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Model Tests of the New Canadian Polar Icebreaker (John G. Diefenbaker)

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ABSTRACT

This paper provides an overview of a model test program to evaluate performance of the new Canadian Polar icebreaker, *John G. Diefenbaker* design. The National Research Council Canada (NRC), the Canadian Coast Guard, STX Canada Marine (STXM) and Aker Arctic Technology (AARC) worked closely together to develop a test program, to carry out tests and to discuss test results as well as improvements. The model test program included resistance, propulsion and maneuvering (turning circle) tests both in ice and open water; ice ridge penetration tests; the wake survey, seakeeping and stationkeeping tests in open water. The model tests were carried out at the three model basins (ice tank, open water tow tank and ocean engineering basin) at the NRC's facilities in St. John's, NL. The test results were well utilized in the vessel's design development as well as providing performance evaluation tools at the conceptual design stage. Some of the test results are presented here.

KEY WORDS: Polar Icebreaker, John G. Diefenbaker, model testing, ice tank, offshore engineering basin, towing tank.

INTRODUCTION

The Canadian Coast Guard (CCG) is planning to build a new Polar icebreaker, *John G. Diefenbaker*, to replace the icebreaker *Louis S. St. Laurent*. The new icebreaker will be able to break 2.5 m thick level ice with 30cm snow (total 2.6 m thick ice) at a speed of 3 knots, which will substantially increase the operational limit and extend the serviceable season to strengthen northern sovereignty in the Canadian Arctic. The design of the vessel also considered a new type of propulsion system, a podded propulsor, as well as conventional fixed shaft propeller system. Main parameters of the vessel are shown in Table 1.

Table 1 Main parameter of new polar icebreaker

Length, LOA	149.10 m
Length, LBP	130.67 m
Maximum Beam at waterline	27.29 m
Design Draft	10.50 m
Displacement	24,107 tonnes
Number of Propellers	3

The purpose of this paper is to explain the extensive test program, which took more than 18 months. This significant test program was planned a couple of years before the model test actually started. After model testing started, the test program continuously evolved due to the lessons learned from the test results. Some tests were created/ modified/ canceled due to the dynamic nature of the tests. The test program consisted of three phases. Phase 1 was focused on ice tank tests to determine the best hull form in terms of performance in ice. Phase 2 was focused mainly on seakeeping tests to evaluate the seakeeping performance for the chosen/modified design from Phase 1. Phase 3 involved the final open water resistance/powering. Phase 3 also includes ice maneuvering tests in order to confirm the improvement from a stern form modification. Initially, two phases were planned but during the course of the test program, the hull design was slightly modified for better performance. Consequently overall test program was extended.

Target ice condition for ice resistance tests was relatively thick, at 2.6 m thickness with the flexural strength of 500 kPa in full scale, compared to typical model tests carried out at NRC. Therefore the model testing was quite challenging in terms of producing model ice sheets 104mm thick with the flexural strength of 20 kPa in model scale. Because of the thick ice conditions, there were some concerns about the scalability of the model ice and model ice behavior such as a piece size of the ice, and model-full scale correlation. Two reports were produced in order to support the test results (Lau and Wang, 2012; Lau et al., 2012). For less severe ice condition (up to 1.75m thick at 360 kPa), several model/full scale correlation studies were available. Spencer and Jones (2001), Wang and Jones (2008), and Jones (2006) showed good agreement between model test results and full scale measurement by using the models of the CCG's *R-Class icebreakers*, *Terry Fox* and the USCG's *Healy*, respectively. These papers also describe NRC's standard ice test procedure that was used for the current ice tests.

At a conceptual design stage, the ship designer, STXM and AARC, developed three model configurations. Each of these model configurations was tested in ice in order to select the optimum hull form and propulsion configuration. All three had the same bow shape but two had a knuckle side hull, and the third one had a sloped side hull. The knuckle side model had two propulsion system configurations. The first had three shafted propellers and the second had two wing shaft propellers with one podded propulsor in the centre. The slope side model was equipped with three shaft propellers. It is noted that NRC fabricated two complete models (knuckle and sloped side) and both models were capable of changing their propulsion configuration. A detailed explanation for the model configuration is addressed in Table 2 in PHASE 1 – ICE TEST section. As a final configuration, a model with two shaft wing propellers and one centre pod was selected as the best performer from the ice tests in Phase 1. As the model test program progressed a couple of refinements were carried out on the stern form in Phases 2 and 3 and these are described in the paper.

