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MODEL-SCALE/FULL-SCALE CORRELATION OF NRC-OCRE'S MODEL RESISTANCE, PROPULSION AND MANEUVERING TEST RESULTS

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ABSTRACT

There are a variety of model ices and test techniques adopted by model test facilities. Most often, the clients would ask: "How well can you predict the full scale performance from your model test results?" Model-scale/full-scale correlation becomes an important litmus test to validate a model test technique and its results. This paper summarizes the model-scale/full-scale correlation performed on model test data generated at the National Research Council - Ocean, Coastal, and River Engineering's (NRC-OCRE) test facility in St. John's. This correlation includes ship performance predictions, i.e., resistance, propulsion and maneuvering. Selected works from NRC-OCRE on the *USCGC icebreaker Healy*, the *CCGS icebreaker Terry-Fox*, the *CCGS R-Class icebreakers Pierre Radisson* and *Sir John Franklin* and the *CCGS icebreaker Louis S. St. Laurent* were reviewed and summarized. The model tests were conducted at NRC-OCRE's ice tank with the correct density (CD) EGADS model ice. This correlation is based on the concept that a "correlation friction coefficient" (CFC) can be used to predict full-scale ship icebreaking resistance from model test data. The CFCs have been compared for correlation studies using good-quality full-scale information for the five icebreaker models in the NRC-OCRE's model test database. The review has shown a good agreement between NRC-OCRE's model test predictions and full-scale measurements.

The resistance and power correlation were performed for five sets of full-scale data. Although there is substantial uncertainty on ice thickness and ice strength within the full scale data sets that contributes to data scattering, the data suggest a conservative estimate can be obtained to address reasonably this uncertainty by increasing the model prediction by 15% that envelopes most data points.

Limited correlation for maneuvering in ice was performed for the *USCGC icebreaker Healy*. Selected test conditions from the sea trials were duplicated for the maneuvering tests and turning diameters were measured from the arcs of partial circles made in the ice tank. Performance predictions were then compared to the full-scale data previously collected. Despite some discrepancy in ice strength and power level between the model tests and sea trial, the model data agree well with the sea trial data except for three outliers. Otherwise, the maneuvering data show a good correlation between the model test and sea trial results.

INTRODUCTION

There are a variety of model ices and test techniques adopted by model test facilities. Most often, the clients would ask: "How well can you predict the full scale performance from your model test results?" Model-scale/full-scale correlation becomes an important litmus test to validate a model test technique and its results. This paper summarizes the model-scale/full-scale correlation performed on model test data generated at the National Research Council - Ocean, Coastal, and River Engineering's (NRC-OCRE) St. John's facility in support of the evaluation of full-scale prediction from the NRC-OCRE's *CCGS Polar Icebreaker* model test result (Wang et al, 2014). This correlation includes the ship performance predictions, i.e., resistance, propulsion and manoeuvring.

Due to the preliminary nature of this investigation, only selected works from NRC-OCRE's publications, i.e., Jones and

Lau (2006) on the USCGC icebreaker Healy, Wang and Jones (2008) on the CCGS icebreaker Terry-Fox, Spencer and Jones (2002) on the CCGS R-Class icebreakers Pierre Radisson and Sir John Franklin and Spencer (1992) on the CCGS icebreaker Louis S. St. Laurent, were reviewed and summarized.

The model tests were conducted at OCRE's ice tank with the correct density (CD) EGADS model ice.

MODEL-SCALE/FULL-SCALE CORRELATION

Principles of the Correlation

Measurements of ice-hull friction coefficient at full-scale (Mäkinen et al 1994, Schwarz 1986) result in a very wide range of values from 0.01 to 0.6; therefore, most ice tanks test a model at two or more hull-ice friction coefficients, and the friction coefficient that gives the best correlation with full-scale data is found. This is called the "correlation friction coefficient" (CFC), and it can then be used for other models. This concept is analogous to the correlation allowance used in clear-water testing. If the CFC falls in a narrow band of values for all ships of similar hull surface condition, it is assumed that full-scale performance for another similar hull can be predicted from model tests based on the same CFC.

