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Resistance and Propulsion of CCGS *Terry Fox* in Ice from Model Tests to Full Scale Correlation

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ABSTRACT

The first resistance and propulsion tests of a Terry Fox model were carried out in 1988 at the Institute for Ocean Technology, IOT (formerly Institute of Marine Dynamics, IMD). More recent resistance and propulsion model tests were again conducted in 2007. This paper describes not only the correlation with full scale but also the reproducibility and quality of the test data and test method over 20 years. The model has been tested with three different hull-ice friction coefficients, 0.11, 0.045, and 0.005 and several different ice conditions. The empirical formula to predict the full-scale resistance is given based on the IOT's standard analysis method. Towed propulsion tests were carried out in ice and in open water using an overload method.

During the full-scale tests conducted in 1990 by Fleet Technology Limited, the flexural strength of the ice was 150 kPa and the thickness was 1.55 m. It was quite soft but thick ice. Due to the thick ice, significant propeller ice interaction was reported, but unfortunately model tests were not done with corresponding full-scale ice thickness. Some of the other full-scale measurements (in 1986 by Arctec Canada Limited) had a snow cover, hummocks, and melt-pools which could affect the resistance value. These effects were not taken into account in the model tests.

The present paper shows the usefulness of a non-dimensional method to predict resistance with four components (breaking term, clearing term, buoyancy term and open water term). Overall resistance prediction is good, but the power prediction shows some discrepancies possibly due to propeller ice interaction. The model results from the 1988 to 2007 tests were consistent over the twenty years between the tests, and the prediction method for full-scale power is appropriate with a friction coefficient of about 0.05, as has been found before at IOT.

KEY WORDS: resistance in ice; propulsion in ice; model tests in ice tank; Terry Fox; Kalvik

INTRODUCTION

The aim of the paper is to present the correlation of the resistance and propulsion tests in ice tank with the results of the full-scale measurements in ice of the Terry Fox. The model test data used here was collected between 1988 and 2007, so that the consistency and quality of the test results are also evaluated. Test methods for ship resistance and propulsion in ice tank are briefly presented and empirical formulae for each hull-ice friction coefficients are derived.

The Terry Fox is a Canadian Icebreaker built in 1983 as a supply tug and for icebreaking in the Beaufort Sea. She is a CASPPR Arctic Class IV icebreaker, now owned by the Canadian Coast Guard (CCG), and operates in the Gulf of St. Lawrence during the winter and in Canadian eastern Arctic during the summer. To date, several full-scale measurements have been carried out with both Terry Fox and her sister ship, MV Kalvik. Two sets of full-scale measurements were used in this paper: one of them was carried out in 1986 by Arctec Ltd with the Kalvik and the other was done in 1991 by Fleet Technology Ltd with the Terry Fox. Detailed measurement data and methods are addressed in the section of Full Scale Measurement.

Figure 1: CCGS Terry Fox in ice (from Fisheries and Oceans Canada)

The Terry Fox is one of the IOT's standard models and it has been tested since 1988. In order to change or maintain a hull-ice friction coefficient, the model was repainted more than 3 times. The very first runs had an hull-ice friction coefficient of 0.11 and later after re-painting it was changed to 0.045 and 0.005. A test log for the present data is shown in Table 1. For the tests in 1988, the creeping speed tests were not done due to the lack of the established test procedure at that time. In the table, one set means the same ice conditions.

Table 1: Test log

Year	Number of Sets	Friction Coefficient	Creep Tests	Resistance	Propulsion
1988	3	0.11	N	Y	N
1989a	4	0.045	Y	Y	Y
1989b	3	0.005	Y	Y	N
1991	2	0.005	Y	Y	N
2001	1	0.005	Y	Y	N
2002	2	0.005	Y	Y	N
2005	1	0.005	Y	Y	N
2007	1	0.005	Y	Y	Y

Some of data were compiled from raw data and some of them were from the reports: 1988 (Spencer et al., 1988); 1989a (Nordco Ltd, 1989); 1989b (Spencer, 1990); 2001 (Derradji et al. 2002); 2002 (Derradji and Coëffé, 2003); 2007 (Wang and Lau, 2007). As per IOT's standard method (IOT standard method, 2000) for ice resistance tests, most tests were done with level ice, presawn, and pack ice conditions, and additional creep tests in presawn ice to derive the buoyancy resistance. Brief explanation for the analysis method is given in the Test Method section.