TEST FACILITIES AND INSTRUMENTATION

Ice Tank

The useable area of the tank for ice testing is 76 m long, 12 m wide and 3 m deep. In addition, a 15 m long setup area is separated from the ice sheet by a thermal door to allow equipment preparation while the test ice sheet is prepared, as shown in Fig. 1. The towing carriage is an 80 ton steel structure and the range of operating speed is from 0.0002 to 4.0 m/s. The test frame of the carriage can move transversely and vertically in order to control the test position. The service carriage is an independent hydraulically operated unit and it is useful for ice control and sampling.

Ocean Engineering Basin (OEB)

OEB is 75 m long, 32 m wide and 4 m high. Waves are generated using 168 independent, computer-controlled segmented wavemakers arranged in a fixed "L" configuration as shown in Fig. 2. Segments are 2 m high and 0.5 m wide and are grouped together in fours to form a module. Each module can be vertically adjusted to accommodate water depths varying from 0.4 m to 3.2 m. The segments can be operated in three articulation modes: flapper (with a maximum excursion of 15 degrees), piston (with a maximum excursion of 400 mm) or a combination of both. These modes are used to optimize segment motion for generating waves in deep, shallow and intermediate water depths, respectively. The multi-segmented wavemaker system can generate unidirectional or multidirectional regular and irregular waves in any direction up to 0.5 m significant wave height. Passive wave absorbers are fitted around the other two sides of the tank. The facility has a recirculating water system based current generation capability with current speed dependent on water depth, extensive video coverage and is serviced over its entire working area by a 5 ton lift capacity crane.

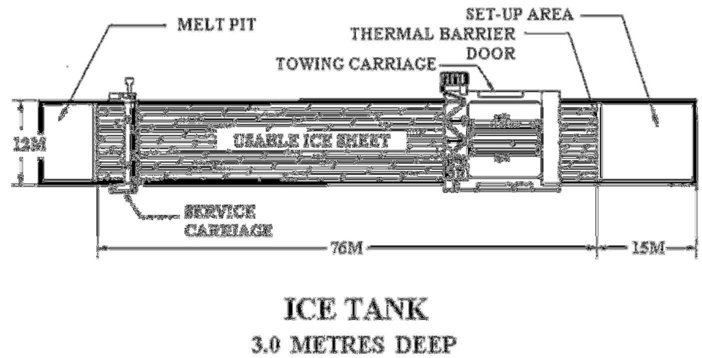

Figure 1. Ice tank

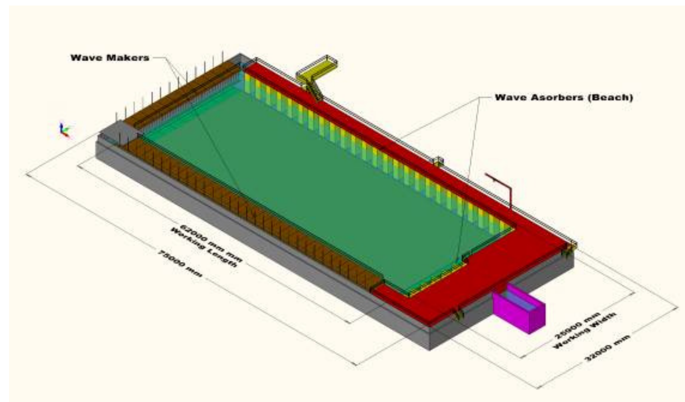

Figure 2. Ocean Engineering Basin (OEB)

Open Water Towing Tank (OWTT)

OWTT is 200 m long, 12 m wide and 8 m high to the top of the wall. It is filled with fresh water to a constant depth of 7 m and is equipped with a dual flap wavemaker. Phasing of wavemaker motions is automatically chosen to optimize the wave profiles. The wavemaker is installed on a raised level with the lower and upper hinges located 4.0 m and 1.2 m below the water level, respectively. This computer controlled hydraulic dry-back wavemaker system can generate unidirectional regular and irregular waves within its performance envelope. Waves are absorbed at the opposite end of the tank by a parabolic beach constructed of a steel frame and covered with wooden slats.

Instrumentation

Towed model set-up
For the resistance and propulsion tests in both ice and open water, the model was instrumented to measure tow force and motions such as heave, roll and pitch. Also measured were carriage speeds, shaft speeds, pod/rudder angles, and thrust and torque for the propellers.

