Icebergs Towing Experiments in the Barents and Kara seas in 2016-2017

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ABSTRACT

This paper presents field results and analysis of iceberg towing experiments performed in the Barents and Kara seas in 2016-2017.
The influence of oscillations during the towing process is demonstrated. For a wide range of towing speeds, iceberg-water resistance coefficients (drag force coefficient) are determined for icebergs of various sizes and shapes. Simplified formulas for determining the iceberg towing force are proposed for stationary mode. Formulas for calculating parameters of long-period oscillations are also derived. Possibility of iceberg destruction by vessel's circulation shown in warm water is shown.
The results can be used both for planning and performing ice management operations by deflecting icebergs from offshore oil and gas facilities, as well as for long distance iceberg towing evaluations.

KEY WORDS: Iceberg; towing; defense; water; Artic; Kara; Barents; drag; force.

INTRODUCTION

Possibility to change iceberg's drift trajectory in order to prevent its' collision with offshore oil and gas facilities is an important factor for ensuring safe and economical developments in polar offshore regions. This approach is well known and has been used for several decades by oil companies in areas of Newfoundland and Labrador Peninsula (Randell et all. 2009). Timely detection (Pavlov et.al. 2018) and towing of such giant and unsymmetrical objects as icebergs is associated with a number specific features, correct determination of which requires field tests and proper analysis.

In order to test the technology of iceberg security for Russian Arctic conditions Rosneft Oil Company (Moscow, Russia) together with Arctic and Antarctic Research Institute (AARII, St. Petersburg, Russia) with participation of Arctic Research Center (Moscow, Russia) performed field iceberg experiments with various technical means in autumn periods of 2016-2017. Experiments were carried out in vicinity of archipelagoes Novaya Zemlya, Severnaya Zemlya, Franz Josef Land (FJL) with diesel icebreakers "Captain Dranitsyn" (expedition "Kara-Summer-2016", 10.09-10.10.2016) and "Novorossiysk" (expedition "Kara-Summer-2017", 09.09-19.10.2017) equipped with all necessary deck equipment (Fig. 1).

It should be noted that some limited efforts on iceberg towing in Russian arctic were made by AARII in 2004-2005 (Stepanov et al., 2005 a,b) while 2016-2017 experiments discussed in this paper were more complex and successful.

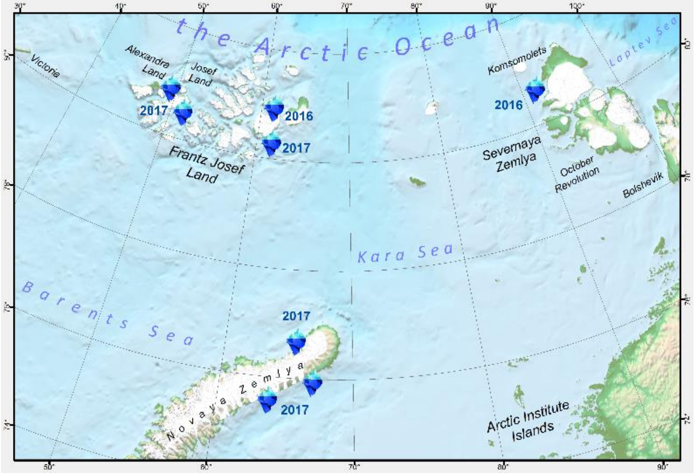

Fig. 1. Iceberg towing areas in 2016-2017

The paper consists of three sections and conclusion:
Field experiments of iceberg towing
Section describes performed experiments, describes characteristics of the towing system, indicates parameters recorded during experiments, as well as the operations sequence during field trials.
Analysis of empirical data
The section describes assumptions taken, processing algorithm and observed oscillations during towing.
Drag force coefficients determination for icebergs of various forms
Section defines the dependence of icebergs' towing drag coefficient on

speed and linear dimensions, and proposes simplified formulas for calculating required tow force on iceberg's speed.