FULL SCALE MEASUREMENT

1990 Tests with Terry Fox (Cowper, 1991)

In these tests full-scale resistance was measured by towing the Terry Fox with the MV Ikaluk. This gave a direct measurement of resistance. The resistance values included hull resistance and the drag from a single centerline rudder, but propeller drag was subtracted. For level ice resistance tests, the two vessels were 500 - 700 m apart in an "infinite" level ice sheet. The results are shown in Table 2.

Table 2: Full scale resistance in level ice (Cowper, 1991)

Velocity (Knots)	Resistance (MN)
0.4	0.42
2.4	0.83
3.3	0.95

The average values for ice thickness, flexural strength and hull-ice friction coefficient are shown in Table 3. The flexural strength was estimated based on the cantilever beam measurements. The friction coefficient was measured by using Tribometer. This device had a rotating arm with 10cm by10cm ice pieces, which was placed at the end of the arm and touched the ship hull as shown in Figure 2. The normal/parallel forces were then measured when the arm rotated.

Table 3: Ice Properties

Ice Thickness	Flexural Strength	Friction coefficient (-)
1.55 m $\pm$ 0.11	150 kPa	0.18

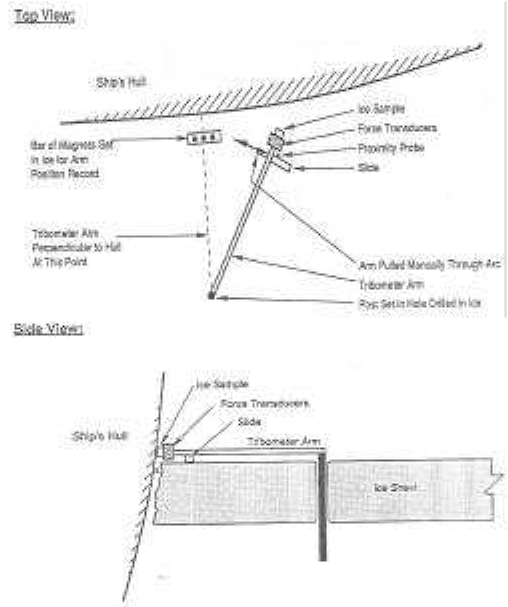

Figure 2: Apparatus for Tribometer (after Cowper, 1991)

Table 4 shows the results from the self-propulsion tests in level ice. A total of four different speeds were used and power and thrust were measured. Significant propeller-ice interaction was reported but the increase in power due to the ice milling was no more than 7 % over the time intervals analyzed.

Table 4: Full scale self propulsion tests in level ice (Cowper, 1991)

Velocity (Knots)	Power (MW)	Thrust (MN)
1.5	5.5	0.75
2.3	8.5	0.97
2.9	10.6	1.16
3.6	14.0	1.34

1986 Tests with Kalvik (Glen et al., 1987)

Another set of full-scale trials has been carried out with Terry Fox's sister ship, MV Kalvik in ice by Arctec Ltd (Glen et al., 1987). They evaluated the ship performance in level ice and in a broken channel and also analyzed ramming mode and turning capability in ice. Tests were performed in 5 days, and ice conditions varied depending on the test regions and time. Some of the level ice had hummocks and melt pools, and the flexural strengths estimated from salinity/temperature varied from about 230 to 580 kPa. The level ice was usually covered by 2-15 cm of snow. The full-scale results used here were all from tests which did not use the Kalvik's bubbler system. Thrust and power were measured and resistance was calculated based on the estimated thrust deduction fraction (1-t) by Cowper et al. (1992). The results are shown in Table 5.

MODEL TESTS

Test Facility and Model Ice

IOT's ice tank has a useable ice area of 76 m long and 12 m wide and a depth of 3m. In addition, a 15 m X 12 m setup area is separated from the ice sheet by a thermal door allowing test set-up while the test sheet is prepared (Figure 3). The carriage speed ranges from 0.0002 to 4.0 m/s. The test frame allows positioning of the model at any location across the width of the tank (Jones, 1986). The EG/AD/S model ice was used in these experiments. It is a diluted aqueous solution of ethylene glycol (EG), aliphatic detergent (AD), and sugar (S). The EG/AD/S model ice provides correct scaling of mechanical properties of columnar sea ice (Timco, 1986; Spencer and Timco, 1990).

