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OSIS-IHI SIMULATION OF THE MANEUVERING PERFORMANCE OF USCGC MACKINAW (WLBB-30): PART II – THE SIMULATION

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ABSTRACT

A series of OSIS-IHI (Ocean Structure Interaction Simulator – Ice-Hull Interaction) simulations is conducted in support of the subsequent USCGC Mackinaw model test and to explain the maneuvering behavior observed of the USCGC Polar Icebreaker indicative design previously tested. This and the accompanied paper document the result of these simulations. The accompanied paper focuses on validation and calibration of the numerical model; while, this paper presents the correlation between simulation and model test results.

KEY WORDS: OSIS-IHI, simulation, model test, maneuvering, ice, Mackinaw

INTRODUCTION

A series of OSIS-IHI (Ocean Structure Interaction Simulator – Ice-Hull Interaction) simulations were conducted to support the Mackinaw model test by providing numerical evidence to explain the observed maneuvering behavior of the indicative design. The accompanied paper (Lau, 2021a) focuses on validation and calibration of the numerical model; while, this paper presents the correlation between simulation and model test results. Lau (2021b) further explores effects of hull geometry and tightness of turns on ship maneuverability as part of this work. For background, scope and objectives of this work, as well as the validation and calibration of the numerical model, please refer to Lau (2021a).

SIMULATION OF MACKINAW IN MODEL TEST CONDITION

The manager of the Mackinaw model test project identified representative sea-trial runs for a case-by-case modeling in OCRE-RC's ice basin. These include three runs in 0.493 m freshwater ice conducted on March 5, 2007 and two runs in 0.610 m conducted on March 6, 2007. (St. John et al., 2012) OSIS-IHI simulation of these test cases was then performed to assist in model test preparation and subsequent data validation. Test types simulated included straight ahead and turning circle maneuvering in ice.

Typical to all rectangular ice tanks with limited tank width, a complete 180° turn required for a tactical diameter simulation is rarely done in OCRE-RC; instead, turning arc maneuvers are performed with the ship stopped prior to 90° heading change. The diameter from such arc is assumed to be representative and sometimes reported as tactical diameter. This practice calls into question the validity of the reported value. Hence, a second series of OSIS-IHI simulations was conducted to examine the validity of such practice by tracking the ship speed, yaw rate and the instantaneous turning diameter for a range of tactical diameters representative of gentle turns made by icebreaking tankers with conventional propeller configurations to the much tighter turns made by podded icebreaking ships.

In addition, a third series of simulations was also conducted with the model in a standard condition of 0.493 m ice thickness and 700 kPa flexural strength, σ_f, but with its shear strength, σ_s, varied, to examine the effect of the σ_s/σ_f ratio on the resulting tactical diameter, since this ratio for the CD-EG/AD/S model ice is significantly higher than that of the freshwater ice encountered in the ice trials (Lau, 2021a). Such difference may have a large influence on the vessel's turning performance.

Model Ice Condition

For ship performance modelling in ice, the primary target for model ice sheets is defined by their flexural strength and thickness, while the shear strength, compressive strength and the elastic modulus can be related to the flexural strength. The two ice thicknesses of 0.493 and 0.610 m encountered at the ice trials were selected (three in 0.493 m conducted on March 5, 2007 and two in 0.610 m conducted on March 6, 2007). The flexural strength was targeted at 700 kPa.

The typical ratio of compressive strength to flexural strength σ_c/σ_f of CD-EG/AD/S used in OCRE-RC's ice tank is about 2 to 3. In this simulation, σ_c was assumed to be 3 times the σ_f.

Since the measured elastic modulus E shows a wide range due to the variation of salinity, temperature, loading rate and orientation,

generally E/σ_f ratio of 2000-8000 can be used for most model tests (Timco, 1986). At OCRE-RC, the average E/σ_f ratio for CD-EG/AD/S can range from 2000 to 3000. In this simulation, E was assumed to be 2000 times the σ_f.

Shear strength σ_s is not typically measured in OCRE-RC; however, Lau et al. measured and reported a value of σ_s/σ_f ratio averaged at 1.33 (Lau et al., 2000) and 1.8 (Lau et al., 1993) for two of their tests at OCRE-RC with CD-EG/AD/S model ice. In this simulation, σ_s was assumed to be 2 times the σ_f. Analysis from a later section suggests negligible effect on simulation results when shear strength increases beyond 800 kPa, i.e., $\sigma_c/\sigma_f > 1.14$ (see top figure of Fig. 5); hence, selection of a σ_c/σ_f ratio as low as 1.14 would not affect significantly the result of this simulation.

Simulation Results of the Main Series

A series of resistance and turning circle simulations was conducted with the Mackinaw in model ice. The test condition of these tests is summarized in Tables 1 and 2, respectively.

Table 1. Test condition for resistance simulation of the Mackinaw in model ice (σ_f = 700 kPa, σ_c= 2100 kPa, σ_s= 1400 kPa, E = 1.4 GPa and μ = 0.05)

Run #	V_A (m/s)	h_i (m)
R1	2.57	0.493
R2	4.12	0.493
R3	6.17	0.493
R4	2.57	0.610
R5	4.12	0.610
R6	6.17	0.610

Table 2. Test condition for turning circle simulation of the Mackinaw in model ice (σ_f = 700 kPa, σ_c= 2100 kPa, σ_s= 1400 kPa, E = 1.4 GPa and μ = 0.05)

Run #	V_A (m/s)	θ (°)	h_i (m)
T1	3.60	30	0.493
T2	4.63	30	0.493
T3	2.83	30	0.610
T4	3.60	35	0.493
T5	4.63	35	0.493
T6	2.83	35	0.610

For towed resistance, simulation was performed in captive mode, while the turning circle test was conducted in the free-run condition. Same procedure adopted in the ice-trial simulation was adopted with a preliminary matching between the propeller speed and ship speed performed prior to the simulation (Lau, 2021a). Appropriate propeller speed was selected to ensure the ship reached the approaching speed specified for each run prior to activating the specified pod deflection. Each run was conducted until the vessel reached at least 540° heading.