Free running model set-up
For the maneuvering tests in ice, seakeeping and stationkeeping tests in open water, the model was instrumented to measure 6 degree of freedom motions, surge, sway and heave accelerations at the model's centre of gravity (CG). Model speeds, shaft speeds, pod/rudder angles, and thrust and torque of the propellers were also measured.

The following instrumentation was installed in the model:

- A Qualisys optical tracking system was used as the primary system to measure model motions, positions and speeds;

- A MEMSIC VGA (Vertical Gyros Assembly) 700 CB model was used as a backup system to measure pitch and roll angles, pitch, roll and yaw rates and x, y and z accelerations;
- Inclinometers were used for static roll and pitch measurements;
- An accelerometer (model: Q-Flex 3) was used for vertical accelerations at the bow for slamming;
- Relative motion probes were used at both the port and stbd at the bow, noted that they were installed only for seakeeping and stationkeeping tests;
- Dynamometers were used for thrust and torque of the propellers, propeller rotating speeds, pod/rudder angles, and mass displacement from the anti-roll and heeling system (moving mass system).

All instruments and sensors were in-situ or bench calibrated prior to testing. The sampling rate of most channels was 50 Hz.

PHASE 1 – ICE TESTS

Phase 1 ice tests were performed in four months (from Aug to Nov, 2012). Three different configurations were tested at the various ice conditions shown in Table 2. They were designated as KT, KP and ST. KT stands for Knuckle side with Triple screw, KP stands for Knuckle side with centre Pod/wing shaft propellers and ST stands for Sloped side with Triple screw. All models had the same bow form. NRC constructed two complete 1/25 scaled models (OCRE Models 914 and 915) with triple screw propellers and a rudder. The rudder/centre propeller of both models could be replaced by a podded propulsor. For the tests, the knuckle side model was converted from KT to KP to allow testing of the model equipped with a podded propulsor. The resistance and propulsion tests were performed in the towed condition, whereas the maneuvering and ridge penetration tests were carried out with a free running setup with a wireless controlled system. An active heeling system using movable weights was fitted in the model for the maneuvering tests.

Table 2 Model and test ice conditions

	KP	ST	KT
Hull Side	Knuckle Side	Slope Side	Knuckle Side
Stern Configuration	2 x 5.9 m (open) + 1 x 5.6m (pod)	3 x 5.9m (open)	3 x 5.9m (open)
Resistance, Proulsion Tests	2.0 and 2.6 m thick ice	2.6 m thick ice	1.4 m thick ice
Maneuvering Tests	2.3 m thick ice	2.3 m thick ice	2.3 m thick ice
Ridge Tests	1st year ridge	1st year ridge	1st year ridge

Model tests were performed in order to choose the best performing hull form and propulsion configuration in terms of ice resistance, powering, maneuverability and ridge penetration. The shape of the ridge was based on a typical geometry of the first year ridge proposed by Timco et al. (2000).

Resistance in Ice

In the ice resistance analysis, total ice resistance was assumed to be composed of four different components: the ice breaking resistance (R_{br}), the ice buoyancy resistance (R_b, which is a speed-independent term) the ice clearing resistance (R_c, which is a speed-dependent term) and the open water resistance (R_{ow}). From the level ice tests, total resistance in ice was obtained, which was performed at the centre point of the tank. Then the model moved to the south quarter point. Ice sheet at the south quarter point was pre-cut, which is called "pre-sawn ice," based on the bow print from the previous resistance tests. The purpose of the pre-sawn ice tests was to identify the ice breaking resistance (R_{br}) because the total resistance in the pre-sawn consisted only of the R_b, R_c and the R_{ow}. The breaking resistance was calculated by subtracting from the resistance in level ice. The creep speed (0.02 m/s) test with the pre-sawn ice provided directly the ice buoyancy resistance and the ice clearing resistance at test speed can then be calculated from the total pre-sawn ice resistance. Open water resistance tests were performed prior to ice tests to obtain $R_{ow.}$ Fig. 3 shows a snapshot of the resistance test in ice and Fig. 4 shows the pre-sawn ice.