Table 5: Kalvik resistance and propulsion tests (Glen et al., 1987)

Ice Thickness M	Snow Cover cm	Ship Speed knots	Thrust MN	Power MW	Resistance MN
1.7	3	6.4	1.55	14.9	1.06
1.9	10	6.3	1.40	14.2	0.96
1.9	10	5.0	1.48	14.4	1.05
1.9	10	2.5	1.40	12.2	1.10
1.9	10	3.6	1.32	12.2	0.98
1.9	10	2.3	1.07	8.6	0.85
1.7	5	3.1	1.33	11.5	1.01
1.7	5	1.0	1.19	8.7	1.05
1.9	7	2.9	1.22	10.2	0.94
1.9	7	6.1	1.46	14.2	1.01
1.2	5	6.2	1.45	14.2	1.00
1.5	2	3.8	1.47	13.4	1.09
1.7	6	3.1	1.51	13.6	1.15
1.5	15	4.6	1.44	13.3	1.04
1.8	3	3.9	1.52	14.3	1.12
1.8	3	4.6	1.52	14.5	1.09
1.8	3	3.1	1.42	13.0	1.08

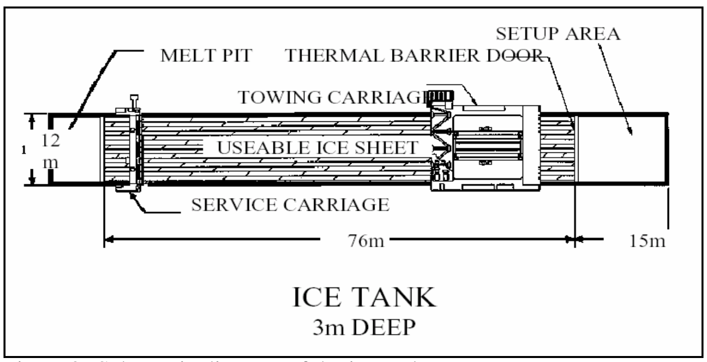

Figure 3: Schematic diagram of the ice tank

Test Method

Since the IOT standard methods for resistance and propulsion tests in ice have been published in other papers (Jones et al., 1994; Spencer and Jones, 2001; Jones, 2005), only brief explanation is given here.

Resistance in ice

Ice resistance tests are usually carried out in three different ice conditions (level ice, pre-sawn ice and pack ice) in one parent ice sheet. For this, the ice sheet is divided by three strips in Centre, North Quarter Point, and South Quarter Point. The level ice and pre-sawn ice tests are carried out in the Centre and either SQP and NQP, respectively, and the whole ice sheet is then broken and controlled to simulate various pack ice conditions.

For the resistance analysis, total ice resistance is assumed to be composed of four different components: the breaking resistance (R_{br}), the buoyancy resistance (R_b), the clearing resistance (R_c) and the open water resistance. From the level ice tests, total resistance in ice can be obtained. Because there is no breaking resistance in the pre-sawn ice, the breaking resistance can be identified after the pre-sawn tests. From the creeping speed tests (0.02m/s carriage speed) in the pre-sawn ice, the buoyancy resistance can be obtained and the clearing resistance can be calculated. The ice components are presented by non-dimensional coefficients as below.

$C_{br} = R_{br} / \rho_i BhV_m$: Breaking resistance coefficient (1)

$C_c = R_c / \rho_i BhV_m$: Clearing resistance coefficient (2)

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

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. There are two additional non-dimensional parameters, which are the Strength Number ($S_N = V_M / \sqrt{\sigma_f h / \rho_i B}$) and the ice thickness Froude Number ($F_h = V_m / \sqrt{gh}$). The breaking resistance and clearing resistance coefficients are dependent on the Strength Number and Froude Number, respectively.