The result is reported as the advancing velocity and yaw rate at 180° heading, V_{180} and $\dot{\gamma}_{180}$, the advancing speed and yaw rate at 360° heading, V_{360} and $\dot{\gamma}_{360}$, the tactical and final diameters, D_{180} and D_{360}, the non-dimensional tactical diameter, D_{180}/L (where L is the ship's length between perpendiculars), the ratio of advancing speed at 180° heading to the approaching speed, V_{180}/V_A, and the ratio of advancing speed at 180° to the speed at 360° heading, V_{180}/V_{360}.

Simulation with 35° pod deflection was also performed for each run condition in order to compare the result with the turning circle test data from the RV Araon to gauge the consistency of this simulation to other data sets.

Resistance

Results of the resistance simulation is summarized in Table 3. Fig. 1 plots the total resistance as a function of ship speed for the Mackinaw in open water, 0.493 m ice and 0.610 m ice.

Table 3. Result of the Mackinaw resistance simulations in model ice

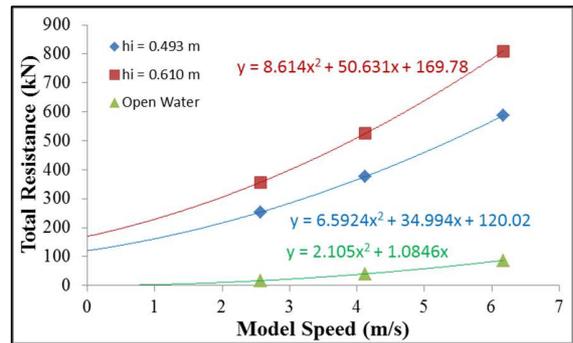| Run #	V_A (m/s)	h_i (m)	σ_f (kPa)	R_{ow} (kN)	R_i (kN)	R_t (kN)
R1	2.57	0.493	700	16.6	236.9	253.5
R2	4.12	0.493	700	40.3	335.8	376.1
R3	6.17	0.493	700	86.8	500.2	586.9
R4	2.57	0.610	700	16.6	340.2	356.8
R5	4.12	0.610	700	40.3	484.3	524.6
R6	6.17	0.610	700	86.8	723.4	810.1

Figure 1. Total resistance as a function of ship speed for the Mackinaw in open water, 0.493 m ice and 0.61 m ice.

Turning Circle

The results of turning circle simulations are summarized in Table 4. The representative plots of ship speed, yaw rate, and instantaneous turning diameter as a function of heading and the ship's maneuvering track for each run are given in Fig. 2.

Table 4. Result of the Mackinaw turning circle simulations in model ice speed and 30° pod deflection

Run #	V_A (m/s)	θ (°)	h_i (m)	σ_f (kPa)	V_{180} (m/s)	$\dot{\gamma}_{180}$ (°/s)	V_{360} (m/s)	$\dot{\gamma}_{360}$ (°/s)	D_{180} (m)	D_{360} (m)	D_{180}/L	V_{180}/V_A	V_{180}/V_{360}
T1	3.60	30	0.493	700	2.74	1.41	2.74	1.41	225.0	226.7	3.08	0.76	1.00
T2	4.63	30	0.493	700	3.54	1.98	3.54	2.04	202.7	203.1	2.77	0.76	1.00
T3	2.83	30	0.610	700	2.08	0.82	2.08	0.82	291.0	294.5	3.98	0.74	1.00
T4	3.60	35	0.493	700	2.45	1.48	2.45	1.47	190.7	194.9	2.61	0.68	1.00
T5	4.63	35	0.493	700	2.46	1.49	2.46	1.48	193.0	193.7	2.64	0.53	1.00

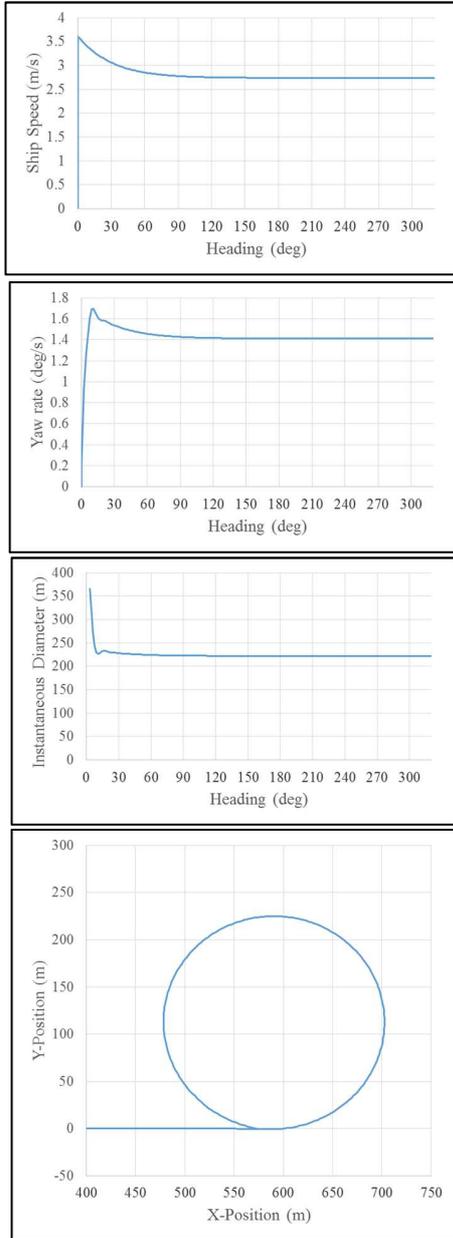| T6	2.83	35	0.610	700	1.87	0.85	1.87	0.85	252.2	255.0	3.45	0.66	1.00

