SHIP POWERING PREDICTION USING LOAD VARYING SELF-PROPULSION TESTS

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Ship Powering Prediction Using Load Varying Self-Propulsion Tests

By

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Abstract

A method for predicting full-scale ship power performance from model load-varying test data is presented. It has been named E2001. Although presented here for a conventional twin screw icebreaker, E2001 is also being developed as an alternative to conventional ITTC 1978 based methods for ships fitted with unconventional propulsors, including those using podded propulsion systems. The method uses the load varying tests in isolation of resistance and propeller open water tests. Values of a form factor, a resistance and a thrust deduction fraction are found from an analysis of the under/overload tests. The effects of using different friction lines are included in the analysis. A discussion of the choice of appropriate correlation coefficients is provided. A final form of the method is given for the data used. Comparisons are made between the results of the extrapolation done using both the E2001 and ITTC 1978 methods and the corresponding full-scale trials.

Acknowledgements

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List of Symbols [IMD internal document]

υ_M	Kinematic viscosity of water for the model test facility, m^2/s
υ_S	Kinematic viscosity of water for the ship, m^2/s
ΔK_Q	Scale effect correction on propeller torque coefficient
ΔK_T	Scale effect correction on propeller thrust coefficient
η_R	Relative rotative efficiency
ρ_M	Water density for the model test facility, kg/m^3
ρ_S	Water density for the ship, kg/m^3
A	Submerged cross sectional area of tank, m^2
A_V	Projected frontal area of ship above the waterline, m^2
$c_{0.7}$	Model propeller blade chord at 0.7 radius, m
C_A	Incremental resistance coefficient for model-ship correlation
C_{AA}	Air resistance coefficient
C_{DM}	Model propeller section drag coefficient
C_{DS}	Ship propeller section drag coefficient
C_{F1957}	Skin friction correction coefficient in propulsion test based 1957 method
$C_{FSchlichting}$	Skin friction correction coefficient in propulsion test based on Schlichting's method
$C_{FGrigson}$	Skin friction correction coefficient in propulsion test based on Grigson's method

C_{FD}	Skin friction correction coefficient in propulsion test (based on V_M and S_M)
C_{FM}	Frictional resistance coefficient for the model
C_{FM15}	Frictional resistance coefficient for the model at 15°C
C_{FMP}	Frictional resistance coefficient for the model at the propulsion test temperature
C_{FS}	Frictional resistance coefficient for the ship
C_{RM}	Residuary resistance coefficient of model
C_{RS}	Residuary resistance coefficient of ship
C_{TM}	Total resistance coefficient for the model
C_{TM15}	Total resistance coefficient for the model at 15°C
C_{TMP}	Total resistance for the model at the propulsion test temperature
C_{TS}	Total resistance coefficient for the ship
D	Propeller diameter, m
D_M	Model propeller diameter, m
D_S	Ship propeller diameter, m
F_D	Skin friction correction in self propulsion test, N
F_M	Self-propulsion test towing force on model, N
Fn	Froude number for the ship and model
g	Gravitational acceleration (9.806 m/s^2)
J_{bol}	Dimensionless propeller rate of rotation for bollard tests
J_O	Advance coefficient in propeller open water test
J_P	Advance coefficient for model in propulsion test

k	Form factor
k_P	Full scale propeller blade roughness, m
k_S	Mean hull surface roughness, m
K_{FD}	Skin friction correction coefficient in propulsion test (based on D_M and n_M)
K_{QO}	Propeller torque coefficient in open water test
K_{QOS}	Propeller torque coefficient for full scale propeller
K_{QP}	Propeller torque coefficient in propulsion test
K_{TO}	Propeller thrust coefficient in open water test
K_{TOS}	Propeller thrust coefficient for full scale propeller
K_{TP}	Propeller thrust coefficient in propulsion test
L_M	Model length on waterline, m
L_S	Ship length on waterline, m
n_M	Model propeller rate of rotation, rps
n_S	Ship propeller rate of rotation, rps
N_S	Ship propeller rate of rotation, rpm
P_D	Delivered ship power, W
P_E	Effective ship power, W
Q_S	Ship propeller torque, Nm
R_F	Frictional Resistance
$Rnco$	Propeller Reynolds number based on chord at 0.7 radius
Rn_M	Reynolds number for the model
Rn_S	Reynolds number for the ship

R_{TM}	Total resistance for the model, N
R_{TS}	Total resistance for the ship, N
S_M	Wetted surface area of the model, m^2
S_S	Wetted surface area of the ship, m^2
t	Thrust deduction fraction
$t_{0.7}$	Maximum propeller blade thickness at 0.7 radius, m
T_P	Average test temperature for propulsion tests °C
T_R	Average test temperature for resistance tests, °C
T_S	Ship propeller thrust, N
V_A	Advance velocity of propeller, m/s
V_{KN}	Ship speed, knots
V_M	Model speed, m/s
V_S	Ship speed, m/s
w_T	Taylor wake fraction
w_{TS}	Ship Taylor wake fraction
Z	Number of propeller blades

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Chapter 1

1 Introduction

Ship design relies on model testing to determine the propulsive power of a ship. Powering predictions for the full-scale ship are extrapolated from the results of testing in a towing tank facility. Data from model scale is converted to full-scale predicted values using both theoretical and empirical methods. The methods of extrapolating the model test data to full-scale have been developed and reviewed through the work of many researchers and conferences, in particular the International Towing Tank Conferences (ITTC). The 1978 International Towing Tank Conference (ITTC 1978) began a process that sought to develop a method of powering prediction that could be adopted as a standard in the industry, called the ITTC 1978 method. However, propulsion systems have developed to include a greater variety of propulsion systems and assemblies. Powering prediction of ships from the results of testing unconventional propulsion systems using the ITTC 1978 method or modified versions of this method have proven unsatisfactory [Bose *et al.*, 1999]. An alternative to the traditional ITTC 1978 method is developed and analysed here and is recommended as a possible solution to extrapolation of power for both standard and unconventional propulsion systems. The method is less complicated computationally and requires less testing time than the ITTC 1978 method, thereby reducing expense in the towing tank.

When analysing model data from the idealized conditions of test facilities and extrapolating to ship-scale, the difference in the effects of forces from model to full-scale need to be considered. Correction factors allow for ship surface roughness and still air resistance. Also, additions are necessary for wind and wave resistance, and the effects of tank boundaries. A form factor is used to account for the form of the vessel and reflects the characteristics of the hull shape. Some of these factors are specific to individual test tanks, are empirically determined and have hindered data transfer between institutions.

The ITTC 1978 method is presented in its original form, although it should be understood that aspects of the method are often modified in individual testing institutions. An alternative method is developed and a final version with correction factors is recommended. This proposed method is designated in the thesis as Extrapolation 2001 or E2001 in shortened form. Model test data are used to develop the new method, and compare its final results with the ITTC 1978 method. In order to perform a valid comparison it is crucial to have a set of full-scale trials for each data set with which the extrapolated data are compared. Using data that consists only of model testing would have been irrelevant for this study because there would be no guide indicating how well the predicted power approximated that of ship trial conditions. Complete data sets of this kind can be difficult to acquire, primarily due to their proprietary nature. Therefore a limited amount of data was used to illustrate the method and indicate its potential. The model used is the Canadian *R-Class* icebreaker, for which corresponding full-scale trials results are available [Spencer *et al.*, 1992].

A JAVA^{TM} computer program developed for this thesis assisted in the analysis of variation of correction factors and polynomial approximations of the data; this is discussed where relevant in the text.

The ITTC 1978 method is fully described in the proceedings of the 15th conference [Lindgren *et al.*, 1978] and in Principles of Naval Architecture Volume II [Manen & Oossanen, 1988]. The procedure described is for a single screw ship and was appropriate for the limited computing power available at the time. The method involves three sets of tests: resistance, open water and self-propulsion, all performed in a towing tank. As mentioned, this method forms the basis for many of the extrapolation procedures used in modern facilities. Although the ITTC 1978 method was intended to be refined over time, it has never been completely re-published with significant changes. The committee acknowledged that there were shortcomings with aspects of the method, in particular the scale effect corrections [Lindgren *et al.*, 1978, pg. 360-363].

Advances in computing power have increased the extent and variety of analysis of both the ITTC 1978 method of extrapolation and alternate proposals.

The E2001 method gives results that are comparable with those obtained using the ITTC 1978 method but it is considerably less complicated. It uses less data, and fewer empirical correction factors. The method was developed by first constraining the extrapolation to data acquired solely through load varying self-propulsion tests. Next using methods based on work by Luigi Iannone, Jan Holtrop, Christopher Grigson and others, a number of variations were considered and a selection combined to produce a satisfactory extrapolation method. Two procedures of extrapolating thrust were considered. The first extrapolated the ship resistance and indirectly the full-scale thrust (shown later in Equation 15). The second is a direct Froude scaling, the extrapolation of resistance using the assumption that the coefficient of residual resistance is the same at model and ship scales, and can be seen in Equation 17 [Iannone, 1997]. Once evaluated, these procedures were found to be identical when the resistance value from the self-propulsion test was used and so the direct scaling approach is the method outlined within E2001.

E2001 was first evaluated using the same data, predetermined corrections and form factors as the ITTC 1978 extrapolation for purposes of comparison, and is presented in a stepwise procedure in section 4.1. Once the method was established various correction factors were evaluated and compared with the full-scale trials results. Three methods of obtaining the frictional coefficient were compared. Next an alternative form factor calculation was studied. Finally, the effect of wake scaling was considered and a recommended value used in the final presentation of the method.

Once the final version of E2001 was illustrated, a full comparison of all the results with both the full-scale trials and the ITTC 1978 method results was made and is presented here. Recommendations are made for further evaluation when additional data sets are acquired. It is of particular importance to develop a database of correlated data with which to determine an appropriate range of correction factors for ship forms and types.

E2001 is shown to be reliable, comparable to the ITTC 1978 method and relatively simpler as an analysis method. E2001 also shows promise as an alternative to the ITTC 1978, which has been used in a variety of modified forms for the extrapolation of unconventional propulsor model test data [Bose *et al.*, 1999].

Chapter 2

2 Data information

The *R-Class* vessel used is the CCGS *Sir John Franklin*, an icebreaker that has been owned and operated by the Canadian Coast Guard since 1979. It is powered by six diesel electric generators feeding power to two propellers and it has a centerline rudder. Trials were performed in Conception Bay, Newfoundland, in February 1990 [Spencer *et al.*, 1990].

The model was made from glass-reinforced plastic and was fitted with twin propeller shaft bossings and a single center line rudder [Murdey, 1980]. The particulars and scaled ship values are found in Table 1.

The propellers used in the *R-Class* model tests were geometrically similar to the full-scale propellers, the particulars are found in Table 2. While using a scaled version of the full-scale propeller is more expensive than using a stock propeller, it gives superior and more reliable results.

Table 1: *R-Class* Model and Ship data [Spencer *et al.*, 1992]

***R-Class* Data**					
			Full Scale Particulars		***Model Particulars Model #327***
Hydrostatic particulars without appendages					
				Scale	1:20
Length between perpendiculars	*LPP*	m	87.90		4.397
Length on waterline	*LWL*	m	92.14		4.691
Waterline beam at midships		m	19.31		0.968
Waterline beam at maximum section		m	19.32		0.968
Maximum waterline beam		m	19.32		0.969
Draught above datum at aft perpendicular		m	7.24		0.358
Draught above datum at forward perpendicular		m	6.76		0.335
Area of maximum station		m^2	118.72		0.309
Wetted surface area		m^2	2084.24		5.476
Area of waterplane		m^2	1413.84		3.598

Table 2: Propeller data [Murdey, 1980]

Propeller					
			Full Scale Particulars		***Model Particulars 66L&R***
				Scale	1:20
Number of blades	Z		4		4
Diameter	D	m	4.12		0.206
Pitch to Diameter ratio	P/D		0.78		0.775
Expanded area ratio			0.67		0.67
Design					Stone Manganese
Rotation	Port		-ve		-ve
	Starboard		+ve		+ve
Chord Length @ 0.7 radius		m	~1.6		~0.08

The full-scale trials recorded the shaft power and the motor power during testing. The extrapolation of model scale data predicts delivered power, P_D, which is power delivered to the propeller and not the shaft power, P_S. The correlation of the predicted data is, however, made between the predicted delivered power and the full-scale shaft power. Because of this a correction is often included. For instance MARIN use P_D/P_S = 0.975 as their standard correction if there is none given that is specific to the ship being tested. IMD does not have a standard correction, so the shaft power is correlated as acquired from the trials. This will have an effect on the closeness of the correlation and must be taken into consideration when evaluating the comparison of the extrapolation method with the full-scale trials.

