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ICE MODEL TESTING OF PROPULSION SYSTEMS FOR A COAST GUARD PATROL VESSEL

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ABSTRACT

The Swedish Defence Materiel Administration, FMV has designed a new class of patrol vessel, KBV 201, for the Swedish Coast Guard with conventional hull lines for high open water speed and good sea keeping performance. There is also a requirement for independent operation in level ice with a thickness of 0.30 m. The vessel is 46.2 m long between perpendiculars, max. beam 8.60 m and has a stem angle of 35°. To verify the ice performance a series of model tests has been performed at the HSVA (Hamburgische Schiffbau-Versuchsanstalt). Both a conventional twin shaft propulsion and an azimuthing thruster system with non-ducted propellers were tested and evaluated. The flow of broken ice along the hull and the interaction between ice and propeller was studied.

The ice model tests show that the predicted ice performance of the KBV 201 will meet requirements. Model test results with full scale predictions are presented. The propeller/ice interaction observations show that the thruster arrangement experiences less ice interaction than the conventional propulsion arrangement.

The model testing was performed by Chalmers University of Technology in co-operation with Swedish partners supported by HSVA technicians and engineers. The project was financed within the European Communities Program for Large Scale Facilities and co-ordinated by the European Commission for Science, Research and Development (DG XII).

1. INTRODUCTION

A new concept for a patrol vessel has been developed by the Swedish Coast Guard (KBV) in close co-operation with the Swedish Defense Material Administration (FMV). The vessel is designed for offshore operations with tasks such as: maritime law enforcement, search and rescue and oil spill recovery, with all-year service under almost all weather conditions.
The design is a mono-hull, all steel vessel with the following main dimensions:

Length oa.:	49.95 m
Length pp.:	46.20 m
Beam at dwl:	8.10 m
Draft:	2.30 m
Displacement:	431 m³

The design speed is 22 knots and the ice performance requirement is: the vessel shall be able to operate unassisted, in ice-covered waters with an ice thickness up to 30 cm. The basic propulsion system consists of two 2.6 MW engines, each running a controllable pitch propeller of 1.9 m diameter via a conventional shaft with bossing. The optional propeller arrangement consists of two azimuthing thrusters with open propellers of the same size.

The ship will be built to meet the rules of Det Norske Veritas (DNV) for ice class 1C. The first ship, in the initial batch of two, is planned for delivery during the year of 2000, and is designated KBV 201, giving name to the class of vessels (Figure 1).

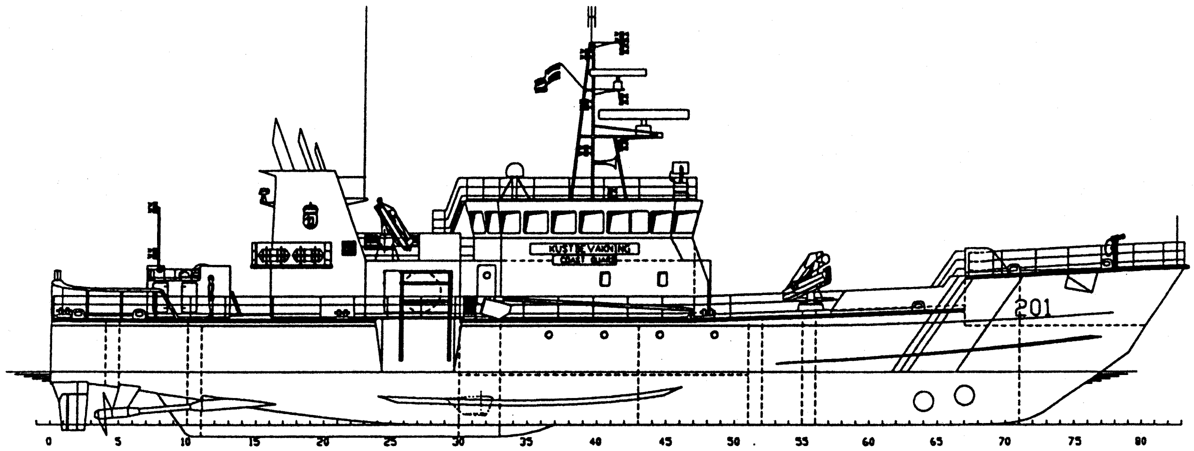

Figure 1 Profile of KBV 201

The modest ice-going capability combined with demands for good station keeping performance during oil spill operations, has created an interest in comparing and evaluating the conventional propulsion system versus azimuthing thrusters, especially thrusters of the pulling type. Another area of interest is the backing performance in ice and the issue of improved performance by adding an angled structure in the waterline area of the transom. This structure is by its appearance nicknamed the "duck tail". The ship is designed with bilge keels located between frames 24 and 46, with the purpose to give the ship good seakeeping performance. However, bilge keels are not considered well suited for ships operating in ice. The reason is their vulnerable position and ability to trap ice floes under the hull. The behavior of bilge keels when operating in ice was accordingly evaluated.

2. EXPERIMENTAL PROGRAM

The tests were conducted in the large ice basin of HSVA. The basin is 78 m long, 10 m wide and 2.5 m deep. The basin has a motor driven carriage weighing 50 tonnes. The speed of the carriage is 1 mm/s to 3000 mm/s and the maximum towing force is 50 kN.

2.1 Model of the Coast Guard Patrol Vessel

The model was manufactured according to the lines and drawings provided by FMV to the scale 1:8.143 (Figure 2). It was built out of wood and painted orange-red to make contrast to the white ice. By using a matt paint the friction coefficient between ice and model surface was adjusted to FID = 0.1. The friction coefficient was checked in a separate friction test using a test plate which was painted together with the model.

To save time rebuilding the model between the tests, two different aft bodies were made, one outfitted with the conventional propulsion arrangement and the other with the azimuthing thrusters. The two versions of the model were numbered 3950.0001 (conventional) and

3950.0002 (thruster). The forward and aft section were held together with bolts at the midship bulkhead.

