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Propulsion and Maneuvering Model Tests of the USCGC Healy in Ice and Correlation with Full-Scale

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ABSTRACT

Propulsion model test results of the *USCGC Healy* are reported here and correlated with full-scale data. The design requirement for the *Healy* was for "continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength". The full-scale trials were designed to test this capability. Unfortunately, the ice strength found on the trials was approximately half of that specified. One of the objects of the model tests was to determine the effect of ice strength on the delivered power necessary for the Healy to meet her icebreaking specification. Propulsion overload tests in open water combined with limited ice tests, and the IOT standard method for analyzing propulsion tests in ice, gave consistent results for delivered power, which agreed well with the available full-scale data from the *Healy*. A correlation friction coefficient of 0.05 was again shown to be appropriate. From the analysis of the resistance and propulsion tests, the *Healy*, with its total shaft horsepower of 30,000, was shown to be capable of its design requirement. Using a similar analysis, an imaginary "Polar 8" icebreaker of the *Healy* design was shown to require 85,000 HP to continuously break ice of 2.44 m (8 ft.) thickness, of 500 kPa strength, at 3 knots. Free running maneuvering tests performed in the ice tank gave arcs of circles whose diameters agreed well with the full-scale data of turning circles obtained on the ship trials.

KEY WORDS: USCGC Healy; ship performance; icebreaker; propulsion in ice; maneuvering in ice; ice-ship interaction

INTRODUCTION

Following the successful full-scale trials of the USCGC Healy in 2000, it was decided to conduct a complete set of resistance, propulsion, and maneuvering model tests of the vessel for correlation with the full-scale data. The proceedings of the POAC '01 conference (Frederking et al. 2001) contain several papers outlining the results of the full-scale trials. Jones and Moores (2002), at the IAHR conference in Dunedin, have summarized the results of the resistance tests conducted at IOT. This paper details the propulsion and maneuvering model tests conducted at IOT and their correlation with the full-scale data.

USCGC HEALY

The USCGC Healy was launched on 15 November 1997 from Avondale Industries in New Orleans. She was delivered to the US Coast Guard on 10 November 1999, departed New Orleans on 26th January 2000, and proceeded north for extensive full-scale ice trials before arriving in Seattle on 9th August 2000.

The essential details of the Healy are shown in Table 1.

Table 1. Characteristics of USCGC Healy

Length, Overall	420ft 128 m
Beam, Maximum	82' 25 m
Draft, Full Load	29'3' 8.9 m at delivery
Displacement, Full Load	16,000 LT at delivery
Propulsion	Diesel Electric, AC/AC Cycloconverter
Generating Plant Drive Motors	4 Sultzer 12Z AU40S 2 AC Synchronous, 11.2 MW
Shaft Horsepower	30,000 Max
Propellers	2 fixed pitch, 4 bladed
Fuel Capacity	1,220,915 gal. 4,621,000 l
Speed	17 knots @ 147 RPM
Endurance	16,000 NM @ 12.5 knots
Icebreaking Capability	4.5 ft (1.4 m) @ 3 knots (continuous) 8 ft (2.44 m) Backing and Ramming
Accommodations	19 Officer, 12 CPO, 54 Enlisted, 35 Scientists, 19 Surge, 2 Visitors

The design icebreaking capability of the Healy was for continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength. The full-scale trials were designed to test this capability. Unfortunately, the ice strength found on the trials was approximately half of that specified. One of the objects of the model tests was to determine the effect of ice strength on the delivered power necessary for the Healy to meet her icebreaking specification.

MODEL CONSTRUCTION

Model 546 was constructed, in accordance with IMD's standard method, at a scale of 1:23.7. This scale was chosen so that we could use an existing set of propellers, namely our R-Class propellers 66L and 66R. The model's principal dimensions were:-

Table 2. Particulars of Model 546

Overall length (LOA)	5.40 m
Length between perpendiculars (LBP)	5.10 m
Maximum beam	1.05 m
Depth at midships (D)	0.54 m
Design waterline (DWL)	0.36 m
Draft at even trim	0.37 m
Vertical C. of G. (VCG)	0.416 m
Displacement	1240 kg
Propeller diameter	0.198 m

A non-removable ice knife and two bossings, also non-removable, were fitted, together with the twin rudders and propellers. Fig. 1 shows the model in the ice tank.

