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PROSPECTS OF OBTAINING SAMPLES OF BOTTOM SEDIMENTS FROM SUBGLACIAL LAKE VOSTOK

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The paper proves the timeliness of obtaining and examining bottom sediments from subglacial Lake Vostok. Predictive geological section of Lake Vostok and information value of bottom sediments have been examined. Severe requirements towards environmental security of lake examinations and sampling of bottom sediments rule out the use of conventional drilling technologies, as they would pollute the lake with injection liquid from the borehole. In order to carry out sampling of bottom sediments from the subglacial lake, it is proposed to use a dynamically balanced tool string, which enables rotary drilling without any external support on borehole walls to transmit counter torque. A theoretical analysis has been carried out to assess the operation of the tool string, which is a two-mass oscillatory electromechanical system of reciprocating and rotating motion (RRM) with two degrees of freedom.

Key words: Antarctica, drilling, borehole, subglacial lake, bottom sediments samples, core, ice, geological section

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Introduction. Deep ice drilling at «Vostok» station in the Antarctica, which has been carried out by Russian scientists since 1970, has had a primary goal of exploring structural and physical properties of Antarctic ice cover, as well as paleoclimate, basing on the results of ice core examination. Until 1993, mainly thermal-drilling string tools were used, development and application of which have been marked with significant achievements of our researchers [4, 5, 7]. The second important goal of drilling was to obtain core samples of subglacial rocks, which dictated a transition to mechanical drilling.

The final objective of drilling changed, when the Lake Vostok had been discovered [10], and the borehole had to penetrate its waters. This fact and significant changes in physical and mechanical properties of ice at depths over 3,000 m required serious modifications of the technology and the work plan [3, 15, 19].

Drilling of a deep ice borehole 5G at «Vostok» station allowed to obtain valuable information about climate changes and air composition in the course of the latest 420,000 years [13]. In 2012 the borehole reached the surface of the lake [9]. This technical achievement has claimed wide recognition in Russia and abroad; however, results associated with investigations of lake water (sampled after its freezing in the borehole) have no serious scientific significance so far. In January 2015 the lake was successfully penetrated for the second time, and this confirms reliability of the developed technology and assessment of pressure-temperature conditions on the contact between the glacier and the lake water.

Important discoveries can hardly be expected even after lake exploration through existing borehole, using special underwater equipment (sonde), as many parameters of the water layer have already been assessed through investigations of congelation ice (ice, forming at the bottom from the lake water) and water, frozen in the borehole after lake penetration. Seismic tests in the proximity of Lake Vostok show that lake depression is filled with stratified loose sediments, and that is why much more valuable information can be obtained from sampling bottom sediments of the lake, that contain a priceless archive of natural data.

Recently USA, Great Britain and China have developed projects of drilling and sampling of placer bedrocks in the Central Antarctica and intend to implement those in the next 5 years. Among these projects only one (Great Britain, Ellsworth Lake Drilling [17]) is aimed at sampling bottom sediments (no deeper than 10 cm) of the subglacial lake in the West Antarctica, all the others (USA, Rapid Access Ice Drilling Project and China, Gamburtsev Drilling Project) stated their intention to examine ancient underlying formations of the East Antarctica. Field work has only been started by