2.1 Programming the methods

The methods were each programmed using JAVA™, which proved to be an ideal choice in that it handled the moderate amount of data rapidly on a modern computer. JAVA™ may not be considered an optimal choice for numerical computational work but it can be compiled to run at an increased speed. The object orientation of JAVA™ constructed the methods into compact subroutines that allow relatively easy alterations and modifications. A vast library of translated FORTRAN code was used and allowed more complex routines to be slight modifications of existing code. JAVA™ is also designed to easily accommodate the introduction of a graphical user interface that is intended to be developed at a later date. Difficulties experienced while programming were primarily confined to the ITTC 1978 method. The method consists of numerous data inputs and corrections that come from a variety of sources and so do not follow in a straightforward stepwise format. The three-test analysis creates a much larger and more complicated program than the one-test method that is being proposed. It proved to be considerably easier to develop three separate stages for the ITTC 1978 method and create new input files for each subsequent stage, however this process took time and had the goal been to automate the ITTC 1978 then more time would have been spent linking the stages.

Chapter 3

3 ITTC 1978 Method

Standard procedures of ship model testing and extrapolation have been continually evolving since William Froude's memorandum to the British navy regarding the use of experimentation to measure the resistance of ships [Harvald, 1983, p.94]. In 1978 at the 15^{th} International Towing Tank Conference (ITTC), work was completed that led to the adoption of a tentative standard method of powering performance prediction. Based on the results and considerations of the institutions that participated in the development of the standard by performing analysis on single screw ship tests according to a series of given methods (including the method developed at the conference in 1957), a common prediction method was agreed upon. Although each of the test basins that submitted data to the performance committee of the conference used the same analytical methods, there were significant discrepancies in the results. Therefore the common method agreed upon was intended to be implemented with correction factors individual to the tank performing the tests. The empirical nature of the correction factors has however caused many model basins to pursue alternative methods of analysis. The ITTC 1978 standard was first developed for single screw ships and some institutions have made additions to accommodate two or more screws [Lindgren *et al.*, 1978, pp.359-363 & IMD Internal].

The ITTC originally formed to "promote the improvement of all aspects of ship model work and to reach agreement on basic procedures and methods of presentation of results for publication". It is a "voluntary association of world-wide organizations that have responsibility for the prediction of hydrodynamic performance of ships and marine installations based on the results of physical and numerical modeling" [22nd ITTC's homepage, An Introduction to the ITTC, http://203.241.88.124/ITTC/index1.html].

The procedure for performance prediction involves first testing a model in a towing tank and accumulating data points that can then be extrapolated using a method such as that developed by the ITTC in 1978. The physical testing is achieved by towing the model down a test tank such as pictured in Figure 1. The model is attached to a carriage and information is recorded at different speeds. Three different tests are performed in order to gain the required information for the extrapolation procedure: a resistance test, a propeller open water test and a self-propulsion test. The resistance test is done without a propeller while the remaining tests include the propeller and measure additional data from the propeller shaft.

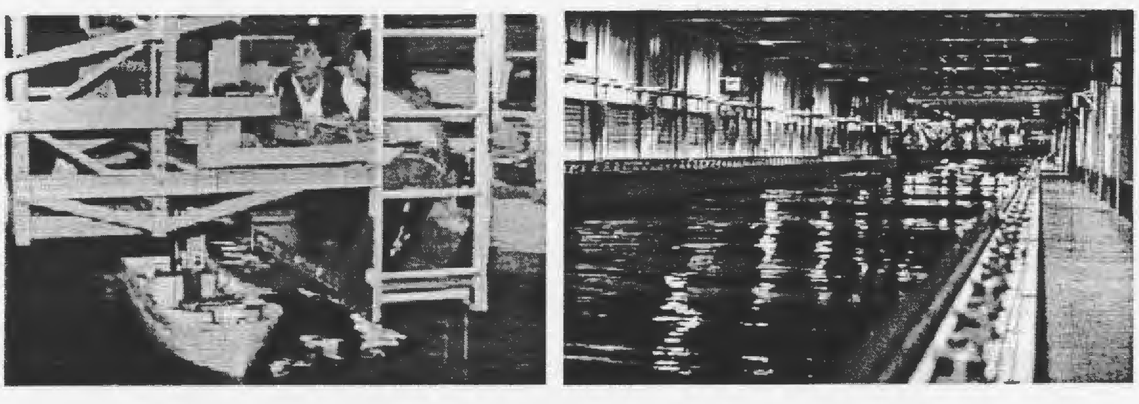


Figure 1: Tow tank Facilities at MUN and IMD [Oceanic Consulting & IMD, http://www.oceaniccorp.com/, http://www.nrc.ca/imd]

3.1 The Resistance Test

The detailed procedure of the entire ITTC 1978 extrapolation analysis has been reported by Manen and Oossanen [1988 & Lindgren *et al.*, 1978]. The purpose of the resistance test is to determine a form factor, k, calculate the wave making resistance coefficient, C_R, and thence determine the full-scale resistance, R_{TS}. The form factor is calculated according to Prohaska's method using results from low speed resistance tests [Lindgren *et al.*, 1978, pg.364]. The values are calculated using the data acquired from the test runs:

- model velocity V_M in m/s
- total model resistance R_{TM} in gm or N
- temperature of tank water in °C or °F.

The following equations from Manen and Oossanen [1988] outline the extrapolation. First the data is used to calculate non-dimensional coefficients that are extrapolated to full scale using correction factors (see List of Symbols) which are detailed in Manen and Oossanen.

Equation 1: Total resistance coefficient of model

$$C_{TM} = \frac{R_{TM}}{\frac{1}{2}\rho_M V_M^2 S_M}$$

Equation 2: Frictional coefficient of the model (1957 coefficient)

$$C_{F1957} = \frac{0.075}{(\log_{10} Rn_M - 2)^2}$$

Equation 3: Total resistance coefficient of ship

$$C_{TS} = (1 + k)C_{FS} + C_{RS} + C_A + C_{AA}$$

Equation 4: Residuary resistance

$$C_{RM} = C_{TM} - (1 + k)C_{FM}$$
$$C_{RM} = C_{RS}$$

Equation 5: Resistance of the ship

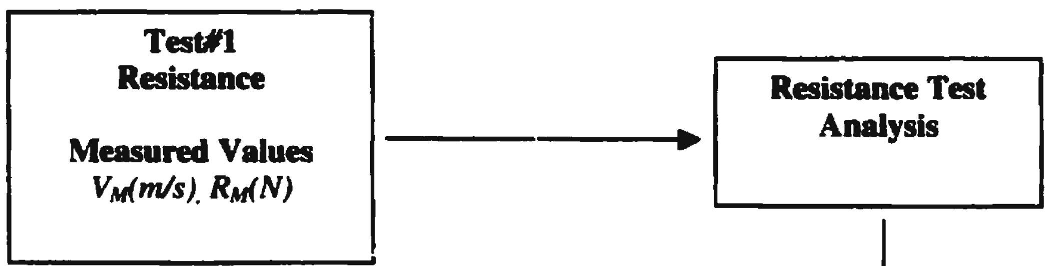
$$R_{TS} = C_{TS}\left(\frac{1}{2}\rho_S V_S^2\right)S_S$$

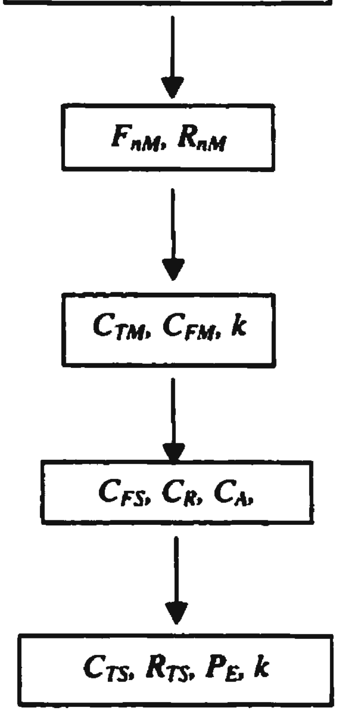
Equation 6: Effective power

$$P_E = R_{TS}V_S$$

The extrapolation involves separating the resistance into a number of components. The frictional resistance is estimated using the 1957 model-ship correlation line, Equation 2. The form effect, k, of the ship on frictional resistance is estimated in the ITTC 1978 extrapolation method using Prohaska's method. The residuary or wave-making resistance is then the difference between the total and frictional resistances, Equation 4. For the *R-Class* icebreaker the form factor k was calculated as 0.4 using Prohaska's method [Manen & Oossanen, 1988, p.13-15]. While this appeared high it is used in the extrapolation of model to full-scale values. This residuary resistance, Equation 4, is of particular overall importance, according to Froude it remains the same for model and ship at the corresponding speeds. However, it must be noted Froude's hypothesis is being questioned by theoreticians in the field [Grigson, 2000, pg. 27].

Flow Chart 1: Resistance test analysis





For the extrapolation presented the C_{AA} value of Equation 3, the still air resistance, is not explicitly included, as it is usually fairly small and can be considered as part of the correlation allowance C_A. The correlation allowance, C_A, then incorporates the correction factors for roughness and still air resistance and is used as a general correction factor with some physical significance as opposed to simply a fudge factor. The standard calculation for roughness that is given in the ITTC 1978 procedure was calculated and the values of C_A chosen were varied around that value (~0.0004).

The IMD report with the model and full-scale *R-Class* data being referenced here has noted that the correlation allowance used in the report was large due to the very rough surface of the *R-Class* full-scale vessel during testing [Spencer et al., 1992]. Once all of the components are calculated, the final ship resistance is then used to determine the effective power P_E (Equation 6), of the full-scale ship.

The flow charts presented within these chapters are a condensed version of the test analysis procedure. They show the order in which data acquired from the test are analysed to determine values that will be used in the extrapolation. The intermediate blocks indicate the order of calculation of the various coefficients. The final block in each flow chart has the data that will be passed to the method.

While these coefficients are widely used it has proven difficult to apply them universally to the wide variety of shapes and materials in use. Very full ships which may have separation on the after-body and the propeller-hull interaction of unconventional propellers such as ducted, partially ducted and vane wheels may not be properly accommodated for with these traditional equations.