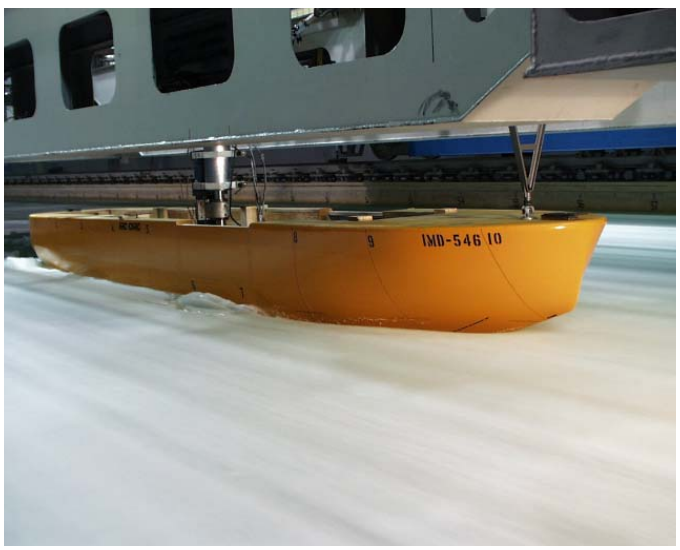

Fig. 1. Model 546 of the USCGC Healy in the ice tank at IOT.

Ice-hull friction coefficient

The ice-hull friction coefficient requested was 0.05. However, for unknown reasons, it was much smaller at 0.014 (Low friction) so the resistance tests were repeated after re-painting, at a friction coefficient of 0.034 (High friction). From these results, the resistance for a friction coefficient of 0.05 was extrapolated. The ice density was maintained constant for the different ice sheets at 0.870 ± 30 Mg/m^3.

TEST PLAN METHOD

A total of 14 ice sheets were used for the resistance and propulsion tests. In addition, open water resistance and propulsion tests, including overload tests, were conducted. The resistance tests were analyzed in accordance with IOT's standard method (Standard # TM7) and the propulsion tests were analyzed in accordance with a draft standard method (TM 8 D1). Performance predictions were then made and compared to full-scale data previously collected. Further details of the test method can be found in an internal IOT report (Jones, 2004).

RESISTANCE RESULTS

Open Water

Open water resistance tests were conducted. Since the open water term is a small contribution to the total icebreaking resistance, a least squares polynomial was fitted to the data and this was used to calculate the open water term as needed. Fig. 2 shows the result for the low friction model. This equation was used in order to subtract the open water term from the total resistance in ice.

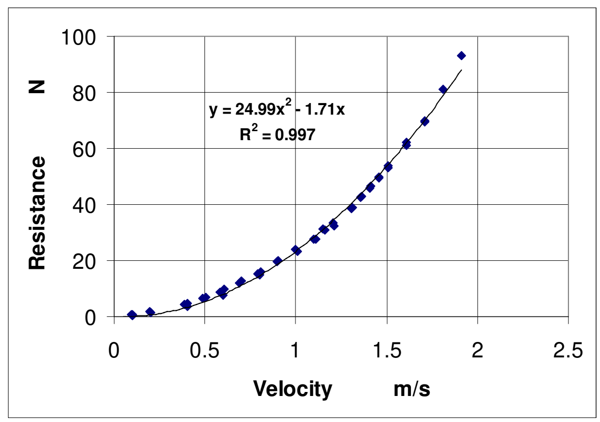

Fig. 2. Open water resistance of the USCGC Healy model 546, low friction.