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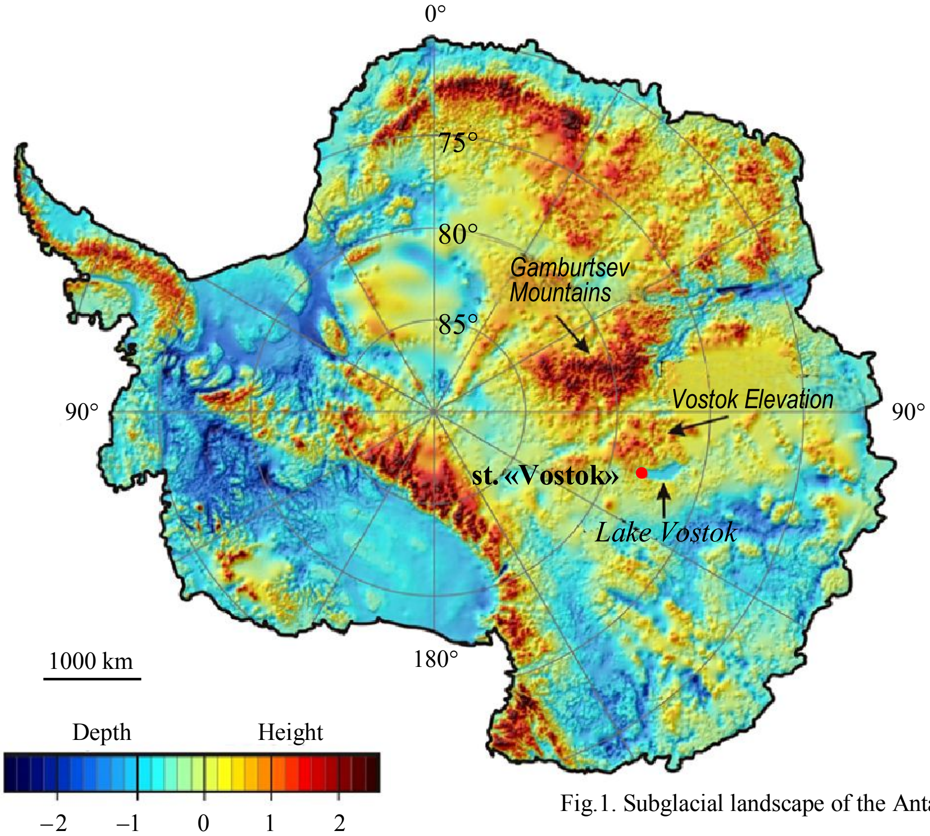

Fig.1. Subglacial landscape of the Antarctica [12]

Great Britain, but suspended at the earliest stage due to technical problems. Necessity to continue drilling in the Antarctica to solve geological tasks has been mentioned in the Strategy for the development of the Russian Federation activities in the Antarctica for the period until 2020 and longer-term, as approved by Government executive order on 30 October 2010 № 1926-r. In the Strategy it is stated that «conventional geophysical methods of sediment cover investigation can be complemented by more efficient methods of stratigraphic drilling...». Taking into account the experience of our operations and existing infrastructure of Russian Antarctic Expedition (RAE), the most reasonable and efficient option will be to use the borehole 5G, drilled at «Vostok» station, to explore subglacial Lake Vostok. Not only will this allow to obtain absolutely unique information in various scientific fields, but it will also substantially raise Russia's standing in Antarctic research. Severe requirements towards environmental security of lake exploration and sampling of bottom sediments rule out the use of conventional drilling technologies, as they would pollute the lake with injection liquid from the borehole. In this context it becomes necessary to develop sampling equipment in line with the fundamental concept of research technology on subglacial Lake Vostok [19].

Subglacial Lake Vostok. The lake is located below a thick (3,700-4,000 m) ice cover of Antarctica at a significant distance (more than 1,000 km) from its shores, within the tectonically stable platform of the East Antarctica [14] (Fig.1). It takes up a vast depression of continental bedrock approximately 300 km long and 40-80 km wide. According to seismic data, average depth of the lake amounts to 1,000 m below sea level and 1,200-1,500 m compared to its shores [9].

After completing geophysical tests in the proximity of Lake Vostok, an assumption has been made that the accommodating depression is a link in a huge Post Paleozoic-Early Mesozoic rift system, stretching from the shore of Cooperation Sea along the foothills of Gamburtsev Mountains to the high-latitude region of Central Antarctica [1, 16].

Seismic tests, carried out in the southern part of Lake Vostok, show that the layer of sediments is quite thin – dozens, maybe first hundred of meters, with underlying rocks of crystalline basement [6, 12]. This indicates low rate and (or) considerably short period of sedimentation and contradicts the hypothesis for ancient formation of lake depression, because in the latter case it would have been filled with terrigenous sediments of considerable thickness (kilometers).