Figure 2. RUN T1: from top to bottom, (a) ship speed, (b) yaw rate, and (c) instantaneous turning diameter as a function of heading for the Mackinaw in 0.493 m / 700 kPa ice at 3.6 m/s approaching speed and (d) its maneuvering track

Figs. 3 and 4 plot the tactical diameter D_{180} and the advancing speed to approaching speed ratio V_{180}/V_A as a function of ice thickness for the Mackinaw in 0.493 m and 0.610 m ice and two pod angles of 30° and 35°. As expected, the tactical diameter increased with ice thickness and decreased with pod angle, which is consistent with existing data of ships turning in ice. The tactical diameter ranged from 2.77 to 3.98 times the ship length for the 30° pod angle, and 2.61 to

3.45 times the ship length for the 35° pod angles. The speed drop increased with a tighter turn at 35° pod angle and was less sensitive to ice thickness. The speed drop at 180° heading was around 25% of the approaching speed for the 30° pod angle and 38% for the 35° pod angle.
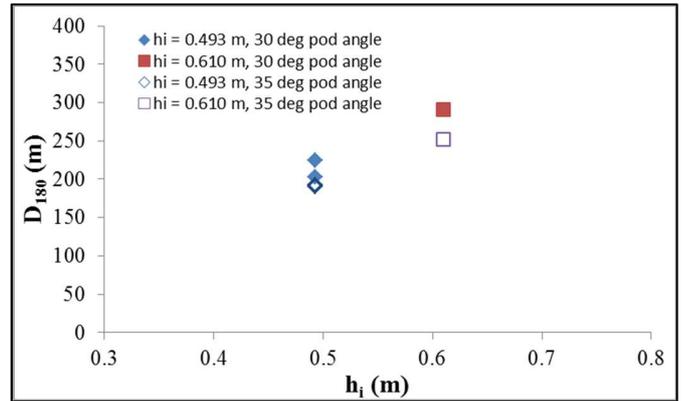

Figure 3. Tactical diameter D_{180} as a function of ice thickness h_i for the Mackinaw in 0.493 m and 0.610 m ice and two pod angles of 30° and 35°
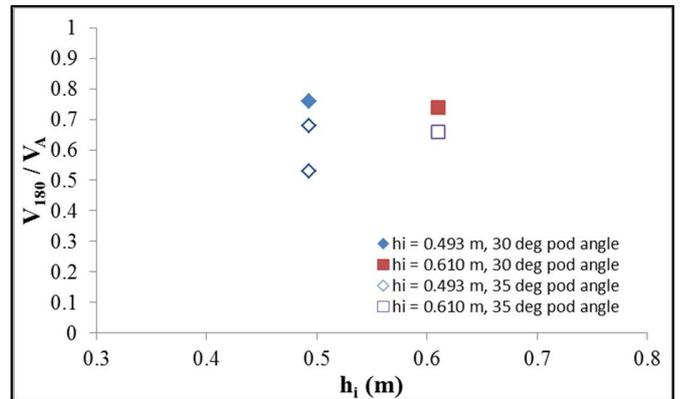

Figure 4. Advancing speed to approaching speed ratio V_{180}/V_A as a function of ice thickness h_i for the Mackinaw in 0.493 m and 0.610 m ice and two pod angles of 30° and 35°

The Mackinaw model has reached constant speed at 180° heading in both the 0.493 m and 0.610 m ice sheets when making the 30° or 35° turn, i.e., $V_{180}/V_{360} = 1$; hence, there is no further increase in turning diameter beyond 180° heading.

The non-dimensional tactical diameter D_{180}/L ranges from 2.77 to 3.98, whereas the ice-trial measurement ranges from 1.51 to 2.31. This can partially attributed to the higher shear strength of the model ice material as will be shown by result of the next series of simulations.

The instantaneous diameter for all cases has already or almost reaches a constant value at 90° heading as shown in Fig. 2. This allows prediction of the rest of the maneuvering track with confidence, and the tactical and final diameters can be estimated from data at 90° heading with accuracy. An additional series of runs to examine this further with

tighter turns is presented in a later section.

Effect of Shear Strength on Turning Diameter

The occurrence of edge shear at a steep slope and high speed in combining with low shear strength as a possible load limiting mechanism of ice has been discussed by Lau (2021a) in the context of cone-ice interaction. For ship turning in ice, edge shear failure may occur at the steeply sloped bow and aft shoulders, if the shear strength is low enough in comparing with the other strengths. As the shear strength decreases further, region of edge shear ice failure may extend further into the bow section at a lower ice-hull interaction angle; hence, it may further reduce the resisting yaw moment.