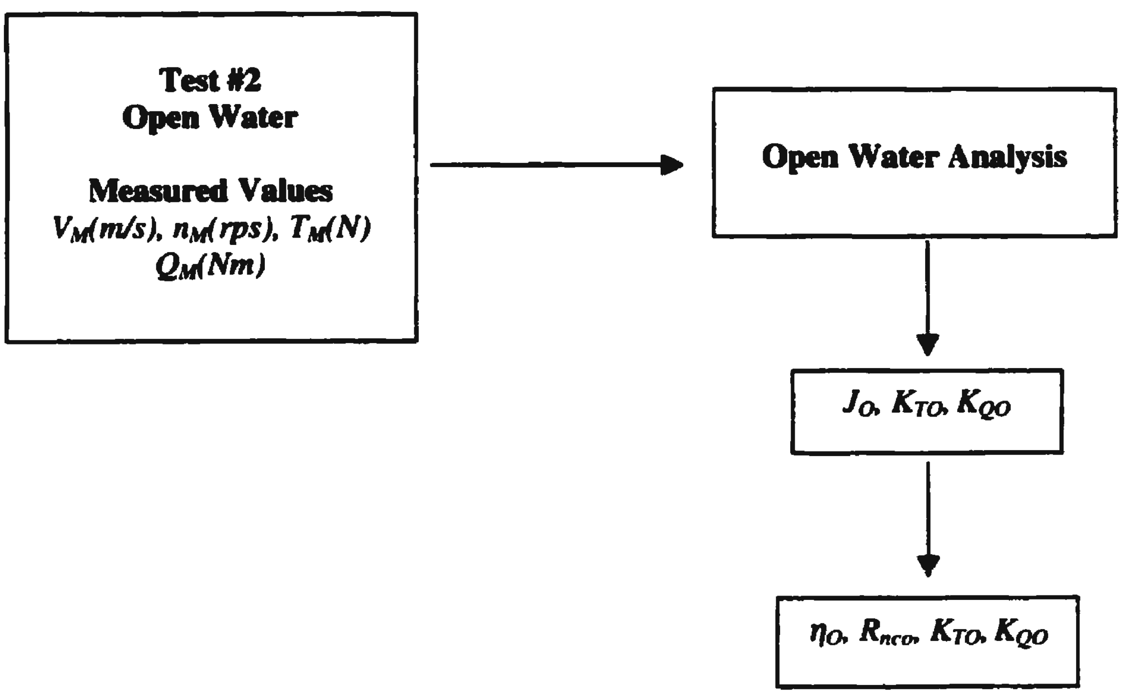
The increasing length of modern ships (>250m) also raises questions regarding the scale effects from models of 6 to 8m in length [Artjushkov, 1999].

3.2 The Open Water Test

The purpose of the open water test is to determine the performance of the propeller in a homogeneous inflow field. The working propeller operates in the ship wake, meaning the flow of water to the propeller has been altered due to the ship hull form. The data from the open water test when combined with the data from the self-propulsion test allow the wake fraction, w_T, to be calculated using the advance coefficient J_{TM} (section 3.4) [Manen & Oossanen, 1988, p.156]. The non-dimensional thrust and torque values, Equation 8 and Equation 9 below are corrected for differences in frictional coefficients due to Reynolds numbers (R_n) [Manen & Oossanen, 1988, p.155]. They are then used as the coefficients that determine the full-scale operating point of the ship propeller. Also, knowledge of how the propeller performs in uniform flow can be of great value in itself to determine and compare different propeller designs.

In an open water test, a model propeller is towed in a tow tank without its corresponding hull model. This allows the inflow of water to be unaffected by the hull. Once the measured data is acquired the non-dimensional characteristics of the model propeller are plotted in the traditional open water chart, an example of which is shown in Figure 2.

Flow Chart 2: Open water test analysis



Equation 7: Advance coefficient

$$J_O = \frac{V_M}{n_M D_M}$$

Equation 8: Thrust coefficient

$$K_{TO} = \frac{T_M}{\rho_M n_M^{\ 2} D_M^{\ 4}}$$

Equation 9: Torque coefficient

$$K_{QO} = \frac{Q_M}{\rho_M n_M^{\ 2} D_M^{\ 5}}$$

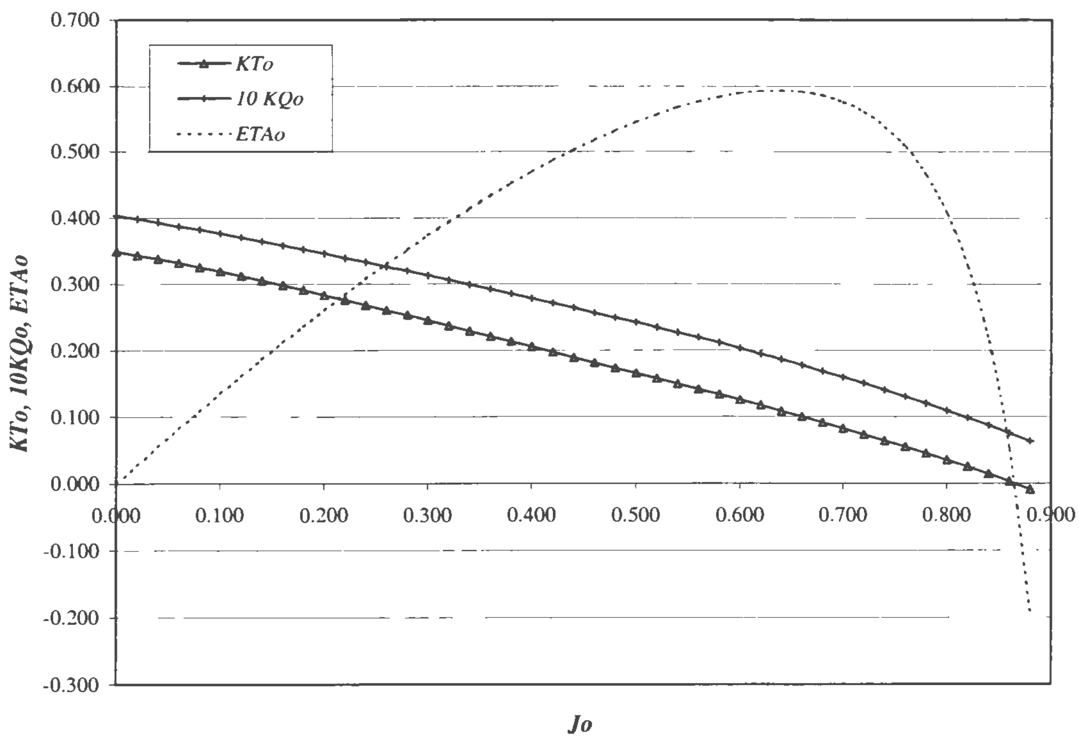


Figure 2: Open Water chart for IMD propeller 66L (*R-Class* propeller model)

3.3 The Self Propulsion Test

The self-propulsion test models as closely as possible the ship operating condition, i.e. the appendages are in place and the propeller is operating in a non-uniform flow due to the model wake. In addition, the experimental arrangement ensures that the model is free to heave and pitch and sometimes also free to roll and surge. If the model propeller balances the model resistance and fully self-propels the model then it will be working at a higher thrust loading than the full scale. This is due to the difference in frictional coefficients between the model and full-scale and the allowance at the full scale for roughness and still-air through the correlation allowance. In order to compensate for this difference the model is pulled with a force that is equal in magnitude to F_D (see section 4.1). When the propeller revolutions are adjusted to effectively give a reading of F_D on the resistance dynamometer the model is said to be at the ship self-propulsion point.

Equation 10: Self-propulsion point towing force

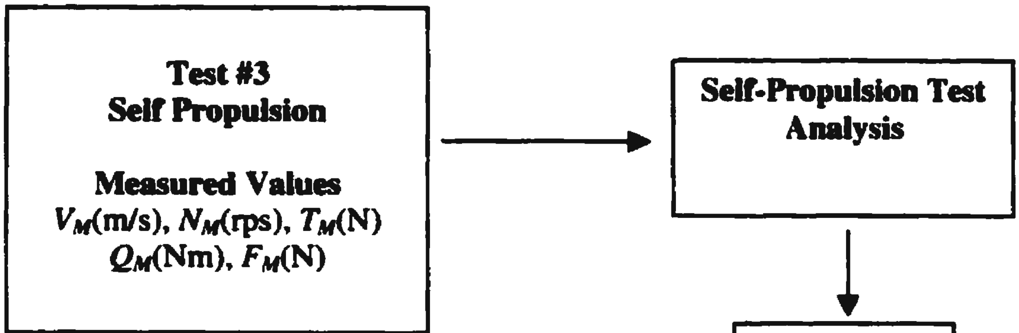
$$F_D = \frac{1}{2}\rho_M V_M^2 S_M\left[(1+k)(C_{FM} - C_{FS}) - C_A\right]$$

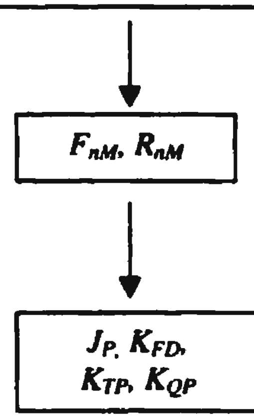
Equation 11: Towing force coefficient

$$K_{FD} = \frac{F_D}{\rho_M n_M^2 D_M^4}$$

This exact towing force can be very difficult to accurately obtain during the tank test [Manen & Oossanen, 1988, p.154].

Flow Chart 3: Self-propulsion test analysis





Therefore another method, the load-varying self-propulsion test or British method, can be used. This involves interpolating the self-propulsion point by towing at forces around that of the expected self-propulsion point and interpolating to find the actual self-propulsion point. This is effectively achieved by varying the propeller revolutions.

This second method is generally used by the Institute for Marine Dynamics, the facility that supplied the test results that are examined here [IMD Internal Document].

The non-dimensional coefficients determined in the self-propulsion test, K_{TP}, K_{QP}, J_P, are calculated in the same manner as the open water test (Equation 8, Equation 9 and Equation 7). They are used to estimate the change in propeller performance from a homogeneous to a non-homogeneous inflow field in effect, due to the wake.

3.4 The Performance Prediction Method

The results of the analysis from each test are inputs to the performance prediction analysis. The load-varying method requires the interpolation of the self-propulsion point. The method used here involves first plotting the non-dimensional towing force coefficient K_{FD} from the self-propulsion test analysis against the advance coefficient. An additional curve, which is the towing force coefficient as a function of J^2 and represents the value of F_D at the ship self-propulsion point as calculated from Equation 10 (see Equation 13) is also plotted. Figure 3 shows the intersection of these two towing force coefficient curves; this is the ship self-propulsion point.

Equation 12: Model tow-force coefficient

$$C_{FD} = C_{TMP} - C_{TS}$$

$$C_{TMP} = C_{TM} + (1+k)(C_{FMP} - C_{FM})$$

C_{FMP} - Frictional Coefficient of the Model at the temperature of the self-propulsion test

C_{TM} and C_{FM} are at a common temperature, often the standard temperature of 15°C.

Equation 13: Curve of required C_{FD} as a function of J_P^2

$$\frac{K_{FD}}{J_P^2} = \frac{C_{FD} S_S}{2 D_S^2}$$

Flow Chart 4: Performance Prediction

Performance Prediction Input Values
C_{TS}, R_{TS}, P_E, k, J_O, K_{TO}, K_{QO}, η_O, R_{nco} J_P, K_{FD}, K_{TP}, K_{QP}

→ **Extrapolation**

↓

C_{FD}, K_{FD}/J^2
Model Self Propulsion Point
J, K_{TM}, K_{QM}, J_{TM}, K_{QTM}

↓

w_{TM}, t, η_R, w_{TS}

↓

C_{DM}, C_{DS}, K_{TS}, K_{QTS}, K_{TS}/J_O^2
Ship Self Propulsion Point

↓

n_S, P_D, T_S, Q_S, P_E, η_T

At the intersection of these curves J and K_{TM} (both port and starboard for the *R-Class* data) are read and used to evaluate the thrust and hence the thrust deduction fraction t (since the thrust can be compared with the resistance at the same speed, $R=T(1-t)$) [Harvald, 1983, pg. 180]. The K_{QM} (again both the port and starboard values for the *R-Class* data) is also read in order to use in the determination of the relative rotative efficiency (see Manen & Oossanen)

If there is only one open water curve as is the case with the *R-Class* propeller data where the open water curves of the two propellers (66L&R) were found to be indistinguishable [Murdey, 1980, pg.3], the average K_{TM} value can be used to find the average advance coefficient. Because the R-Class data is twin screw however, averages need to be clearly noted so that when required the average value can be doubled.