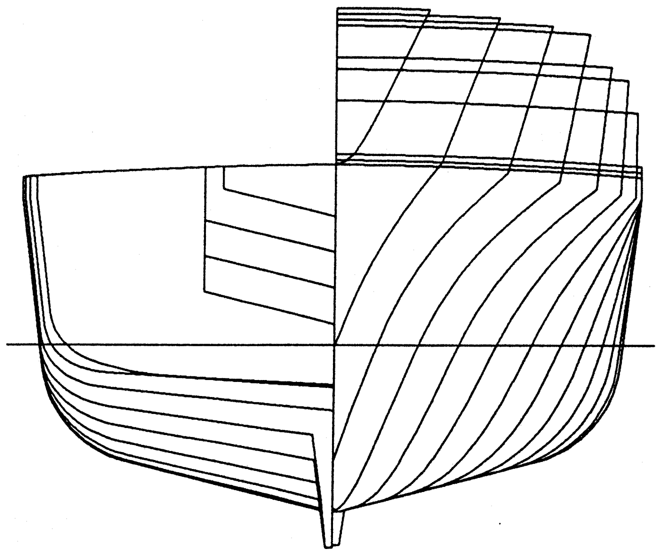

Figure 2 Body plan of KBV 201

The duck tail was detachable and could be moved and fitted to both aft bodies. The positions of the bow thrusters and sea water inlet were marked with white paint on the hull so that the flow of ice around these areas could be observed. Since no maneuvering tests were to be performed, the rudder angles were kept fixed during all tests.

The model was fitted with devices for measuring:

- Speed ahead, V
- Pull force ahead, Fp
- Rate of revolutions, port propeller, Np
- Rate of revolutions, starboard propeller, Ns
- Torque, port propeller shaft, Qp
- Torque, starboard propeller shaft, Qs
- Thrust on port propeller, Tp (3950.0001 only)
- Thrust on starboard propeller, Ts (3950.0001 only)
- Force on port thruster unit, X-direction, FXp (3950.0002 only)
- Force on port thruster unit, Y-direction, FYp (3950.0002 only)
- Force on starboard thruster unit, X-direction, FXs (3950.0002 only)
- Force on starboard thruster unit, Y-direction, FYs (3950.0002 only)
- Angular movement, roll direction, PHIR
- Angular movement, pitch direction, THETAP

Before installing all the measuring equipment, the longitudinal center of gravity and gyradius were determined. This was done by hanging the model in long wires from the ceiling and measuring the yaw period time. The longitudinal gyradius was then calculated. Fully equipped and calibrated, the model was launched into the trim tank. Weights were placed aboard and heeling tests were made. This was done to give the model correct displacement, trim, metacentric height and longitudinal gyradius, giving correct motional behavior to the model. Due to the weight of the thrusters, which were placed in the far aft position, the longitudinal gyradius of model 3950.0002 was slightly higher than specified, but this was considered a minor deviation, not really affecting the test results.

2.2 Model Setup

During the tests, the model was towed through the ice using a setup where the towing carriage was pushing the work carriage using push rods. The work carriage is normally self propelled, but in this mode, its motors were disabled. The model was connected to the work carriage with a towing rod. The pull force was measured with a dynamometer mounted at the model's bow. The cables for power, measurement signals and controls were taken straight up to a boom and then into the control room on the towing carriage. Since there were no means of steering the model while towing, spring tensioned guiding wires were tied between the bow and the push rods on both sides of the model (Figure 3). To prevent them from adding any relevant longitudinal forces to the model, they were stretched athwartships with a tolerance of less than 0.1 degrees to the towing direction.

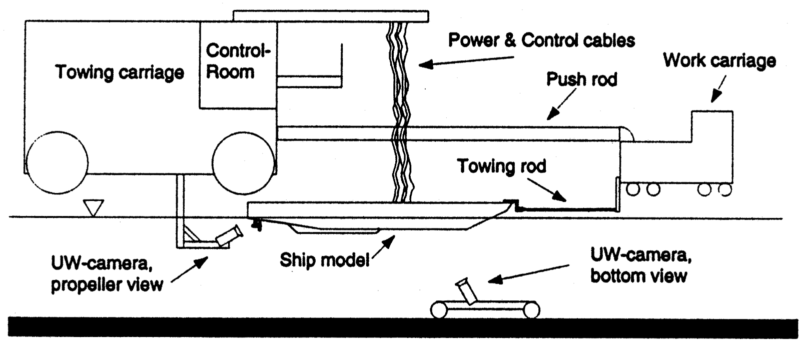

Figure 3 Model setup in the ice tank

The tests were documented by video cameras from three different directions. One camera was placed at a fixed position at the bottom of the tank, filming the breaking process as the model passed overhead. The camera was mounted on a movable carriage, running on rails on the bottom, which enabled it to be placed at different positions along the tank for the different tests. The second camera was mounted on an L-shaped arm mounted on the towing carriage and running behind the model. This camera filmed the propellers, documenting the propeller-ice interaction during the runs. The third camera was placed on a tripod on the work carriage and was used for surface video documentation. The camera was manually operated and was also used for documentation of activities between runs. For the backing tests, the camera was repositioned to the towing carriage, filming the ice movement around the transom. Additional photos were taken with a hand held camera.

2.3 Preparation of the Ice Cover

Testing was conducted in level ice, broken channel and pack ice. Full scale ice thickness of 0.3 m and 0.45 m, corresponding to model ice thickness of 37 mm and 55 mm, were tested. Fine grained model ice of the columnar type was used. To simulate ice conditions valid for the southern Baltic, an approximate full scale ice strength of 400 kPa was used. In order to achieve a realistic breaking behavior, the strength of the model ice had to be scaled to a value of 49 kPa. The procedures and preparation of the HSVA model ice are thoroughly described by Evers and Jochmann in reference [1].

2.4 Test Sequences

All tests performed were towed propulsion tests, which means that the model was towed by the carriage with a constant velocity and the propeller rpm was altered two or three times during each run. Three different speeds were used: 0.36, 0.72 and 1.08 m/s, which is equivalent to the full scale speeds: 2, 4 and 6 knots. The rpms were changed alternately between high and low values. This resulted in distinguished steps in the data curves, which made it easier to recognize the different portions of the test run.