Level Ice Resistance Results

These results have been given in Jones and Moores (2002) and will only be summarized here. The standard IOT method breaks the total resistance down into four terms:-

$$R_T = R_{BR} + R_C + R_B + R_{OW}$$

where, R_T = total resistance
R_{BR} = resistance due to breaking the ice
R_C = resistance due to clearing the ice
R_B = resistance due to buoyancy of the ice
R_{OW} = resistance due to open water

The end result of the analysis is two equations for the resistance, one for each ice-hull friction coefficient tested, from which the resistance can be calculated for any value of ice thickness, strength, friction coefficient, and ship speed. The two equations are:-

$$R_t = R_{OW} + 1.290\Delta\rho_i g B h_i T + 1.239\left(\frac{V_M}{\sqrt{gh_i}}\right)^{0.771}\left(\rho_i B h_i V_M^2\right) + 0.866 S_N^{1.6845}\left(\rho_i B h_i V_M^2\right)$$

for the low friction (0.014) model and

$$R_t = R_{OW} + 1.138\Delta\rho_i g B h_i T + 1.035\left(\frac{V_M}{\sqrt{gh_i}}\right)^{-0.642}\left(\rho_i B h_i V_M^2\right) + 1.167 S_N^{-1.771}\left(\rho_i B h_i V_M^2\right)$$

for the high friction (0.034) model.

Fig. 3 demonstrates that the above equation (2) is indeed a good fit to the model data. A perfect fit would give a slope of 1.0.

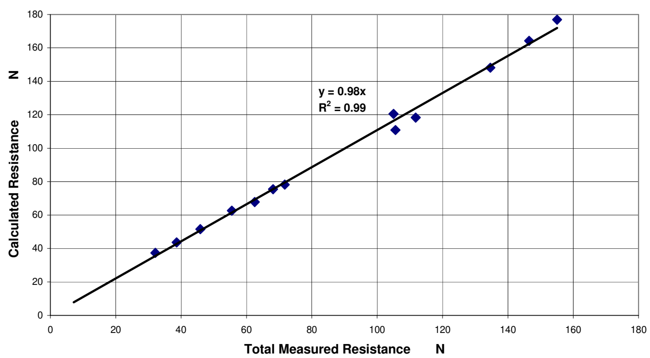

Fig. 3. Calculated versus measured total resistance for the low friction, 0.014, Healy model.

Other resistance results obtained can be summarized as follows:-

Effect of velocity on the total ice resistance, $R_{IT} = R_T - R_{OW}$, can be best fitted to a linear equation

$R_{IT} = 68.5v + 49.1$, where v is the velocity in m/s, and R_{IT} is in N.

Effect of ice thickness can be best fitted to

$R_{IT} = 0.02h_i^2 + 1.35h_i$, where h_i is in mm and R_{IT} in N.

Effect of friction was found to be best described as an increase of 15% in total ice resistance for an approximate doubling (from 0.014 to 0.034) in the friction coefficient.

Effect of ice strength was best described as a doubling of the ice strength caused R_{IT} to increase by 25% in thin ice (27mm) and 40% in thick ice (76mm).

Further details of the resistance tests can be found in Jones and Moores (2002) and Jones (2005).

PROPULSION RESULTS

Propulsion tests were conducted according to IOT's Standard Method TM8, D1.

Background and Theory of the Method

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 in this method 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_i/D where h_i is the ice thickness and D is the diameter of the propeller (Molyneux, 1989).

This method has certain advantages. If hydrodynamic effects can be separated from ice effects, some aspects of propulsive performance, for example, the effects of propeller pitch variation on tow force, can be investigated using only open water experiments. The torque due to ice can be considered as a function of the ice parameters (thickness, strength etc.) and added to the open water values. This method has the practical advantage that, because the towing carriage arrangement for resistance in ice tests and overload propulsion in ice tests are similar, it is possible to change quickly from one to the other. Thus, resistance and propulsion experiments in the same ice sheet are possible, provided that the propellers can be fitted or removed easily.

Self-propulsion tests in open water using an overload method

The *Healy* model was equipped with the *R-Class* propellers, 66L and 66R. First, overload tow force tests were conducted in open water to give equations relating the tow force to rps for a given speed. The model was towed at a constant speed given by the carriage, and the rps was varied from 0 to between 12 and 18 rps depending on the speed. For a speed of 0.02 m/s the maximum rps was 12, for 1.2 m/s the maximum was 18 rps. The data were fitted to second order equations with high levels of accuracy. The results are shown in Fig. 4 below for the port side propeller. Similar equations were derived for the torque, Q, as a function of RPS, during these overload tests, as