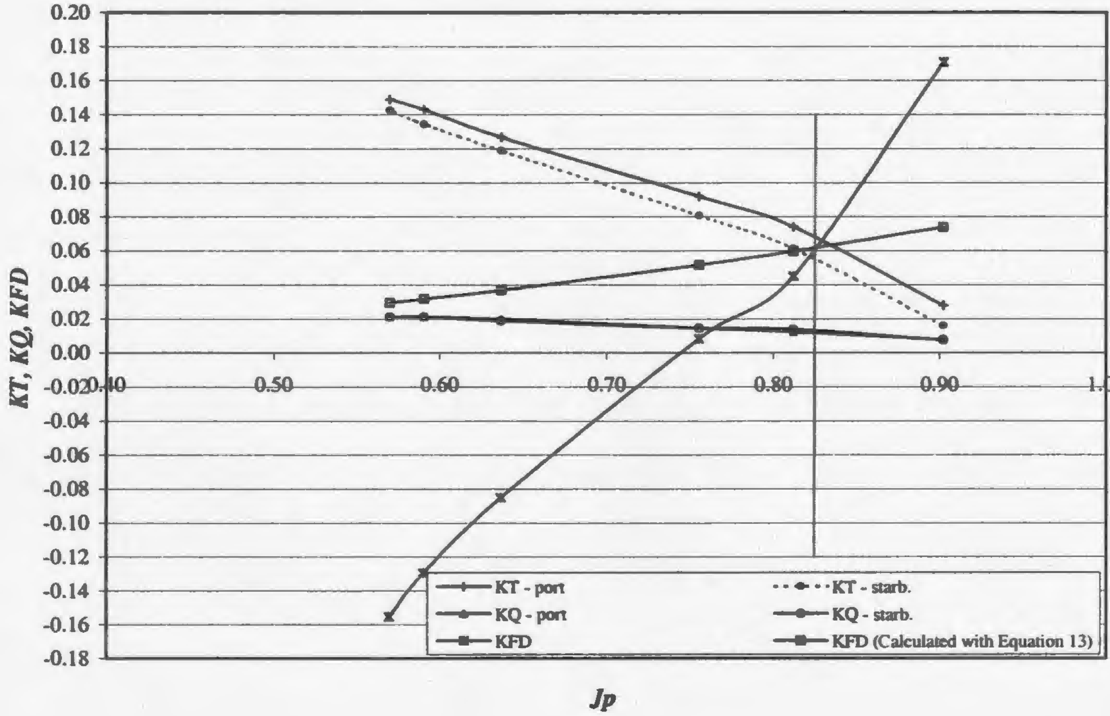


Figure 3: Method for determining the self-propulsion point, *R-Class* data

At the value of the thrust coefficient from the open water chart equivalent to that obtained from the self-propulsion chart, $K_{TO} = K_{TM}$ (the thrust identity) the advance coefficient value is read; this is J_{TM}. The K_{QTM} value is then found at this J_{TM} and the relative rotative efficiency, η_R is found from $\eta_R = K_{QTM}/K_{QM}$. The wake fraction of the model w_{TM} is determined using the advance coefficients from each of the charts, $w_{TM} = 1-J_{TM}/J$. Once these values are known the wake fraction is scaled to ship scale w_{TS} [Manen & Oossanen, 1988, pg. 155].

The ship propeller operating point is interpolated using the intersection of the K_{TS} curve and the curve of K_{TS} as a function of J_O^2 found from Equation 14 in the same manner as above. The K_{TS} and K_{QS} curves are the open water propeller data corrected for full-scale Reynolds number (see section 3.2). This gives the values of J, K_T and K_Q for the ship, see Figure 4. Care was taken to ensure that Equation 14 reflected the twin screw form of the R-Class data that was used. The C_{TS} reflected the resistance coefficient for the ship as a whole so the K_T had to be the total K_T of the two propeller thrust coefficients ($K_{Tport} + K_{Tstarboard}$).

Equation 14: Ship propeller operating point interpolation curve

$$\frac{K_{TS}}{J_O^2} = \frac{S_S C_{TS}}{2D_S^2(1-t)(1-w_{TS})^2}$$

The full-scale thrust and torque coefficients are then used to obtain the full-scale shaft speed, delivered power, propeller thrust and torque, and effective power [Manen & Oossanen, 1988, pg.155-157].

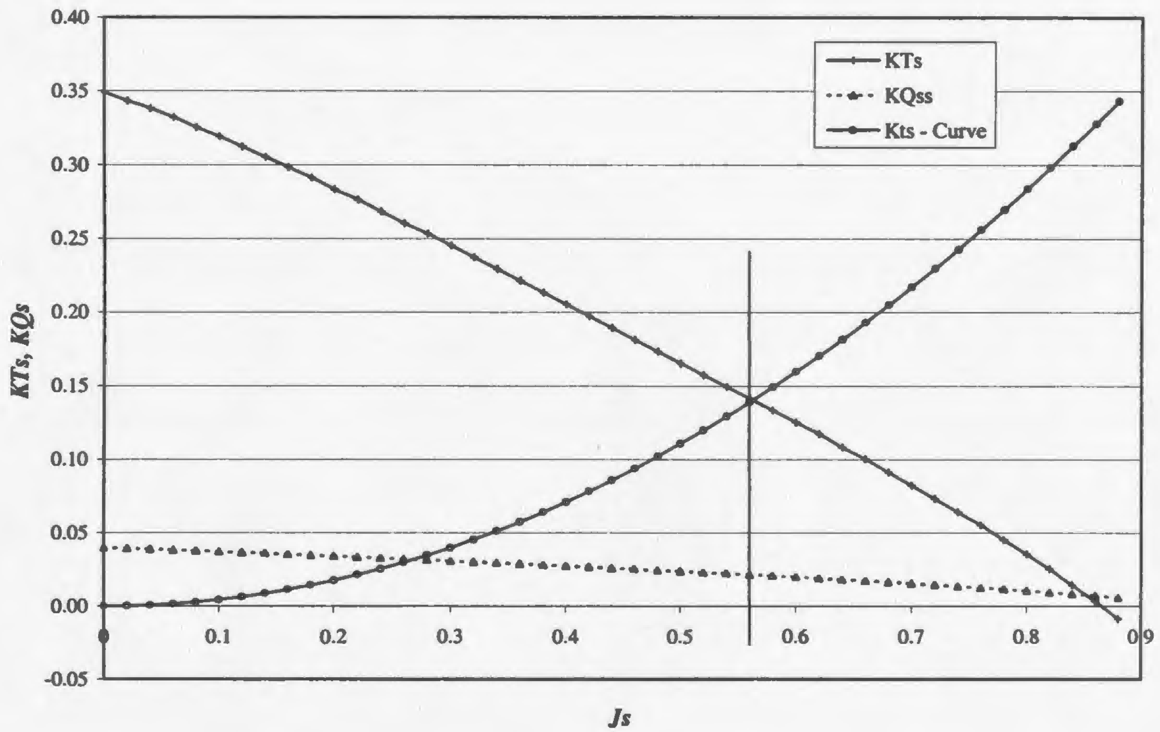


Figure 4: Determining ship propeller operating point, *R-Class* Data

3.5 Programming the ITTC 1978 Method

When programming this method, the initial approach was to separately analyse the different tests, then link the results within a program. This was due to the fact that the three tests were performed separately. While each run of the tank was made at a specific speed the speeds were not the same across the tests and so data at one speed for all three tests could not be input into one program. C_{TS}, Equation 3, is used in the determination of the ship propeller operating point, Equation 14, at a specific speed.

It proved to be more useful to take the resistance data and apply a regression analysis that would give the resistance at the speed or Froude number of the self-propulsion test being analysed and therefore allow it to be included in an input file for that speed or Froude number. The polynomial curve fit within EXCEL™ was used to get a representation of the resistance data (Figure 5) and was considered a satisfactory fit.

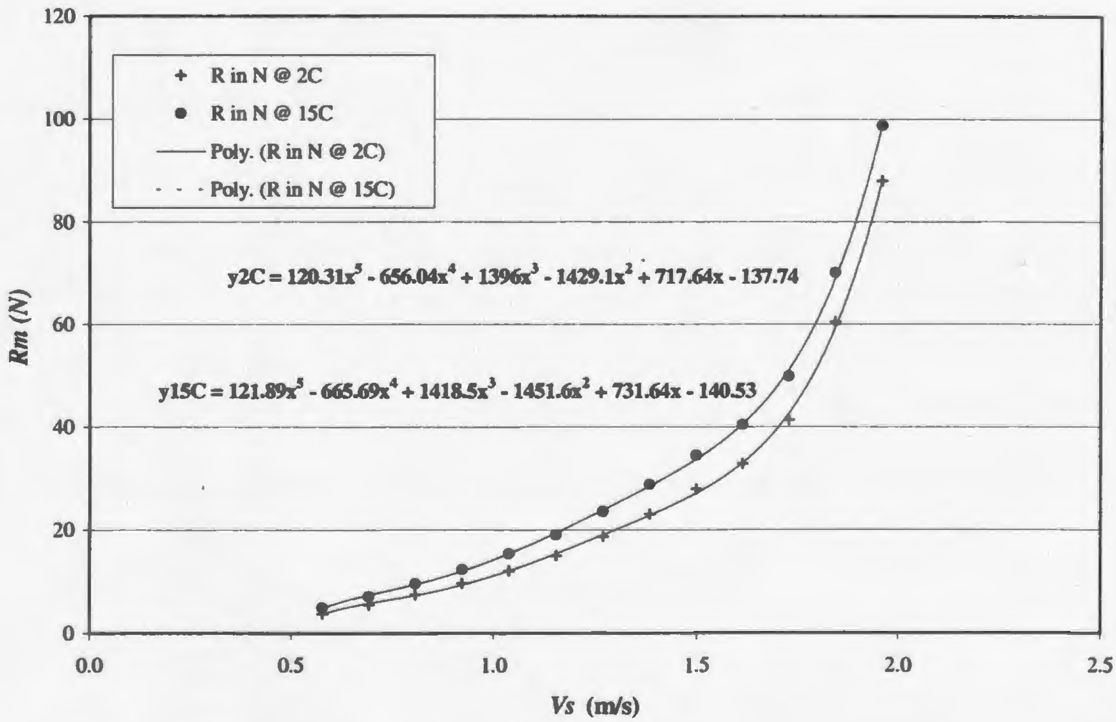


Figure 5: 5th order polynomial curve fit to resistance data

The curve was checked at speeds above and below those included in the chart and found to behave within the trend shown in Figure 5.

The resistance value was combined with the self-propulsion test results and the relevant particulars of the model (length, scale etc.) and test (temperature, viscosity, etc.). This data was input to the computer program, which calculated the various values discussed in the previous chapters using subroutines. The program then used a least-squares analysis to determine best-fit curves to the K_T and K_Q data (Figure 3) in terms of J. These were compared with the data outside of the program and the second order polynomial curve fits were found to be acceptable representations of the data. The intersection of the two K_T curves (again, Figure 3) was found through simultaneous equations. For each speed of the *R-Class* data there was a positive and negative root, the positive root was the correct one. The roots were output for verification with each run of the program.

A separate input file for the open water data was used. Again, the values were determined and a least squares analysis was performed to find the best polynomial representation for the K_{QO} data. The K_{TO} versus J_O curve was represented in terms of K_{TO} so that the K_{TM} value from the intersection in Figure 3 could be input to determine the J_{TM} at that value of K_{TM} (Figure 2) and then the K_{QTM} value from the representation of the K_{QO}.

The intersection for the ship propeller operating point was also found using simultaneous equations of the K_T and K_Q curve fits from the open water data corrected for full-scale Reynolds number (see section 3.2) and Equation 14.

Once these intersections were identified, the remainder of the program involved straightforward calculations of the various coefficients and predicted values.

The use of numerical methods to determine the intersection of the different curves within the program without the need for external verification was considered. However, it was not complicated to find the exact intersection point using this method with the quantity of data being analysed.

3.6 Results of the ITTC 1978 method compared with full-scale trials

The delivered power of the full-scale trials was the power delivered to the propeller. The shaft and motor powers were recorded so the shaft power was used in the correlation as discussed in chapter 2. A regression curve that was used to approximate the actual data (fit through a function in EXCEL™) was used to compare the shaft power at specific speeds. This regression curve was a close fit (shown later in Figure 23) but it must be recognized that it is an approximation of the data when comparing the predicted power from the extrapolation methods.