2.5 Overload Tests

In order to calculate the thrust deduction due to ice interaction, similar towed propulsion tests were made in open water, as the ones made in ice. The overload tests were performed in ice-free water. The model 3950.0002 was tested on February 24, before the first ice sheet was frozen and the model 3950.0001 was tested on March 9, after the 3000-series.

2.6 Ice Tests

The ice tests were carried out in three series, each series corresponding to one ice sheet.

- Test series 1000, Nos. 1010-1090

Date: 980226 ; Model: 3950.0002 ; Hice: 37 mm ; σf: 49 kPa
The backing tests Nos. 1080 and 1090 were performed with the propellers working in pulling mode. This was accomplished by manually turning the thruster units 180°.

- Test series 2000, Nos. 2010-2080

Date: 980303 ; Model: 3950.0002 ; Hice: 55 mm ; σf: 49 kPa
The backing tests Nos. 2060 - 2080 were performed with the propellers working in pushing mode. The propellers were dismounted and refitted in the other direction so that the model could be run astern with outward rotating propellers. No tests ahead were performed in pack ice.

- Test series 3000, Nos. 3010-3100

Date: 9803063 ; Model: 3950.0001 ; Hice: 37 mm ; σf: 49 kPa
During the two previous series it was discovered that when backing, the L-shaped arm for the propeller view camera was in some cases pushing the ice floes out of the way from the transom. To achieve a more realistic flow of ice around the stern, the L-shaped arm with camera was removed during test Nos. 3080 and 3090. The camera was then reinstalled and an extra backing run was performed in order to get video documentation, hence the extra test No. 3100. No data was recorded during this run.

2.7 Numerical Evaluation

The large quantity of measured data from the level ice and overload tests was recorded into a PC, where thrust, towing force and torque were averaged with respect to a wide range of rates of revolutions. These values were then put into a comprehensive Excel spread sheet, where data was evaluated. The evaluation process is thoroughly described by J.H.Hellmann in reference [2].

2.8 Level Ice Tests

The power of the two 2.6 MW engines is fully sufficient for continuous breaking level ice of 0.45 m thickness at a speed of 6 knots. Level ice is considered as a reference for the icebreaking performance, since undisturbed ice of this uniform thickness is unlikely to be found in the southern Baltic. Both conventional twin shaft propulsion and azimuthing thrusters were tested in level ice equivalent to a full scale thickness of 0.30 m. The curves (Figure 4), correlate well and the differences in predicted performance is very small.

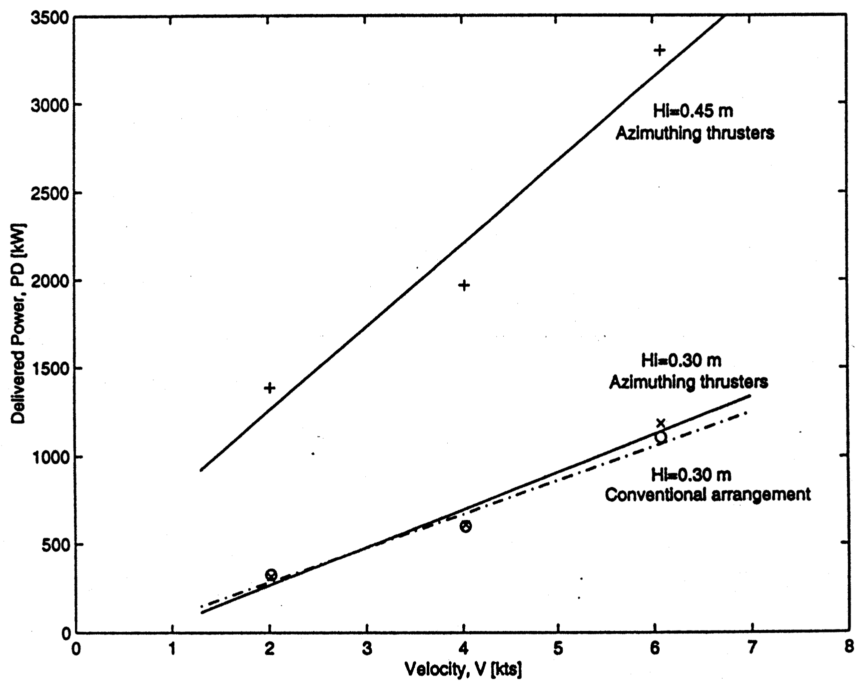

Figure 4 *Towed propulsion tests ahead in level ice. Full scale values.*

2.9 Broken Channel Tests

These tests were carried out to assess the performance of the vessel in a previously broken channel. The broken channel was created by "reassembling" about 90% of the broken ice in the track. The channel was not refrozen but can be considered as a channel broken by a wider ship/icebreaker with marginal ice clearing ability. Extrapolation of curves (Figure 5), should be used with caution as only predictions for two speeds are made. The model equipped with azimuthing thrusters shows a slightly better predicted performance compared than the model equipped with a conventional propeller arrangement.