Figure 3. Towed resistance test in ice


Figure 4. Presawn ice

The ice components are non-dimensionalized and represented by coefficients C_{br}, C_c and C_b as shown in Eqs 1, 2, and 3. There are two additional non-dimensional parameters, which are the Strength Number (S_N) and the Froude Number (F_h) as shown in Eqs. 4 and 5. The ice breaking resistance and ice clearing resistance components are dependent on the Strength Number and Froude Number, respectively. Eq. 6 shows the total resistance in ice for the knuckle side model.

$$C_{br} = R_{br} / \rho_i BhV^2{}_m : \textit{Breaking resistance coefficient} \quad (1)$$

$$C_c = R_c / \rho_i BhV^2{}_m : \textit{Clearing resistance coefficient} \quad (2)$$

$$C_b = R_b / \Delta\rho_i gBhT_m : \textit{Buoyancy resistance coefficient} \quad (3)$$

$$S_N = V_M / \sqrt{\sigma_f h \ / \rho_i B} : \textit{Ice number} \quad (4)$$

$$F_h = V_m / \sqrt{gh} \text{ : Froude number} \quad (5)$$

$$\begin{aligned} R_{Total\,in\,Ice} = {} & 0.699 \times S_N^{-1.885} \times \rho_i \times B \times h \times V_m^2 \\ & + 1.452 \times F_h^{-0.804} \times \rho_i \times B \times h \times V_m^2 \\ & + 1.48 \times \Delta\rho \times g \times h \times B \times T \\ & + R_{ow} \end{aligned} \quad (6)$$

Where ρ_i is the ice density, B is the model beam, h is the ice thickness, V_m is the model speed, $\Delta\rho_i$ is the density difference between ice and water, g is the gravitational acceleration, and T_m is the maximum draft of the model.

Fig. 5 shows the total resistance in ice for the knuckle side model with three different ice thicknesses. Fig. 6 shows the resistance comparison between knuckle side and sloped side models. For ice resistance perspective knuckle side model showed much less resistance than that from the sloped side model. Although the bow shape is the same, the results showed quite different values. From video analysis, more friction events along the side of the model were observed on the sloped side model. At 3 and 4 knots of the ship speed, thick/broken ice pieces were trapped between the side of the hull and the edge of the channel, which consequently caused higher resistance. For knuckle side model, the knuckle effectively prevented ice pieces from sticking out of the water and consequently the frictional resistance was less.

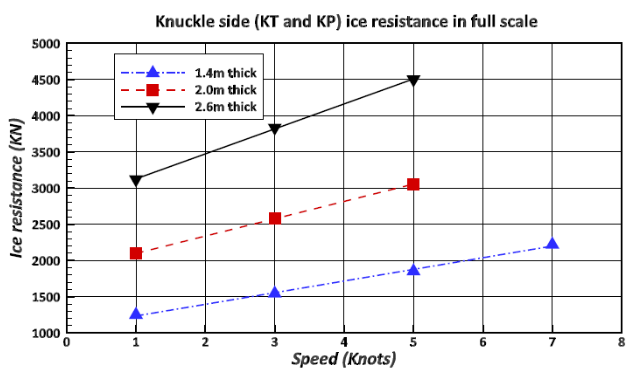

Figure 5. Ice resistance for the knuckle side mode

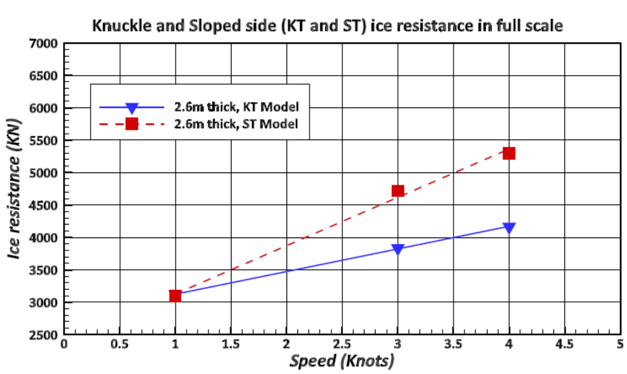

Figure 6. Ice resistance comparison between knuckle and sloped side models

Maneuvering in Ice

The objective of these tests was to assess the vessel's maneuverability in ice. The tests included turning circle, channel breakout, steady ahead, backing and filling, close quarters, towing a beset vessel, and freeing the beset polar model. Since these tests were performed in a free running condition, the primary measurements were the model's motions, including speed and trajectory using the Qualisys™. All maneuvering tests were performed in 2.3 m thick ice at 500 kPa flexural strength in full scale.

Steady ahead

The ability of the model to make steady progress was assessed from the steady ahead tests. In these tests the model was propelled ahead in a straight line at a given steady target speed. A run distance of at least 2 times the ship's length was used for each test. The steady ahead and turning tests were carried out as one test.