The validity of CFC concept has been studied using good-quality full-scale information for five icebreaker models in the NRC-OCRE's model test database (Newbury and Williams, 1986; Spencer, 1987; Spencer et al, 1988; Nordco Ltd, 1989; Spencer 1992; Jones and Moores, 2002; Jones and Lau, 2006). Table 1 gives the CFCs obtained from each of these studies (Spencer, 1992; Spencer and Jones, 2001; Jones and Lau, 2006; Wang and Jones, 2008). These studies suggest a good correlation between model test data and full-scale measurements by painting the models with a hull-ice friction coefficient of 0.05. For details of the NRC-OCRE's CFC methodology, the reader is referred to Spencer and Jones (2001).

The datasets selected for this study included models with hull-ice frictions close to 0.05, if available. Since each model was at least tested at two hull-ice frictions, the resistance data can be adjusted to 0.05 prior to comparison with full-scale measurements. For this adjustment we assumed a linear relationship between resistance and friction.

Full-Scale Trials and Model Test Data

The model tests and associated sea trials are summarized in Table 1 and they are briefly described as follows. For details, please refer to the cited publications.

CCGS R-Class Icebreakers Several full-scale speed-power icebreaking trials have been conducted with the *R-class icebreakers CCGS Pierre Radisson* and *CCGS Sir John Franklin.*

The *CCGS icebreaker Pierre Radisson* was tested soon after delivery in 1978 during transit in the Central Arctic with ice thickness in the range of 0.8 to 1.3 m and ice flexural strength estimated at 200 kPa. In February 1979, further tests were conducted in thinner but stronger ice in the St. Lawrence River where ice thickness ranged from 0.2 to 0.7 m and ice flexural strength varied from 400 to 500 kPa (Edwards et al, 1979).

Tests were conducted on the *CCGS icebreaker Sir John Franklin* in Notre Dame Bay, Newfoundland in February 1991, where ice thickness was between 0.5 and 0.6 m, and flexural strength ranged between 200 and 300 kPa (Williams et al, 1991 and 1992).

Model level ice resistance tests were conducted at NRC-OCRE on a 1:20 scale model covering a wide range of speed, ice thickness and strength with two hull-ice friction coefficients of 0.03 (Spencer et al, 1992) and 0.09 (Newbury, 1988). Newbury and Williams (1986) summarized R-Class icebreaker model test results.

CCGS Icebreaker Terry-Fox The full-scale trial for the *CCGS icebreaker Terry-Fox* used in this study was conducted in 1990 by Fleet Technology Limited (Cowper, 1991). The ice thickness was 1.55 m and the flexural strength was 150 kPa. In this trial, the Terry-Fox was towed by the *MV Ikaluk* to measure resistance directly. Self-propulsion tests were also conducted to measure power and thrust.

A 1:21.8 scale model has been tested with three different hull-ice friction coefficients (0.11, 0.045 and 0.005) and several ice conditions over a period of more than 20 years. The datasets used in this review were from Spencer et al (1988) with a hull-ice friction of 0.11 and Nordco Ltd. (1989) with a hull-ice friction coefficient of 0.045.

CCGS Icebreaker Louis S. St. Laurent Full-scale data was obtained from ARCTEC Canada (Noble and Comfort, 1979) in its July 1979 Strathcona Sound trials. Immediately prior to these trials, a new INERTA 160 coating was applied over the ship's bow and waterline regions; thus the hull condition during these trials may be similar to a new ship on its maiden voyage. Ice thickness varied from 0.76 to 1.36 m, and mean flexural strength was only 150 kPa averaged over five cantilever beam tests. Snow cover was very light and was not a factor in these trials. Shipboard measurements were shaft speed (RPM) and ship speed. Ship resistance was estimated from RPM only in model overload tests.

Resistance of the 1:15 scale model of Louis S. St. Laurent was extensively measured at NRC-OCRE (Spencer, 1987) with a hull-ice friction coefficient of 0.13 and ice thicknesses of 47, 67 and 100 mm corresponding to 0.7, 1.0 and 1.5 m full-scale for the ship. The target ice strength was 30 kPa corresponding to 450 kPa full-scale. It was subsequently refinished and tested with a 0.07 hull-ice friction coefficient (Fleet Technology Ltd., 1992) and the same target ice thickness and ice strength.