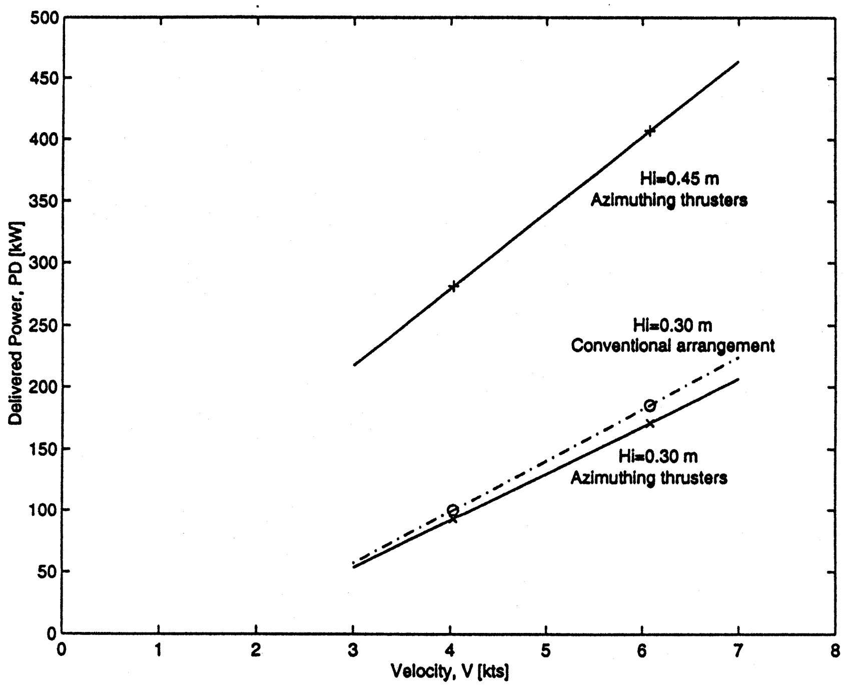

Figure 5 *Towed propulsion tests ahead in broken channel. Full scale values.*

2.10 Ahead Tests in Pack Ice

The pack ice test is a simulation of ice conditions common in the southern Baltic. The pack ice field was prepared by breaking up the remaining level ice into irregular ice floes having a typical edge length of 15 m (f.sc.). This manual arrangement of the ice surface usually yields a covarage of 9/10+. The curves shown (Figure 6) must be regarded as a good indication of expected performance in realistic ice conditions. The model equipped with the conventional propeller arrangement performs notably better at higher speeds than the one equipped with azimuthing thrusters.

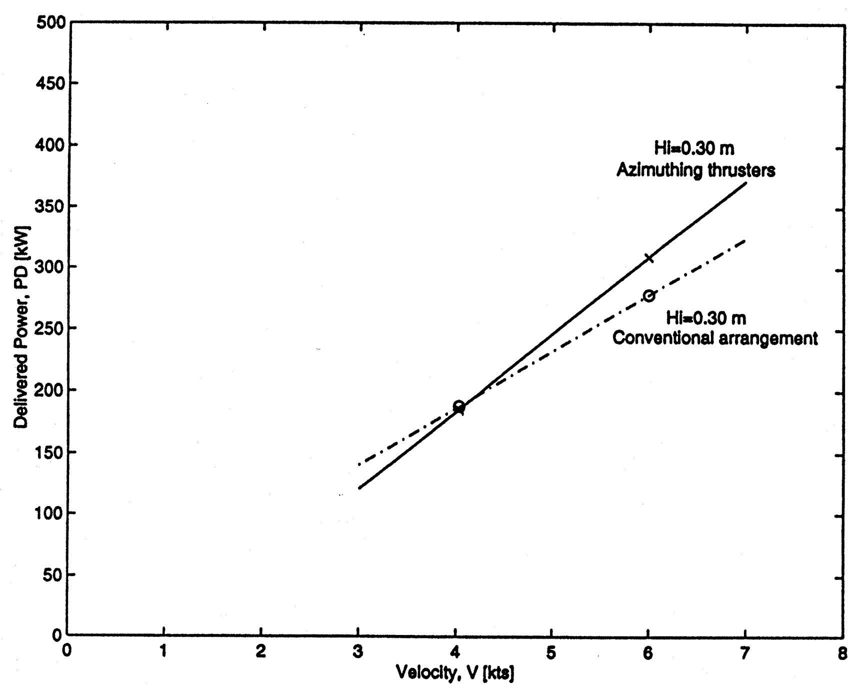

Figure 6 *Towed propulsion tests ahead in pack ice. Full scale values.*

2.11 Total Resistance in Ice

The total ice resistance is presented (Figure 7) and the general impression of the curves is that there is a good correlation. The values associated with the ice thickness of 0.45 m show a constant ratio to the values associated with the lower thickness, which is considered reasonable. The model equipped with azimuthing thrusters performs notably better than the model equipped with a conventional propeller arrangement at the equivalent ice thickness of 0.30 m.

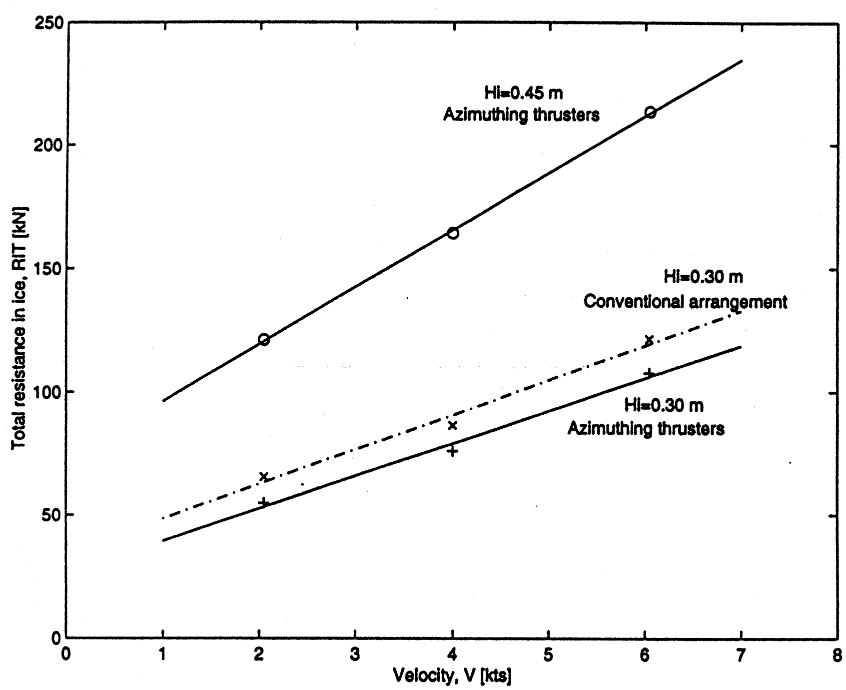

Figure 7 Total resistance ahead in level ice.