FIELD TRIALS OF ICEBERG TOWING

Areas of experiments were chosen based on satellite information. Satellite imagery frames were taken in order to detect possible presence of dangerous ice objects and identify iceberg in planed location of the icebreaker.
In the "Kara-Summer-2016" expedition two areas were selected:

- west coast of Komsomolets island (Severnaya Zemlya archipelago);
- north coast of Vilczyk island (FJL archipelago).

In the "Kara-Summer-2017" expedition:

- Inostrantsev Bay (west coast of the Novaya Zemlya archipelago);
- Roze-Vershinsky glaciers area (east coast of the Novaya Zemlya archipelago);
- Renown glacier area (FJL archipelago);
- The British Channel and the Alexandra island area (FJL archipelago).

During the field trials the following types of physical impact on icebergs of different sizes were implemented in a variety of weather conditions:

- iceberg towing using a floating rope (29 experiments);
- iceberg towing using an ice net (6 experiments);
- directed water jet from vessel's fire hydrant (1 experiment);
- vessel's circulation around iceberg (1 experiment).

Most of the experiments were performed by floating rope towing system, which is the most effective, applicable and flexible method of physical impact on an iceberg.

Two towing systems were used - floating synthetic rope and ice net. The synthetic rope was used for towing relatively big icebergs with largest linear size of over 50 m. The net was used for small icebergs and debris in the size range from 8 to 50 m. In both cases tow load did not exceed the maximum rope loading of 115 tons. Typically the working load varied up to 100 tons, the working range of iceberg towing loads in Canada (Comprehensive…, 2010).

Structural parts of the towing system for both variants of assembly (total number of units, including spare tools is shown in parentheses) were the following:

- polystyrene rope of 80 mm diameter (13 coils of 220 m);
- polyamide rope of 60 mm diameter and 100 m length (1 pc.);
- polystyrene sling with lights at the ends of 80 mm diameter and about 15-20 m length (1 pc.);
- rope of 20 mm diameter for lashing and buoy-line (1 coil of 220 m);
- guide rope of 20 mm diameter and about 70 m length (1 pc.);
- dynamometer with maximum tensile force up to 100 tons (2 pcs.);
- rigging shackles with a workload up to 100 tons (3 pcs.)
- rigging shackles with a workload up to 50 tons (3 pcs.);
- floating anchor of 2000 mm diameter (4 pcs.);
- signal buoys and inflatable buoys-fenders (15 pcs. + 15 pcs.);
- weighting anchors for underwater branch of the ice net up to 5 kg each (50 pcs.).

Illustration of tow line assembled at «Novorossiysk» icebreaker is shown in Figure 2.
Steel cable (2) of the towing winch, threaded through the roller block (3), is fixed to the bollard (4). Polystyrene sling (5) passed through the block connects vessel's towing line with the main towing element (12) - a floating rope or net - through a dynamometer (8). The latter is included in the system with shackles (11) fixed on both its sides.
Floating polystyrene rope was assembled from separated pieces, eye-spliced with each other. Working length of the rope was adjusted by increasing (reducing) additional (redundant) two-hundred-meter coils, depending on the size of towed iceberg. During expedition period, the maximum length of the rope reached 1500 m (7 bays) when towing the largest iceberg of 1.1 million tons.

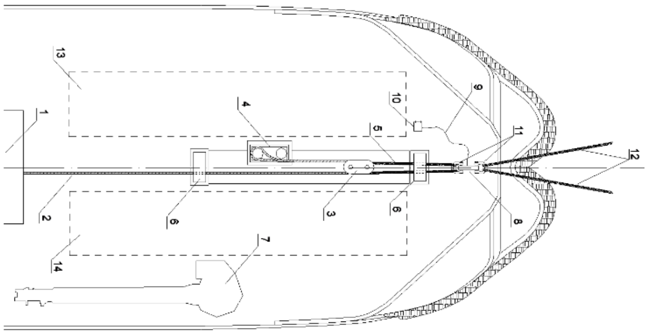

Fig. 2. Towing system designed at «Novorossiysk» icebreaker
1 – towing winch; 2 – towing rope; 3 – roller; 4 – bollards; 5 – polystyrene sling; 6 – hawse; 7 – vessel crane; 8 – dynamometer; 9 – dynamometer cable; 10 – hatch cover in helmstock room; 11 – shackles; 12 – cords of rope (net); 13 – space for net storage; 14 – space for rope storage.