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Borehole core examinations have revealed that at the bottom of glacial mass of atmospheric origin, at the depth of 1,538 m, lies a 230 m thick layer of ice, formed as a result of lake water freezing over the foot of a slowly moving glacier. The upper part of this layer at the depth from 3,538 to 3,608 m is filled with mineral unevenly distributed (from 2-3 to 25 in 1 m of the core) inclusions 1-2 mm in size (sometimes up to 1cm). It is suggested that they have been trapped in the process of ice congelation, when the glacier was crossing a shallow litoral area of the Lake Vostok to the north-west from the borehole, and capture the composition of its bottom sediments [12]. After the congelation stabilized around 14 million years ago, the ice sheet of Central Antarctica was characterized by cold «dry» bedrock; glacial erosion in Central Antarctica was very insignificant or altogether absent [18]. Glacial sediments (i.e. sediments formed as a result of glacial transfer) could have accumulated in Middle Pliocene (around 3.3-3.0 million years) and Late Miocene (10.5-8.5 and 6.4-5.9 million years) periods of climate warming, when conditions at the foot of the glacial mass were changing, which contributed to primary rock exaration, displacement of fragmentary material and its sedimentation in the waters of Lake Vostok. Sedimentation rates were still very low and probably did not exceed several millimeters-first centimeters in a million years. The major part of the lake's sedimentary cover must have formed in the period of Antarctic congelation, together with the dynamic ice cover, which existed 14 million years ago. During periods of glacial maximums there was no sedimentation in the Lake Vostok, or it was negligible; thus the Oligocene-Middle Miocene section is represented by interchanging layers, mostly corresponding to warming cycles and maximal reduction of the ice cover. A definite, but probably very insignificant contribution to sedimentary mass accumulation of Lake Vostok has been made by chemogenic processes and formation of authigenic minerals. Inclusions, examined in congelated ice cores, were reported to contain small crystals of sulphides (pyrite, molybdenite, sphalerite), formed in the process of hydrothermal activity, and carbonates (aragonite, calcite), crystallizing in fresh water sufficiently saturated with Ca_2 and CO_3 ions, i.e. presumably weakly alkaline [6]. Existence of carbonates has a crucial significance, as their presence permits to date the sediments lacking any flora or fauna remnants.

Maximal age of the sedimentary mass corresponds to the formation time of Lake Vostok depression, which appeared either at the beginning or in the process of Antarctic congelation, and it should be taken into account when reviewing circumstances of sedimentation and state of natural environment. If the depression has a tectonic origin, then its development was accompanied by an increased heat flow, especially at an early stage. It had a significant impact on basal temperatures, production of melt water and glacier dynamics, creating increasingly favorable conditions for bedrock exaration and intensifying sedimentation processes in the developing depression of Lake Vostok [14]. Later, as the main tectonic phase was over, an active endogenous regime could have been maintained by regular isostatic motions of the Earth crust. Fig.2 presents a predictive geological section of the southern part of Lake Vostok and available data on global climate changes and warming periods (deglaciations) in Late Cenozoic, which are believed to correspond to impulses of fragmentary materials entering Lake Vostok.

Lake Vostok sediments contain unique information about geology, natural environment and climate changes of Central Antarctica. Vision of geology of this region is based primarily on geophysical data and extrapolation of observations from uncovered regions into subglacial areas. Climate and paleo-geographical conditions of the past are investigated using results of ocean drilling and mathematical modeling. Sampling of the lake bottom is an opportunity to obtain exclusive scientific material that can add substantially to our knowledge in a variety of research fields. Sampling even the upper (first centimeters) layer of bottom sediments will have an immense scientific value. As already mentioned, this layer can be composed of a fine-grained (clay-aleurolithic) fraction, and investigation of clay materials will allow to identify conditions of their occurrence and circumstances of sedimentation in Lake Vostok. Apart from that, additional information may be obtained which would confirm the presence of hydrothermal activity, currently being