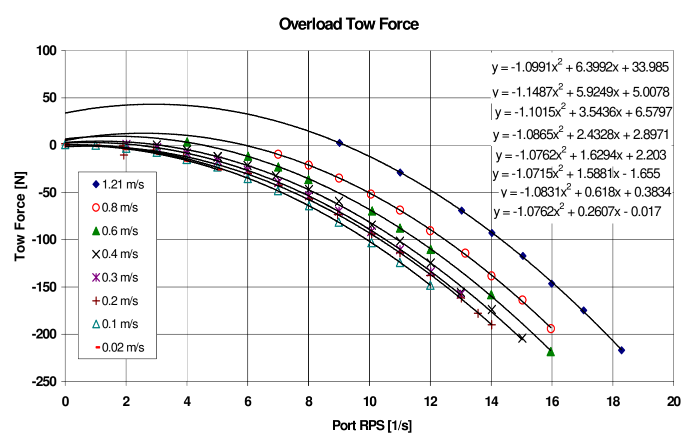

Fig. 4. Tow force in overload tests in of Healy model in open water

shown in Fig. 5. Neglecting ice-propeller interaction for the moment, it is now possible, therefore, to determine delivered power by:-

1. Equating resistance in ice for a specific ice thickness, strength, and speed to tow force from the open water overload tests
2. Determine an rps value from this tow force and Fig. 4.
3. Determine Q for this tow force from Fig. 5.

4. Calculate P_D from (2.π.Q.rps) and scale up for comparison with full-scale.
5. Repeat for different values of ice thickness, strength, and ship speed.

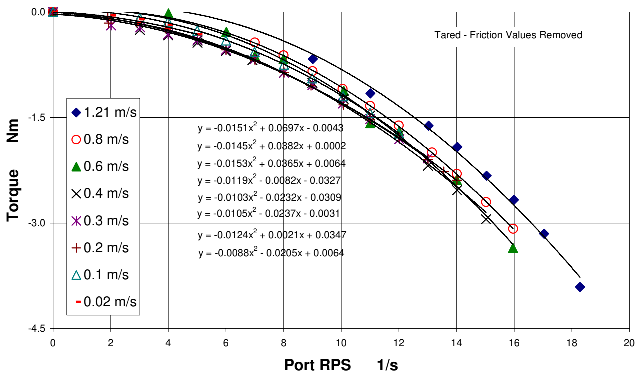

Fig.5. Torque of port side propeller as a function of RPS for the open water overload tests.

Propeller-ice interaction was taken account of as follows. Two ice sheets were used for overload tests, one 39 mm thick and one 27 mm thick. Four speeds were used at five different rps. From these tests two graphs were drawn as shown in Fig. 6 and 7. They show thrust, T_i, and torque, Q_i, plotted against rps. For a given set of ice thickness, strength and ship speed, resistance can be calculated, equated to tow force and an rps found from Fig. 4 above. From this rps, Q and Q_i can be calculated from Figs 5 and 7, and the ratio Q_i/Q determined. A mean value of this ratio is then determined and used to convert Q to Q_i. From this value of Q_i, a value of Delivered Power is obtained and compared to full-scale. The values of Q_i/Q used are shown in Table 3 below.

Table 3. Values of Q_i/Q used in the calculation of P_D for model ice thickness of 0.057 m and strength 15 kPa.

Model speed	Ship speed	Q_i/Q
m/s	kn	
0.10	0.09	1.067
0.02	0.19	1.068
0.10	0.95	1.077
0.20	1.89	1.087
0.30	2.84	1.097
0.40	3.79	1.107
0.60	5.68	1.128
0.80	7.57	1.148
1.00	9.46	1.169
1.20	11.36	1.189

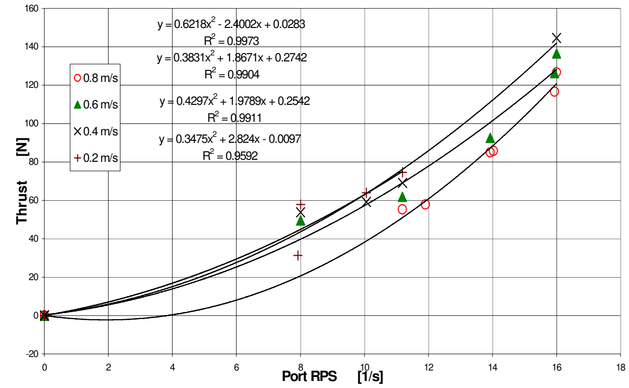

Fig. 6. Thrust developed during overload tests in ice, port side.