Ice net consisted of three main elements: upper branch, lower branch, buoy-lines. The upper branch of the net was made of polystyrene floating rope, the lower one - of sinking polyamide rope. Both branches along the entire length were connected by buoy-lines in selected intervals, and at the endpoints they were connected with each other with the help of lashings. The floating part was marked with signal buoys to ensure it visibility in waves, and additional weights were fixed to the sinking branch of the net. A polystyrene rope of 200 m long was lined to each side of the net.
The following equipment was installed onboard in order to measure movement parameters of the "ship-iceberg" system during towing process:

- dynamometer;
- six-component inertial sensor in the midship;
- portable GPS device;
- IRIDIUM and ARGOS beacons attached to a floating rope.

In the area of work, each of the iceberg towing experiment started with determination of initial parameters of iceberg's drift with the help of the ice radar. The second step was installation of underwater equipment for measurements of sea currents and waves. The third step was above water (with helicopter or unmanned aerial vehicle) and underwater (from a survey boat) iceberg surveys resulting in 3D model of the object. Several drifting satellite and/or radio buoys were also installed on the iceberg to monitor its drift and rotation. Authors are unhappy to note that for some experiments this preliminary part (most often underwater profiling of iceberg) could not be done due to bad weather conditions.

During iceberg towing experiments meteorological parameters were continuously recorded (air temperature and humidity, atmospheric pressure, wind speed and direction). Iceberg movements were observed and recorded both visually and instrumentally, using RUTTER Sigma ice radar.

Iceberg towing started immediately after described preparatory works and systematizing all information about the iceberg were obtained.
When approaching the iceberg, the free end of the rope was released into the water and held in this location due to the floating sea anchor. After that, the ship circled the iceberg, after which the floating end of rope was retained back onboard and fixed on the deck through the second

dynamometer. The vessel smoothly started movement until the rope tightened resulting in iceberg towing with desired trajectory (Figure 3). During towing operations, tension in the cable ends were monitored using dynamometers.

Fig. 3. Iceberg towing, «Kara-Summer-2016»

Upon completion of towing operations, the iceberg was released in reverse order. One of the cable ends is disconnected from the dynamometer, connected to the floating sea anchor and discharged into the water. With the help of ship devices (spire), the rope was tightened to the deck. Assembled ropes and buoys were loosened on the vessel's deck in such a way as to ensure operational accessibility and safe movement of crew.

Towing was carried out for icebergs of various shapes and sizes in a wide range of environmental conditions:

- maximum mass of the towed iceberg was 1.1 million tons;
- minimum mass of the towed iceberg was 3 thousand tons;
- controlled drift (circulation along a predetermined trajectory) of an iceberg of 90 thousand tons;
- maximum iceberg movement per day was 50 miles.
- maximum force applied - 100 tons (rope maximum loading - 115 tons);
- minimum visibility when maneuvering - 300 meters;
- maximum wind speed when maneuvering - 15 m / s;
- maximum wind speed during towing - 20 m / s;
- several successful tows were performed in gray-white ice with a concentration of 8/10;
- simultaneous towing of several small icebergs.

During «Kara-Summer-2017» expedition, the possibility of breaking iceberg from a vessel moving around it was evaluated. For the experiment a deteriorate iceberg with an estimated mass of 15,000 tons (linear dimensions 30 × 30 × 16 m) was selected.

In the course of the experiment, 9 ship circulations around the drifting iceberg were performed, after that the ship did 4 more circulations around the iceberg with directed water jet from vessel's fire hydrant for almost 25 mins (Figure 4).

Wave disturbance caused by the vessel led to small fragments breaking off after the 4th and 5th circulations, and considerable destruction after the 8th circulation. Cleavage of the iceberg's tip led to it's deviation from initial position, the subsequent oscillation and adoption of a new equilibrium position. The iceberg speed in the period from the beginning of the experiment to the 8th circulation was 0.62 m/s at a course of 68 degrees, after the collapse of the tip of iceberg, the speed reduced to 0,55 m/s at a course of 78 degrees.