3. VISUAL EVALUATION OF THE TESTS

In order to examine the overall behavior of the models, the video recordings and photos from the tests were carefully studied to assess following factors:

- Icebreaking process.
- Ice transport along the bottom of the hull.
- Propeller/ice interaction.
- Performance of the ducktail during backing in ice.

3.1 Observations from the Level Ice Tests

An initial crushing of the ice occurred in an area around the bow, about 5 - 7 cm long. Further aft, the ice tended to break in oblong cusps, with their longer axis parallel to the hull. When the speed was increased, the length of the cusps showed a tendency to decrease. On the other hand, an increased width was observed. With increased ice thickness, there was a clear tendency of increase in the length of cusps. The forward part of the hull bottom was in all level ice tests completely covered with ice floes being submersed by the bow.

In the thinner ice, the mass of ice tended to separate by the keel, forming an ice-free path around the centerline of the model. The width of the path varied from about 45% of the beam in the slowest runs to almost no recognizable path during the fastest runs. The separation point was located at the forward edge of the keel at slow speed, at the midpoint of the keel at medium speed, and at the aft edge of the keel during the fastest runs, when separation was observed.

The runs in the thicker ice at low speed showed some minor separation at only one side of the keel, whereas minor separation was noted at the aft edge of the keel in the medium speed runs. The fastest runs resulted in the hull being completely covered with ice. The bilge keels tended to prevent the ice floes from sliding away from the hull and immersing under the ice sheet. This phenomena was best observed during the slowest runs through the thinner ice. As the path widened, it reached a constant width which remained the same until the ice pieces reached the aft end of the bilge keels. At this point, the ice pieces started to move sideways.

The flow characteristics of the ice floes changed with the increase of speed. At low speeds, the floes glided gently along the hull, forming an even layer of ice pieces, almost like a puzzle. When the speed of the model increased, the ice floes reached a point where the resistance against the hull prevented it from sliding any faster. When subsequent floes caught up with those in front, they were forced downwards below the others, some forming multiple layers, others tumbled freely under the hull. These two conditions showed such similarities to fluid dynamics, that we later on refer to them as: laminar-like and turbulent-like ice flow.

Propeller/ice interaction was observed during all level ice tests. It varied from minor, single incidents during slow runs through thinner ice, to the almost constant milling of ice during the fastest runs in the thicker ice. The condition where the most significant difference between the two propulsion systems was observed, was when the ice pieces moved in the laminar-like flow mode. Ice sliding along the hull, that reached the propeller area, passed through the clearance between the propeller and the hull without, or with just minor contact with the propeller blade tips. Less blade tip contacts were observed with the thruster arrangement than with the conventional propeller arrangement. Smaller pieces getting into the propeller disc area were almost immediately disintegrated. Larger floes were thrown against the rudder, or the vertical struts of the thrusters, being either crushed or split into smaller pieces. No ice getting stuck against the rudder shafts or between the rudders was observed.

The clearance between the propeller and the hull was not wide enough to allow the thicker ice to pass without contact with the blade tips. Therefore, the amount of blade tip contact increased considerably during test runs in thicker ice.

For the conventional propeller arrangement, one major difference in behavior was observed: Ice floes that reached the struts of the propeller shaft, were observed riding up along the shaft. The shaft acted like a ramp that deflected the ice floes away from the hull and directly into the lower front part of the propeller disc (Figure 8).

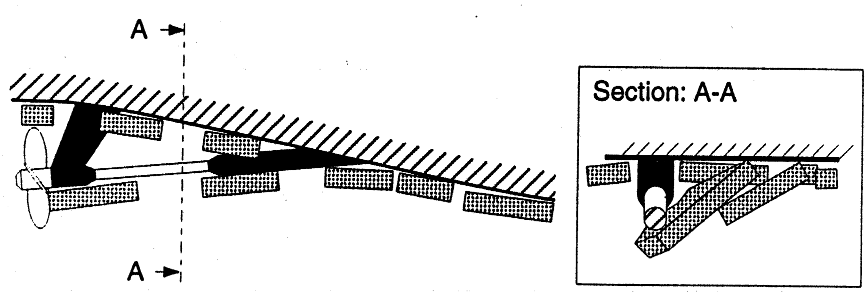

Figure 8 Flow of ice for the conventional propulsion arrangement.

This phenomenon was first observed in the medium speed run. In the slower run, the ice floes passed outwards of the struts and was not influenced by them. During the turbulent-like conditions, the freely flowing floes were sucked directly into the propellers. The floes hit the propeller disc mostly with their edges first. Some single events occurred, when the ice floe were sucked with its flat side into the propeller (Figure 9). As a result they first hit the hub and split into smaller pieces, which were further milled by the propeller. The turbulent-like flow behavior worsened with increasing speed. During the fastest runs, a constant flow of ice floes were seen leaving the hull and milled by the propellers.

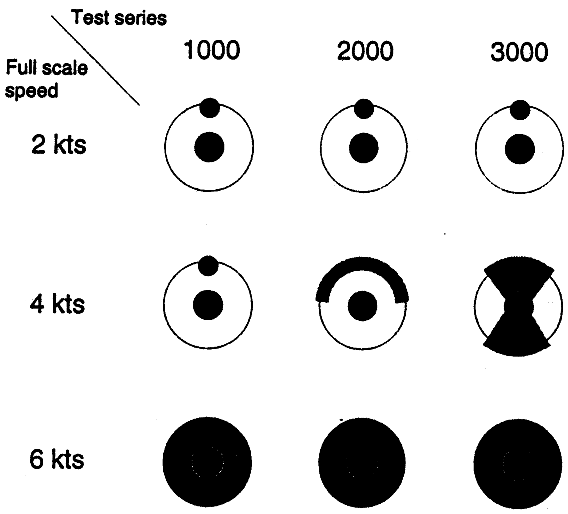

Figure 9
Ice contact during level ice runs.
(starboard propeller)

3.2 Observations during Runs in Broken Channel

When the model was moving ahead in the broken channel, no unusual behavior was observed. The ice pieces in the channel were pushed gently aside by the bow. The width of the ice free path under the hull varied slightly from about 90% of the beam B, at slow speed, to 80% of B at higher speed. Observations of ice/propeller interaction in the thinner ice were few. They occurred only when single ice floes occasionally followed a deeper path under the otherwise ice free bottom.