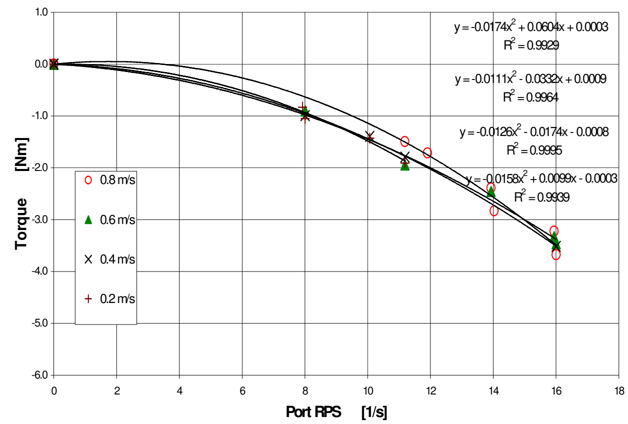

Fig. 7. Torque developed during overload tests in ice, port side.

Fig. 8 below shows the results of these calculations for the specific ice conditions of 1.36 m thickness and 351 kPa strength, which was the mean strength found during the full-scale trials for this thickness. The three "model" lines correspond to three friction coefficients; 0.014 and 0.034 as model tested, and 0.05 as extrapolated from the two others. The friction value 0.05 is the value that IOT has found gives best agreement between model-scale and full-scale, for a new hull in ice with little snow. The full-scale data was taken from Sodhi et al (2001) and was the delivered power measured independently on the propeller shafts by both torsion meters and strain gauges.
A shaft speed measurement system was also installed on each shaft. The shaft speed and torque measurements were then combined to determine the power delivered to each shaft. The two measurements of shaft torque agreed with each other within 1%.

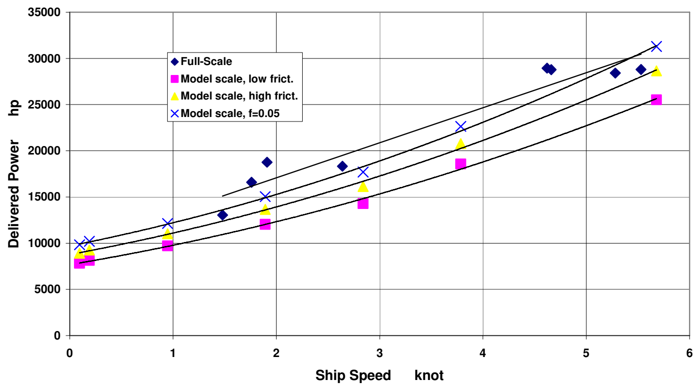

Fig. 8. Delivered power for the Healy calculated from the model tests for three friction coefficients, the two experimental ones, 0.014 and 0.034 and extrapolated to 0.05, compared to the measured full-scale power. Ice conditions, 1.36 m thick of strength 351 kPa.

Good agreement can be seen in Fig. 8 between the model scale data for a friction coefficient of 0.05 and the full-scale data. Similar good agreement was found for the other ice thicknesses and strengths measured on the full-scale trials, although the power predicted from the model tests was always slightly lower than that measured at full-scale. Possible reasons for that are frictional losses in the ship's shaft bearings aft of the point at which the power was actually measured, and the fact that we were not using true *Healy* propellers in the model tests, but stock R-Class propellers.

The *Healy* was designed for "continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength". We have calculated, therefore, the delivered power required to do this, based on the model tests. The result is shown in Fig. 9 for the two friction coefficients tested and the 0.05 value extrapolated from them, in which it can be seen that the power required is just slightly greater than the 30,000 HP available on the *Healy*. Given the errors expected in both the full-scale and model-scale measurements of at least ±5%, we conclude that the *Healy* is capable of its design requirement.