USCGC Icebreaker Healy Extensive full-scale ice trials of *USCGC icebreaker Healy* (Sodhi et al., 2001) were performed in 2000 shortly after its delivery to the US Coast Guard with ice thickness in the range of 0.6 to 1.75 m and ice flexural strength from 190 to 400 kPa. Snow depth ranged from 3 to 20 cm. At full power of about 28,800 HP, the ship broke 1.75 m level ice with an average flexural strength of 360 kPa at 2 knots, and the ship achieved 4.66 to 5.33 knots in 1.37 m level ice with the same flexural strength. Besides continuous icebreaking, the Healy trials also included manoeuvring.

Following the full-scale trials, a complete set of resistance, propulsion and manoeuvring model tests with a 1:23.7 scale model of the ship were performed at NRC-OCRE in scaled ice conditions for correlation with the full-scale data. Jones (2005) has summarized the results of the resistance and propulsion model tests, and Lau (2006) the manoeuvring tests. Two hull-ice friction coefficients of 0.014 and 0.034 were used.

Ship Resistance Correlation

The correlation between full-scale and model scale tests in ice is shown in the following manner. First, full-scale open water bollard and speed-power trials are compared with corresponding model tests to confirm that the model tests accurately predict the ship performance in open water. In general, a ship moving through an ice sheet is in an overload condition. Thus, a thrust deduction factor is determined from open water and overload model tests. While it would be preferable to measure the thrust deduction factor at full-scale, these tests are expensive. An alternative is to use thrust deduction factors derived from model overload tests. The full-scale resistance in ice for the ship is then determined from the measured trials data and the thrust deduction factor mentioned above. Detailed procedure is given in Spencer and Jones (2001).

IOT standard method for analyzing resistance tests in ice (Jones and Moores, 2002) was followed to compute model resistance in ice and then it was scaled to full-scale according to Froude's law prior to comparison.

The resistance correlation was performed for five sets of full-scale data, including the trials for the *CCGS icebreaker Louis S. St. Laurent*, *CCGS icebreaker Terry-Fox*, *CCGS icebreaker Pierre Radisson* and *CCGS icebreaker Sir John Franklin* (See Table 1).

The result of the ship resistance correlation is given in Fig. 1. The 1:1 fit line indicates perfect correlation. The figure shows a good correlation between the full scale prediction from model test data and the sea trial measurement when the friction of the ship's hull is considered. Correlation is even better with thicker ice, i.e., the range of interest, which corresponds to higher resistance. There is substantial uncertainty on ice thickness and ice strength within the full scale data sets that contributes to data scattering. A 1:15 fit line is plotted on the figure that envelopes most data points. This suggests a conservative estimate can be obtained to address this uncertainty reasonably by increasing the model prediction by 15%.

Ship Power Correlation

IOT standard method for analyzing propulsion tests in ice includes propulsion overload tests in open water combined with limited ice tests. The principle of the method is that overload experiments in open water are used to predict the hydrodynamic torque required to develop a thrust sufficient to move the hull against a force equal to the hull resistance in ice. Because such open water tests cannot take account of any ice-propeller interaction, it is necessary to conduct a corresponding experiment in ice to determine the increase in torque due to propeller-ice interaction. It is assumed that propeller-ice interaction has a negligible effect on the thrust developed by the propulsion system. This has been shown to be true for small values of h/D where h is the ice thickness and D is the diameter of the propeller (Molyneux, 1989). The background and theory of the method is given in Jones and Lau (2006).

The power correlation was performed for 5 sets of full-scale measurement, including the trials for the *USCGC icebreaker Healy*, *CCGS icebreaker Terry-Fox*, *CCGS icebreaker Pierre Radisson* and *CCGS icebreaker Sir John Franklin* (see Table 1). Model self-propulsion tests in ice were not performed so delivered power for the model had to be estimated from the model ice resistance tests and the performance of the model in overload conditions in open water. Again, the resistance data were adjusted to the correlation friction coefficient of 0.05 by assuming a linear relationship between resistance and friction prior to power computation.

The result of the ship power correlation is given in Fig. 2. Again, the figure shows a good correlation between the model test prediction and the sea trial measurement. The 1:15 fit line envelopes most data points suggesting that a conservative estimate can be obtained by increasing the model prediction by 15%.

TABLE 1 SUMMARY OF MODEL-SCALE/FULL-SCALE STUDIES. THE CFC IS THE FRICTION COEFFICIENT WITH WHICH A PERFECT CORRELATION IS ACHIEVED BETWEEN THE MODEL-SCALE AND FULL-SCALE DATA.