3.3 Observations during Pack Ice Runs

When the model encountered the larger ice floes in the pack ice field, the sharp bow often split the floe into two pieces and pushed them apart. When the floes could not be pushed aside, they were broken and/or submerged at the shoulders of the model. The size distribution among the ice floes in the pack ice field lead to an irregular flow of ice pieces along the bottom of the hull. The width of the ice free path varied from 20% to 80% of the beam. Increased ice interaction was observed when larger ice floes were broken and slid along the hull. In most cases, the floes struck the propeller in the region close to the hull.

3.4 Observations during Astern Runs

When the model was running astern through the pack ice field, ice floes were initially being pushed by the transom, in the direction of motion. This compression of the pack ice field reached a point where the ducktail started to deflect the floes downward, under the transom. The L-shaped arm for the propeller video was interfering with this breaking process and as a result, the ice resistance was not corrected and supposedly too low. When the arm was removed, the ice floes were pushed in a process, which was considered closer to the real behavior of the transom. The hull bottom was completely free from ice at lower speeds, except when occasional ice floes were flushed beneath the hull. When the speed was increased, large amounts of slush from the propellers blocked the camera view.

In the tests where the thrusters were used in pulling mode, the propeller was situated just below the ducktail. In the same instance as a floe was submerged by the ducktail, it was sucked down by the propeller, passing through the clearance between the propeller and the hull, striking the blade tips on the way. When the thrusters were used in the pushing mode, ice floes too large to pass between the vertical struts got stuck between them. A pile of ice floes was soon gathered, which forced other floes to slide even deeper and forced them into the propeller disc. When the speed was increased, in the faster runs, a constant flow of ice milling by the propellers was observed.

Only one test run with the conventional propeller arrangement was recorded by the propeller viewing camera. During this run, a large amount of ice was forced down under the transom. The ice knifes were observed to split the floes heading for the rudders, but there were several incidents where ice floes were split against the trailing edge of the rudders. A constant flow of ice pieces passed around the rudders and the propeller was observed to ingest large quantities of ice.

4. INFLUENCE OF ICE MILLING ON THE PROPULSIVE EFFICIENCY

In order to quantify the efficiency losses due to propeller ice interaction the propulsion coefficients in ice were determined and compared with those from overload tests performed in ice-free water. In the graphs (Figures 10 and 11), examples of the propulsion coefficients KT (KFX, respectively, for the thrusters) and KQ as well as the propeller/propulsor efficiency ETABV are shown for both model variants (conventional propulsion systems and thrusters) being towed in 0.30 m level ice at a constant speed of 6.05 knots. The data reflect the propeller performance in behind condition from near idling to somewhat above the self propulsion point in ice. In the case of azimuth thrusters the thrust coefficient KFX is determined using the system thrust i.e., it includes all hydrodynamic and ice interaction with the pod.

The graphs (Figures 10 and 11) clearly show that for the higher propeller speeds (lower advance coefficients) the additional torque caused by ice milling is the major factor for the propeller efficiency loss in ice. Compared to the torque the thrust is less affected when ice is passing the propeller disc area. For the conventional propulsion systems the thrust coefficient KT even increases slightly in ice, while for the thrusters the thrust coefficient of the system (KFX) is somewhat lower in ice. The decrease of KFX can be explained by the interaction of ice pieces with the vertical struts. In 0.30 m level ice at a speed of 6.05 knots the self propulsion point is reached for apparent advance ratios JV between 0.31 and 0.33.

For practical purposes it is more reasonable to compare the propulsive efficiencies in ice-free water and in ice for the same values of thrust and speed, rather than for the same JV values. Provided that the towing speed in ice and in open water is the same, the thrust will also be the same for equal values of KT/JV^2. In the graphs (Figures 12 and 13) the ETABV values are plotted together with the ratios of ETABVice/ETABVow as functions of KT/JV^2. The self