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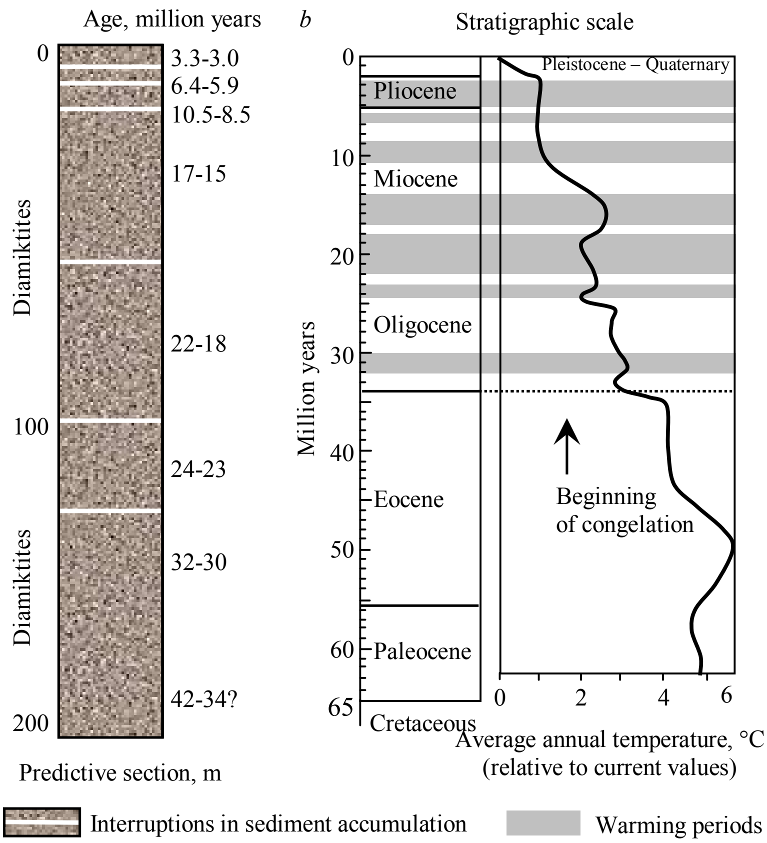

Fig. 2. Predictive geological section of sedimentary cover of the southern part of Lake Vostok (*a*) and global climate changes (*b*) [11]

only a hypothesis based on indirect evidence (isolated discovery of thermophile bacteria genes, ratio of oxygen isotope in congelation ice, overall mineralization of the lake water).

Examination of mineral grain morphology (primarily, quartz – the most common mineral in the inclusions) will help to define the character of terrigenous mineral transfer, influence of subglacial stream flow and duration of the transfer. Examination of rock fragments will provide direct information about the composition of bedrocks on the western shore of Lake Vostok, where the ablation of terrigenous material started from. Examination of isotope-geochemical characteristics and age of detrital uranium-bearing minerals will expand current notion of source area composition, considered to be located in subglacial Gamburtsev Mountains in the Central Antarctica. Sampling of the first several or dozens meters will reveal stratification of sedimentary section, caused by the change in sedimentation modes, which in its own turn has to correlate with the fluctuations of ice cover and climate dynamics. Greater amount of sedimentary material will broaden opportunities to reconstruct geological structure of source areas located in the Central Antarctica. Another important research field is a search for microorganisms. Subglacial environment of Central Antarctica and Lake Vostok in particular have been isolated from Earth atmosphere for more than 30 million years and have had no contact to the outside world. Hence, entirely unknown microbiological forms could have developed here and may still be preserved in sedimentary layers.

Technology of sterile sampling of bottom sediments from Lake Vostok. Suggested method of penetrating Lake Vostok [19] implies the use of specific physical characteristics of the system «ice cover – subglacial Lake Vostok». The fundamental fact is that the glacial mass is in a floating state and that the pressure on the contact «ice – water» corresponds to the weight of the ice column (ground pressure). In the process of ice drilling the ground pressure is compensated by hydrostatic pressure of the injection liquid in the borehole. By decreasing the amount of injection liquid, under-compensation of ground pressure can be achieved, i.e. such conditions should be created, so that the pressure of lake water in a given point exceeds the pressure of the injection liquid column. Under these conditions, in the moment of contact between the bottomhole and the lake surface, the injection liquid should be displaced by the lake water up along the borehole at a height of under-compensated ground pressure.

The key requirement towards subglacial lake exploration is environmental safety of operations. The lake water must not get contaminated with modern microorganisms or dangerous substances (kerosene and freon). Equipment, lowered down into the lake water, should not have any contact with the injection liquid in the borehole in the process of its delivery to the surface of the lake.

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Fig.3 contains a layout chart of hauling assembly in the borehole in its working position near the surface of the lake. In order to meet the imposed requirements, equipment will be transported to the lake surface in a sealed container, with the pressure inside equal to atmospheric pressure on the surface. The module must be locked in an isolated compartment of the hauling assembly, which along with the measurement module has to be treated on the surface to rule out any contamination of the lake.

As it reaches the working area, the hauling assembly stops 1-2 m from the lake surface, and the measurement module is lowered down on a thin cord, coiled around the cathead of a small-size winch, located in the upper part of a sealed compartment.