	Sea Trial					Model Test	Correlation	
	Date	Location	Thickness (m)	Flexural Strength (kPa)	Reference	Reference	Correlation Friction Coefficient	Reference
CCGS Pierre Radisson	July & August 1978	Central Arctic	0.8 - 1.3	200	Edwards et al, 1979	Newbury and Williams, 1986	0.05	Spencer and Jones, 2001
CCGS Pierre Radisson	Feb. 1979	St. Lawrence River	0.2 - 0.7	400 - 500	Edwards et al, 1979	Newbury and Williams, 1986	0.06	Spencer and Jones, 2001
CCGS Sir John Franklin	Feb. 1991	Notre Dame Bay, NL	0.5 - 0.6	200 - 300	Williams et al, 1991 & 1992	Newbury and Williams, 1986	0.065	Spencer and Jones, 2001
CCGS Louis S. St. Laurent	1979	Strathcona Sound	0.76 - 1.36	150	Noble and Comfort, 1979	Spencer, 1987; Spencer 1992	0.05-0.07	Spencer, 1992
CCGS Terry-Fox	1991	Central Arctic	1.55	150	Cowper, 1991	Spencer et al, 1988; Nordco Ltd, 1989	0.05	Wang and Jones, 2008
USCGC Healy	April & May 2000	Baffin Bay	0.6 - 1.75	190 - 400	Sodhi et al, 2001	Jones and Moores, 2002; Jones and Lau, 2006	0.05	Jones and Lau, 2006

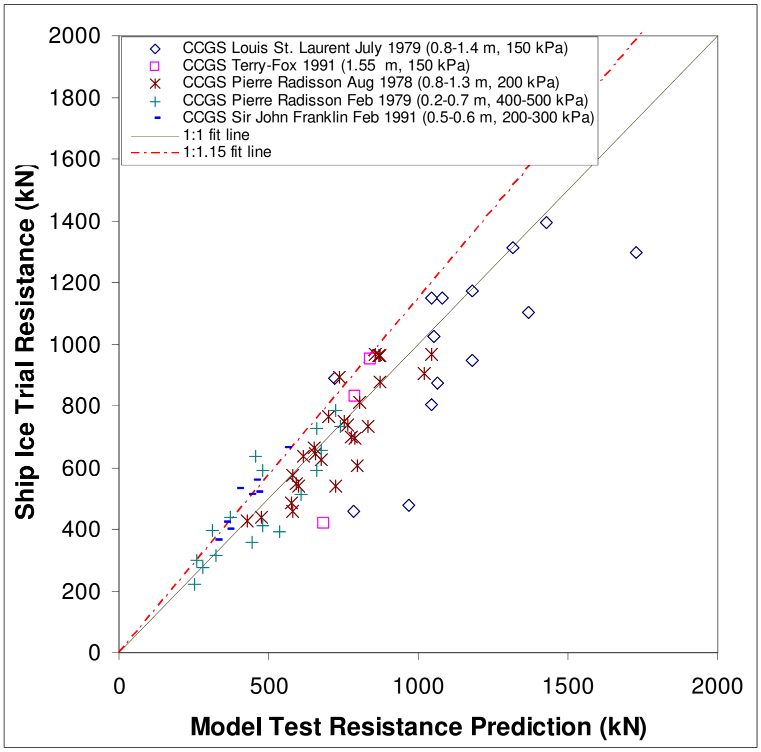

FIGURE 1 RESULT OF THE SHIP RESISTANCE CORRELATION

Ship Manoeuvring Correlation

The manoeuvring correlation was performed for the *USCGC icebreaker Healy* (Jones and Lau, 2006). Selected test conditions from the sea trials were duplicated for the manoeuvring tests and turning diameters were measured from the arcs of partial circles made in the ice tank. The turning diameters were then non-dimensionalized and compared to the full-scale data previously collected. The tests were conducted at a target full-scale ice thickness of 0.75 m and 1 m with an ice strength ranging from 483 to 1,081 kPa. The rudder angle was kept at 30 degrees as used in the sea trials. The delivered power was targeted at around 30,000 hp, which was consistent with the delivered power employed during the full-scale trials.