This experiment showed existence of a quite significant destructive effect on iceberg by jet monitor steerable thrusters, aimed at the iceberg for a long time in relatively warm waters.

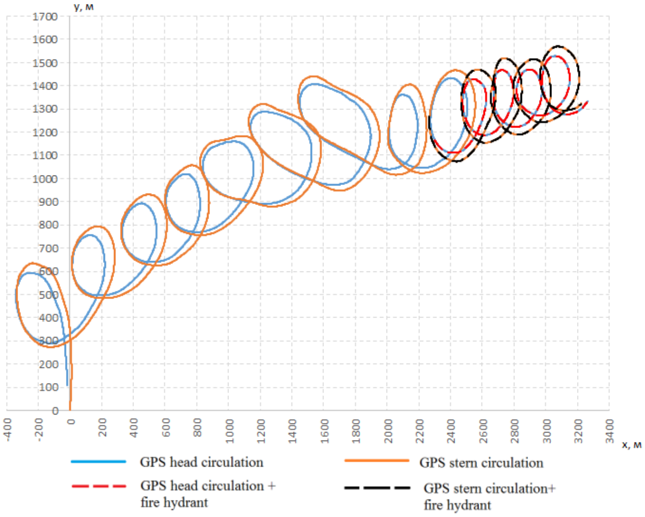

Fig. 4. Vessel trajectory during circulation around the iceberg

ANALYSIS OF EMPIRICAL DATA

Several important observations can be stated from the experimental data gathered during iceberg trials:

1. The "iceberg-attachment point of the rope" distance at a constant modulus of rope/net tension varies slightly, which makes it possible to consider this distance to be constant, depending on the geometry and towing system stiffness;
2. During towing operations, iceberg turns one side to the stern of the vessel. In the 1.1 million tons iceberg tow trial several beacons were installed on the iceberg, transmitting their coordinates in order determine the angular velocity of the iceberg. The angular characteristics of the iceberg's rotation (angular velocity, angular acceleration) coincide with the similar characteristics of the rope rotation in the horizontal plane, which confirms this rule. However there were cases where the iceberg orientation changed during further towing after the rope's strain was relieved;
3. In most of the towing cases the rope does not slip across the iceberg's surface in the horizontal direction. Friction forces between the rope and ice lead to a moment that compensates the hydrodynamic force moment that develops as the iceberg is towed, while the tensions of the rope branches are different.

With the increase in tow force, a "cutting" of the rope into the iceberg is observed, which, on one hand, significantly reduces the possibility of slipping, but on the other hand, can lead to parts of the iceberg calving and development of irreversible dynamic processes. The rope can also slide off the iceberg in the vertical direction when it reaches a certain load, that is relevant first of all for small icebergs, as well as icebergs with a sloping above water surface.

Based on the abovementioned observations, the movement of the "iceberg-rope-attachment point of the rope" system (Fig. 9) can be represented as a plane horizontal motion of a rigid body. According to the velocity addition theorem, the iceberg velocity is the vectorial sum of the stern speed of the vessel and the speed of iceberg rotation relatively to the stern of the vessel; similarly, the iceberg acceleration is the vector sum of the rope anchorage point acceleration and the acceleration of the iceberg rotation around it (taking into account the tangential and normal components).

At the same time, to determine all the kinematic characteristics of the movement, it is necessary to set three parameters —coordinates of the stern of the vessel and the angle in the horizontal plane of the vector between the vessel's stern and the iceberg.

In most cases at the beginning of a tow the towing force vector is not parallel to the initial speed vector of the iceberg. In accordance with the principle of momentum, there are oscillations during towing (Figure 5). These long-period oscillations gradually fade out over time due to water friction, and stationary mode of towing; but with changes of tow force and/or the course of the vessel these oscillations occur again.