For the sake of interest, we calculated the power required for an imaginary "Polar 8" icebreaker, assuming it to be identical in design to the *Healy*, as was proposed some

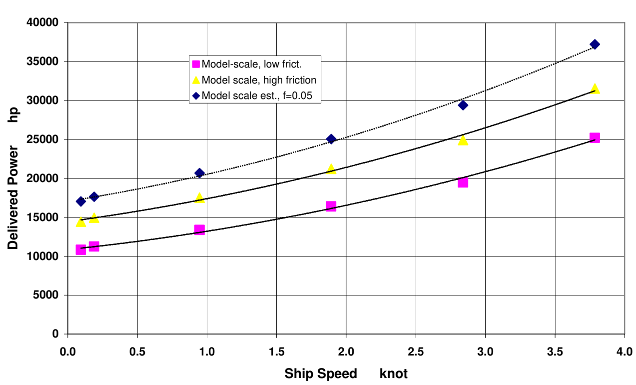

Fig. 9. Delivered power required for the Healy to break 1.37 m ice of 690 kPa strength calculated from the model tests.

years ago in Canada. Fig. 10 shows the result for ice conditions of 2.44 m (8ft) of strength 500kPa. This shows that for continuous icebreaking at 3 knot in these ice conditions, a delivered power of about 85,000HP would be required.

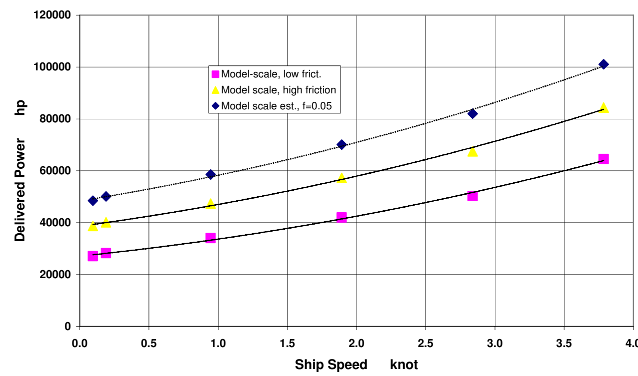

Fig. 10. An imaginary "Polar 8" icebreaker of the Healy design for ice conditions 2.44 m thick and 500kPa strength.

MANEUVERING TESTS

A total of 8 self-propelled maneuvering runs were conducted in three ice sheets. In addition, open water bollard (overload tests carried out at zero speed) and shaft friction tests were conducted. 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. Table 4 shows the three ice sheets (in full scale units) that were used for the tests. Table 5 summarizes the test condition and the result for each run. The first three runs were conducted at a target ice thickness of 75 cm and an ice strength ranging from 483 to 683 kPa. Shaft speed was varied from 9 to 10 to 12 rpm for these runs. The remainder of the tests was conducted at a target ice thickness of 100 cm and an ice strength ranging from 417 to 1081 kPa. The rudder angle was kept at 30 degrees as used in the sea trials. The delivered power was kept at around 30000 hp, which was consistent with the delivered power employed during the full-scale trials.

Table 4. Details of ice sheets used

Name	Date	Thick. (cm)	Strength (kPa)	Density (Mg/m^3)	E/σ_f
Healy16	23 Nov 01	74	562	0.916	1938
Healy17	27 Nov 01	100	749	0.866	2156
Healy18	29 Nov 01	97	667	0.868	1256

Table 5. Summary of test results

Run	Shaft rpm	Ice Thick.	Ice Strength	Diameter	Rudder Angle	Power	HP
	rpm	cm	kPa	m	degree	kW	hp
Healy16-1	12	74.9	519	1321	29.6	22703	30433
Healy16-2	10	74.7	683	1329	29.9	14592	19560
Healy16-3	9	73.7	483	1337	30.4	9291	12455
Healy17-1	12	99.1	1081	1756	30.1	19551	26208
Healy17-3	12	100.7	417	1757	29.9	18546	24860
Healy18-1	12	96.7	621	1738	29.7	23698	31767
Healy18-2	12	97.4	751	1738	29.6	24228	32478
Healy18-3	12	97.6	628	1745	29.8	23630	31676