Steady turn

The model's turning ability in level ice was evaluated as a primary measure of its maneuverability. The model proceeded at a steady speed parallel to tank wall up to 2 times ship's length prior to turning. To initiate turning, the rudder was placed hard to starboard. For selected runs, the heeling system was also activated to assess its effectiveness in improving the vessel's turning ability. When the model reached the far wall, the motors were placed full astern, and the model was stopped. Fig. 7 shows a snapshot of the steady ahead and turning tests. It is noted that roll angles were achieved using the heeling system.

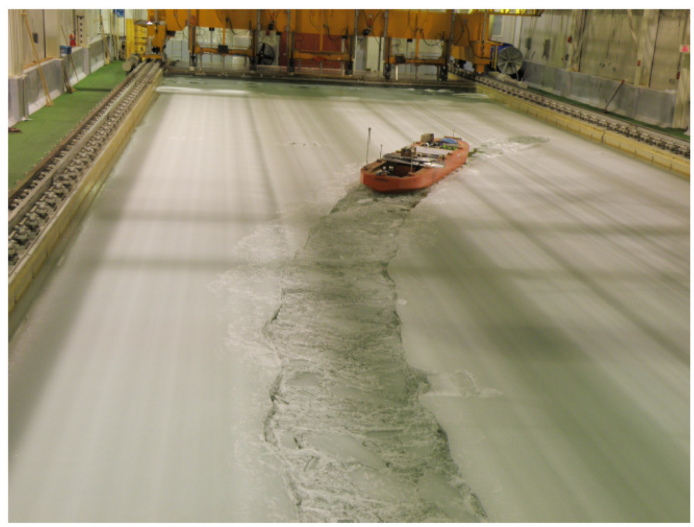

Figure 7. Steady ahead/turn

Channel breakout

Channel breakout tests were performed to determine the ability of the model to break out of its own ice channel. Because of the thick ice and the lengthy model, it was found that channel breakout in ahead motion was quite challenging and time consuming. Although we could create a notch to initiate channel breakout after repeated attempts, which is the same procedure as a real life scenario, we only tested channel breakout in astern in order to save testing time to maintain ice properties for the rest of the tests. Fig. 8 shows a snapshot of the channel breakout test in astern with the KT model.

Figure 8. Channel breakout astern

Backing and filling
The ability to turn the model around in 180 degrees by using a Captain's or Star Turn was carried out at the end of the previously broken channel. This manoeuvre involved a series of ahead and astern motions to complete the 180 degree turn. Fig. 9 shows a snapshot of the backing and filling test with the KT model.

Figure 9. Backing and filling

Turning in close quarter
The objective of the test was to demonstrate the capability of turning in close quarters. During the seeding operation to grow the test ice sheet, one dummy model representative of a typical tanker was moved into a position and frozen. In this test, the polar icebreaker model broke out the beset vessel and towed it. A tow-line load cell was instrumented to measure the tow force. Fig. 10 shows a snapshot of the close quarters by the KT model.

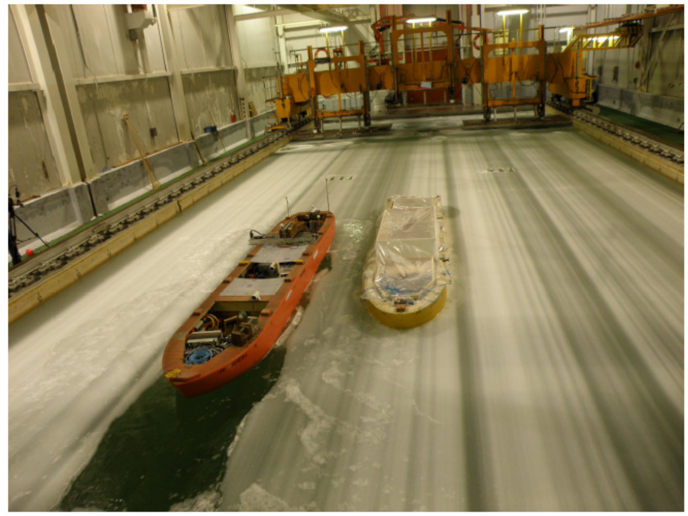

Figure 10. Turning in close quarters

Freeing the beset polar model
The objective of this test was to demonstrate the ability of the beset polar icebreaker model to free itself. During the seeding operation to grow the test ice sheet, the model was moved and frozen into a position. By use of fore and aft thrust and the heeling system, the model broke out of the ice and freed itself. It was noticed that the model was not completely frozen into the ice sheet due to the heat inside the model in order to keep the control and instrumentation system working.