Propulsion in ice

Propulsion tests in ice are similar to the tests in open water. The purpose of the test is to find a self-propulsion point and measure the propulsive power in ice. Unlike typical open water tests, ice tests are very expensive so that effort to save time/money on a large number of ice sheets must be made. At the IOT, overload tests in open water are used prior to the ice propulsion tests in order to predict reasonably accurate self-propulsion points. If no propeller-ice interaction is expected, then the propulsive power will be available from these overload tests in open water: a propulsion test in ice is not needed. However, if propeller-ice interaction is expected, as is usually the case, then we can estimate or measure (from selected ice tests) the ratio between thrust/torque in open water and that in ice so that the propulsive power from the open water tests can be corrected for the ice condition. A detailed description of this method is given in the next paragraph.

From the resistance tests in ice, the ice resistance for a given ship speed can be identified. These values are used for the overloads in open water, so that the rps at a given ship speed and overload can be found. To account for propeller-ice interaction, the ratio between thrust in ice and open water (T_i/T_o) is first identified from measurements with one or more (but usually one) ice sheets, or alternatively it is estimated. The corrected thrust and rps can then be found for that ice condition. For example, if T_i/T_o is assumed to be 0.9, then the decrease in the thrust is equated to an increase in the overload tow force, and a corrected rps can be found from the thrust versus rps curve. Then, from the torque versus rps curve in open water, the torque values at the rps found above are determined. The ratio between torque in ice and open water (Q_i/Q_o) is then determined from a few tests in ice. This ratio is then used to obtain the ice torque Q_i for any given ice condition. From these values of Qi, the propulsive power can be obtained from $2 \cdot \pi \cdot rps \cdot Q_i$.

Model Test Results

Resistance Test with low hull-ice friction coefficient (f=0.005)

Tests with a hull-ice friction coefficient of 0.005 have been carried out since 1989. Figure 4 shows the breaking coefficients against the ice strength number in the log scale. One or several sets of tests were carried out in a certain year. Test results from six different years were considered here. As seen in the figure, the results show good agreement with each other.

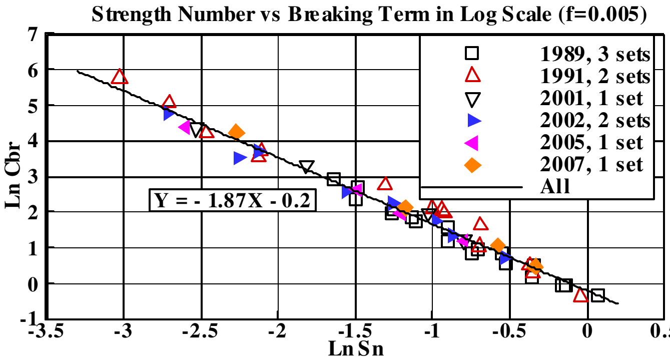

Figure 4: Breaking Coefficients vs. Strength Number (*f*=0.005)

Figure 5 shows the measured buoyancy against the calculated value. The buoyancy values were measured from the creep tests (carriage velocity of 0.02 m/s). There is more scatter in Figure 5 than Figure 4. This is because buoyancy values are quite small (10-20 N), and so it is difficult to measure them accurately. Also during the creep tests, the ice pieces might be rotated or jammed which would result in offset from the averaged values. Because the clearing values are calculated from the subtraction of the buoyancy values from the presawn resistance, not directly measured, they also include uncertainties from the creep tests. Figure 6 shows the clearing coefficients against the Froude number associated with the ice thickness on a log scale. It is encouraging that the results from all the different sets of data collected over 20 years are in such good agreement.

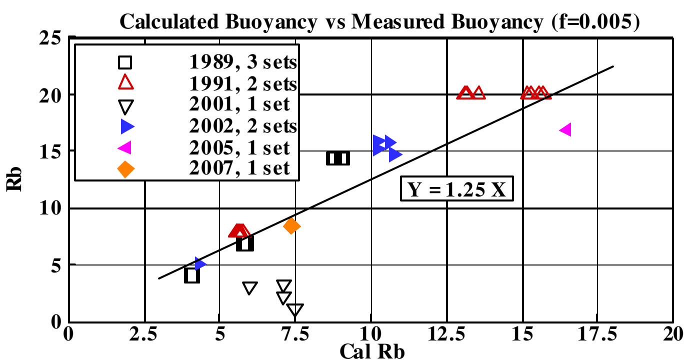

Figure 5: Measured buoyancy vs. calculated buoyancy (*f*=0.005)