Run T2 (see Table 4) was selected as the control case with its shear strength varying from 1400 kPa to 429 kPa, i.e. a σ_s/σ_f ratio ranging from 2 to 0.61, to encompass the highest and the lowest σ_s/σ_f used in the model test and the ice trial simulations (Lau, 2021a), respectively. The total resisting moment experienced by the hull and the resulting tactical diameter are shown in Fig. 5. In this case, shear strength starts to provide a load limiting mechanism when it drops below 800 kPa or a σ_s/σ_f ratio of 1.14. The tactical diameter drops from 203.1 m to 108.3 m or 2.77 to 1.83 times the ship length. This result suggests the shear strength may be an important influencing factor to be considered in ship maneuvering in ice modeling. It also provides a probable explanation for the discrepancy between Mackinaw's model test data and its field measurement.
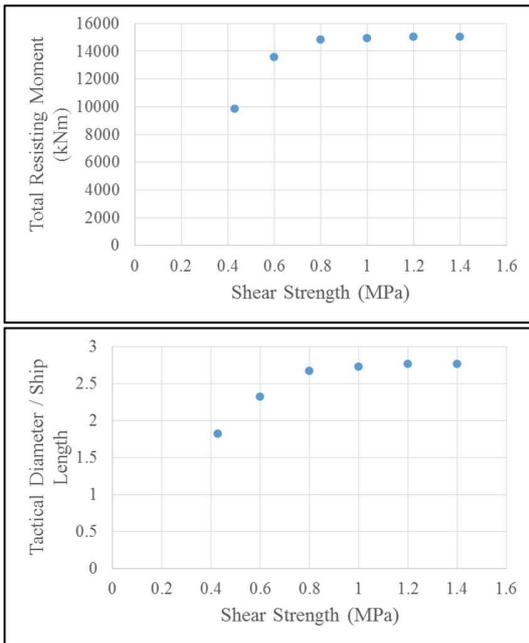

Figure 5. The effect of shear strength: total resisting moment (top) and non-dimensional tactical diameter (bottom) as a function of shear strength for the Mackinaw in 0.493 m / 700 kPa ice at 4.63 m/s approaching speed and 30° pod deflection

The ship speed, yaw rate, and instantaneous turning diameter as a function of heading and the ship's maneuvering track for the runs with 1000 kPa and 600 kPa shear strength are given in Figs. 6 and 7, respectively. When the ship makes a gentler turn, i.e., larger diameter with the higher shear strength of 1000 kPa, it allows sufficient time to

reach a steady turning motion at 90° heading, and hence it results in a true circle when the tactical and final diameters are essentially the same (see Fig. 6d). When the ship makes a tighter turn with the lower shear strength of 600 kPa, there is insufficient time for the ship to reach a steady-state turning motion even when the ship reaches 360° heading. It results in a spiral pattern until the ship reaches a steady speed as observed in the Mackinaw sea trial (see Fig. 7d).

Most ice-going ships are equipped with conventional propellers and designed for operating in an ocean environment. Since model ice seems to model better the σ_s/σ_f ratio of sea ice, modeling challenges from the low σ_s/σ_f ratio for freshwater ice and tight turns enabled by the podded propulsor units of the Mackinaw operating in freshwater ice may not be common. Nevertheless, this modeling issue should be addressed and further investigated as it may contribute to large discrepancy between model predictions and field measurements as exhibited in the Mackinaw model tests.
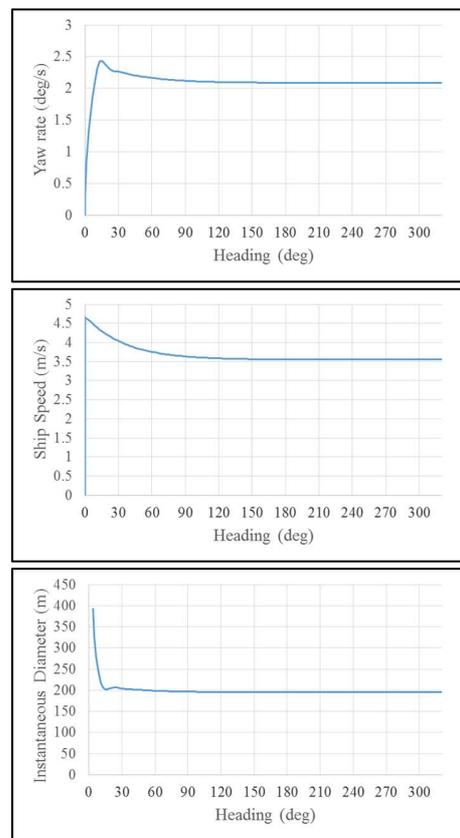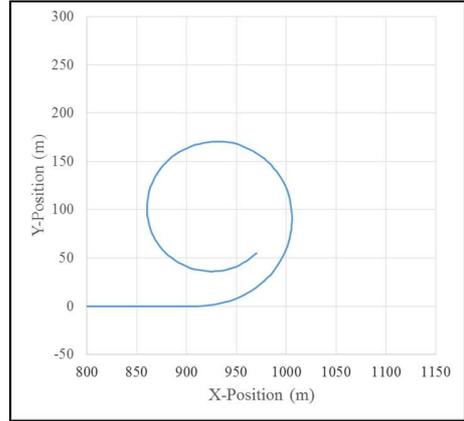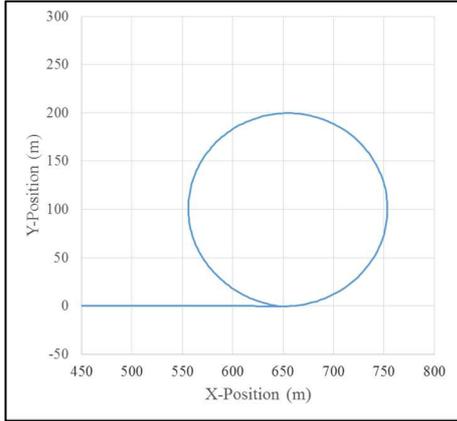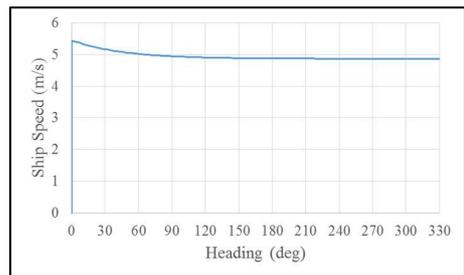
Figure 6. Run T2 with high shear strength of 1000 kPa: from top to bottom, (a) ship speed, (b) yaw rate, and (c) instantaneous turning diameter as a function of heading for the Mackinaw in 0.493 m / 700 kPa ice at 4.63 m/s approaching speed and 30º pod deflection and (d) its maneuvering track