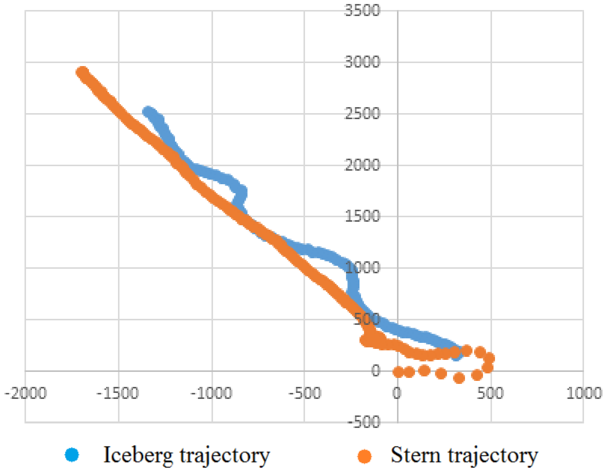

Fig. 5. Trajectories of icebreaker towing 16 thousand tons iceberg (the X, Y axis - meters)

When processing experimental data, authors determined so called towing regimes characterized by:

- constant vessel power;
- constant vessel speed;
- constant tow force;
- minimum iceberg acceleration.

Analysis considered both stationary parts of the iceberg movement, at which its speed was constant in magnitude and direction, as well as zero angular acceleration points when rotating in the horizontal plane of the vector connecting the iceberg center the and the vessel's stern (Figure 6) during unsteady motion.

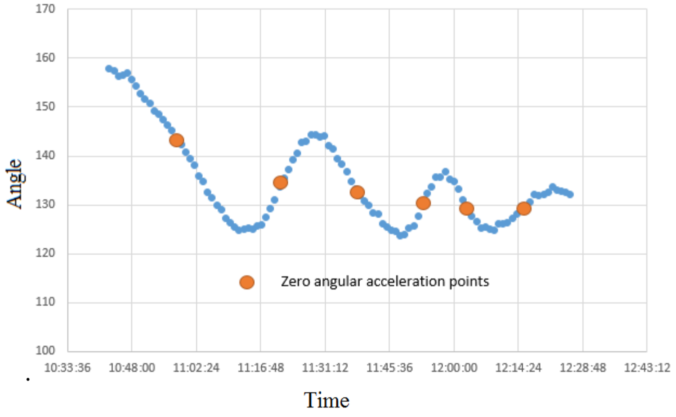

Fig. 6. Vector angle between the center of the iceberg and the stern of the vessel (the Y axis - angle)

To determine the projections of the vessel and instantaneous iceberg speeds, as well as the projections of their acceleration, averaging of not more than 5 minutes was used in each regime, and a series of 15 minutes were used to calculate the angular velocity and angular acceleration of the vector connecting the iceberg center and the vessel's stern in horizontal plane.

For a quantitative assessment of the effect of inertial forces on the movement of icebergs, for each mode, the dynamics were calculated as the ratio of the product of iceberg mass to its acceleration to the rope tension force. For the subsequent analysis, we used modes with a dynamism of no more than 0.05 (in exceptional cases no more than 0.1), which allowed us to neglect the influence of inertial forces in the calculations of the dependence of the drag force of an iceberg on its velocity relative to water. For each mode, the Coriolis force was also calculated, which was taken into account for the drag force determination.

When towing icebergs weighing up to 300 thousand tons, the cosine of the angle between direction of the iceberg-water velocity and the drag force did not exceed 0.9, which made it possible not to separate the drag force (acting parallel to the iceberg speed) and lift force (acting perpendicular to the iceberg speed) upon further analysis , and only use drag force

For each regime the following parameters were determined:

- Iceberg velocity projections (averaging - 5 minutes);
- Projections of vessel's speed;
- Iceberg acceleration projections;
- Projections of vessel acceleration;
- angular velocity and angular acceleration of the vector between the center of the iceberg and the stern of the vessel;
- sea current velocity projections;
- relative iceberg's speed projections;
- drag force projections;
- drag force determining error;
- dynamism mode;
- wind condition on the regime.