The only reliable way to prevent the liquid column from freezing and the borehole from narrowing is to heat the whole water column with a small coverage (1 m) of the boundary «injection liquid – water». This can be achieved by locating heating elements all along the assembly, so that they maintain required temperature in the working area throughout the entire experiment.

To obtain the samples of bottom sediments, the research module will be substituted with a sampling unit. Two modes of operation are available for research or sampling units: self-driven and controlled from the surface.

A self-driven mode will be applied in case of using a thin cord (a string), 1 mm in diameter, to suspend the module lowered down into the lake, for in this case there will be no communication between the research module and the daylight surface. All the operations will be carried out in the automatic mode, and the electricity will be supplied from electrical batteries.

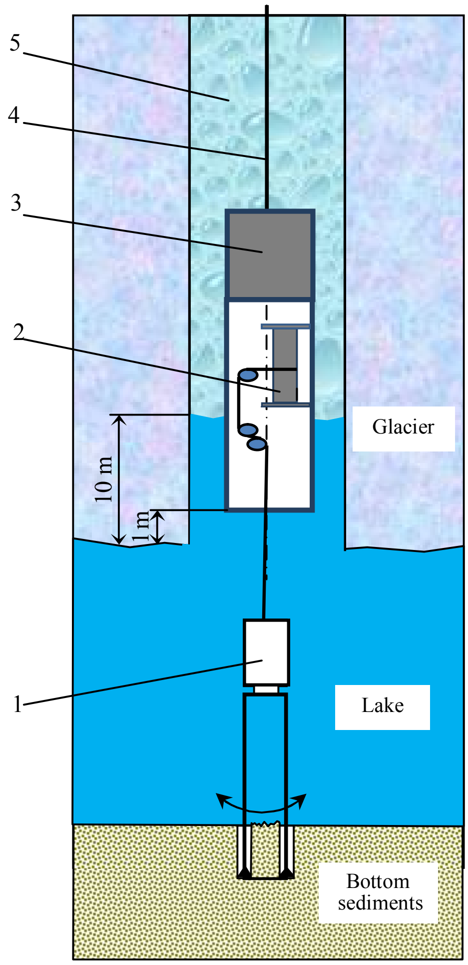

Fig.3. Operation scheme of dynamically balanced tool string in the process of sampling bottom sediments of the glacial lake
1 – tool string; 2 – winch;
3 – hauling assembly; 4 – carrying cable;
5 – injection fluid

In case of using a carrying cable to connect the module to the hauling assembly, there is an opportunity to control the former from the surface, but this will drastically increase the size of the winch drum of the hauling system. For a carrying cable 3-4 mm in diameter the length of the winch drum has to be increased by factor of 10, which poses an almost insurmountable obstacle to creating such mechanism. Development of a carrying cable 2 mm in diameter would make this task manageable.

Different options of technical instruments are reviewed for bottom sediment sampling: bailers, dynamically balanced tool string (DBTS) [2], automatic underwater drilling device, setting the casing between the ice borehole and lake bottom in order to carry out core head drilling on a carrying cable.

Dynamically balanced tool string. The use of DBTS enables rotary drilling without any external support on borehole walls to transmit counter torque. This tool string allows to obtain a core sample, the length of which equals the length of its core barrel, but recurrent penetration of this borehole will be as difficult as when using bailers.

The tool string itself is a two-mass oscillatory electromechanical system of reciprocating and rotating motion (RRM) with two degrees of freedom (Fig.4). The stator part 7 of submersible oil-flooded electrical motor is connected to the rotor part (1, 2, 4) with an elastic element 5 (torsion springs in parallel). A distinction of this tool string from all the other available options is the absence of anchor system, transmitting the counter torque as the drill bit operates in the bottomhole, which simplifies the design and guarantees reliable performance of the tool string in the process of drilling bottom sediments.