Figure 3 shows the comparison of the non-dimensional turning diameter (turning diameter/ship length) as a function of non-dimensional ice thickness (ice thickness/ship beam) for the sea trial and model test data. Despite some discrepancy in ice strength and power level between the model tests and sea trial, the model data agree well with the sea trial data except for the three data points (Runs 506_0015, 515_1532) identified in the figure. The reason for these apparent outliners is not known. Other process may be at play that warrants further study. Otherwise, the manoeuvring data show a good correlation between the model test and sea trial results.

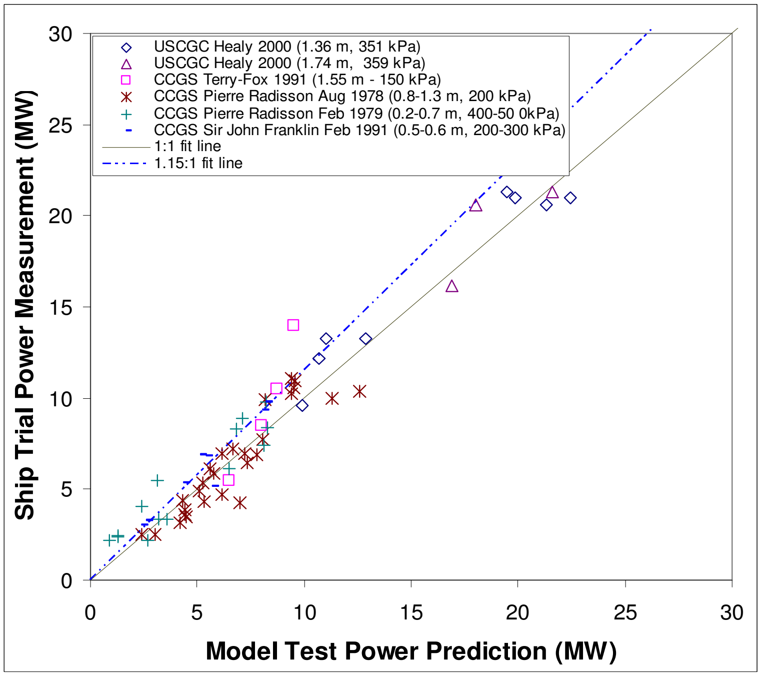

FIGURE 2 RESULT OF THE SHIP POWER CORRELATION

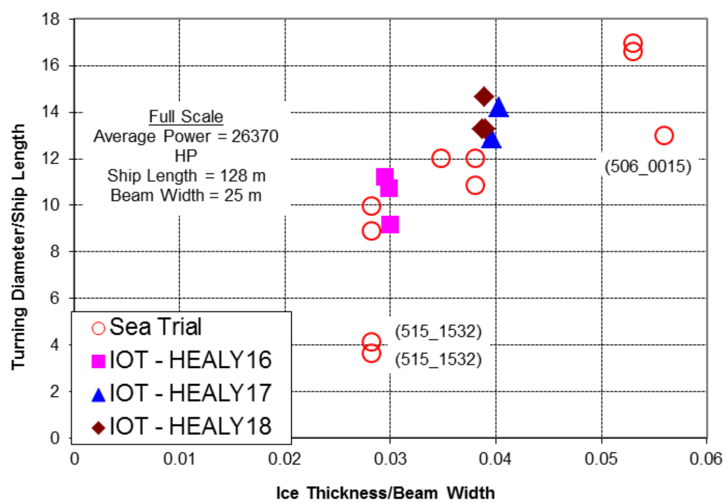

FIGURE 3 THE NON-DIMENSIONAL TURNING DIAMETER AS A FUNCTION OF NON-DIMENSIONAL ICE THICKNESS FOR THE USCSC HEALY SEA TRIAL AND MODEL TEST DATA.

CONCLUSIONS

A brief review of the model-scale/full-scale correlation studies on the *USCGC icebreaker Healy*, *CCGS icebreaker Terry-Fox*, *CCGS R-Class icebreakers Pierre Radisson* and *Sir John Franklin* and *CCGS icebreaker Louis S. St. Laurent* by NRC-OCRE's ice tank has shown a good agreement between NRC-OCRE's model test predictions and full-scale measurements in resistance, power and manoeuvring.

Although there is substantial uncertainty on ice thickness and ice strength within the full scale data sets that contributes to data scattering, the data suggest a conservative estimate can be obtained to address reasonably this uncertainty by increasing the model prediction by 15% that envelopes most data points.

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