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ICEBERG DYNAMICAL MODELLING

by

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ABSTRACT

Experimental tests were carried out on model icebergs. Natural drift tests with a 1:100 scale model on Brienzer See, Switzerland, show the effects of various environmental conditions. Froude similitude formed the basis for these tests. Other experiments, carried out with a 1:60 model in St. Malo harbour, France, show the need for information obtained at this scale, and include assessments of the drag coefficients for various model shapes with or without insulation skirts on the model, the effects of added mass and rotation of the model, and steering possibilities.

INTRODUCTION

The problem of control during an iceberg tow requires the development of a mathematical model which will provide the values of control parameters, such as required towing forces and translation and rotation velocities. Such a model could also be used in studies to simulate routes; in this case, the model would be fed by statistical or recorded data. The elaboration of this model relies on an understanding of the dynamic behaviour of an iceberg. This has been the aim of several papers, which have provided theoretical estimates of the towing forces required to transfer Antarctic icebergs towards desert regions. The present paper describes the programme of model tests carried out by Iceberg Transport International Ltd. during 1978-79. The measurement methodology and similitude aspects of the calculation are emphasized in order to demonstrate the unusual nature of iceberg modelling, and the results, often qualitative, are outlined.

Two models were constructed at scales of 1:100 and 1:60, in accordance with the principle of similitude, which is concerned with the proper relative scaling of the appropriate dimensions of differently-sized objects so that a conveniently-sized object (model) can be used to obtain information on inconveniently-sized objects. Dimensionless parameters are introduced in order to characterize each tested phenomenon. Similitude theories allow the definition of a modelling methodology based on the preservation of the dimensionless numbers and also the extrapolation of the experimental results to full scale. Two dimensionless numbers are used in this paper:

Froude number: $\dfrac{\text{velocity}}{\sqrt{(\text{length} \times \text{gravity})}}$

Reynolds number: $\dfrac{\text{velocity} \times \text{width}}{\text{viscosity}}$

An analysis of iceberg dynamics, such as that outlined by Murphy (1978), led to the conclusion that Froude similitude should be chosen for the analysis of natural drift tests in order to extrapolate all the intervening parameters and to simplify problems associated with variable dimensions. In those tests, turbulence was not reached and the flows do not conform to the real, full-scale values.

On the other hand, hydrodynamical drag tests were carried out without any attempt to attain Froude similitude. In this case, an exact Reynolds similitude was not achieved as the speeds needed were too high for the model. In fact, it can be shown that form drag coefficients remain roughly constant for Reynolds numbers higher than the critical value, as the flow had reached its turbulent state. This means that it is sufficient to work at the model scale with velocities which are a little higher than the value corresponding to the critical Reynolds number.

Drag, whether hydrodynamic or aerodynamic, results from the disturbance of flow around an object. Generally, drag is the resultant of the following components:

(a) The form drag coefficient, related to Reynolds number and the cross-section of the object, results from the re-distribution of the pressures on the surface of the object. The form drag depends mainly on the shape of the object:

$$\begin{aligned}\text{form drag} = 0.5 &\times (\text{density of fluid}) \times \\ &\times (\text{form drag coefficient}) \times \\ &\times (\text{cross-section area}) \times \\ &\times (\text{velocity of object})^2.\end{aligned}$$

(b) The friction drag coefficient, related to Reynolds number and the nature of the object's surface, results from the shearing tangential forces due to the friction between the fluid and the object. The friction drag depends on the roughness of the surface over which the fluid is flowing:

friction drag = 0.5 x (density of fluid) x
x (friction drag of object coefficient) x
x (total area) x (velocity)^2.

(c) The wave resistance component, related to the Froude number and the shape of the water line, results from the interaction between wave fronts from the bow and the stern of a floating object:

wave resistance = (density of water) x
x (wave resistance coefficient) x
x (displacement of object) x
x (acceleration due to gravity).