The extrapolated delivered power as shown in Figure 6 for several correlation allowances is plotted with the full-scale trials data. The power is plotted in linear pieces as opposed to using a curve in this and all the following charts throughout the thesis. The reason for this is that there are only five data points and it was not considered an accurate representation of the data to use curve fits. The C_A of 0.0004 that was recommended in the IMD report [Spencer *et al.*, 1992] looks to be overall the most appropriate choice for this ship taking into consideration a potential 2 to 3% difference in the shaft and delivered powers of the ship. The shaft speed, torque and thrust and effective power are plotted in the following figures. The lowest Froude number, 0.102, shows anomalous results which are attributed to the inherent measurement difficulties at such low resistances and thrusts. The load cells used in traditional testing while appropriate for the loads measured in the tests, have very high bias error when applied in the measurement of the comparatively small forces at the lowest speeds. Using more sensitive load cells at these speeds would increase the accuracy of the force measurements, but the risk of damage to the expensive load cell is high so the cost is not always considered to be justified.

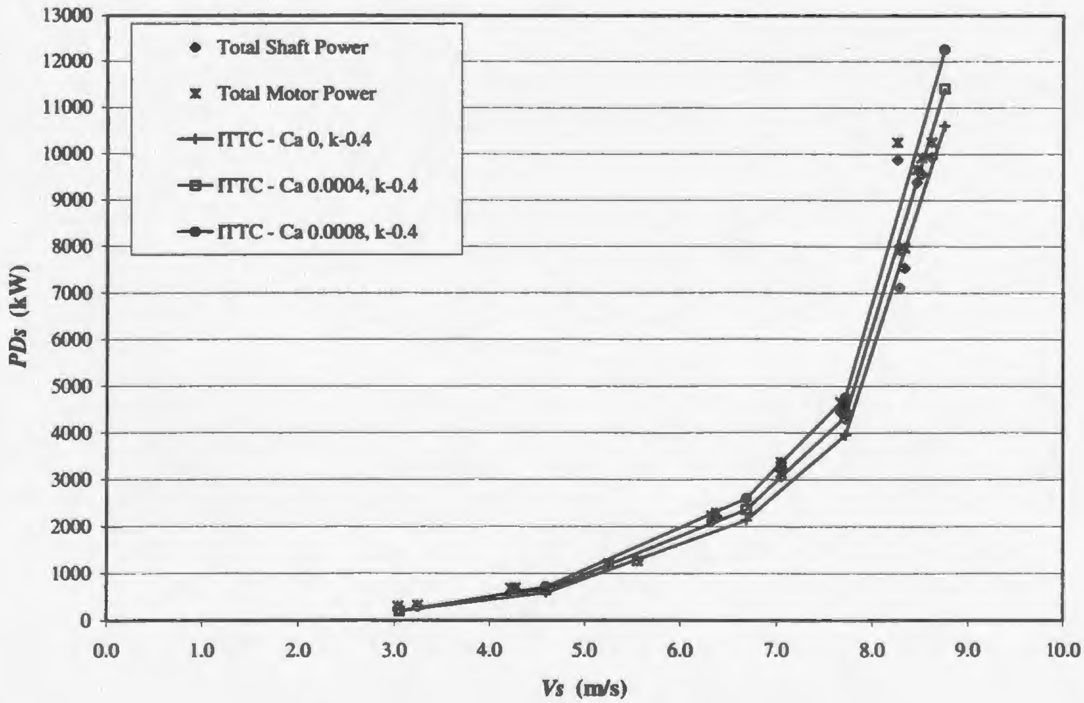


Figure 6: ITTC 1978 method delivered power prediction

There are no full-scale trials results for the effective power, Figure 10; it is used here in an illustrative capacity primarily to indicate the effect of the correlation allowance on the full-scale resistance ($P_E = R_S V_S$).

The ITTC 1978 method is shown above and in the following figures along with the full-scale trials data. The ITTC 1978 method extrapolates this *R-Class* model scale data to give power values that closely follow the full-scale trials data trends. The predictions are close to the full-scale values for all of the ship characteristics presented except the shaft speed where the predictions are significantly lower than the trials data.