Ridge penetration
The objective of the test was to assess the model's ridge penetration capability at the targeted ship speed. Test set-up and measurements were the same as those of the manoeuvring tests. Two first-year, unconsolidated ridges were prepared from a parental ice sheet of 30 mm thickness (0.75m thick in full scale). Each ridge was tested at two locations (the south and north quarter points) allowing a total of four tests to be performed. Two ahead and two astern motions were tested for each model. The shape of the tested ridge was based on the typical geometry of a first year ridge, which has the keel depth of 0.5m and the sail height/width of 0.1m/2.0m in model scale, respectively. The ridge was constructed using the dump truck method developed at NRC. Fig. 11 shows a snapshot of ridge penetration tests.

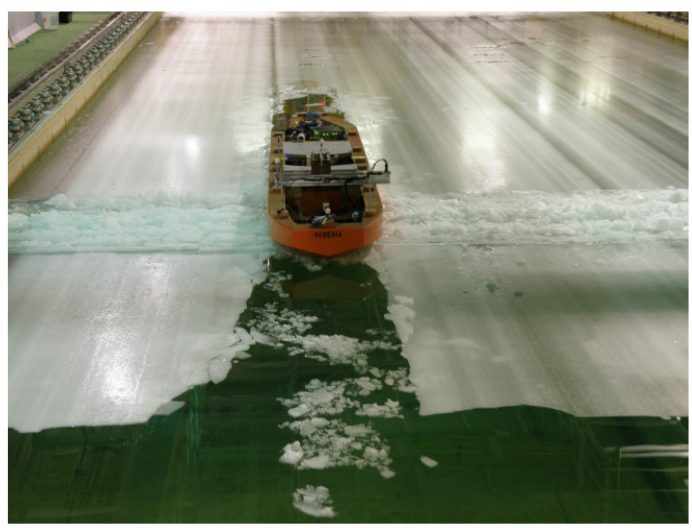

Figure 11. Ridge tests

Conclusion and Discussion for Phase 1

From the Phase 1 model tests, resistance and powering for knuckle side and sloped side models were evaluated. In terms of resistance, knuckle side model showed the best results as it had lower resistance in all ice thicknesses.

In terms of maneuverability in ice, the pod propulsor configuration showed considerably better performance than triple shaft configuration in the ahead mode. The heeling system improved the turning performance for triple screw propeller (KT, ST) but the KP model achieved smaller turning diameters even without using the heeling system. However, during astern maneuvers with podded propulsor it was found that the backing performance was lower than expected. Close examination of the astern ice breaking showed some ice crushing against the pod's strut and further testing at AARC also supported NRC's test results. Based on these test results, a change in the stern lines was made. The main change introduced with the modification was to lower the hull in way of the pod by about 500 mm. The purpose of this change was to ensure that the ice would break on the hull when the ship was backing and before the ice struck the pod strut.

PHASE 2 – WAKE SURVEY AND SEAKEEPING TESTS IN OPEN WATER

After the Phase 1 model tests were complete, CCG held a workshop to select the optimum hull form and propulsion configuration for further design development and model testing in Phase 2. The KP model with the proposed stern modification was selected because it was found to have the lowest ice resistance and best manoeuvring performance. The Phase 2 model tests included propeller open water tests, wake survey/flow visualization, roll decay, slamming/deck wetness, parametric roll, seakeeping, stationkeeping, and turning circle in open water.

After modifying the stern from the existing model with knuckle side, a wake survey was performed. During the tests, an unstable wake in the centre propeller area was found and modifications were recommended in order to improve the wake. Flow visualization tests where then carried out to discover the source of the turbulence. These tests found that there was flow separation where the centre skeg joins the hull and aft of the wing shaft hull bossings. The source of the turbulence was theorized to be caused by the width and shape of the centre skeg gondola and a misalignment of the wing shaft bossings to the flow. In order to ensure that the powering was carried out with the final stern configuration, NRC/CCG/STXM agreed to postpone the resistance and propulsion tests until the 3rd version of the stern was designed by STXM and AARC. STXM and NRC also used a CFD to verify the improvement of the new stern (3rd version stern). Figs 12 and 13 show the CFD results for comparison of two stern versions. For seakeeping tests, it was decided to continue with the 2nd version stern because seakeeping performance wouldn't be greatly affected by minor change of centre skeg. NRC also performed a numerical simulation using Shipmo 3D with original and simplified skeg and confirmed that there was little difference in terms of seakeeping performance.