ICEBERG MODEL, SCALE 1:100

The model was built on site, in the form of a wooden pontoon 10 m by 5 m by 2.5 m deep. The rigidity of the structure was maintained by tube scaffolding clad with laminated panels. The whole unit had a draught of 2.10 m and was kept at this depth by polystyrene foam blocks. This design permits the construction of a cheap model which can be taken apart easily.

Brienzer See, Switzerland, was chosen as the test site, as a small river feeding the lake causes a steady geostrophic current. The velocity of this current varies between 30 and 50 mm/s, and corresponds to the reduced current of the Southern Ocean.

The major problem in making measurements is to find a suitable frame of reference against which to measure velocity. A net of drogued buoys was preferred to a traditional log to avoid the effects of motion in the mass of water in the vicinity of the drifting model. The net drifted at the same speed as the surface current and the depth of the drogues corresponded to the draught of the model in order to include the current in the surface layer independently of wind and wave effects.

Results

Several drift tracks were recorded and shown to have the same trajectories as full-scale icebergs. Figure 1 shows the heading and the acting wind vector for a model trajectory. Extrapolations are based on a Froude similitude in spite of the fact that critical Reynolds numbers had not been reached for the air and water flows. Such extrapolations lead to the conclusion that current and speed of the model relative to the water have the same order of magnitude. The main axis of the model is, on average, perpendicular to the wind vector. The movement of the model with respect to the water was in the same direction as the mean wind.

During the analysis of wind effects on the model, corrections were made (a) to the wind-speed gradient linked to the height above the water surface, (b) linked to the alteration of the incident wind angle due to flow around the model, (c) due to the presence of the bracket, hand-rails, and operators.

Self-propulsion tests were carried out, using an outboard motor. A propeller with a low pitch was employed to suit the poor incoming flow behind the model. It was located one metre behind the aft vertical wall at a depth of 0.6 m and the engine was fixed to a bracket. The self-propelled model was very unstable owing to its low length : width ratio. This point appears to be more important than expected.

Systematic rotation tests allowed the investigation of the frictional hydrodynamic torque. The model was equipped with two small outboard engines at opposite corners. Thrust was exerted and led to a steady rotation velocity after a transient state. The thrust of each engine was 60 N and the rotation velocity was 0.021 rad/s. The torque is given by $\Gamma = 0.5\rho C_r I\omega^2$, where Γ (Nm) is the moment of the exerted torque about a vertical axis passing through the centre of gravity of the model, it is assumed that the centre of gravity is the centre of rotation, ρ(kg/m^3) is the density of the water, C_r is the rotation drag coefficient, I is a specific moment of inertia which corresponds to the moment of rotation, and ω(rad/s) is the rotation speed.

If $C_r = 1.1$ with a pseudo Reynolds number (Re) of $\frac{L^2 + l^2}{2v}$, then Re = 1.1×10^6, where L is the length of the model, l is the width and v is the viscosity of the water.

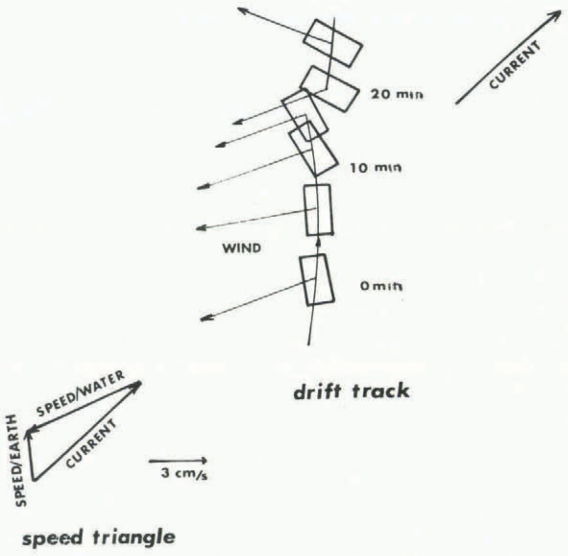

Fig.1. Drift track test.

