Instrumental Real-Time Monitoring and Prediction of Sea Ice Compression and Ridging

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ABSTRACT

This paper describes dynamic processes in the sea ice observed during ice monitoring in the Kara and Laptev seas. Wave events are studied instrumentally under assumption that sea ice is an interaction indicator of the air-ice-water system. Wind waves and free swell waves from far storms in the open water are considered as background oscillations. Compression/ridging events and heterogeneity of ice drift generate periodic micro-shearings that can be registered in ice cover as mechanical horizontally polarized waves. Ice compression/fracture event can be predicted by analyses of ice micro-shearings. This short-term method of ice compression and ridging forecast showed good results for processes in drifting and fast ice.

KEY WORDS: Kara; Laptev; sea ice; monitoring; dynamics; forecasting.

INTRODUCTION

Forecasting of extreme ice events is based on ice cover monitoring and in particular its physical and mechanical changes and large-scale dynamic reactions. Oscillation and wave processes in the ice give a lot of important information for analysis. The most typical dynamic processes in sea ice are vertical and horizontal displacements. These ice movements and failures occur continuously and determine the ice cover structure. Extensive fractures, ridges of hummocks and open-water channels can originate from significant ice compression forces.

First big-scale experiments of ice cover monitoring were carried out by authors in the Kara sea during Rosneft Oil Company expedition "Kara-winter-2014". Fluctuations of ice drift velocity and ice horizontal displacements were continuously registered during the tests by special measurement complex. It is shown how sea ice drift is accompanied by ice deformations during different ice events (compression, formation of cracks). Ice drift depends not only on local wind and on sea currents but also on wind in neighboring areas. Displacement velocity in consolidated compressed ice for measurements in a distance of 100 km reached 3 cm/s (Legenkov, 1988). Estimation of ice forces in the periods of intensive compression allows to obtain external forces and investigate their distribution along the ice drift trajectory. Due to the total mass and acceleration of ice, these forces of drifting ice interaction can reach hundreds of kilonewtons (Sheikin et al., 2006).

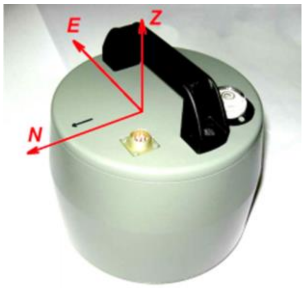
Authors performed real-scale measurements of dynamic processes in ice cover in order to develop a method of short-term forecasting of ice cover compression, ridging and failure events. Assembled measurement complex consisted of seismometers, deform-meters, tilt-meters and GPS-receivers. Also here are determined the ice deformation mechanics and ice failure parameters, the appearance of wave and large-scale self-excited oscillations processes, the influence of swell and internal waves onto ice cover.

Instrumental monitoring of the sea ice state gives great possibilities for obtaining new results in the polar oceanology and mechanics of ice cover. Besides of obtaining climatic data another important is improvement of ice drift models and fracture mechanics. It is important for ensuring safe navigation in polar ice and for design of ice formations impact on offshore structures of the Arctic shelf (Palmer and Croasdale, 2012).

SEA ICE COVER MONITORING

For sea ice state monitoring authors registered oscillations and wave processes in ice cover caused by cracks, fractures, ridging and propagation of swell waves. For this purpose, pendular and molecular-electronic seismometers, tilt-meters and deform-meters were used (Smirnov et al., 2017).

Seismometers CME-4111 register wave processes in the ice in range of frequencies from 0.0167 to 50 Hz (Fig. 1). Mobile recorder of high-resolution seismic signals “Baikal - 7HR” records signals in a wide frequency range with reference to the absolute time. Intensity of oscillation processes (amplitudes of oscillation velocity, displacement, acceleration) are presented in units of electric voltages which are converted into units of displacement or acceleration according to seismometer technical characteristics.