Figure 7. Run T2 with low shear strength of 600 kPa: from top to bottom, (a) ship speed, (b) yaw rate, and (c) instantaneous turning diameter as a function of heading for the Mackinaw in 0.493 m / 700 kPa ice at 4.63 m/s approaching speed and 30º pod deflection and (d) its maneuvering track
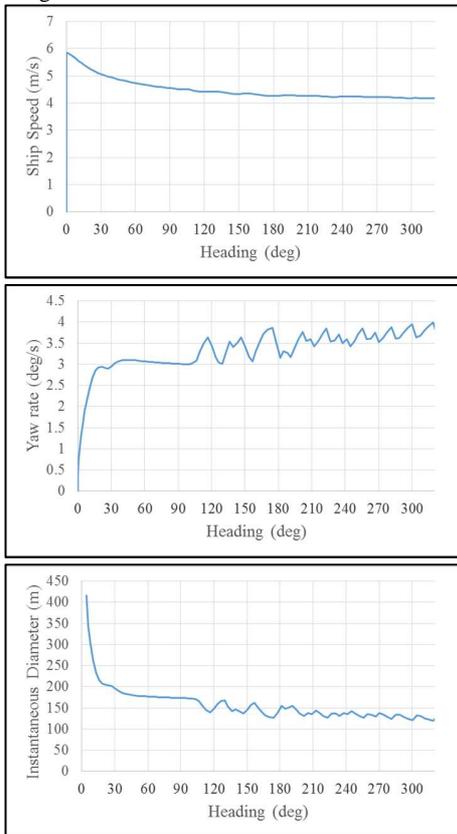
Effect of Turn Tightness to Turn Diameter Evolution