Propulsion by large floating anchors was studied. A model of a floating anchor was made from a rectangular piece of reinforced plastic film, maintained in a vertical plane by means of a system of weights and floats, with dimensions of 14 m by 1.5 m which correspond to 1 400 m by 150 m at full scale. The pull was applied through two floating ropes. Weights were fastened to the ends of the ropes and exerted the required pull through two pulleys fixed to the model. The range of movement was determined by the length of the ropes which were about 100 m long in this case, depending on the depth of the lake. The following steady velocities were reached:

velocity of the model relative to the water represented by the floating sticks, $v_m = 0.17$ m/s,

velocity of the ropes through the pulleys, $v_r = 0.25$ m/s,

velocity of the floating anchor, v_{fa} (obtained by $v_r - v_m$) = 0.09 m/s.

They correspond to the steady state of the system which satisfies the following equations:

$$(M_m + M_w) \times \frac{dv_m}{dt} + 0.5 \times \rho \times C_m \times S_m \times v_m^2 =$$

$$= M_{fa}\ (t)\ \frac{dv_{fa}}{dt} + 0.5\rho C_{fa}S_{fa} \times v_{fa}^2 + T,$$

where M_m is the mass of the model, M_w is the added mass of the model, ρ is the density of the water, C_m is the drag coefficient, S_m is the cross-sectional area, M_{fa} is the mass of water within the floating anchor, S_{fa} is the total area of the floating anchor, and T is the traction created by the weights.

The appropriate values for the tests are:

$M_m = 10^5$kg
$M_w = 50 \times 10^4$kg
$\rho = 1\ 000$ kg/m^3
$C_m = 0.9$
$S_m = 10.5$ m^2
$M_{fa} = 30 \times 10^4$ kg
$C_{fa} = 1.7$
$S_{fa} = 21$m^2
$T = 140$ N

Smaller weights (2 kg) were tried in order to fit the similitude conditions. The results were affected by the weights of the ropes, the presence of wind, and so on. This towing idea seems promising.

Anchoring tests were also carried out. The model was anchored in the current. The measurement of the force on the anchoring line leads to a value of about 1.5 for the frontal form drag coefficient when the Reynolds number is 2.5×10^5. This method can give significant results if the measurements are not altered by wind and waves.

ICEBERG MODEL, SCALE 1:60

After having collected qualitative results on the 1:100 scale model iceberg, ITI decided to investigate the dynamic characteristics of a 1:60 scale model. As suggested by Basmaci and Jamjoom (1978), the main aim of these tests was to determine the drag coefficient of parallelepiped-tabular icebergs in translation as well as rotation in order to evaluate the towing forces. Other aspects of the dynamic iceberg problem have been tackled: the added mass of water, the influence of insulating skirts, variations of the shape and the sails used, and steering methods.

A steel pontoon of dimensions 19 m by 9 m by 4 m thick was used; this constituted a suitable model to represent an iceberg of size 1 140 m by 540 m by 240 m thick. The pontoon was chamfered at the corners and could be ballasted to a chosen draught.

The tests were carried out in the Bouvet basin of the harbour at St. Malo; this measures 700 m by 200 m by 7 m deep. The time chosen was between high tides when the harbour chamber was not working, thus avoiding unpredictable water currents. The tests consisted of towing the model, equipped with various measuring devices in order to determine the relationship between the drag forces and the towing speed. These two parameters were measured by first towing the model from one side of the basin to the other, the towing force being exerted through a rope which passed through a pulley fixed at the point towards which the model was towed. This rope was connected to a small self-propelled pontoon which generated the towing force. Observation of the rope velocity at the pulley permitted the measurement of the transfer velocity of the model, and a dynamometer set up on the model allowed the measurement of the towing force. The orientation of the model relative to the rope-towing direction could be measured with a protractor. Observations made with a magnetic compass from the quayside allowed monitoring of drift during the sail tests.