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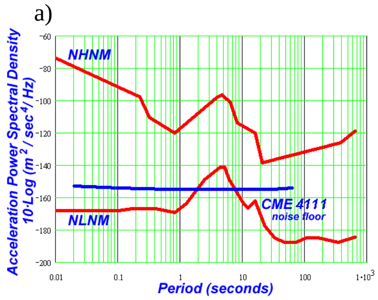


b)

Fig. 1. Electronic-molecular seismometers CME-4311 with indication of sensibility axes a) amplitude-frequency characteristics of seismometers of CME type, b) frequency range 0.01 – 60 Hz (period 0.01 –100 sec)

In addition to seismometers, tilt-meters are used which can record processes with oscillation periods from tens of minutes to static deflections of ice with a range of measurements +/-1746 μRad. Tilt-meters and seismometers are installed on special pedestals, frozen in ice. Contact deform-meters measure the relative displacements of two points of ice, which are within a distance of up to tens of centimeters from each other.

The development of methods for monitoring and identifying extreme ice parameters was carried out on the fast ice of the Laptev Sea and in the Kara Sea. Devices were used on ice fields. Sensor signal registration was carried out automatically into the logger internal memory card. The same signals were transmitted real-time on the radio channel to the base station located on the "Yamal" icebreaker. The software and hardware part of the complex, located on the icebreaker, performed the functions of recording signals from sensors into the storage device, as well as function of real-time visualization of signals transmitted from sensors, placed on the ice.

The following chapter contains a general description of the measuring system of the drifting and fast sea ice dynamics, as well as the modules included in the system.

The field modules of digitization and data transmission receive analog data from the attached sensors and send the digitized data over the radio channel to the data collection and processing server. Digitization and data collection modules perform data collection synchronously in time. Time synchronization between modules is ensured by means of the global satellite positioning system signals. The base station of data collection and processing receives the digital data from the field modules tin a certain time range. The monitor shows real time time-synchronized data received from the field modules sensors.

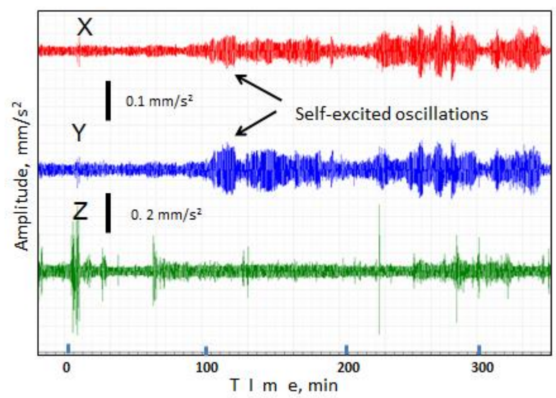
The above described monitoring system was used for the first time during the "Kara-Winter-2015" expedition. Signals from the on-ice sensors were transmitted on a radio channel for a distance more than 500 meters to the base installed on the "Yamal" icebreaker. In 2017 the device was also tested to receive signals of crack formation and fracture of the Nordenskiöld glacier on the Svalbard archipelago with data transmission via radio to the base for a distance of 12 km (Smirnov et al., 2017).

In the sea ice spectrum of oscillations and waves generated by mechanics of ice failure expand by stress waves from the sea gravity waves. The bending deformations of compression and stretching of ice, caused by the surface gravity wave, in many cases form parallel cracks at a distance of half the wavelength from each other. Results of theoretical and experimental researches of oscillations and waves in ice are presented in other papers (Smirnov, 2017).

EXAMPLES OF EXTREME PARAMETERS OF ICE EVENTS IN THE SEA ICE

Features of dynamic processes can be illustrated by results of ice fields state monitoring in the Kara and Laptev seas in 2014-15. Registration of parameters of the background and dynamical events in drifting fields of ice were carried out at ice stations in different ice stations. Average ice thickness was from 0.5 to 2 m. It should be noted that only indirect signs of compression and movements of the ice massive were recorded: the displacement velocity of the interacting ice floes, acceleration during collisions and stress relief in ice during cracking, bending deformations of the ice field from the passage of surface waves. Several examples of extreme characteristics in the Kara and Laptev seas are considered below.

Natural oscillations of the ice field on the ice station at April 15 2014 are presented by records from three-components seismometer installed directly on the sea ice in 50 m from the icebreaker. Average ice thickness was 0.9 m. The duration of observations was 6 hours 33 min (Fig. 2).