DETERMINATION OF THE DRAG FORCE COEFFICIENTS FOR ICEBERGS OF VARIOUS FORMS

To calculate the drag forces, the classical ratio of hydrodynamics is used, in which the sectional area of an iceberg is substituted by the square of its length. This substitution is associated with practical difficulties in determining the iceberg cross-sectional area, while for geometrically similar icebergs the maximum linear size may be used as the only geometric characteristic:

$$F = \frac{1}{2} C_W \rho L^2 V^2 \qquad (1)$$

$F\ (kN),\ \rho\ (kg/m3),\ L\ (m),\ V\ (m/s)$

For large icebergs (table-shaped, pyramidal, inclined) substitution of its' area by a square length is not justified to the same extent as for smaller icebergs, where their length becomes the main determining parameter.
The coefficient of iceberg drag force to movement in water Cw is generally a function of the dimensionless Reynolds number, while kinematic viscosity of water was assumed to be 1.5 * 10-6 m2 / s for a water temperature of 5 degrees Celsius.

$$Re = \frac{V * L * \rho}{\mu} \qquad (2)$$

Analysis of experimental data revealed 72 regimes characterized by minimal acceleration. To obtain the drag force coefficients only 37 high-quality regimes characterized by linear motion of the system and relatively small influence of sea current and wind were used (Figure 7).

Analysis of the data shows a noticeable difference in the movement of small/medium icebergs and large icebergs. This is primarily due to the variability in iceberg shapes: icebergs with a length of more than 75 m are mainly tabular, wedged and pyramidal shapes, that affects the nature of flow around the waterline; whereas icebergs having lengths less than 75 meters, were fragments of icebergs and depredating icebergs.

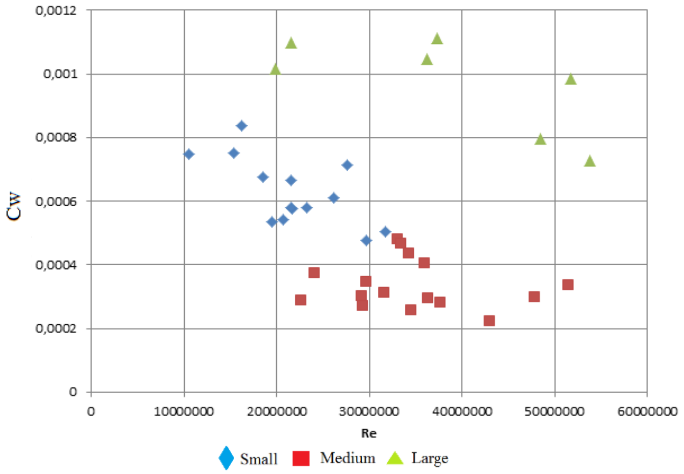

Fig. 7. Dependence of Cw on Reynolds number for icebergs of different groups

At the same time for all groups of icebergs there is a tendency for the drag coefficient to decrease with an increase of the Reynolds number, which may be associated with a decrease in the role of lateral oscillations of the iceberg with increasing ship speed and tow load. For icebergs less than 75 meters long, the following expression can be used to estimate the drag coefficient decrease with increasing of the Reynolds number:

$$Cw = 366 * Re^{-0,8} \tag{3}$$

The variable nature of the drag coefficient for iceberg towing is indicated in the paper Stepanov et al., 2005. In the present work the authors derived a power dependence (exponent - 1.4) of drag force on towing speed.

For icebergs clusterization the following grades of mass and length are used, based on a significant differences in the nature of their movement:

- small icebergs (up to 40 meters length, up to 12.5 thousand tons weight)
- average icebergs (40-75 m length, 12.5-80 thousand tons weight)
- large icebergs (75-160 m length, 80-400 thousand tons weight).

Separate selection of "Small" and "Medium" groups of icebergs was due to the fact that when towing icebergs of less than 40 m length ("small") the drag coefficient during stationary and non-stationary movement remains almost constant; whereas for icebergs with a 40 to 75 m length ("average"), the drag coefficient in some cases with non-stationary oscillatory motion can be 1.2–1.5 times higher than in stationary mode.