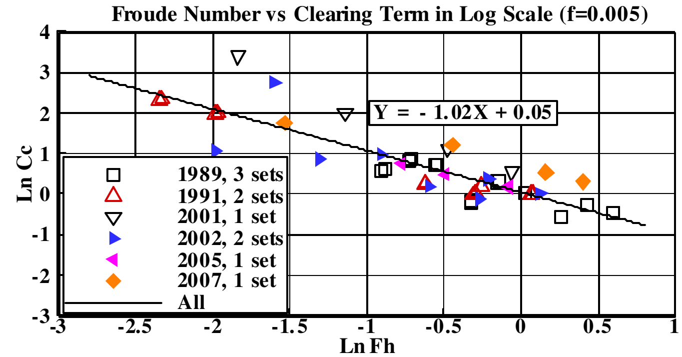

Figure 6: Clearing Coefficients vs. Froude Number (*f*=0.005)

Resistance Test with all friction coefficients (f=0.005, 0.045 and 0.11)

The Terry Fox model has been tested with three different hull-ice friction coefficients. Figure 7 shows the effect of the hull-ice friction coefficient on the breaking coefficients. Three linear equations were derived as the best fit to the data. The slopes of the equations are similar, but the y-intercepts are increased as the friction coefficient increases. The figure clearly shows that the friction coefficients play an important role in the breaking coefficients in the model tests.

Figure 8 shows the buoyancy values with two different hull-ice friction coefficients, 0.045 and 0.005. Figure 9 shows the clearing coefficients against the Froude number associated with the ice thickness on a log scale.

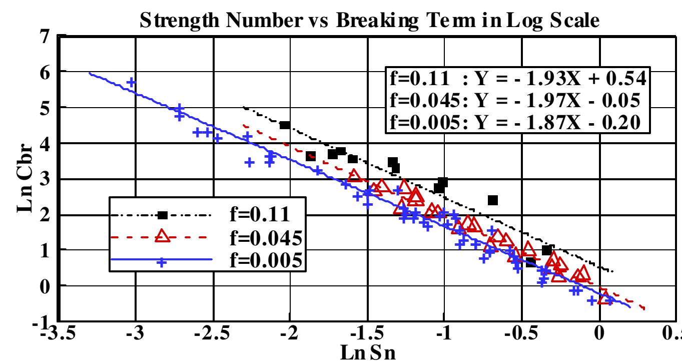

Figure 7: Breaking Coefficients vs. Strength Number

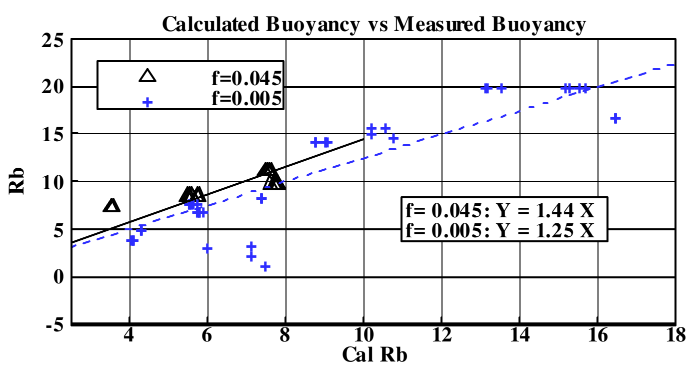

Figure 8: Measured buoyancy vs. calculated buoyancy

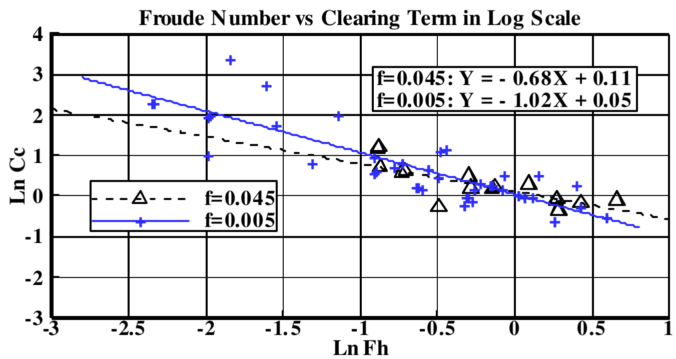

Figure 9: Clearing Coefficients vs. Froude Number

The empirical formulae for each hull-ice friction coefficient are given below.

