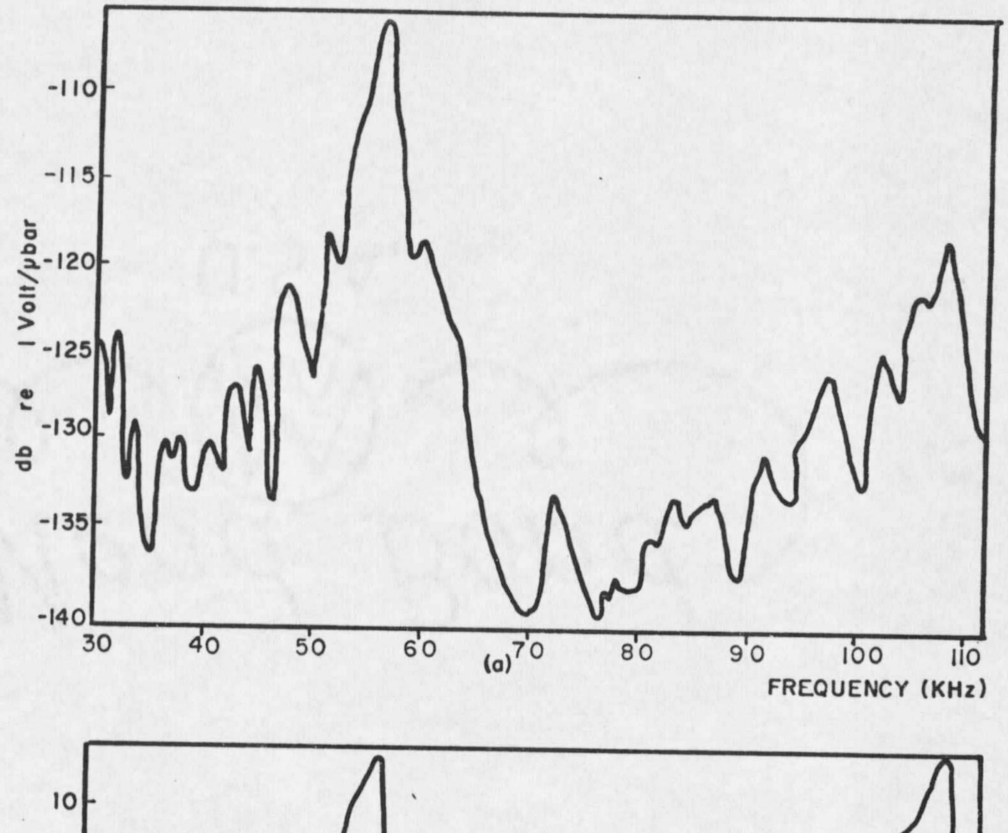

Figure No. 1. (a) Transducer calibration curve. (b) Wave analysis of an acoustic emission from snow.

rely on observations that have been made of the structural changes that take place in snow during the deformation process. From these observations we can tentatively identify possible emission sources. For deformation rates, which produce a brittle response in the snow, Kinosita (1966) observes that failure is characterized by the break- of bonds between ice crystals composing the snow matrix. For this type of deformation we detect both ultrasonic and audio signals emanating from the snow. Since Kinosita indicates that intercrystalline fracture is the only means by which snow deforms at high rates, we are probably correct in assuming that for these rates some form of intergranular movement generates the acoustic signal observed.

For snow that is deformed at rates which produce a plastic response, acoustic emissions may be due to a number of mechanisms. Observations reported by Wakahama (1966) on the compression of snow at slow rates indicate that the structural changes, which take place in the snow matrix, are basal glide, slip at grain boundaries and separation of ice grains. It appears plausible that acoustic emissions can originate from the formation of slip planes in the ice grains and also from the separation of ice grains. In the case of the formation of the slip plane this takes place at a rapid rate in the ice grain. A number of these slip planes forming simultaneously in the ice crystal comprising the snow matrix might produce an acoustic signal at a level that can be detected. If the separation of ice grains takes place in a rapid manner this may also represent an acoustic source. In the case of slipping at grain boundaries it would appear that this kind of process would not generate sufficient power to produce a detectable acoustic signal. Wakahama (1966) also reports that in addition to these primary mechanisms of grain fracture, void formation and grain boundary migrations are also observed. In considering these mechanisms as possible acoustic sources, it is probable that grain fracture and void formation within grains could generate transient acoustic signals. A number of experiments are now being planned which will attempt to look at each of the above mechanisms as possible emission sources. Brown (1972) is presently considering, on a theoretical basis, the form of the stress wave which might emanate from these mechanisms.