For small/medium icebergs a simplified formula for calculating iceberg resistance can be used, which does not take into account the drag coefficient decrease with increasing speed, but gives a convenient ratio between the tow force and the iceberg speed:

$$F = K(L)V^2 \tag{4}$$

F (kN), L (m), V (m/s)

The dependence of the coefficient K (L) on the length of the iceberg is linear for small and medium icebergs. K (L) = a * L (Figure 8)

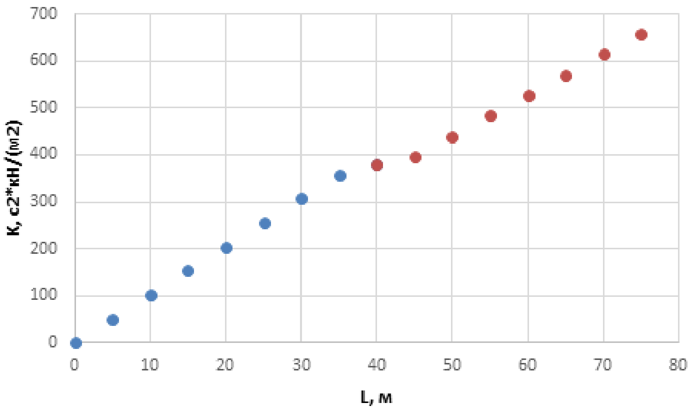

Fig. 8. The dependence of the coefficient K on the length of small/medium icebergs

Practically important information for calculation of the dependence of the drag force on towing speed and size of icebergs is summarized in Table 1. The error was calculated by comparing the calculated values of the drag force with the experimental data.

Table 1. Dependence of drag force summary

Iceberg cluster	F (kN) Dependance on V (m/s) and L (m). Simplified formula	F (kN) Dependance on V (m/s) и L (m). with Cw (Re)	V*L (m2/s) range
Length L< 40 m; Mass M< 12,5 thousands t.	$F = 10{,}23LV^2$ Error < 20%	$F = 1{,}227(VL)^{1{,}618}$ Error < 20%	10-50
Length 40 m <L< 75 m; Mass 12,5 thousands t.<M < 80 thousands t.	$F = 8{,}79LV^2$ Error < 30%	Cw weakly dependent on Re, 0,000335 in average	30-80
Length L> 75 m Mass M> 80 thousands t.	$F = 341L^{0{,}36}V^2$ Error < 40%	Almost linear dependence F on V	30-80

Iceberg towing efficiency (the ratio of power spent on iceberg towing to the total power of the propeller-rudder system) for icebergs with a length of less than 75 meters varies from 11% to 23% with an average of 18% and a standard deviation of 3%; at the same time, the efficiency is practically independent of the propeller-rudder system power.

For estimation of oscillations parameters when towing icebergs symmetrically in plane view, it is possible to use an analytical approach from the analysis of small oscillations (Lurie, 2001).

The equation of the principle of momentum of movement around the moving axis (the point of attachment of the rope to the vessel) (Figure 9):

$$-KR\left(V_{vessel}^2 + 2\omega RV_{vessel}\sin\varphi + \omega^2R^2\right)^{0,5}(\omega R + V_{vessel}\sin\varphi) - Ma_{vessel}R\sin\varphi = MR^2\frac{d\omega}{dt} \tag{5}$$

R – distance from the iceberg to the vessel's stern;
φ – iceberg deflection angle from the vessel's trajectory;
ω – angular velocity of rotation of the rope in the horizontal plane;
V_{vessel} , a_{vessel} –speed and acceleration of the vessel (rope attachment points);
T – tension force of the rope;
F –drag force;
K – iceberg moving in water drag force coefficient; the quadratic dependence is taken for F =K(L)V2;
M = Mice+ Matt – iceberg mass in accelerated motion with regard to the entrained water.