-For the friction coefficient of 0.005,

$$R = 0.816 \times SN^{-1.87} \rho BhVm^2 + 1.048 \times Fh^{-1.02} \rho BhVm^2 + 1.25 \times \Delta\rho ghBT + Open\ Water \tag{4}$$

-For the friction coefficient of 0.045,

$$R = 0.954 \times SN^{-1.97} \rho BhVm^2 + 1.117 \times Fh^{-0.68} \rho BhVm^2 + 1.44 \times \Delta\rho ghBT + Open\ Water \tag{5}$$

-For the friction coefficient of 0.11,

$$R = 1.721 \times SN^{-1.93} \rho BhVm^2 + 1.117 \times Fh^{-0.68} \rho BhVm^2 + 1.44 \times \Delta\rho ghBT + Open\ Water \tag{6}$$

It is noted that the creep tests were not carried out for the case of f=0.11, therefore the buoyancy and clearing terms were assumed to be the same as those for the case of f=0.045.

Overload Tests in Open Water (friction coefficient f=0.005)

Figure 10 shows the results from the overload tests in open water. The measured tow force can be assumed to be equal to the ice load (overload). Figure 11 shows the torque values against rps. It is noted that the torque was measured only on the port side in the model tests and it was doubled for the comparison with the full-scale results. The average ratio between the torque in ice and in open water (Qi/Qo) from the model tests (for the thickness and flexural strength of 23mm and 30 kPa, respectively) was about 1.1.

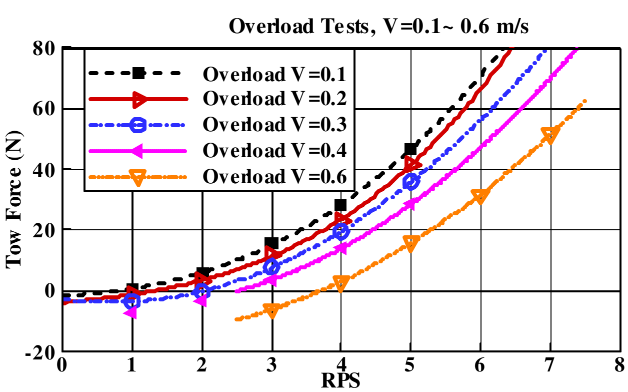

Figure 10: Towed force against RPS in open water

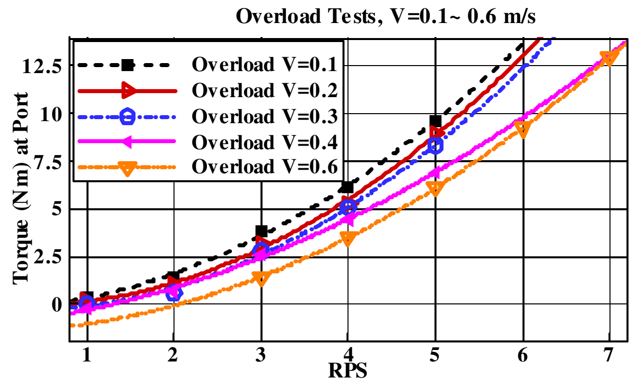

Figure 11: Port Torque against RPS in open water

Comparison with full-scale data

1991 full-scale results for resistance

Figure 12 shows the comparison between the model test prediction and full-scale direct measurements of resistance made in 1991. At low ship speed (0.4 knots), all empirical formulae from the model tests show higher values of resistance than measured ones. As the ship speed increased, the prediction from the hull-ice friction coefficient of 0.045 shows a good agreement with the full-scale measurements.

Since the scale ratio for the model was 21.8, the ship speed of 0.4 knots would be 0.04m/s in the model scale. This speed may not properly simulate dynamic motion of ice such as a breaking event in the model tests, and the empirical formula was derived from higher speed tests, more than 0.1 m/s, which had a large portion of breaking resistance in the total resistance.