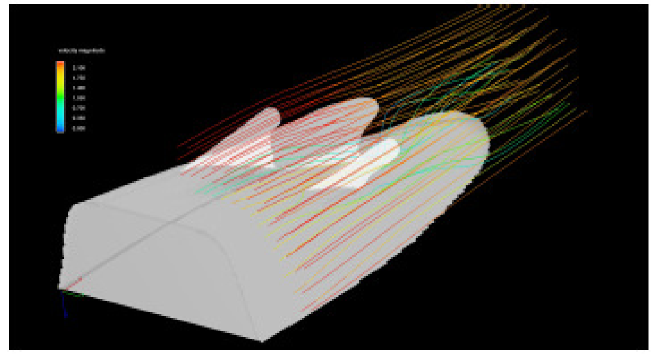

Figure 12. CFD analysis with 2nd version stern

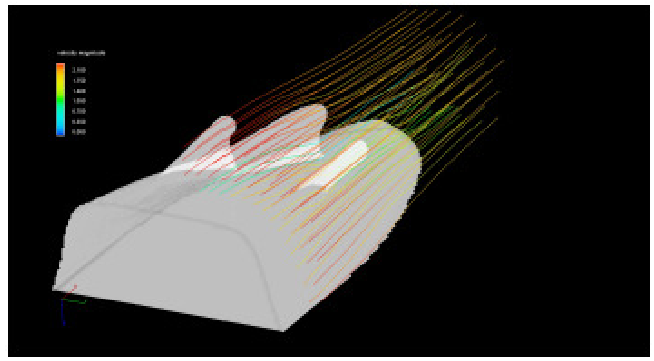

Figure 13. CFD analysis with 3rd version stern

Seakeeping Test Results

Seakeeping results were very good for an icebreaker and met all performance criteria specified by the CCG. Tests in head seas and following seas were carried out in the open water tow tank with a free running set up. Parametric roll tests were also carried out. No significant parametric roll was found in the tests. The seakeeping tests in the OEB were carried out using a 20 min full scale wave spectrum. The anti-roll system was modeled by a moving mass system, which was designed for small roll angles. Most tests were done without anti-roll system in order to provide the baseline data set to validate numerical results for the designer. Selected seakeeping test results (roll standard deviation) with and without anti-roll system are shown in Figs 14 and 15. Before each run, the speed check was performed to confirm that the model speed was within 10 percent error of a target nominal speed. For the zero speed tests, the model was not able to keep the original heading angles due to the tendency of rotating to be beam on in the seas. Consequently the motions at the zero forward speed appear to be overestimated (in Fig. 15). Figs. 16 and 17 show snapshots from seakeeping and stationkeeping tests.