The objective of this series of simulations is to examine the effect of turn tightness on the turn diameter evolution. Of particular interest are the ratio of the instantaneous diameter when the ship reaches a heading of 90º to the tactical diameter D_{90}/D_{180} and the ratio of tactical diameter to final diameter D_{180}/D_{360}. As indicated from the data presented in the previous section, it is advantageous to know when an instantaneous diameter is representative of the tactical diameter or final diameter. The test condition for the turning circle simulation of the Mackinaw at ice trials (Run OT1 with 0.493 m freshwater ice, 5.82 m/s advancing speed, 60º pod deflections, 980 kPa flexural strength, 2300 kPa crushing strength, 600 kPa share strength, 1.4 GPa elastic modulus and 0.0479 friction) was selected as the control case with its pod deflection varying from 5º to 85º. The results from the 20º and 60º pod deflections (representative of gentle and tight turns) are shown in Figs. 8 and 9, respectively. The simulation results in a wide range of tactical diameter from 825.9 m at 5º pod deflection to 35.1 m at 85º pod deflection with the D_{180}/L ratio ranging from 11.29 to 0.48 are shown in Fig. 10.
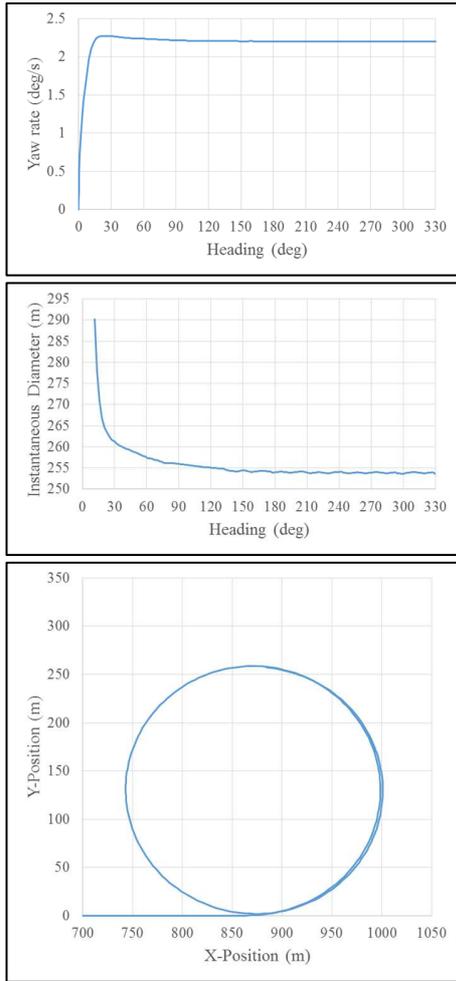
Figure 8. Simulation of run OT1 with a gentle turn at 20° pod deflection: from top to bottom, (a) ship speed, (b) yaw rate, and (c) instantaneous turning diameter as a function of heading for the Mackinaw in 0.493 m/ 980 kPa ice at 5.82 m/s approaching speed and (d) its maneuvering track
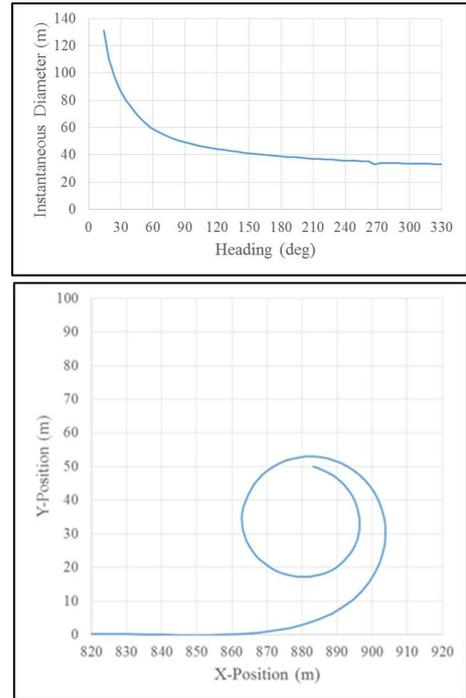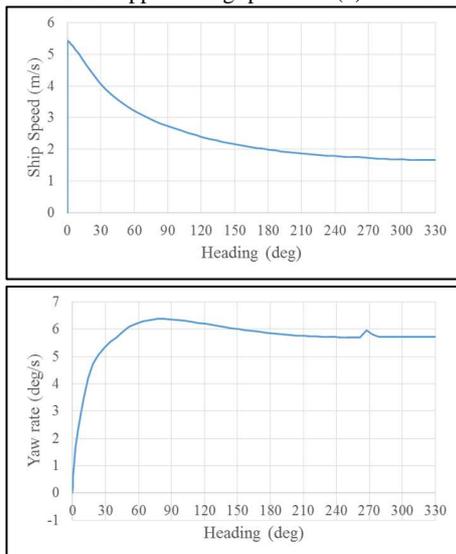

Figure 9. Simulation of run OT1 with a tight turn at 60° pod deflection: from top to bottom, (a) ship speed, (b) yaw rate, and (c) instantaneous turning diameter as a function of heading for the Mackinaw in 0.493 m / 980 kPa ice at 5.82 m/s approaching speed and (d) its maneuvering track
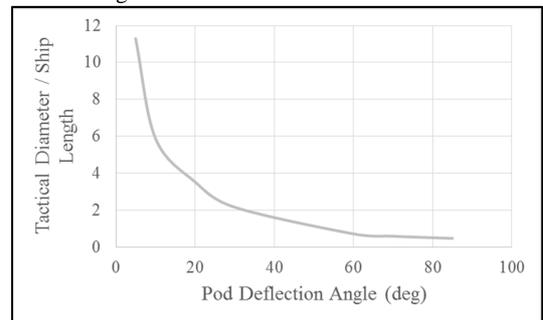

Figure 10. The effect of pod deflection angle on tactical diameter: the Mackinaw in 0.493 m freshwater ice at 5.82 m/s approaching speed (Run OT1)

Figs. 11 shows the ratio of speeds at 180° heading to 360° heading V_{180}/V_{360} and the ratio of tactical to final diameters D_{180}/D_{360} as a function of non-dimensional tactical diameter D_{180}/L, whereas the ratios at 90° heading to 180° heading D_{90}/D_{180} are given in Fig. 12. For this test case, the Mackinaw will reach steady speed even at 90° heading with a non-dimensional tactical diameter as small as 3. This corresponds to a pod deflection angle of less than 25°. This data may serve as a reference to preliminary assess the likelihood of the model reaching a steady motion at 90° heading.
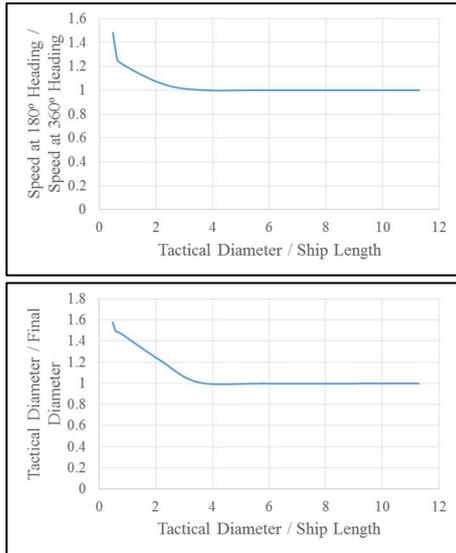
Figure 11. Simulation based on sea trial condition Run OT1: the ratio of speed at 180° to speed at 360° V_{180}/V_{360} (top) and the ratio of tactical to final diameter D_{180}/D_{360} (bottom) as a function of non-dimensional tactical diameter D_{180}/L for the Mackinaw in 0.493 m / 980 kPa ice at 5.82 m/s approaching speed
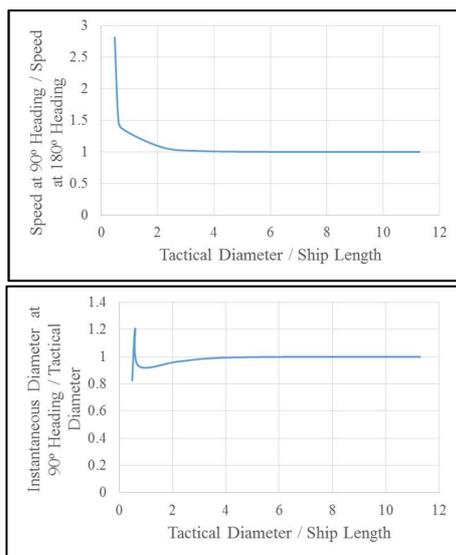