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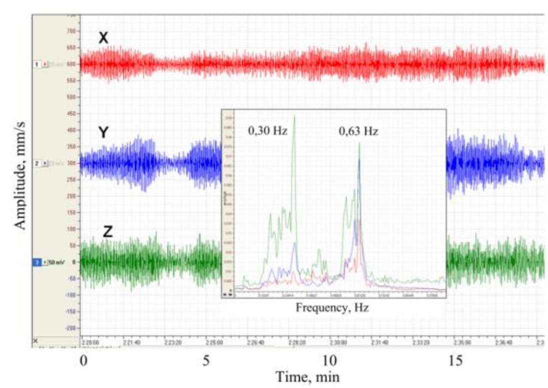

b)

Fig. 2. A record of natural oscillations of the ice field caused by shearings in the ice massive - a). X, Y are horizontal and Z is vertical components. The scale of the vertical component is reduced in 2 times. Amplitude spectrum of the fragment of the oscillations with duration of 17 minutes - b). Kara Sea April 15 2014

This period of observations is characterized by an increase of intensity of oscillations at all components and a periodicity of events with duration to an hour was clearly noted. This period of observations is characterized by increase of oscillations intensity of at all components while a periodicity of events with duration to an hour was clearly noted. There have been oscilatons/waves events with frequencies 0,30, 0,41 и 0,63 Hz. During several hours the ice field was exposed to a periodical dynamical impact. At this time chaotic events changed stable horizontally polarized oscillations.

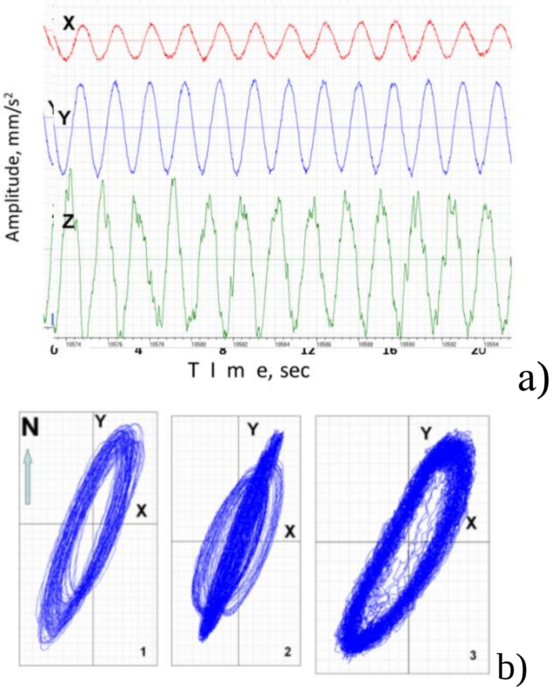

Fig. 3. A record fragment of a self-oscillating process in the ice field - a). Polarization of horizontal components of self-excited oscillations - b) with duration in the range 610-710 sec (1) and 1600-1753 sec (2), 10807-10971 sec (3), frequency 0.63 Hz

The examples of polarization of horizontal components, shown in Figure 3, allow to say that there was a process of transition of chaotic oscillations into a relatively short, ordered and directional movement in certain periods of the drift. This is a classic example of self-excitation of oscillations in a nonlinear system consisting of consolidated blocks of ice of different scale and subject to compression. Thus on April 15 2014 oscillations of ice field were registered as a reaction to ice events (compression, variability of the drift velocity) in the surrounding ice massive. This event was noted on horizontal and vertical components of seismometers during 6 hours. Wave profiles and amplitude spectrum of the ice field oscillations fragments allow to speak about past shearings in the ice massive surrounding the ice station. Observed self-excited oscillations in the ice field can be considered as main signs of compression and ridging of consolidated ice fields.

Registration of parameters of background and dynamical events on June 5 2014 was carried out at ice thickness of about 1 m. The period of observations was 18 min (Fig. 4).