Table 6. Summary of maneuvering data from the sea trial

Test	Ice Thickness	Power	Diameter	Dia./B	h/B	Dia/L
#	Cm	HP	m			
000420_1740	87	20780	1538	61.5	0.0348	12.0
000421_1348	95	28377	1538	61.5	0.0380	12.0
000421_1901	95	28830	1388	55.5	0.0380	10.8
000506_0015	140	23848	1666	66.6	0.0560	13.0
000515_1258	132.5	29254	2174	87.0	0.0530	17.0
000515_1400	132.5	29414	2128	85.1	0.0530	16.6
000515_1532	70.5	27222	470	18.8	0.0282	3.7
000515_1532	70.5	23234	528	21.1	0.0282	4.1
000515_1532	70.5	23440	1142	45.7	0.0282	8.9
000515_1615	70.5	29299	1274	51.0	0.0282	10.0
Average	96.4	26370	1385	55.4	0.0386	10.8

The full scale data have been reported in by Sodhi et al (2001). They are summarized in Table 6 for completeness.

Comparison with full-scale data

Figure 11 shows the non-dimensional turning diameter as a function of the non-dimensional ice thickness for both the model and the full-scale 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 identified in the figure. These 3 points should be further investigated which were seen as outliers in the full-scale report.

A multi-variance regression of the turning diameter conducted for the eight test runs as a function of ice thickness, ice strength, and the power level gave the following equation:

$$D = -2.502 + 21.67 h_i - 0.226 \sigma_f - 0.0095 P_D \qquad \ldots(1)$$

where D is the turning diameter (in m), h_i is the ice thickness (in cm), σ_f is the flexural strength of ice (in kPa), and P_D is the power level (in kW). The influences of ice thickness and delivered power on the turning circle are expected. It is not clear why increasing the ice strength would result in a decreasing turning diameter, and this is thought to be an anomaly due to applying a least squares fit to limited, somewhat scattered, data and for which the ice strength varied little.

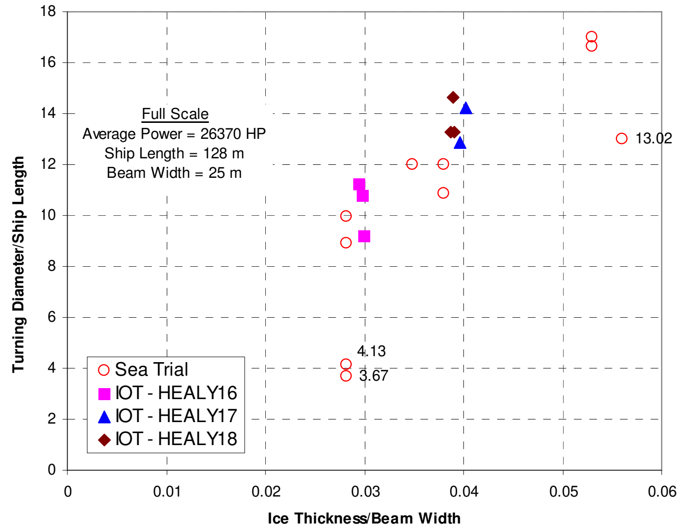

Fig 11. The non-dimensional turning diameter as a function of non-dimensional ice thickness for the Healy sea trial and model test data

DISCUSSION AND CONCLUSIONS

Propulsion overload tests in open water combined with limited ice tests have demonstrated that the IOT Standard Method for analyzing propulsion tests in ice gives consistent results for delivered power, which agree well with the available full-scale data of the *Healy*. A correlation friction coefficient of 0.05 is again shown to give good agreement between model and full-scale..

From the analysis of the resistance and propulsion tests, the *Healy* is shown to be capable of its design requirement of "continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength" with its 30,000 HP.

An imaginary "Polar 8" icebreaker of the *Healy* design would require 85,000 HP to continuously break ice of 2.44 m (8 ft.) thickness, of 500 kPa strength, at 3 knots.

A preliminary analysis of the maneuvering test data showed a good correlation between the model test and sea trial results. Multi-variance regression was performed with the model test data and the result compared with selected full-scale measurements. The turning diameter obtained during the model tests was the same in one case and slightly larger than its counterpart measured at sea trial in another case. The three outliers associated with the sea trial results (identified in Figure 11) warrant closer re-examination of these data points. The hull friction, 0.034, used in the model tests was slightly lower than the target of 0.05. The effect of this discrepancy was not incorporated in the maneuvering analysis.

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