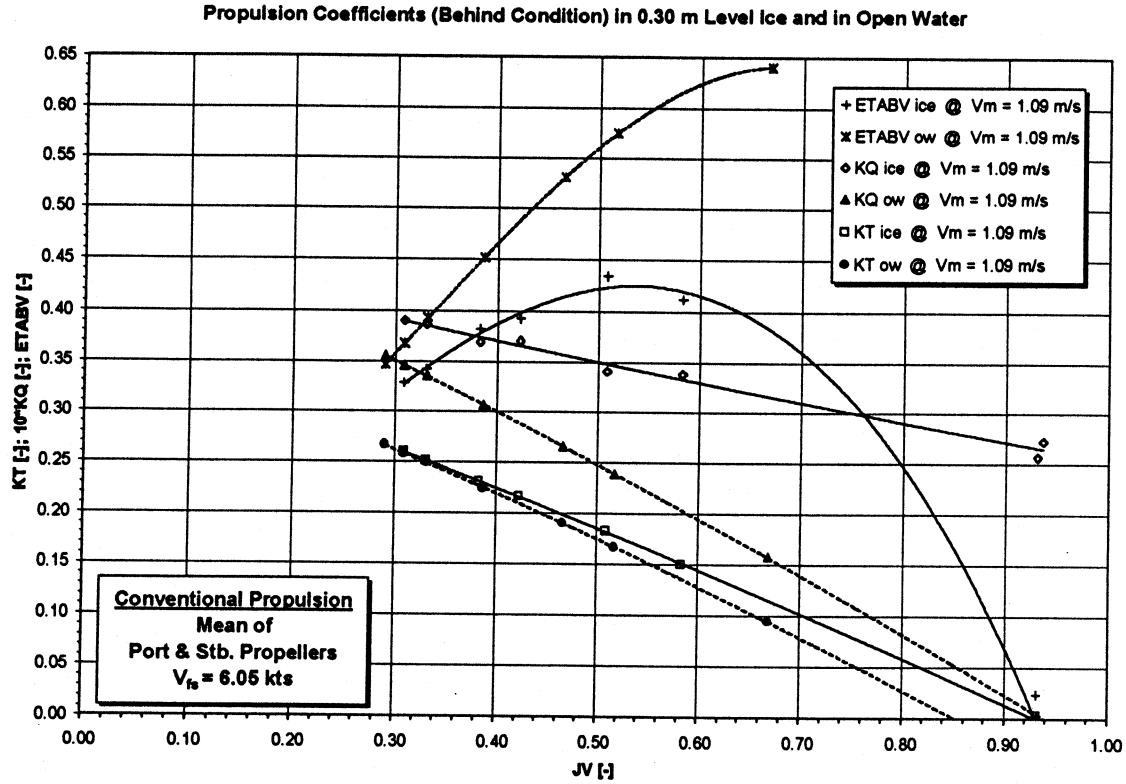

Figure 10   Propulsion coefficients for the conventional system

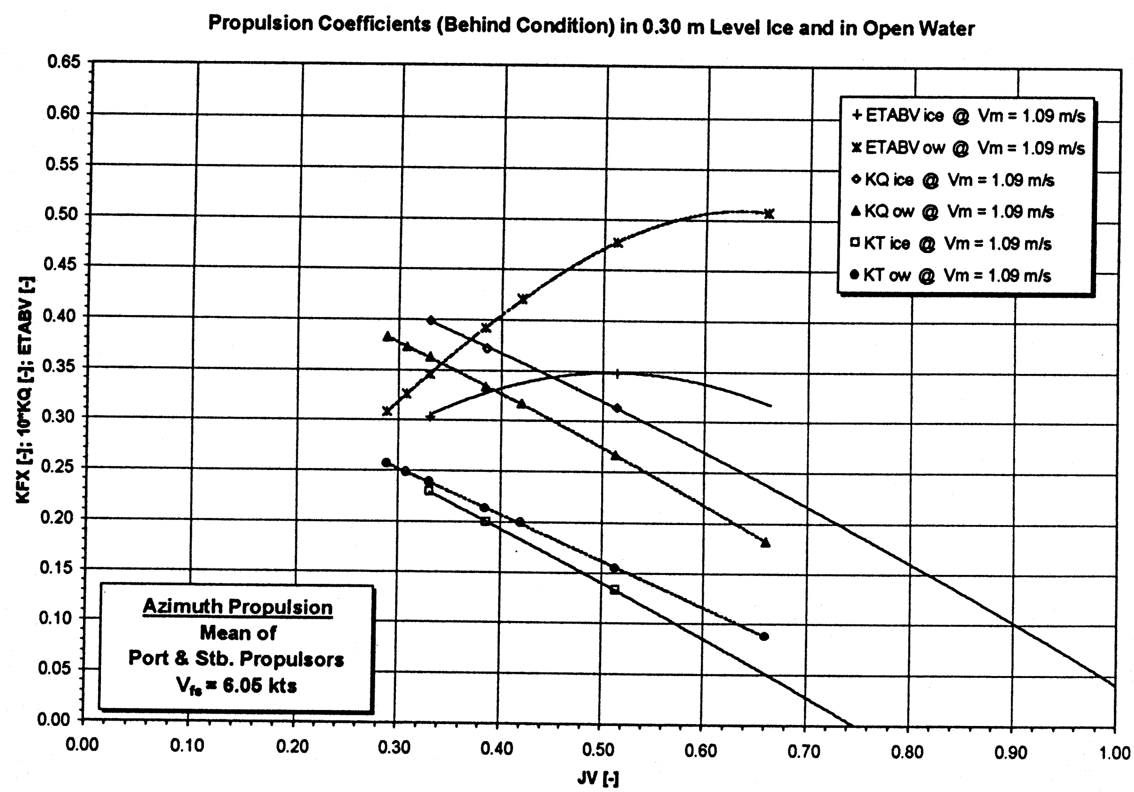

Figure 11   Propulsion coefficients for the azimuth system

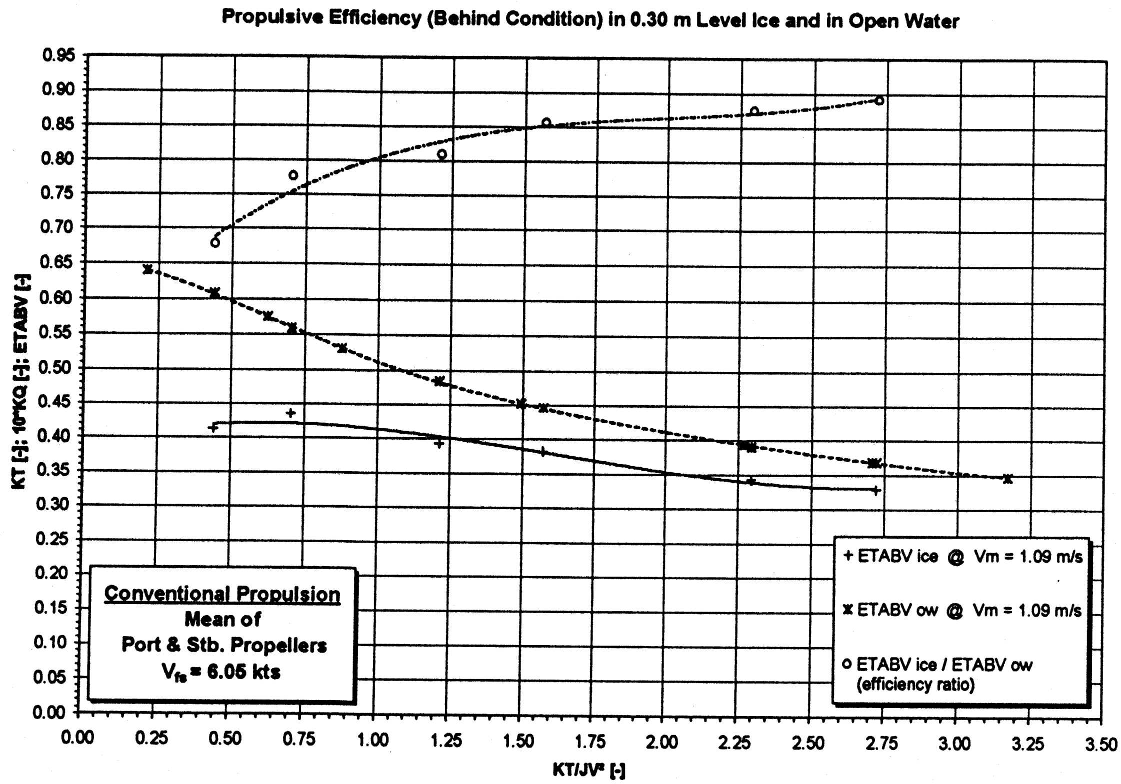

Figure 12 Propulsive efficiency for the conventional system

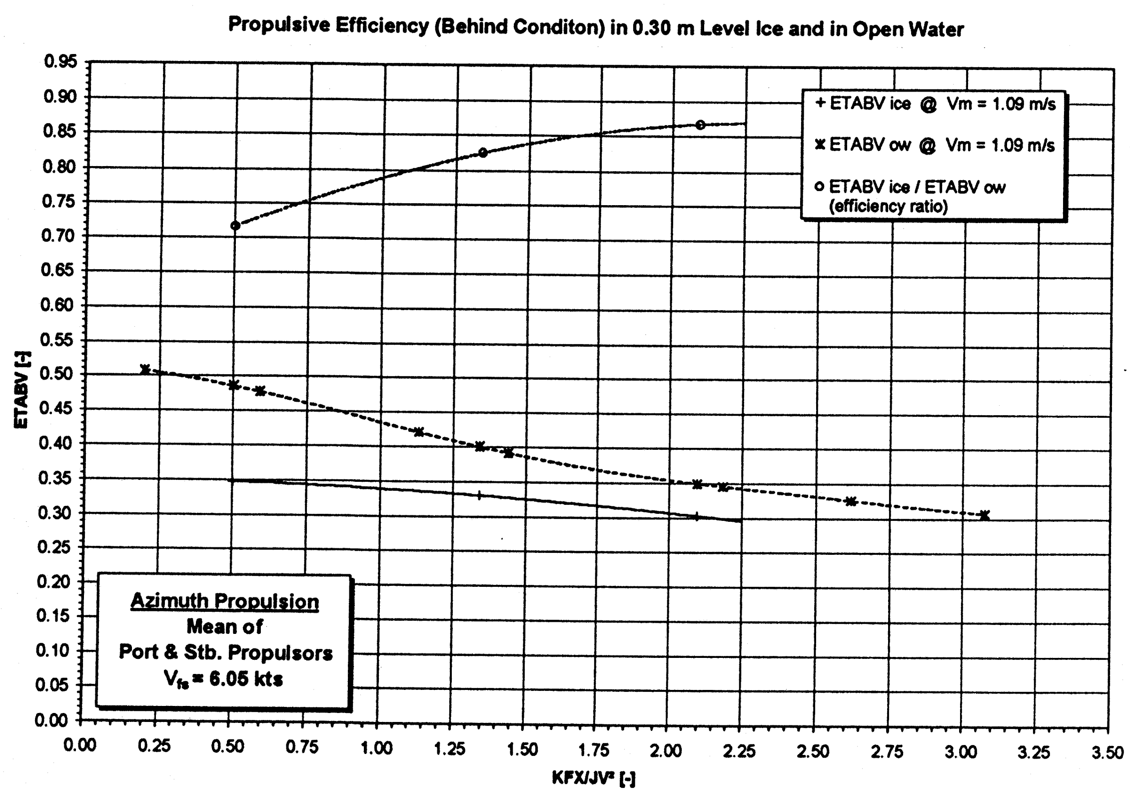

Figure 13 Propulsive efficiency for the azimuth system

propulsion point is reached for KT/JV^2 values between 2.0 and 2.5. In this range the efficiency losses due to ice are less than 15%, and are nearly identical for both of the propulsion systems investigated. This is deemed to be a realistic value for full scale also.

5. CONCLUSIONS AND ACKNOWLEDGEMENTS

The ice model tests show that the KBV 201 with the available power has an ice performance in excess of 0.45 m of level ice at a speed of 6 knots. Both propulsion arrangements allow this performance. To obtain the design operability in 0.3 m of ice, only a fracture of the installed power is needed. Another conclusion is also that great precautions must be taken when operating the ship in ice, not to exceed design loads of the hull and the propulsion system as governed by the ice class. In pack ice this is even more critical as with varying ice thickness and ice concentration the vessel will easily accelerate beyond the structural strength of the hull.

The general impression of the test results was that the thruster arrangement had slightly lower predicted total resistance and delivered power than the conventional arrangement.

The thruster arrangement provides better ability to avoid ice interaction compared to the conventional propeller arrangement. The difference was best observed during the level ice runs. One of the explanations is the way the ice is allowed to pass in the clearance between the hull and the propeller. Of importance is also that the ice is allowed to slide as undisturbed as possible along the hull, before reaching the propeller area. The conventional arrangement had the disadvantage of having the struts deflecting some of the ice floes into the propeller, especially during the medium speed condition.

Running the ship astern with the thrusters in the pushing mode was discovered being the least favorable condition. The fact that ice floes so easily got stuck between the rudder shafts is one reason. Another reason is that the further away from the transom the propeller is working, the weaker is the suction field submerging the ice floes at the transom. The pulling thrusters showed the best performance when backing in pack ice. The position of the propeller enables the ice floes to be submerged and passing through the clearance between the propeller and the hull, with minor ice interaction.

The aft body used to test the thruster arrangement was not fully optimized for the installation. This could be a subject for future studies of the azimuthing thruster arrangement.

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