Results

Fifteen drag tests were performed at different towing forces and orientations. At the end of each traverse, the model had reached 98% of its full speed in a long tow. In other words, it was still accelerating at the end of the tow owing to inertia. Form drag coefficients have been computed taking into account the frictional drag, the effects of the narrow dimensions, and the inertia correction. These coefficients are a function of the angle α between the model velocity and its main axis, and the angle between the towing force and the main axis are related by $\alpha = \tan^{-1}(0.5 \tan \theta)$.

Figure 2 shows how the form drag coefficient varies with Reynolds number for $\theta = 0°$. These variations in drag coefficient resemble the general pattern observed at the critical Reynolds number for bodies with poor drag profiles (Hoerner 1965). The critical Reynolds number value appears to be 5×10^5. It is assumed that the form drag coefficient remains constant after the transition to turbulent flow. The obtained value of 1.14 for this coefficient is higher than previously cited values.

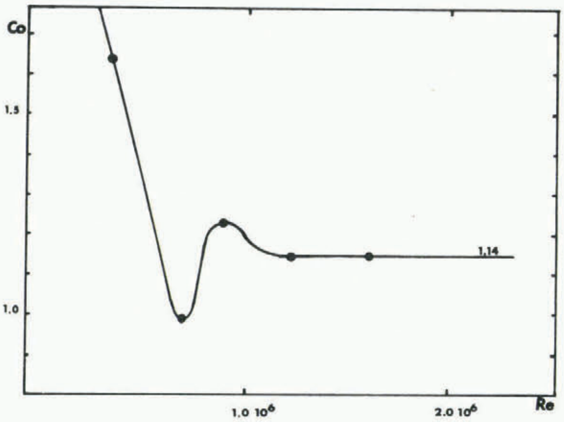

Fig.2. Form drag coefficient ($\theta = 0$).

The water flow around the iceberg is obviously limited by the water surface. This effect has not been taken into account as the drag coefficients which have been used apply to flow in continuous media. This could be an explanation for the obtained results. Figure 3 shows the variation of the drag coefficient with the orientation θ of the drag relative to the main axis of the model. The curve obtained has been fitted to a Lagrangian polynomial:

$0(\theta) = 1.14 + 7.29 \times 10^{-3}\theta + 2.10 \times 10^{-4}\theta^2,$

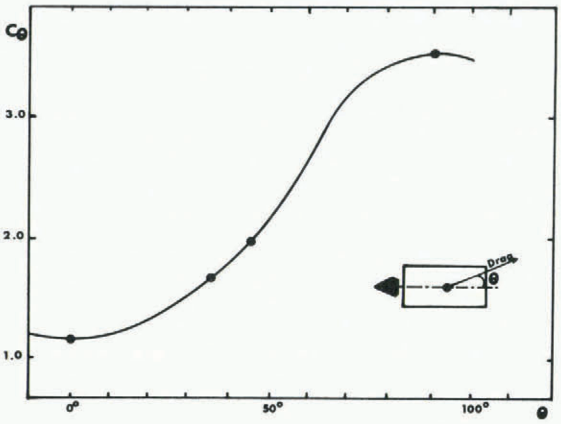

Fig.3. Form drag coefficient (Re > 1.2×10^6).

in which $O(\theta)$ is referred to as the "small cross-section" (width x draught).

The results concerning the hydrodynamic form drag coefficient can also be applied to the part of the iceberg above the surface during the analysis of the wind action.

It appears that towing along the main axis is necessary to minimize the artificial towing force, as the drag coefficient increases "quickly" with the incidence of the flow. Nevertheless, the drag tests also show that this state is difficult to reach and control, as orientation of the model oscillates around the 0° during the tow.