Figure 12. Simulation based on sea trial condition Run OT1: the ratio of speed at 90° to speed at 180° D_{90}/D_{180} (top) and the ratio of instantaneous diameter at 90° heading to final diameter D_{90}/D_{180} (bottom) as a function of non-dimensional tactical diameter for the Mackinaw in 0.493 m / 980 kPa ice at 5.82 m/s approaching speed

Comparison with Data from Other Ships

The Mackinaw performs much better in the ice trials with the non-dimensional tactical diameter D_{180}/L measured between 1.5 to 2.3, whereas the OSIS-IHI predicts a slightly higher ratio of 2.2 to 2.8 for the same ice conditions. (Lau, 2021a) Furthermore, OSIS-IHI predicts

an increase in tactical diameter with increasing ice thickness, contrary to the trend observed in the ice-trial data. (See Tables 8 and 11 of Lau, 2021a). Comparison with data from other data sets may shed light on the discrepancy.

Fig. 13 shows the turning performance of a number of existing ice-going vessels equipped with conventional propulsors. The data show a clear trend in increased non-dimensional turning radius, R/L (or D_{180}/L), with ice thickness. Furthermore, the non-dimensional turning radius ranges from 4 to 13, i.e., 8 to 26, for the non-dimensional tactical diameter, D_{180}/L.

Data for the turning performance of podded ships in ice are scanty. Sasaki and Atlar (2017) gave a review on the maneuvering applications of steerable pods and duct units driven vessels. The non-dimensional tactical diameter made by the podded icebreaker MASTERA is in the order of 2 to 3 as shown in Fig. 14.

Fig. 15 compares the model test data from the Korean icebreaker RV Araon with the OSIS-IHI prediction and ice-trials measurement on the Mackinaw. Since the turning diameter is sensitive to pod angle, result from OSIS-IHI simulation of the Mackinaw at 35° angle is also given to compare the relative performance between the RV Araon and the Mackinaw. The hull form and twin pods between RV Araon and Mackinaw are similar, and they are expected to exhibit similar maneuvering performance. Both vessels have shown superior maneuverability - the trademark of a podded vessel; however, the RV Araon and the MASTERA operating in sea ice have a higher D_{180}/L ratio of 2 to 3 in comparing with 1.5 to 2 for the Mackinaw in freshwater ice. The discrepancy between these sets of data is partially explained by the influence of different σ_s/σ_f ratio between freshwater and sea ices.

Both Figs. 13 and 15 show the maneuvering performance of any vessel generally decreases as ice thickness increases disregarding of the type of propulsors, contrary to the trend suggested by the Mackinaw sea-trial data. Furthermore, OSIS-IHI prediction of the Mackinaw in model ice agrees well with the model test data from the RV Araon since they are using similar ice conditions, e.g., higher σ_s/σ_f ratio. Despite the fact that OSIS-IHI predicts a much larger tactical diameter than that from the Mackinaw ice trials for the 0.61 m ice sheet, the OSIS-IHI prediction agrees well with the data for the 0.493 m ice sheet. The reason for the much lower turning diameter reported for the 0.61 m ice at ice trials in comparing with the other data set is not known that needs further investigation.
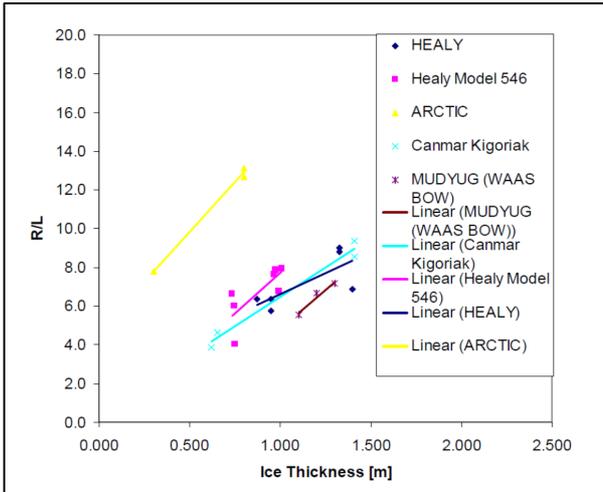
Figure 13. Turning radius to ship length (R/L) vs. ice thickness a number of existing ice-going vessels equipped with conventional propulsors (reproduced from Lau, 2010)
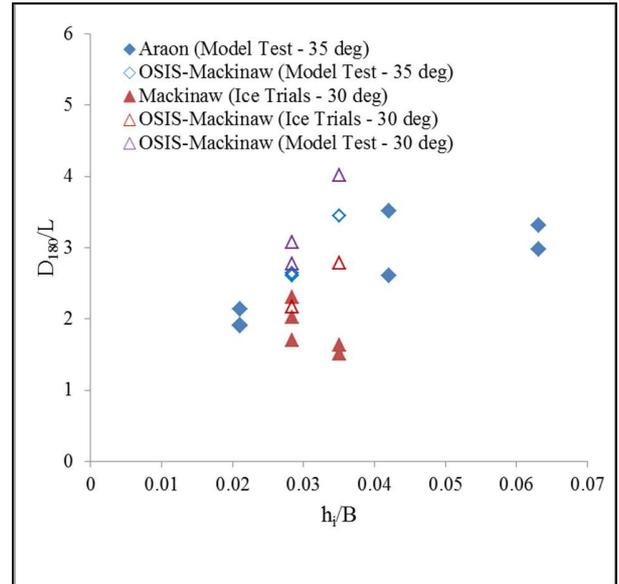