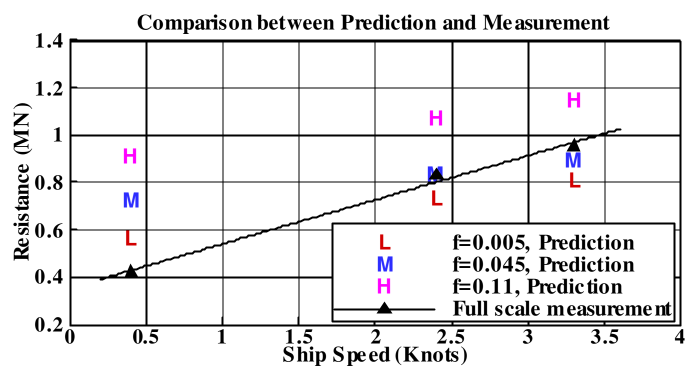

Figure 12: Comparison between prediction and measurement (1991 resistance data)

1991 full-scale results for propulsion

We also compared the full-scale propulsion measurements made in 1991 with our model propulsion tests. Because the ice thickness was 1.5m during the full-scale measurements, significant propeller-ice interaction was reported. As the ship speed increases, the propeller-ice interaction would be expected to be more severe. The measured ice strength, however, was soft (150 kPa), so that the constant ratio (Qi/Qo =1.1) was applied to the model test results. In Figure 13, the delivered power against ship speed for model and full-scale measurement is shown. There is some discrepancy at the higher speeds even though the resistance values were appropriate as shown in Figure 12. We believe this is due to significantly more ice-propeller interaction in the thick ice, which would result in a higher Qi/Qo ratio than that used here. The propeller geometry was also different: the full-scale ship used the controllable pitch propellers, but the model used the fixed pitch propellers. It is also expected that during the propeller-ice interaction, the full-scale rps could be slower than that in no ice condition due to the high load from ice, but it could not happen in the model tests.

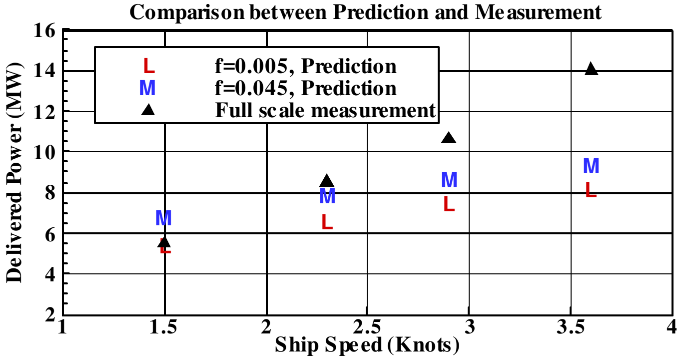

Figure 13: Delivered power vs. ship speed (Q_i/Q = 1.1)

1986 full scale results for resistance

The 1986 trials did not measure resistance directly, but calculated values from torque values. Figures 14 to 16 show the comparison with full-scale measurement from these trials. The prediction was made for the three different friction coefficients, namely 0.005, 0.045, and 0.11. The flexural strength varied from 230 to 580 kPa and level ice included some hummocks and melt pools, which were not taken into account for the prediction. Since the flexural strength was widely varied, only minimum and maximum values were considered. Based on the thickness and flexural strength, the prediction from the model tests are shown in the figures. The effect of snow was not considered. It is noted that the full-scale measurement data used the figures are shown in Table 5.

In Figure 14, the predictions from the friction coefficient of 0.005 are compared with the full-scale measurements. The prediction with low flexural strength shows reasonably good agreement with measurements. In Figure 15, the friction coefficient of 0.045 was used for the prediction. Compared to the Figure 14, the prediction for the low flexural strength was about 13 % higher due to the higher friction coefficient. Five out of 17 points matched well with the measurements and the rest were slightly over-predicted. In Figure 16, most values at all speeds were over-predicted. The low flexural strength and a friction coefficient between 0.005 and 0.045 give reasonable agreement for this 1986 full-scale correlation.