The linearized (taking into account small angular displacements) differential equation of iceberg oscillations within the straight-line movement of the vessel is written as:

$$\ddot{\varphi} + \left(\frac{KV_{vessel}(t)}{M}\right)\dot{\varphi} + \left(\frac{KV_{vessel}^2(t)}{MR} + \frac{a_{vessel}(t)}{R}\right)\varphi = 0 \qquad (6)$$

For special cases of straight-line movement of the vessel, this expression is simplified:
Steady ship motion (V_{vessel} = const)

$$\ddot{\varphi} + \left(\frac{KV_{vessel}}{M}\right)\dot{\varphi} + \left(\frac{KV_{vessel}^2}{MR}\right)\varphi = 0 \qquad (7)$$

For a practically important case of small resistance (KR / M <4), the iceberg oscillations are periodic with an initial oscillation period:

$$\tau = \frac{2\pi}{V_{vessel}}\sqrt{\frac{4M^2R}{4KM-K^2R}}$$

The relationship of two consecutive amplitude deviations of the system from the equilibrium position in one direction (attenuation coefficient):

$$\psi = e^{\frac{\tau K V_{vessel}}{2M}} \qquad (8)$$

Uniformly accelerated motion of the vessel (a_{vessel}=const)

$$\ddot{\varphi} + \left(\frac{Ka_{vessel}t}{M}\right)\dot{\varphi} + \left(\frac{Ka_{vessel}^2t^2}{MR} + \frac{a_{vessel}}{R}\right)\varphi = 0 \qquad (9)$$

Time corresponded to maximum distance between iceberg and vessel movement axis:

$$T_{max} = \frac{4}{3}\sqrt{\frac{R}{a_{vessel}}} \qquad (10)$$

CONCLUSION

Field expedition tests on iceberg towing during 2016-2017 and subsequent data analysis showed the following results that can improve the efficiency of planning and carrying out actions of physical impact on icebergs, including their deviation from offshore oil and gas facilities and long-term towing:

1. Proposed technical solutions for towing characteristic icebergs in the Barents and Kara seas were tested on the site and showed good performance; mobilized vessels, personnel and equipment showed high efficiency when carrying out similar work in the Russian Arctic;
2. The possibility of iceberg capsize/destruction with vessel moving in it's vicinity increases when water is relatively warm;
3. There is a deviation from the quadratic relationship between towing speed and towing force during iceberg towing; a resistance coefficient decrease is observed with an increase of Reynolds number. Based on the diagram of the iceberg drag coefficient on the Reynolds number dependence, clusterization of the most frequently encountered icebergs of the Russian Arctic is proposed on the basis of their movement pattern;
4. Length of the iceberg (maximum linear size) can be considered as the main geometric parameter for calculating resistance force; for icebergs less than 75 meters length, towing force calculation error according to the proposed formula does not exceed 30% for a given towing speed.

Authors believe that for further understanding of iceberg towing mechanics a deeper research should be done in order to:

1. Analyze the effect of short-period oscillations "iceberg-rope-attachment point of the rope" system;
2. Perform numerical and basin modeling of iceberg towing with real forms of the underwater part;
3. Determine (numerically and experimentally) the wind forces and moments of these forces acting on the studied icebergs.

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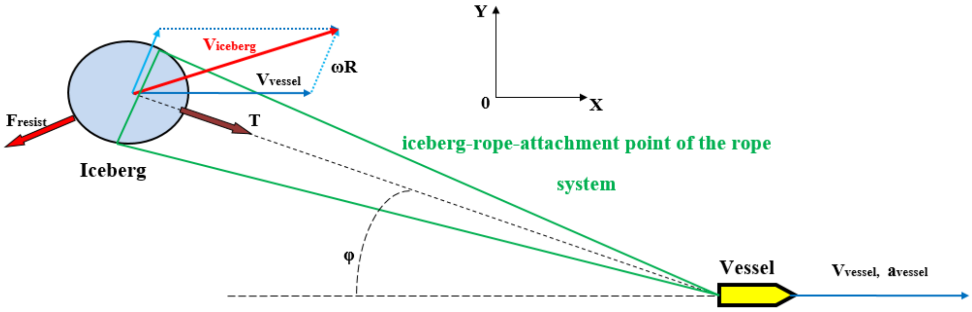

Fig. 9. Calculated iceberg oscillation scheme