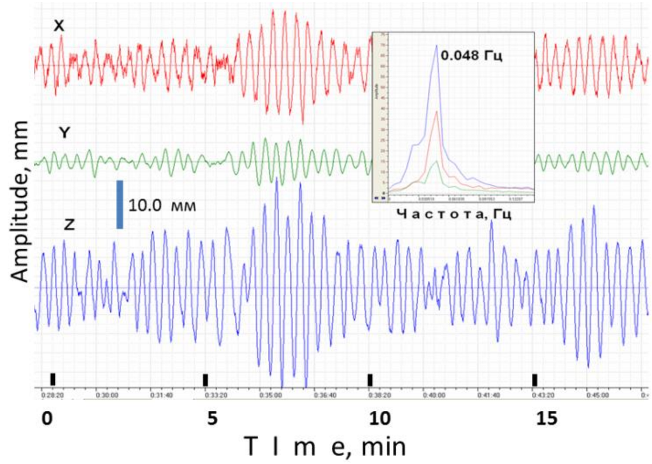

Fig. 4. A record of oscillations and a spectrum of a record fragment of swell waves in the ice

According to Fig. 4 the changeable level of swell waves with periods of 18-20 sec was present in the ice field. A maximum range of oscillations reached 50 mm. Absence of self-excited oscillations means that the ice massive was weakly consolidated and ice compression was not noted. There was registered a dynamics event of the ice field caused only by drift and long-period swell from a storm area.

Formation of cracks and failures in ice fields is accompanied by expansion of a wide spectrum of oscillations and waves. Flexural-gravity waves are one of the main indicators of sea ice dynamics. The horizontal and vertical components of the oscillations of ice can differ significantly, due to the predominant polarization of the waves in the horizontal plane. In the consolidated sea ice cover there are horizontal movements belonging to the class of self-oscillatory processes. Duration and intensity of such movements with friction along the fracture in the ice are caused by elastic-viscous-plastic properties of ice. Periodic pulsations of the ice field can turn into quasi-harmonic self-excited oscillations when a process of stable sliding with friction along the fracture generates almost sinusoidal oscillations. A transition to discontinuous relaxation oscillations depends on relative velocity of displacement of fracture walls. Friction and cohesion forces on boundaries of the fracture in the ice cover are damping mechanisms. Self-oscillating movements in the ice cover are capable to envelop significant areas of the ice.

During ice works on drifting ice on April 18 2014 a wave event with duration about 6 hours was noted. In the beginning there was registered a comparatively calm background with an oscillation period caused by wind influence and formation of vertical oscillations (Fig. 5, scale of the vertical component is reduced in 5 times). In the end of the record there were registered signals during the formation of a main rupture/shear along the formed extended crack in the ice cover. Physical-mechanical processes observed during this event can be considered as unique and important for sea ice failure mechanics research.

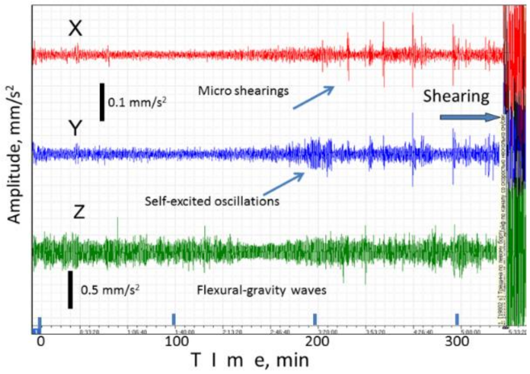

Fig. 5. A record of a natural background of oscillations of the ice field, periodic micro shearings of ice and fracture of the ice field. X, Y are horizontal and Z is vertical components

Fig. 6 represents a record of the event described in the Fig. 5 with oscillations spectrum and elliptical horizontal polarization of oscillations in the ice field for 2 hours before the fracture. Duration of the analyzed fragment is 3 min. In the insert the polarization of self-excited oscillations in the horizontal plane is shown.

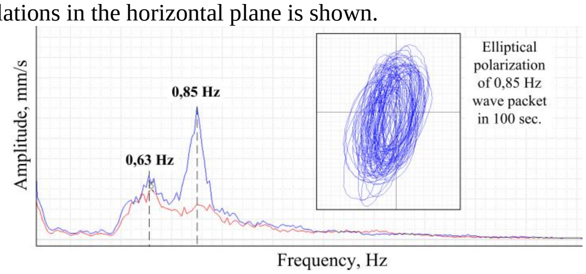

Fig. 6 Amplitude spectrum of the process described in the Fig. 5 and elliptical horizontal polarization of oscillations in the ice field 2 hours before the fracture.