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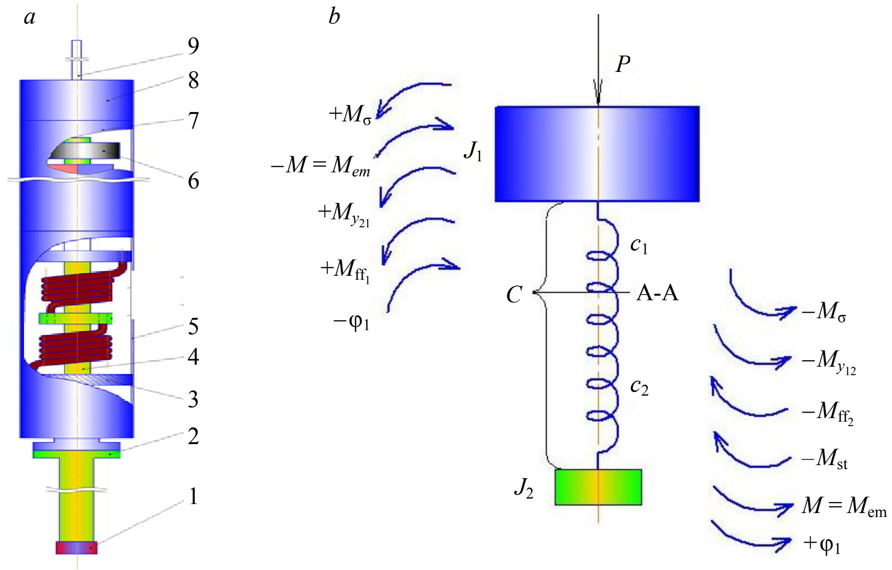

Fig.4. Structural (*a*) and computational (*b*) schemes of a dynamically balanced tool string

1 – drill bit; 2 – core barrel; 3 – motor body; 4 –rotor shaft of the motor; 5 – elastic element (torsion spring); 6 – non-contact sensor of RRM speed; 7 – stator of the electrical motor; 8 – cable lock; 9 – carrying cable

Fig.4, *b* represents a computational scheme of DBTS, where the stator part with rotational inertia J_1 under the influence of electromagnetic moment of the motor M_{em} turns through an angle φ_1 in a fixed coordinate system. The rotor part with rotational inertia J_2 under the influence of the same electromagnetic moment M_{em} rotates trough an angle φ_2 in the opposite direction. Reciprocating and rotating motion of the stator relative to the rotor part occurs in a fixed junctional section A-A of the elastic element, whose location depends on the correlation between rotational inertia and loads on stator and rotor parts of DBTS.

On the part of elastic element, represented by a torsion spring with stiffness *c*, stator J_1 and rotor J_2 parts experience the influence of elastic moments $M_{y_{12}} = M_{y_{21}}$, defined by the swirl angle of the torsion spring and stiffness coefficient. On the parts of the drill bit and core barrel, rotor part with rotational inertia J_2 and stator part with rotational inertia J_1 experience the influence of resistance moment M_r in the form of additive composition of viscous and dry frictions, as well as a random component of the load moment M_{σ}.

In case of operation at resonant frequency of the electromechanical system, oscillation amplitudes reach their maximum values, and the sum of rotation moments, acting on these parts, equals zero, i.e. the tool string is dynamically balanced.

To develop a mathematical model of the system, it is reasonable to use Lagrange equations of the second kind, where rotation angles of stator φ_1 and rotor φ_2 parts are selected as generalized coordinates,

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} + \frac{\partial \Pi}{\partial q_i} = Q_i, \qquad (1)$$

$$q_1 = \varphi_1;\ q_2 = \varphi_2,$$

where T – kinetic energy of the system; П – potential energy of the system; D – dissipative function of the system; Q_i – generalized forces.

Kinetic energy of the system:

$$T = \frac{1}{2} J_1 \varphi_1^2 + \frac{1}{2} J_2 \varphi_2^2. \qquad (2)$$

Potential energy of the system:

$$P=\frac{1}{2}c(\varphi_1-\varphi_2)^2=\frac{1}{2}c\varphi_1^2-c\varphi_1\varphi_2+\frac{1}{2}c\varphi_2^3. \tag{3}$$