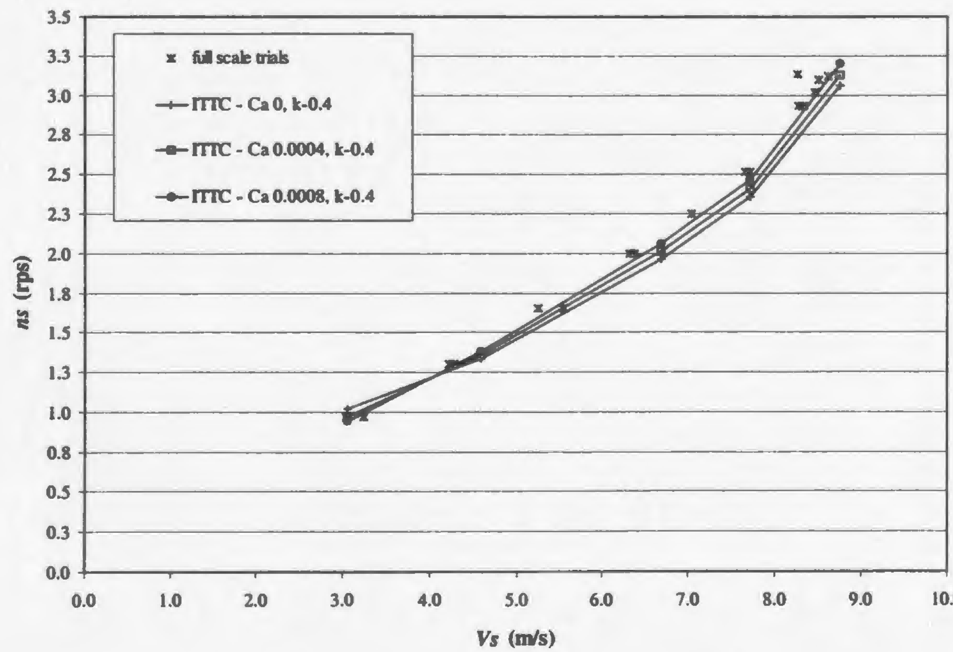


Figure 7: ITTC 1978 method shaft speed prediction

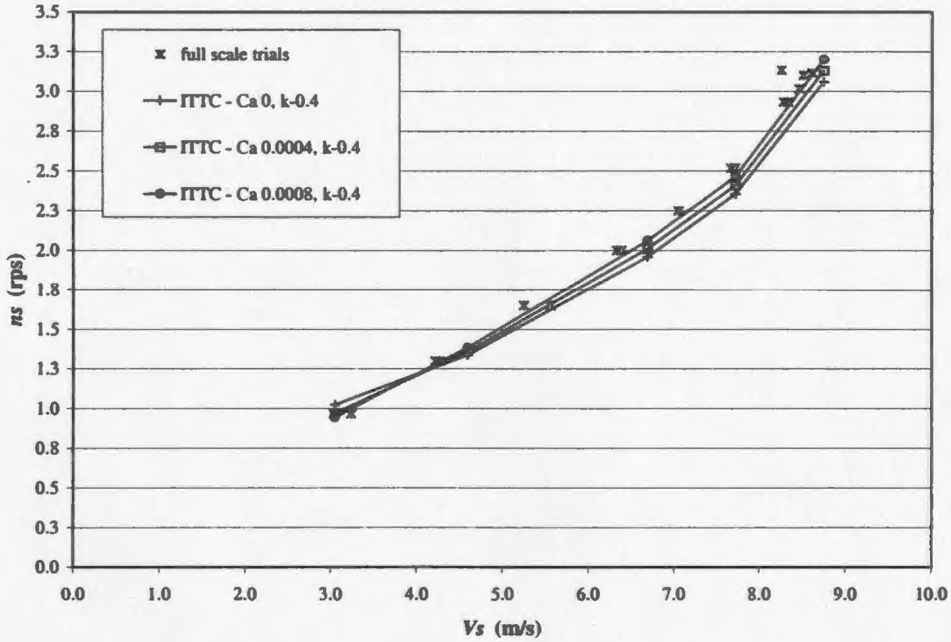


Figure 8: ITTC 1978 method torque prediction

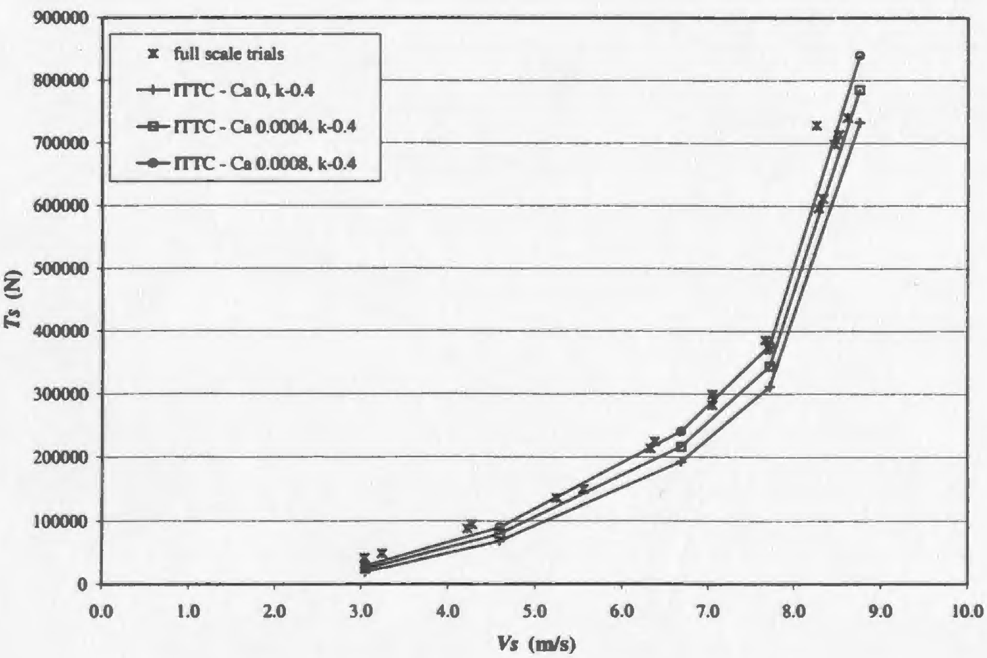


Figure 9: ITTC 1978 method thrust prediction

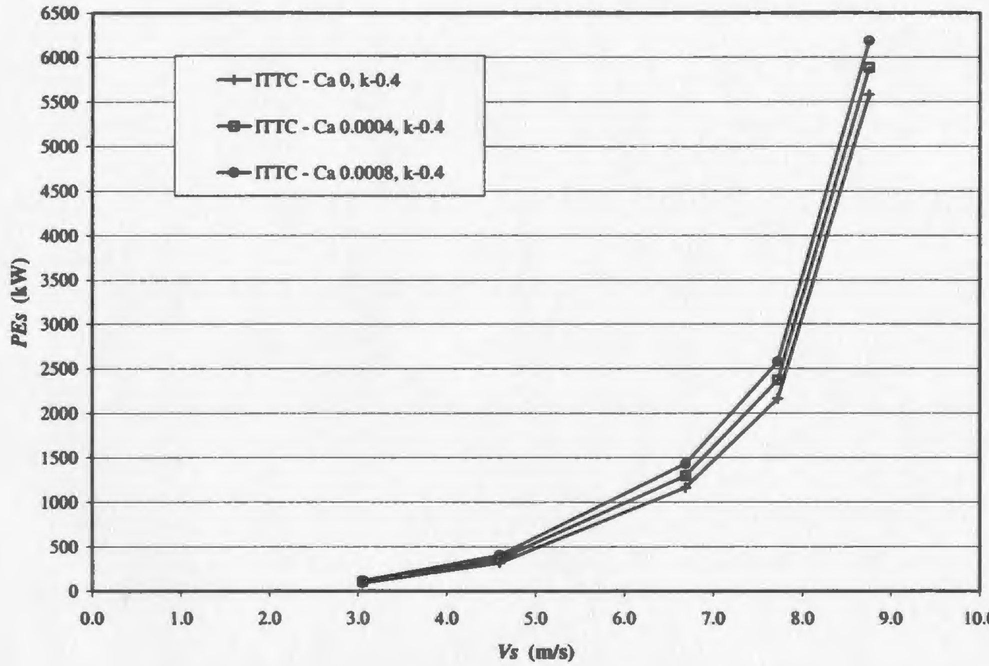


Figure 10: ITTC 1978 method effective power prediction

3.7 Sensitivity to Ship Self-Propulsion Point

The powering prediction is dependent on the interpolated values obtained through the use of the method. Due to the use of data from three sets of tests, the points are often interpolated manually, i.e. using spreadsheet software. When spreadsheet software is used the self-propulsion point is determined from the plot of non-dimensional curves and the K_{TM} obtained (section 3.4) is used to find J_{TM} and K_{QTM} from a plot of open water non-dimensional curves. These three values are then used to calculate the wake fraction and thrust deduction fraction [Manen & Oossanen, 1988, pg. 156] which scale the non-dimensional values from the open water chart and again using interpolation, non-dimensional coefficients are read from the chart (Figure 4). As can be inferred, the potential for variation in the values read from the charts is high and reliability of the final power result is in a margin ± 2 to 10% if all the possible variations are considered; this may be an unacceptable range for some ship owners. It is preferable therefore to have a standard method of completing the analysis with a computer program to avoid this source of rounding error and build up a database that identifies the quality of the correlation of the prediction results with post-construction correlation trials. However, there will remain differences based on the curve fits of the data used; some individuals may allow "rogue" points that others would exclude. Experience would assist the analyst in understanding the significance and origin of scattered points. For example: in some cases it may indicate model behaviour during the test in others it may indicate unreliable testing equipment.

While analysing data before the computer program was completed, it was found that changes in the self-propulsion point, (from repeated readings of plotted charts) caused a ripple effect through the wake and thrust deduction fractions that caused changes in the predicted power by up to 10% in some cases (such as when all the different values were varied or rounded off). An analysis of effects of interpolated values and the terms calculated using those results was performed.

The two self-propulsion points are interpolated from charts. The results of the first self-propulsion point, those obtained from Figure 3, are combined with the open water chart results to determine the wake fraction, $w_{TM} = 1 - J_{TM}/J$. Also, they are combined with resistance test results to calculate the thrust deduction fraction, $t = (T_M + F_D - R_M)/T_M$ [Harvald, 1983]. (Note that there is an additional source of variation from the true value; the resistance test results are fit to a regression curve to determine the resistance at that speed).

Table 3 gives an indication of the effect on the final power prediction when the first self-propulsion point is altered by, 2 to 10 %. In this case the self-propulsion point from the computer program is taken as the datum and the percentage change is from the full-scale power obtained using the program. Here, each value of the self-propulsion point is changed evenly by a specific percentage. When using spreadsheets however the different thrust and torque coefficients could be rounded up and down in ways that could result in some values increasing 2 to 5% and others decreasing by similar amounts. In this light the table is presented as an illustrative example of the effect on power of small changes in the self-propulsion point.

Trends observed in Table 3 show that with a decrease in the self-propulsion point there is a corresponding increase in the power and vice versa. Although the percentage changes are not consistent the average is that every ~1% change in self-propulsion point results in a ~0.25% change in power for 6.686 m/s ship speed; the power change is closer to 0.15 to 0.2% for 7.719m/s.

Table 3: Sensitivity of power to changes in self-propulsion point

V_S		Full-scale predicted power using program
m/s	knots	kW
6.686	12.996	2365

Self-propulsion point from program		-2% Change	difference @ -2%	-5% Change	difference @ -5%	+5% Change	difference @ +5%	+10% change	Difference @ +10%
Ktport	0.085742	0.0840272	-0.00171	0.081455	-0.00429	0.090029	0.00429	0.094316	0.00857
Ktstbd	0.079810	0.0782138	-0.00160	0.075820	-0.00399	0.083801	0.00399	0.087791	0.00798
Kqport	0.014098	0.013816	-0.00028	0.013393	-0.00070	0.014803	0.00070	0.015508	0.00141
Kqstbd	0.014928	0.0146294	-0.00030	0.014182	-0.00075	0.015674	0.00075	0.016421	0.00149
Power difference (kW)			12.95		35.37		-25.47		-43.32
% difference in delivered power			0.55%		1.50%		-1.09%		-1.87%

V_S		Full-scale predicted power using program
m/s	knots	kW
7.719	15.004	4348

Self-propulsion point from program		-2% Change	difference @ -2%	-5% Change	difference @ -5%	+5% Change	difference @ +5%	+10% change	Difference @ +10%
Ktport	0.093554	0.091683	-0.00187	0.088876	-0.0047	0.098232	0.00468	0.102909	0.00936
Ktstbd	0.091427	0.089599	-0.00183	0.086856	-0.0046	0.095999	0.00457	0.100570	0.00914
Kqport	0.014856	0.014559	-0.00030	0.014113	-0.0007	0.015599	0.00074	0.016341	0.00149
Kqstbd	0.015772	0.015456	-0.00032	0.014983	-0.0008	0.016560	0.00079	0.017349	0.00158
Power difference (kW)			15.95		45.07		-29.34		-59.93
% difference in delivered power			0.37%		1.03%		-0.68%		-1.40%

3.8 Sensitivity to w_T and thrust deduction fraction t

The wake and thrust deduction fractions are both calculated directly from the self-propulsion point as previously stated (section 3.7). Table 4 and Table 5 indicate the influence that variation in these terms has on the full-scale power. This also introduces the effects of changes attributable to reading the values from the open water chart and of fitted lines to the resistance tests. The wake fraction is determined from the readings of self-propulsion and open water charts. The thrust deduction fraction is calculated using the self-propulsion chart and the resistance regression curve. These tables therefore indicate the potential effects that changes in open water readings and resistance curves can have on the final power.

Table 4: Sensitivity of power to wake fraction, w_T

V_S		w_T from program	w_T	0.09	0.1	0.15	
m/s	knot						
6.686	12.996	0.0941867	difference in w_T	-0.00419	0.00581	0.05581	
			% difference in w_T	-4.45%	5.81%	37.21%	
Power difference (kW)				8.74	-12.08	-113.67	
% difference in delivered power				0.37%	-0.51%	-4.81%	
V_S		w_T from program	w_T	0.09	0.095	0.1	0.125
m/s	knot						
7.719	15.004	0.0927010	difference in w_T	-0.00270	0.00230	0.00730	0.03230
			% difference in w_T	-3.00%	2.42%	7.30%	25.84%
Power difference (kW)				9.64	-8.19	-25.95	-113.71
% difference in delivered power				0.22%	-0.19%	-0.60%	-2.62%

The tables show the alteration of only the wake and thrust deduction fractions. This means that the self-propulsion point is calculated using the computer program and just the value in the table is altered in order to see the effect it has on overall delivered power.

Table 4 identifies that increasing the wake fraction leads to decreasing power which physically means that the self-propulsion advance coefficient J is bigger, and increasing in difference, than the open water advance coefficient, J_{TM}, requiring less power. The trend for this data is a change of 1% in the wake fraction results in approximately a 0.08 to 0.1% change in the power.

Table 5: Sensitivity of power to thrust deduction fraction, *t*

Vs		*t from program*	*t*	*0.150*	*0.155*	*0.160*	*0.200*
M/s	*knots*						
6.686	12.996	0.148	*difference in t*	*0.00185*	*0.00685*	*0.01185*	*0.05185*
			% difference in t	*1.24%*	*4.42%*	*7.41%*	*25.93%*
Power difference (kW)				4.52	16.83	29.30	135.27
% difference in delivered power				0.20%	0.71%	1.22%	5.41%
7.719	15.004	0.153	*difference in t*	*-0.00318*	*0.00182*	*0.00682*	*0.04682*
			% difference in t	*-2.12%*	*1.17%*	*4.26%*	*23.41%*
Power difference (kW)				-14.98	8.62	32.54	235.82
% difference in delivered power				-0.35%	0.20%	0.74%	5.14%

Table 5 shows that in this case, with an increase in the thrust deduction fraction there is a corresponding increase in the power, for a 1% increase in the thrust deduction there is approximately a 0.15 to 0.2% increase in the power, a trend seen at both speeds.

While the percentage change in any of the predicted delivered powers under the given situations is not greater than 6%, a combination of changes could result in a change that is significant enough to affect the contract speed of the ship.

Chapter 4

4 Proposed Method - Extrapolation of E2001

The proposed extrapolation method, E2001 is based on results solely from load-varying self-propulsion tests. The absence of a resistance test is justified by the changing forms of vessels, e.g. bulbous stern, and propulsion devices, e.g. pods or ducts. The resistance test does not give a realistic estimation of the resistance of these types of ships under way because it cannot account for the more complicated propeller-hull interaction. The self-propulsion test is performed as required by the ITTC 1978 method, but to obtain the most reliable results using this prediction method, additional tests should be performed at low Froude numbers. These help in more reliable determination of the form factor. Also, supplementary low-thrust tests over a range of Froude numbers assist in more accurately determining the thrust deduction fraction, t and the towing force at zero thrust ($F_{T=0}$).

The following values are acquired directly from a standard self-propulsion test.

(a) model velocity (V_M) in m/s (this is normally set prior to each run)

(b) shaft speed of the model propeller shaft (n_M) in rps (also normally set prior to each run)

(c) thrust of the propeller (T_M) given in N

(d) torque (Q_M) given in Nm

(e) towing force of the model (F_M) given in N

E2001 uses direct and Froude scaling of the model thrust, T_M, to determine the full scale thrust, T_S (see Equation 17). Another option would be to use the scaling of the towing force at zero thrust, $F_{T=0}$, full-scale resistance R_{TS}, and the thrust deduction fraction, t obtained from the difference of the model thrust and this value of $F_{T=0}$ (Equation 15).

Equation 15: Full-scale thrust from full-scale resistance

$$T_S = \frac{R_{TS}}{(1-t)}$$

Each method gives the same results, as they are mathematically equal. The direct and Froude scaling was chosen because it is in a form relevant to the single test nature of the method and does not imply that the value of $F_{T=0}$ represents the resistance as determined through a resistance test.

4.1 E2001

The method consists of two distinct stages; the first focuses on the evaluation of scaling factors and the second following in a logical format (that was easily programmed for straightforward analysis) determines the full-scale characteristics.

The first stage began with an evaluation of the test data. The towing force (pull) was plotted against the thrust, which, as is usually found, lead to a linear relationship [Holtrop, 2000] (Figure 11). Any rogue points that may have skewed the final results were then identified and a decision made as to whether or not to include them in the analysis.