Figure 14. Podded icebreaker MASTERA's turning ability (reproduced from Sasaki and Atlar, 2017)

Figure 15. The non-dimensional turning diameter, D_{180}/L, vs. the non-dimensional ice thickness, h_i/B, for the RV ARAON model test data, OSIS-Mackinaw prediction and Mackinaw ice-trial data
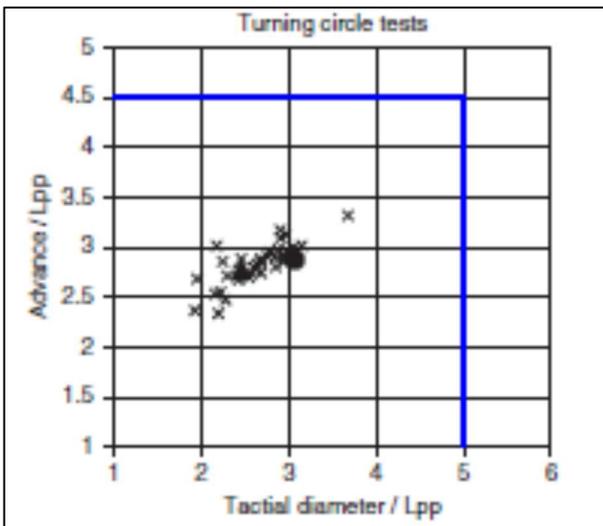
CONCLUSIONS AND RECOMMENDATIONS

This paper documents the result of the OSIS-IHI simulation in supporting the Mackinaw model test at OCRE-RC. This work is preliminary in nature, and important insights have been gained which are worth further exploring to fill in the knowledge gaps, especially in regard to the shear strength and edge shear failure between model and real ice and its implication to model testing.

A number of important findings and conclusions can be made:

• Possibility of edge shear failure at sea trial conditions and its implication: The discrepancy of the OSIS-IHI simulation results between ice trial and model test conditions suggests the importance of adequately modeling the edge shear failure especially for ship maneuvering simulations. The inclusion of the edge shear failure model offers a partial explanation of the higher maneuvering efficiency of the Mackinaw operating in freshwater ice, in comparing with other ships operating in sea ice (or model ice) environments due to their difference in the flexural strength to shear strength ratio. The readers should be cautioned that there is yet no direct evidence reported of edge shear failure associated with the Mackinaw's operation in the Great Lake, and the reported OSIS-IHI result should be treated as preliminary. Nevertheless, the possibility of edge shear failure may have important implications in physical and numerical modeling in certain cases involving high speed, high interaction angle and freshwater ice as demonstrated by the evidences cited in this report.

• Possibility of discrepancy between sea trials and model test data due to different shear strength of ice encountered: The OSIS-IHI simulation results between ice-trials and model test conditions suggest the possibility of discrepancy between ice trial and model test results. It may be expected, as the model is to be tested in model ice with different flexural to shear strength ratio.

• Modeling issues related to shear strength and turn tightness: The effect of shear strength on turning diameter and the effect of turn tightness to turn diameter evolution are also assessed in context of ship turning in ice, especially for podded ships making a tight turn. The result may assist the modelers to interpret their results.

In addition, the following follow-up works are recommended:

• Edge shear related study: The incorporating of edge shear failure as a possible load reduction mechanism has greatly improved the prediction for the sea-trials condition, and partially explained the discrepancy between the model test prediction and sea-trials measurement. Modeling of shear strength is typically not considered in ship-in-ice model testing; hence, shear strength is not measured and its data scanty. From the physical modeling point-of-view, a well-designed bow that favors bow breaking (via flexural failure) or minimizes ice breaking at the aft shoulder (via a shorter and moderate sloped mid-section and sufficiently tapered stern section), any deficiency in modeling shear strength would have minor consequence; however, in the cases where ice frequently interacts with the aft shoulder or mid-section, these deficiency may become an important issue. This issue should be investigated further within the context of model testing.

• Tactical diameter reporting: Some rectangular ice tanks are subjected to limited maneuvering lateral space while doing turning circle maneuvering. Only an arc at early stage of the maneuvers can be obtained (prior to a heading of about 90º) with its turning arc tests due to tank width limitation. For quality control, the validity of the reported tactical diameter should be verified by tracking the instantaneous turning radius to ensure such steady state motion is reached. In the case that it is not reached, a correction procedure to estimate the tactical diameter should be established and standardized.

ACKNOWLEDGEMENTS

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