Dissipative energy of the system:

$$D=\frac{1}{2}\mu_1\varphi_1^2+\frac{1}{2}\mu_2\varphi_2^2. \tag{4}$$

Taking into account distinctions of the system – equal and oppositely directed moments M, acting on rotor and stator parts of the oscillatory electromechanical system with resonant frequency $\omega_p \approx \omega_0$, the presence of junctional section O-O$_1$, where $\varphi = 0$, can be expressed as follows:

$$\omega_0^2=\frac{c_1}{J_1}=\frac{c_2}{J_2}. \tag{5}$$

Due to the fact that torsion springs with stiffness c_1 and c_2 are parts of a single spring and are connected in series, the stiffness of this single spring is defined by an expression:

$$\frac{1}{c}=\frac{1}{c_1}=\frac{1}{c_2}, \tag{6}$$

from which

$$c=\frac{c_1c_2}{c_1+c_2}. \tag{7}$$

Taking into account expression (5)

$$c=\omega_0^2\frac{J_1J_2}{J_1+J_2}=\omega_0^2J_\Sigma, \tag{8}$$

where

$$J_\Sigma=\frac{J_1J_2}{J_1+J_2}.$$

Then

$$\omega_0^2=\frac{c_1}{J_1}=\frac{c_2}{J_2}=\frac{c}{J_\Sigma}. \tag{9}$$

For coordinate φ_1:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial\varphi_1}\right)=J_1\ddot{\varphi}_1;\quad \frac{\partial D}{\partial\varphi_1}=\mu_1\dot{\varphi}_1;\quad \frac{\partial P}{\partial\varphi_1}=c\varphi_1=c\varphi_2=c(\varphi_1-\varphi_2);\quad \frac{\partial T}{\partial\varphi_1}=0. \tag{10}$$

For coordinate φ_2:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial\varphi_1}\right)=J_2\ddot{\varphi}_2;\quad \frac{\partial D}{\partial\varphi_2}=\mu_2\dot{\varphi}_2;\quad \frac{\partial P}{\partial\varphi_2}=-c\varphi_1+c\varphi_2;\quad \frac{\partial T}{\partial\varphi_1}=0. \tag{11}$$

Equations of DBTS motion:

$$\begin{cases} J_1\ddot{\varphi}_1+\mu_1\dot{\varphi}_1+c\varphi_1-c\varphi_2=M, \\ J_2\ddot{\varphi}_2+\mu_2\dot{\varphi}_2+c\varphi_2-c\varphi_2=-M, \end{cases} \tag{12}$$

where $M = A\cos\omega_0 t$.

Writing (12) in the standard form:

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$$\begin{cases} \ddot{\varphi}_1 + \dfrac{\mu_1}{J_1}\dot{\varphi}_1 + \dfrac{c}{J_1}\varphi_1 - \dfrac{c}{J_1}\varphi_2 = \dfrac{M}{J_1}; \\ \ddot{\varphi}_2 + \dfrac{\mu_2}{J_2}\dot{\varphi}_2 + \dfrac{c}{J_2}\varphi_2 - \dfrac{c}{J_2}\varphi_1 = \dfrac{M}{J_2}. \end{cases} \tag{13}$$

Let us set

$$\eta_1 = \frac{\mu_1}{J_1}; \quad \eta_2 = \frac{\mu_2}{J_2}; \quad M_1 = \frac{M}{J_1}; \quad M_2 = \frac{M}{J_2}; \quad k_1 = \omega_0^2\frac{J_1}{J_1+J_2}; \quad k_2 = \omega_0^2\frac{J_2}{J_1+J_2}.$$

Then equation (13) takes on form:

$$\begin{cases} \ddot{\varphi}_1 + \eta_1\dot{\varphi}_1 + k_2\varphi_1 - k_2\varphi_2 = M_1; \\ \ddot{\varphi}_2 + \eta_2\dot{\varphi}_2 + k_1\varphi_2 - k_1\varphi_1 = M_2. \end{cases} \tag{14}$$

Equation (14) allows to analyze normal mode (the load is concentrated on the drill bit, the share on the stator part does not exceed 5-10 %), as well as abnormal and emergency modes of DBTS operation, and to examine symmetrical operation regimes.

Obtained system has one resonant frequency ω_0 and two partial frequencies λ_1 and λ_2 of oscillatory systems with one degree of freedom, composing the initial system, with:

$$\lambda_1 < \lambda_2 < \omega_0. \tag{15}$$

In case of jamming of stator or rotor parts of DBTS, the resonant frequency of electromechanical system becomes equal to the partial frequency λ_1 or λ_2 respectively. Partial frequency λ_2 in case of jamming of the stator DBTS part ($J_1 \to \infty$):

$$\lambda_2 = \frac{1}{2\pi}\sqrt{\frac{c}{J_2}}. \tag{16}$$

Theoretical angle of the drill bit oscillation amplitude relative to fixed axes is defined by the expression:

$$\varphi_o = \varphi_r \frac{J_1}{J_1+J_2},$$

where φ_r = 180 – theoretically acceptable rotation angle of the rotor (oscillation amplitude) relative to the stator, deg.