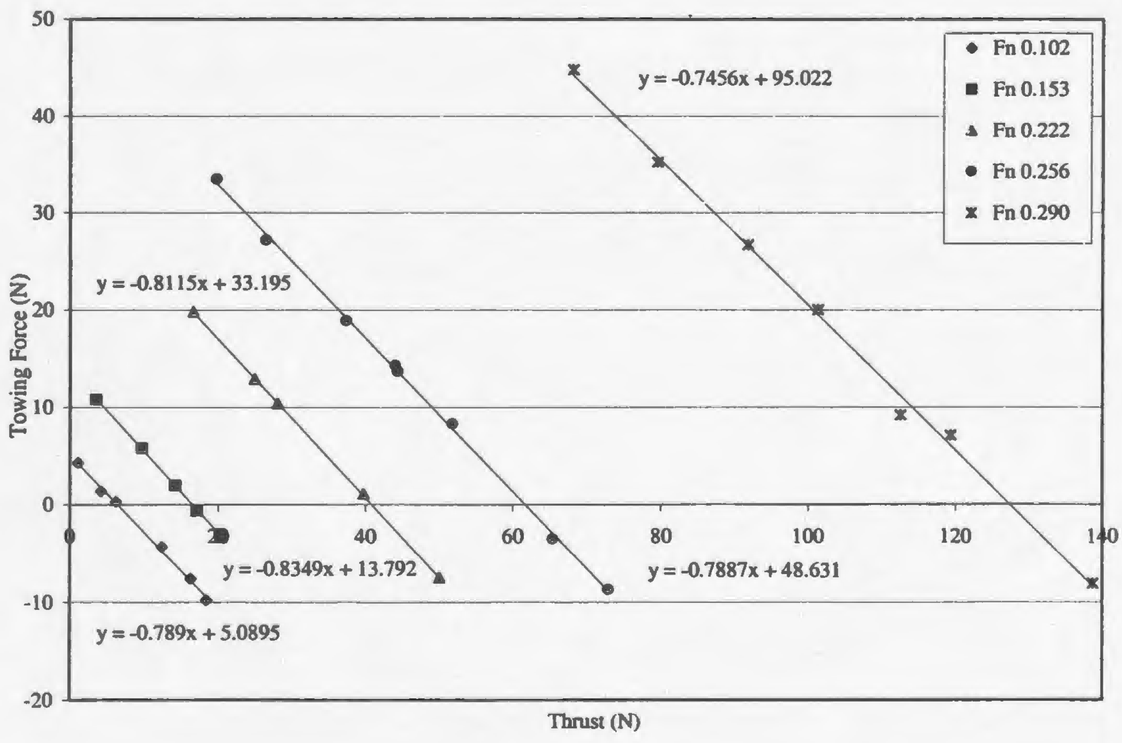


Figure 11: Towing force versus thrust for IMD *R-Class* model test

A linear regression line fitted through the points at each Froude number yields a straight line with a slope of *t-1*, where *t* is a thrust deduction fraction and the y-axis intersection represents a resistance of the model in the self-propulsion test conditions. For this data, *t* varied from 0.163 to 0.211. In order to properly evaluate the data (check for scatter or skew) the thrust deduction was evaluated separately for each speed or Froude number outside of the program rather than automating the process of calculating *t* within the body of the program. Then the thrust deduction fraction at each Froude number was added to the input file for the program.

Equation 16: Linear relationship between thrust and towing force

$$F = T(t-1) + F_{T=0}$$

Example from Figure 11:

For $Fn = 0.222$

$R = 33.2$

$(t-1) = -0.8115$

$\therefore\ t = 0.1885$

This value of towing force at zero thrust, $F_{T=0}$, which can be thought of as the resistance, is not expected to be exactly equal to that of the resistance from the resistance test. This is due to the differing conditions of the self-propulsion test (i.e. all appendages were in place and the effect of the propeller is included). A comparison of the resistance found from the standard resistance test [Spencer *et al.*. 1992] to the value of resistance obtained from the self-propulsion test is shown in Figure 12. This plot shows that both resistances share a similar trend, but the $F_{T=0}$ values are an average of 14% higher than the resistance tests.

Although not performed in this test series, the ranges of each set of points in Figure 11 indicate that further low thrust tests added for each speed would give more information about the near-zero thrust values of towing force and potentially, a more reliable estimation of the towing force at zero thrust ($F_{T=0}$).

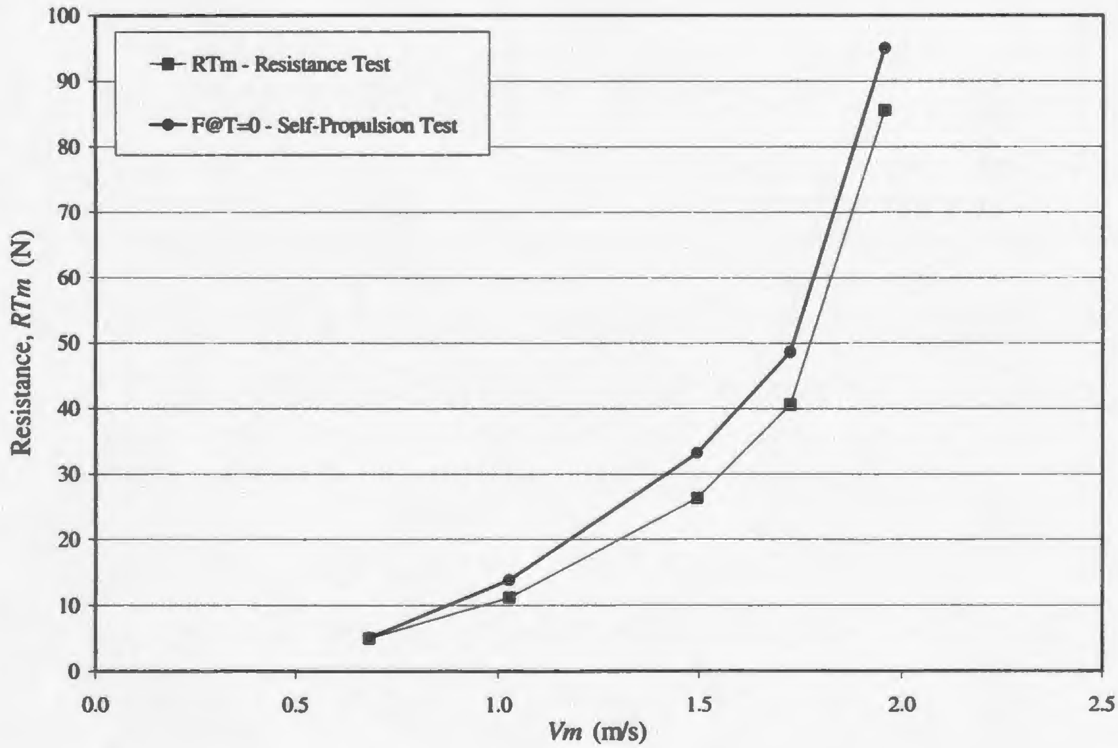


Figure 12: Resistance results from an IMD resistance test of this model and from $F_{T=0}$ values from the self propulsion test

The ship self-propulsion point is the point from which the full-scale values are extrapolated and is interpolated from the load varying data. Holtrop [2000] defines the self-propulsion point well. It is the point at which the towing force applied is equal to the scale effect on the frictional resistance and the correlation allowance, Equation 10. When this force is applied, the thrust of the model propeller is almost dynamically similar to that of the full-scale ship. This is described in discussion of self-propulsion tests, section 3.3.

This towing force F_D is calculated as before in Equation 10:

$$F_D = \frac{1}{2}\rho_M V_M^{\,2} S_M \left[(1+k)(C_{FM} - C_{FS}) - C_A\right]$$

where initially, C_F was obtained from the ITTC 1957 ship/model correlation line, Equation 2. The correlation allowance, C_A accounts for the hull roughness, still air drag and other unknown differences between model and ship. The form factor was initially taken to be 0.4 as was calculated through use of Prohaska's method and reported by Spencer [1992], a further analysis using an alternate method of obtaining the form factor is discussed in section 6.

Once the tow force at the self-propulsion point, F_D, is found, the thrust of the ship T_S can be calculated from direct and Froude scaling of the model thrust [Iannone, 1997, Section 3].

Equation 17: E2001 – full-scale thrust

$$\begin{aligned} T_S &= T_M \lambda^3 \frac{\rho_S}{\rho_M} \\ &= \left\{ T + \frac{F_D - F}{t - 1} \right\} \lambda^3 \frac{\rho_S}{\rho_M} \\ &= \left(\frac{F_D - F_{T=0}}{t - 1} \right) \lambda^3 \frac{\rho_S}{\rho_M} \end{aligned}$$

where T and F are any coordinates on the line for the Froude number being extrapolated (Figure 11). F is found using Equation 16:

$$F = T(t - 1) + F_{T=0}$$

All these values are included in the input file for the program so up to this point the program consists of a series of straightforward calculations. A comparison of the full-scale thrust computed in this manner and the results from the full-scale trials is shown in Figure 13. The results with a C_A of 0.0004 and a k of 0.4 are very close both in trend and value to those from the full-scale trials, especially at the higher speeds.

The total resistance coefficient of the ship, C_{TS}, is found using the ship resistance and calculated using Equation 18 and Equation 3.

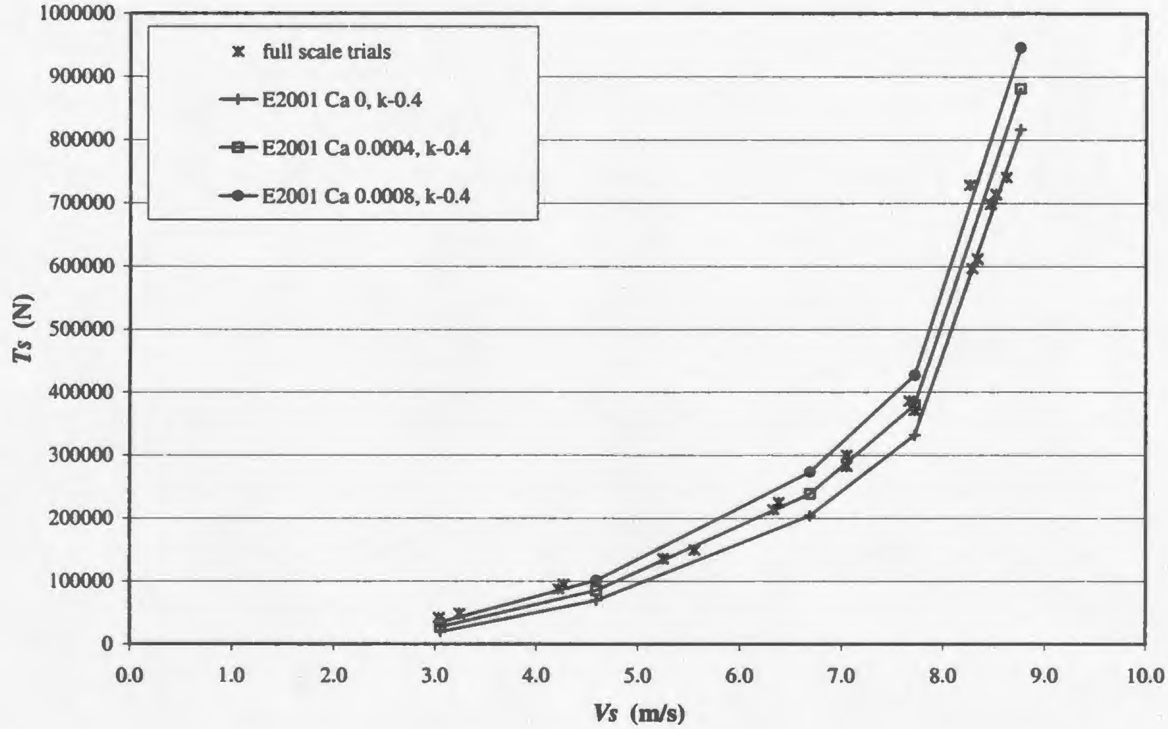


Figure 13: Comparison of E2001 full-scale thrust results with *R-Class* trials data

Equation 18: E2001 - full-scale resistance

$$R_T = T_S(1-t)$$

Using the interpolation procedure similar to that shown in section 3.4 and Figure 4 and fully described by Holtrop [2000] the full-scale propeller operating point was obtained. The non-dimensional coefficients for the thrust (K_T) and torque (K_Q) in the behind condition were plotted against the advance coefficient, J and a least squares analysis was performed within the computer program to get a polynomial fit to the data of the form found in Equation 19 and Equation 20. For this data the results were separate second order fits for each Froude number. To solve for the propeller operating point simultaneous equations using the fitted K_T curve and Equation 21 were used within the program and the roots of the solution were output for verification before proceeding with further analysis.

The propeller correction (ΔK_T & ΔK_Q) was included to account for the Reynolds number difference between the model and full-scales on the frictional coefficient of the propeller blades. The method cited in the ITTC 1978 method [Manen & Oossanen, 1988, pg. 156] was used. Later, in section 7, a wake scaling was added to the full-scale propeller coefficients.