Maximum acceleration in the event of April 18 2014 reached 25 mm/s2 (Fig. 7 and Fig. 8). After the main displacement periodical oscillations were registered.

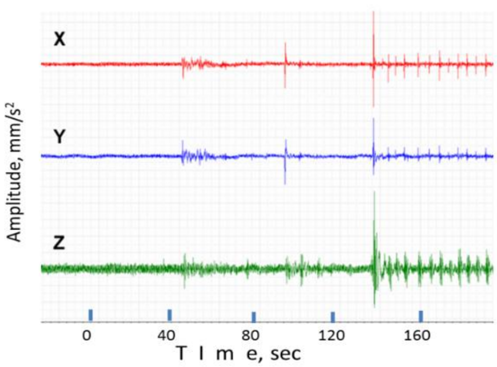

Fig. 7 A record of ice acceleration pulsations during the ice field fracture

A typical record of cyclic shearings appearance in the ice along the crack after a shear fracture April 18 2014 is shown in the Fig. 8. Pulsations with period of every 2-3 seconds indicate the appearance of a self-excited oscillation process along the extensive crack in the area of the ice works. The process under consideration continued with the simultaneous opening of a crack, which created a threat to the further presence of people on the ice. In view of this, a command was given to evacuate people to the ship. The recorded event of a fracture and periodic ice movements on an expedition on April 18, 2014 provided valuable information for subsequent observations on the Arctic shelf.

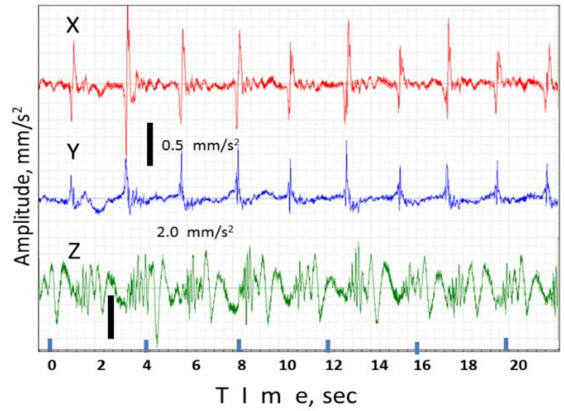

Fig. 8. Appearance of periodical movements on the crack in the ice field after shear fracture.

When monitoring at the ice station on April 21, 2014, a typical level of oscillatory processes was registered on records of a seismometer with duration of 4 hours (Fig. 9). Average ice thickness was 0.4 m. For visual comparison in the Fig. 9 the scale of the vertical component is reduced in 2.5 times, i.e. the vertical component of ice oscillations substantially exceeded the horizontal components. Time of cracks appearance is marked by an arrow. In this example the periodicity of events with duration from minutes to half of an hour was noted. The range of oscillation periods was 3–40 sec. Appearance of the crack in ice field was the main event. Two hours before this event, a slight increase in horizontal displacements in component Y was noted on the records of instruments on ice.

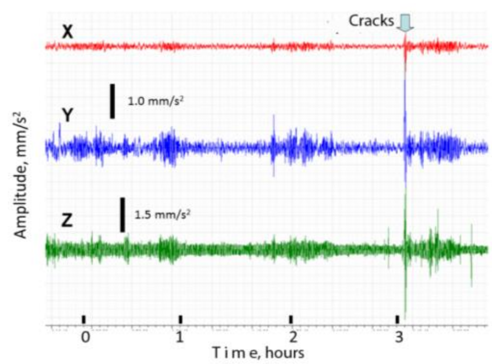

Fig. 9. A record of natural ice field fluctuations

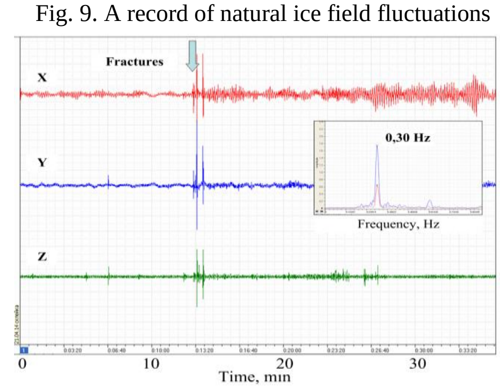

Fig. 10. The record of ice pulsations and spectrum of vibrations after cracks formation at the ice station on April 21, 2014

CONCLUSION

The dynamics of sea ice is considered as a sum of factors leading to significant short-time accelerations during its drift. The dynamic processes include the movements during the compression and ridging of the ice, the occurrence and development of extensive cracks, accompanied by wave and oscillatory events in the range of periods of wind waves and swell.