Towing tests were performed with the point of application of the force located at the centre of the model in order to simulate the combined actions of wind, swell, and towing force during a transfer. It was shown during these tests that an angle for θ of 0° was unstable. A value for θ of 90° was reached after long oscillating times. This means that the point of application of the resultant of the artificial and natural forces must be located in front of the centre of gravity of the model.

During the high Reynolds number tests (5×10^6), no waves appeared at the bow of the model, a very light wave only appearing when the outboard engine supplied its maximum thrust. When the model was equipped with lateral skirts, the resulting drag was lower than in the unprotected model. This is explained by the improvement of the roughness which leads to reduction in the frictional drag.

Several model tests were performed to determine the effect on drag of small variations in the shape of tabular icebergs (Fig.4), modifying this by means of patterns and vertical plastic skirts. The lozenge shape was the easiest to tow, as the form drag coefficient corresponded to only 63% of the equivalent rectangular shape. The corresponding measured speed was equal to 0.25m/s which gives a Froude number of 0.018. A simple extrapolation shows that no wave resistance would exist on a full-scale iceberg of 1 000 m length if its speed relative to the water remained below 1.8 m/s. This means that the form drag coefficient represents the main part of the hydrodynamic drag of the iceberg.

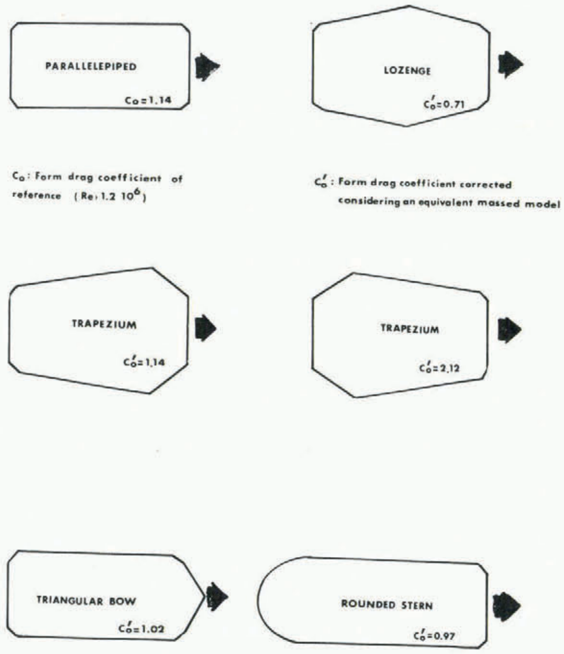

Fig.4. Variations of the model shape.

The drag characteristics and the heading stability of the trapezoidal shape were found to be very different depending on towing angle. The drag coefficient was equal to that of the rectangular cross-section when the maximum width constituted the front of the model but the heading stability was almost perfect (less than 5° on each side). When, however, the maximum cross-section was at the back of the model, the drag coefficient increased by 80% and the heading variations were considerable. The lack of improvement in the drag coefficients could be related to the sharp corners of the main frame which would not exist on a real trapezoidal iceberg.

Towing tests were carried out to determine the influence of bow and lateral insulating skirts on dynamic behaviour. The bow skirt overlapped the model and was weighted in order to remain at an angle of 45° to the vertical. The length of the overlapping part was 1.5 m. The form drag coefficient for the bow part was 63% higher than for the uncovered model. It appears that it would be better not to equip an iceberg with a frontal skirt for a short transfer but to choose an iceberg with a draught high enough to reduce the ratio of drag:ice mass as low as possible.

Acceleration tests were performed in order to determine the equivalent added mass of water at different flow angles. A constant force was exerted on the model. These tests showed that the added mass of water M_W is a linear function of the orientation θ of the drag force relative to the main axis of the model: $M_w = 0.37M_m + 8.9\theta$, where M_m is the mass of the model. These results can be extended to full-scale icebergs because the tests were carried out in turbulent conditions.