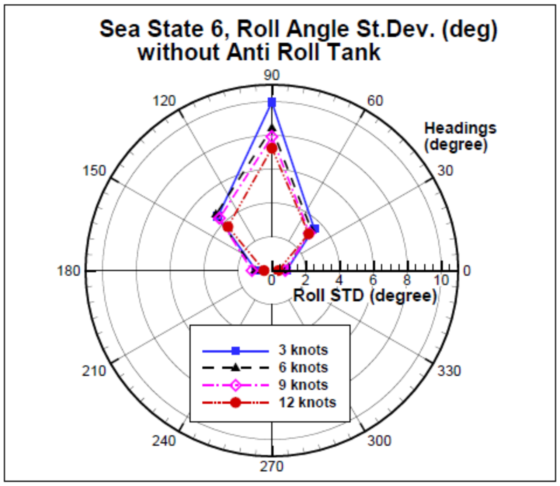

Figure 14. Roll angle standard deviation without anti-roll system

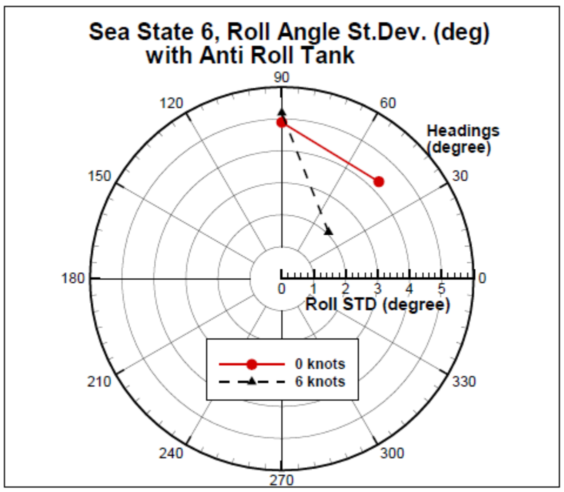

Figure 15. Roll angle standard deviation with anti-roll system

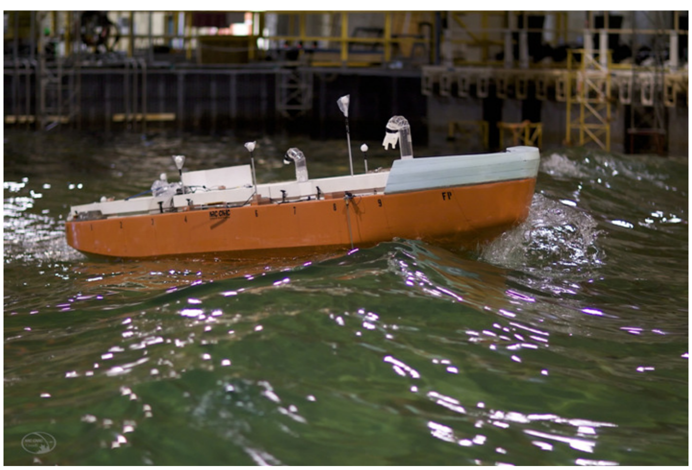

Figure 16. Seakeeping tests

Figure 17. Stationkeeping test

Conclusion and Discussion for Phase 2

From Phase 2 model tests, seakeeping performance of the Polar model was evaluated and promising results were demonstrated. An anti-roll system was designed and used for selected runs. The anti-roll system was quite effective in reducing roll motions; however, an accurate simulation of the anti-roll tank to be fitted on the vessel was difficult to achieve because it required a rapid response of the controlling mass and fast moving mass control algorithm. Since this anti-roll model is valid for a small roll angle only, most seakeeping tests were performed without anti-roll system in order to provide baseline information for numerical validation. Scaling of an anti-roll system is remaining as a research topic to validate the performance with full scale measurement as well as CFD calculation. Station keeping tests were also carried out but the results are still processing at the time of the writing this article.

PHASE 3 – SHIP POWERING IN OPEN WATER

The 3rd stern was modified using the exiting model used for Phase 2. The centre skeg was made narrower and smoother (curvature was reduced). The wing bossing brackets were also lowered to better align with the flow. A wake survey was first performed and the results showed an improvement with much more stable flow. Resistance and propulsion tests in OWTT were then carried out to provide a powering estimation in open water condition. Appended hull resistance was also performed to assess the resistance. Six speeds (5, 8, 12, 15, 18, 19 knots) were tested with various rps for the propulsion tests. For the full scale prediction, ITTC 57 prediction method with an allowance of 0.0004 was used (NRC Standard, 2012). Currently detailed data analysis is being carried out but some selected results are shown. Fig 18 shows the ship powering (effective power and delivery power) estimation.

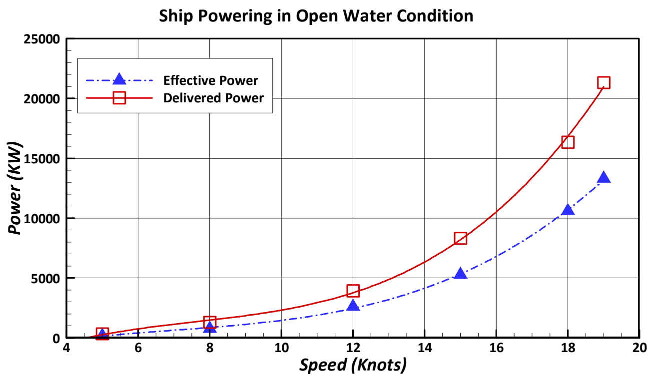

Figure 18 Ship powering in open water condition

CONCLUSION

There were many useful findings from the model tests that were adopted to improve the design. In particular, the tests were used to select between the knuckle side and slope side hull forms and to refine the stern form. A full set of resistance/ propulsion tests in both open water and ice conditions were carried out in order to quantify the expected performance of the ship and the required propulsion power. For the maneuvering tests in ice, various operational scenarios were demonstrated and the results were key factors in the selection of the podded propulsion configuration for the ship. From the seakeeping and stationkeeping tests in open water, NRC found the vessel performed well in waves at all headings. Based on the test carried out with/without anti-roll system, the specified seakeeping criteria are expected to be satisfied.

ACKNOWLEDGEMENT

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