In the unique data of the event of April 18, 2014, it was revealed that 2 hours before the break of the ice field, on which ice research works were carried out, mechanical impulses appeared, considered as signs of the origin and development of the main crack and subsequent formation of a dangerous ice phenomenon.

During the dynamical event at April 21 2014 a crack formation in the ice field was noted both instrumentally and visually. Before this event there were noted the increase of horizontal displacements along the horizontal component in the records of devices on ice. All three components of the seismometer registered elastic displacements in the ice that can be characterized as longitudinal waves with frequency of acoustics range.

Almost all ice stations on expeditions in Kara and the Laptev Sea recorded self-oscillatory processes reflecting the processes of compression and ridging. The duration of self-oscillation processes reached tens of minutes, while the low-frequency horizontally polarized components persistently remained in the oscillation spectrum. The phenomena of cyclic horizontal displacements of ice, belonging to the class of self-oscillatory processes, develop over a considerable ice space. The large-scale mechanics of the considered events allows to say that before the ice fracture there are wave processes which can be considered as harbingers of ice compression, signs of main crack formation and further shear movement.

Analysis of the results of field studies of the compression, ridging and breaking of sea ice fields according to data of expeditions in the Kara and the Laptev Sea allows to solve one of the difficult problems of polar oceanology and ice engineering: developing an operational method for forecasting the breaking of sea ice fields in real time. For this purpose, the measuring equipment is being improved, special software is being created, which allows automatic notification of extreme parameters in ice and possible destruction of sea ice cover.

Fig. 11 shows one of a schemes of data processing during the monitoring process.

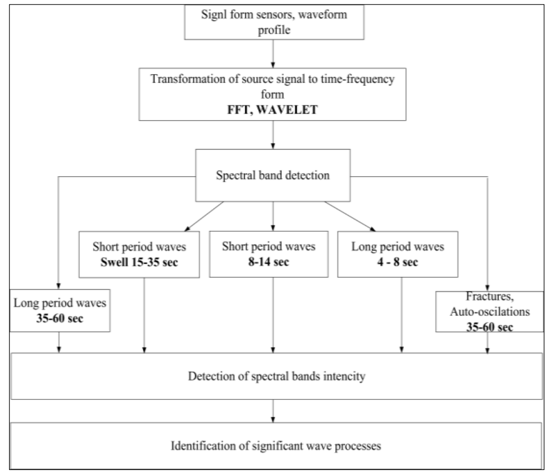

Fig. 11. Identification of sea-ice dynamics elements for monitoring and forecasting

The considered methodology can be used in solving scientific and applied problems of polar oceanology, as well as engineering problems of the Arctic shelf.

REFERENCES

Legenkov A. P. (1998). Podvizhki i prilivnye deformatsii dreifuyushchego l'da. (Shearings and tidal deformations of drifting ice). L. Gidrometeoizdat.p.104.

Palmer, A. C, Croasdale, K. (2012). Arctic Offshore Engineering. World Scientific, London, 357 p.

Sheykin I. B., Smirnov V. N., Kovalev S. M. (2008). An estimation of possibilities of satellite navigational measurements for study kinematics and dynamics of sea ice (using data of Russian drifting stations "North Pole"). Problems of Arctic and Antarctic, 2008, №2 (79), pp.31-43.

Smirnov V. N., Kovalyov S. M., Borodkin V. A., Nubom A. A., Shushlebin A. I. (2017). Instrumental'nyi monitoring i kratkospochnyi prognoz yavlenii szhatiya i torosheniya. (Instrumental monitoring and short-term forecast of events of compression and ridging) S-Pb. AARI, p. 174