CONSIDERATION OF THE DEFORMATION PROCESS IN SNOW

In the previous section a number of possible sources of acoustic signals in snow were considered without being related in a particular manner to the deformation process. In this section we will examine more carefully observations that have been made of the structural changes that take place in snow undergoing deformation.

Since few investigators have reported in detail on the structural changes which take place in snow, we will rely to a great extent on the observations that have been reported by Yosida (1963). Yosida (1963) gives a detailed account of the structural changes that take place in thin sections of snow undergoing uniaxial compression. Although he does not state specifically the strain rates at which these observations are made, he does indicate that the rates are in a range which produce a plastic response in the snow sample. An account of Yosida's observations are reviewed in detail here.

Yosida reports that during the initial rise of the force no changes in the ice matrix occur other than small displacements of the ice grains composing the snow. After the yield point is reached it is observed that slip lines are formed parallel to the basal planes of the ice crystals. As deformation continues phenomena such as slip at grain boundaries, separation of ice crystals, migration of grain boundaries, formation of cells in grains, recrystallization, formation of bend planes, cleavage fracture of grains, and nonhomogeneous lattice bending are observed. In studying this description of the deformation process it is of interest to note that two distinct mechanisms operate during the early stages of deformation. It seems that these two mechanisms operate in a sequential manner, the first mechanism being small displacements between ice grains and the second slip on the basal plane of the ice crystals. These two mechanisms are significant in terms of identifying the source of acoustic emissions. Salm (1971) has apparently used this description of the deformation process as the basis of his failure theory for snow.

Salm (1971) has considered the deformation of snow in terms of a three phase mechanism. In the first stage, immediately after loading begins, he considers the stress to be located on "primary elastic lines." In this phase the deformation is considered to be purely elastic with the deformation taking place between ice crystals. In the second stage of deformation Salm (1971) supposes the establishment of "secondary elastic lines." In this phase of the deformation part of the stress, energy is conserved and part of it is dissipated in the form of viscous flow. In the last stage he assumes that the deformation takes place due to purely viscous elements. In his analysis he indicates that for relatively high velocities elastic and visco-elastic elements operate, while at low velocities the deformation is due mainly to the operation of viscous elements. Salm quantifies his model by introducing a nonlinear Burger's body, this model consists of a linear Hookean element in series with a non-Newtonian fluid element, which in turn is connected to a non-Kelvin element. This non-Kelvin element is intended to replace the normal Kelvin element associated with the Burger's body. Salm's formulation is of interest since it represents a first attempt to characterize the mechanical behavior of snow while giving some consideration to the structural changes taking place.

Considering the load deformation character of snow in terms of the observations of Yosida (1963) and the analysis of Salm (1971) and with information obtained in our own laboratory, it seems appropriate to make the following comments on the specific source of the acoustic activity in snow. It is probable that this phenomena is connected with the small displacements of the ice grains observed by Yosida (1963) during the early stages of deformation. As shown in Figure 2, the maximum rate of acoustic activity takes place during the rapid rise of the load curve. At the point where the stress varies from its initial linear rise (in relatively high rate experiments), we can observe that the emission rate begins to decline. This reduction in the emission rate coincides with the formation of slip bands in the ice crystals. Observation of the emission sequence appears to be consistent with a two phase mechanism during the early stages of deformation. If the motion between ice grains is the source of the acoustic activity in snow, we can hypothesize on the origin of the emission.

In a previous section evidence was presented which indicated that the acoustic activity detected is in the frequency range of 50 KHz to 110 KHz and possibly the primary frequency of the emission is much higher. To generate these frequencies, requires that the energy release takes place over an extremely small time interval; the time interval considered being on the order of microseconds. If the snow is deformed such that the stress between certain grains reaches a critical value, it is possible that the grain will fracture either at the necked portion of the grain or at the grain boundary. Accompanying fracture of