Theoretically, a hull-ice friction coefficient of a model should be the same as that of the full-scale ship, as it is a non-dimensional number. For the trials in 1991, the full-scale friction coefficient was measured as 0.18, which is the higher than any model test values. Based on our experience with many correlation studies the optimum value for the hull-ice friction coefficient for a model is 0.05 for a new hull in ice with little snow. The present results are consistent with this for the 1991 full-scale data, both resistance and propulsion, while the 1986 correlation suggest a lower figure between 0.005 and 0.045. This may indicate that the friction effect for a model test is more sensitive than at full scale. Another factor would be the accuracy of the measured friction coefficient at full-scale, which is a difficult measurement to make.

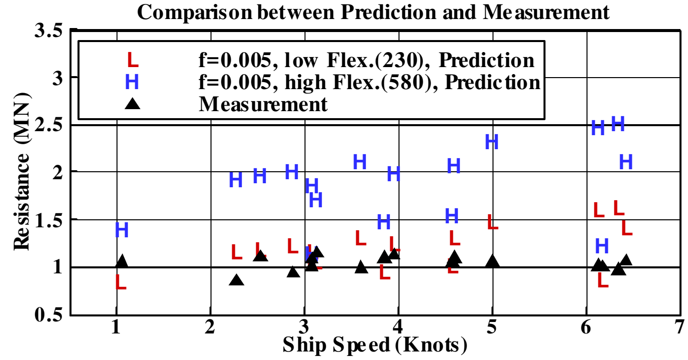

Figure 14: Resistance comparison with the friction coefficient of 0.005

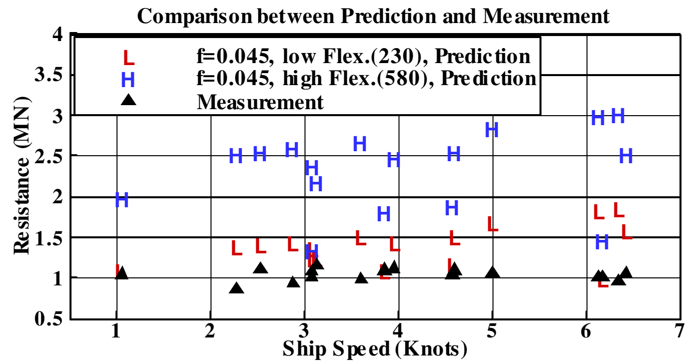

Figure 15: Resistance comparison with the friction coefficient of 0.045

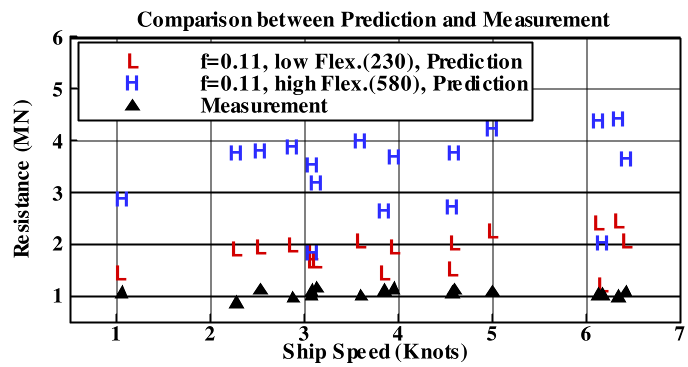

Figure 16: Resistance comparison with the friction coefficient of 0.11

CONCLUSION

Model tests results of the Terry Fox/Kalvik model from 1988 to 2007 were compiled and re-analyzed using the IOT standard method. Empirical formulae for the three different hull-ice friction coefficients were derived and correlated with full-scale measurements. From this study, we evaluated the quality of the test program from IOT's ice tank and the analysis method using four breakdown components with non-dimensional coefficients. From the correlation with both 1986 and 1991 full-scale measurements, the friction coefficient of 0.045 seems reasonable value. For the 1986 trials' correlation, many factors were not taken into account such as the effect of hummocks, melt pools, fracture, and snow and the resistance was not directly measured. These two correlation studies, however, show that this test method is useful to predict the full-scale resistance. The model test results show excellent consistency over 20 years, and the friction coefficient of about 0.05 was again proven as an appropriate friction value.

ACKNOWLEDGEMENTS

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