Rotation tests were carried out using electric outboard motors. Rotation drag coefficients of 1.0 were found for an average pseudo Reynolds number of 8.8×10^5. These results are in agreement with those obtained at the 1:100 scale.

Sail propulsion was tested during this second investigation. Five panels made of sail cloth were arranged on the model; their total area was 22 m^2 which corresponded to 80 000 m^2 at full-scale. The model was ballasted in order to simulate the real ratio between the below- and above-water areas of a tabular iceberg. The model heading relative to the wind direction was self-controlled through a simple system. Drifting rods of 4 m length, ballasted at the same draught as the model, were set around the model; their drift tracks constituted a reference as they were supposed to integrate the variations of the wind action. Tests showed a significant deflection of 10° between the model drift and the reference frame of the rods. The orientation control unit functioned well, maintaining the sail profiles at an incidence of 300° to the wind direction.

A steering device was tested on the self-propelled and towed model. It consisted of two flaps arranged on each side of the bow which could be opened or closed in order to create a rotational torque. This system had little effect on the drag and allowed the model to be steered satisfactorily.

CONCLUSIONS

Natural drift

The 1:100 scale drift experiments will be correlated with the trajectories of full-scale icebergs. These data are being collected at present from transponder beacons. Preliminary results suggest that the same phenomena occur at both scales. Directions and velocities were found to be similar for similar environmental conditions. This is an encouragement to carry out further model tests to investigate the behaviour of natural icebergs.

Self propulsion

Self propulsion could be a reliable solution to the problem of iceberg transfer. It has been shown, at both the 1:100 and the 1:60 scales, that the turbulent wake of a parallelepiped iceberg could be disastrous for the proper operation of propellers. The poor heading stability is another phenomenon which has been revealed during these experiments.

Propulsion by floating anchors

Propulsion at low speeds appears to be a promising technique according to the results of the 1:100 scale tests. A simple extrapolation shows that a propelling efficiency of 50% could be achieved when using this method to move a tabular iceberg of 1 000 m by 500 m by 250 m thick with two floating anchors of 150 000 m^2 at a relative speed of 0.5 knot.

Drag

The form drag coefficient of the chamfer-cornered 1:60 scale model was found to be 1.14 in turbulent flow conditions. It means that in the absence of wind and swell the required force to tow a tabular iceberg of 1 000 m by 500 m by 250 m thick is 4 200 kN for a relative translation speed of 0.5 knot. For such an iceberg, the computed friction drag represents 9% of the total drag.

The choice of shape appears to be important in terms of saving energy. As an example, the force required to transfer a lozenge-shaped iceberg with the same mass as that mentioned above would be 2 800 kN, which represents 67% of the previous towing force. The angle between the main axis and the iceberg track relative to the water is also an important factor. We predict that the lowest consumption of energy will be achieved with an angle of 0°, though the heading stability was found to be poorest in this situation. Wave resistance remains negligible for Froude numbers below 0.018, which corresponds to a towing speed of 3.6 knots for an iceberg 1 000 m long. Lateral insulating skirts improve the dynamic performance of a protected iceberg, whereas a bow skirt has a bad influence on the total drag.

Steering and rotation

A first processing of data collected from transponder beacons led to the conclusion that the average natural rotation velocity of a 1 000 m long tabular iceberg was equal to 15°/h. This indicated that a towing force of 100 kN exerted at one corner of such an iceberg would be sufficient to sustain the same rotation velocity. This result indicates that iceberg steering could be carried out using a source of low power. Passive and active devices have been tested and require further investigation.

Sails

The 1:60 scale experiments show significant differences between model and rod trajectories. These results constitute a first approach to a promising technique which must be studied at larger scales.

Future plans

The next step should be to perform tests on Arctic icebergs, which, in fact, constitute suitable 1:10 scale models of Antarctic icebergs. Synthesis of theoretical studies, results of model experiments, and processed data collected on site will enable the monitoring and control of future iceberg transfers to be carried out using mathematical models.

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