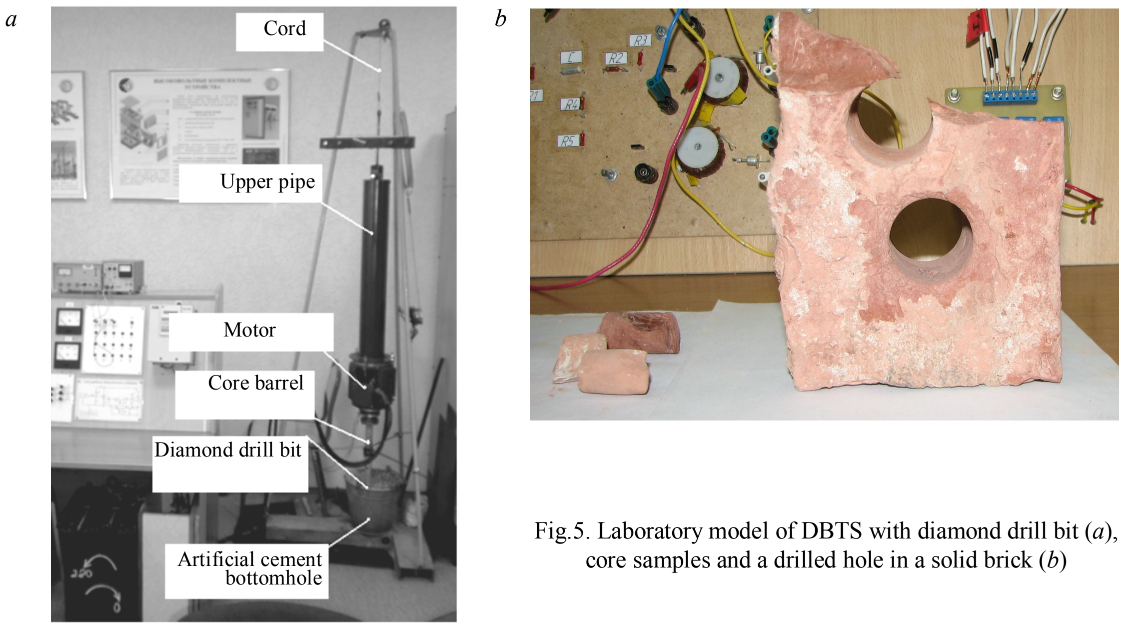

Fig.5. Laboratory model of DBTS with diamond drill bit (*a*), core samples and a drilled hole in a solid brick (*b*)

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Modes of autoresonant oscillations of RRM motor drive have to be insensitive to changes of dynamic parameters (stiffness coefficient of the elastic element *c*, rotational inertia *J*), to the value and character of the load.

Laboratory examinations of symmetrical and asymmetrical modes on imitation and physical models of DBTS motor drive (Fig.5) have confirmed stability of resonance oscillations with a combined load and their wide-range invariance towards changes of dynamic parameters.

Conclusions. Bottom sampling of Lake Vostok is an opportunity to obtain exclusive scientific material, which will add substantially to our knowledge in a variety of research fields. Sampling even the upper (first centimeters) layer of bottom sediments will have an immense scientific value. Investigation of bottom sediment samples from subglacial Lake Vostok will allow to get data, specifying the assumption that the depression, accommodating the lake, is a link in a huge Post Paleozoic-Early Mesozoic rift system, stretching from the shore of Cooperation Sea along the foothills of Gamburtsev Mountains to the high-latitude region of Central Antarctica.

From the viewpoint of continuing examination of subglacial Lake Vostok, the most reasonable option is to use an already drilled borehole 5G, where research on technologies of penetration and maintenance of the borehole in working order takes place.

Operations on creating technical instruments for sampling of bottom sediments are currently at initial stage; however, analysis of different technical solutions, varying in their complexity, allows to express certainty in manageability of this project.

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