Equation 19: Ship thrust coefficient K_{TS} [Holtrop, 2000]

$$K_{TS} = a_1 J^2 + b_1 J + c_1 - \Delta K_T$$

Equation 20: Ship torque coefficient K_{QS} [Holtrop, 2000]

$$K_{QS} = a_2 J^2 + b_2 J + c_2 - \Delta K_Q$$

Equation 21: E2001 interpolation curve

$$\frac{K_{TS}}{J_S^{\,2}} = \frac{T_{TS}}{\rho_S D_S^{\,2} V_S}$$

Once the ship propeller operating point was determined the value of K_{TS} found in combination with the ship thrust (T_S) was used to find the shaft speed.

Equation 22: Full-scale shaft speed

$$n_S = \sqrt{\left[\frac{T_S}{K_{TS} D_S^{\,4} \rho_S}\right]}$$

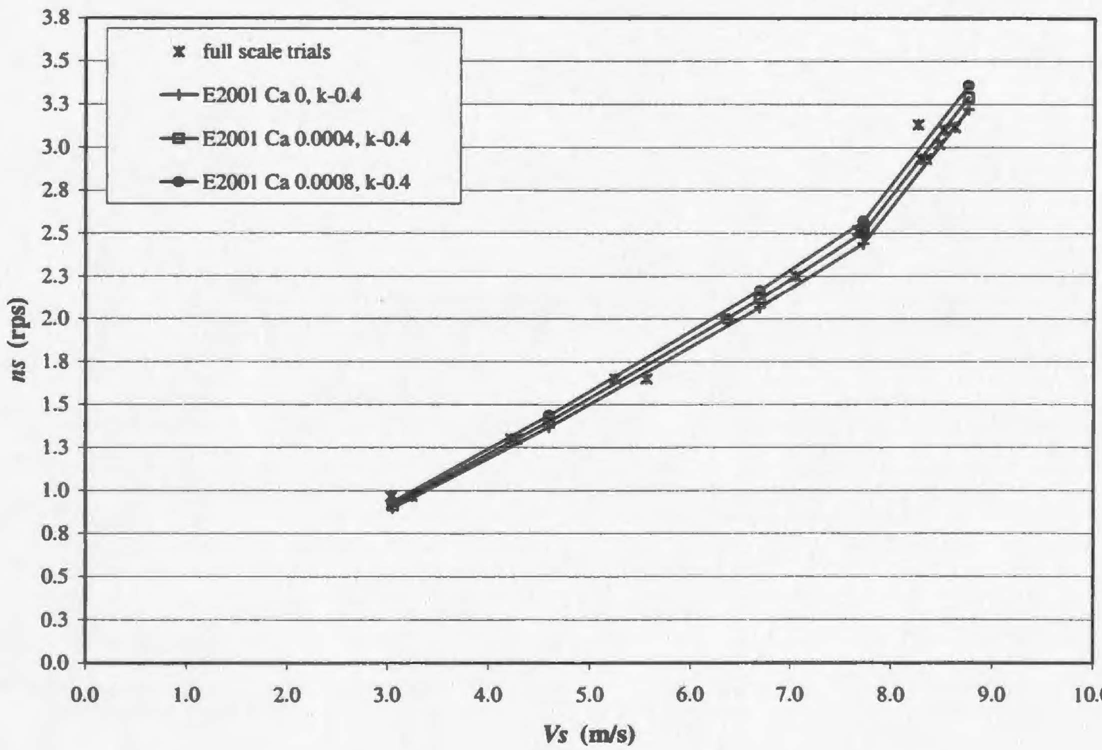


Figure 14: E2001 predicted shaft speed compared with *R-Class* full-scale trials results

Equation 23: Full-scale torque

$$Q_S = \rho_S n_S^2 D_S^5 K_{QS}$$

Using E2001 in this format (C_{F1957}, k=0.4, no wake scaling) the C_A value of 0.0004 produced a curve that, overall, most closely approximated the full-scale trials data. There was a notable absence of the anomalous behaviour at the lowest Froude number that was observed with the ITTC 1978 method (Figure 7).

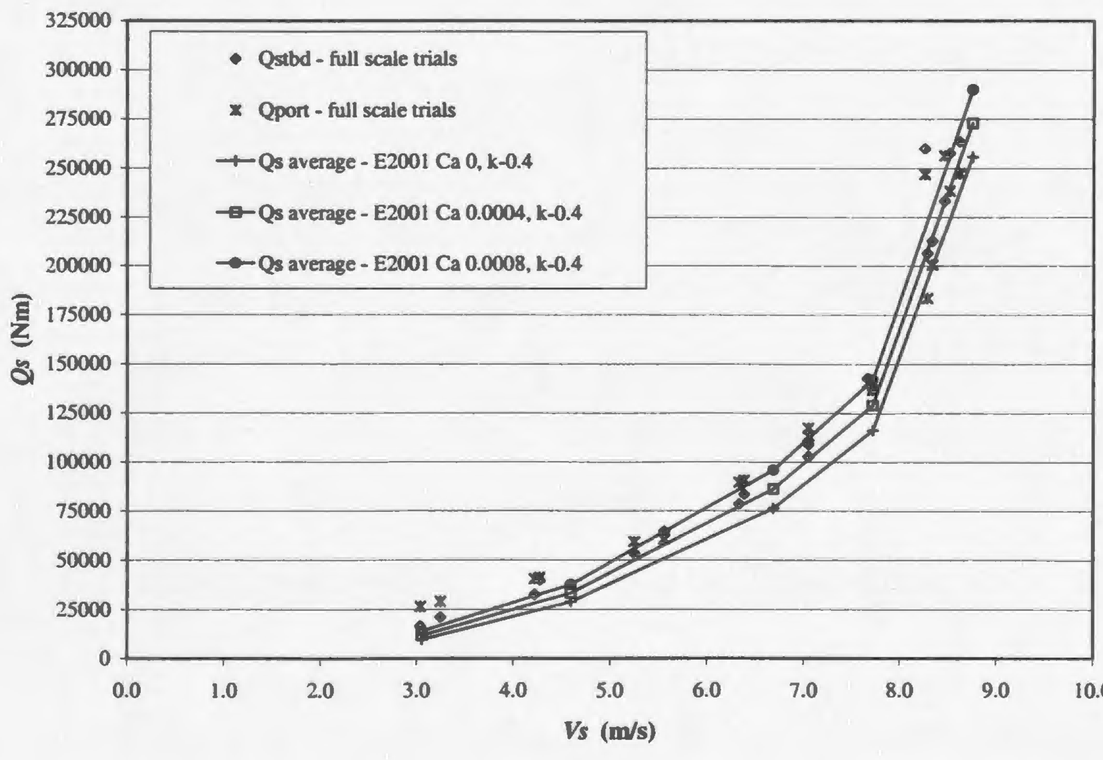


Figure 15: E2001 predicted torque compared with *R-Class* full-scale trials results

Once the shaft speed was determined, the torque (Q_S) was calculated using Equation 23. The torque plot indicates that a C_A value between 0.0004 and 0.0008 may be a more appropriate choice; the curve with C_A 0.0004 under-predicts at a number of points.

In each of the predicted value plots, the high speeds correlate best with the full-scale trials data somewhere between a correlation allowance of C_A of 0.0004 and C_A of 0.0008, and there is poorer agreement at the lower speeds.

Once the torque is determined, the delivered power (P_{DS}) is calculated using Equation 24.

Equation 24: Full-scale delivered power

$$P_{DS} = 2\pi\rho_S n_S{}^3 D_S{}^5 2K_{QS}$$

Using the self-propulsion data alone prohibits the calculation of the relative rotative efficiency used in the ITTC 1978 method and it is therefore not used in the final calculation of the delivered power. In addition, the relative rotative efficiency is primarily used to account for the mismatch in torque coefficient values when the wake fraction is found from the thrust identity using the open water propeller data. This is not used here.

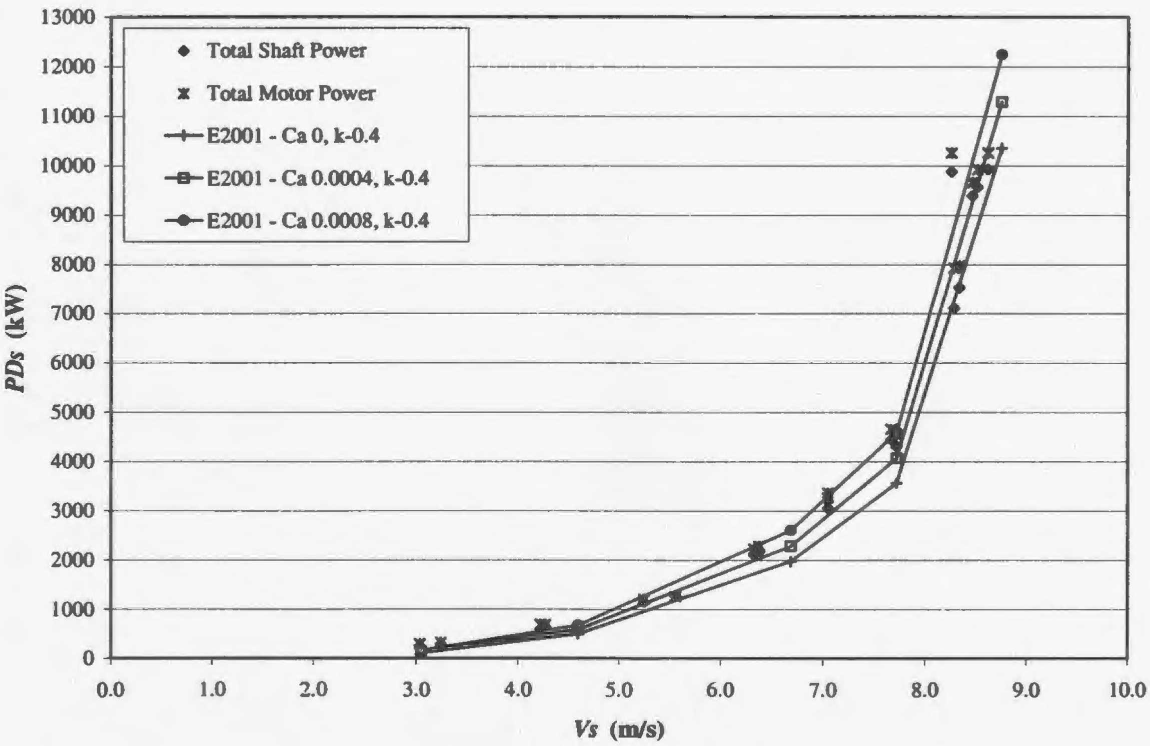


Figure 16: E2001 predicted delivered power compared with *R-Class* full-scale trials results

The delivered power plot most clearly identifies that the appropriate choice for the correlation allowance is between 0.0004 and 0.0008 under these conditions. While alternate frictional coefficients and form factors are considered and a wake scale is introduced, this trend is valuable to note so that the range of correlation allowances used in the analysis in following chapters can be constrained.

Chapter 5

5 Frictional Coefficient

The purpose of calculating the frictional coefficient is to determine an accurate form factor and wave-making coefficient or coefficient of residual resistance, C_R. [Grigson, 1993].

Two alternate methods of determining the frictional correction were considered. The ITTC 1957 model ship correlation line [Manen & Oossanen, 1988, pg. 13] is recommended for use with the ITTC 1978 method. Grigson [1999, pg.25] has suggested an alternate to the ITTC 1957 line and the new method, E2001, was performed using this and the turbulent friction flat plate friction line formulated by Schlichting [1987]. The resulting power predictions are presented below.

Grigson has formulated a new turbulent flat plate friction line after extensive analysis. He has then given an approximation to these results by presenting regression equations that catalogue the difference between these results and the 1957 line [Grigson, 1993].

Equation 25: Frictional coefficient – Grigson (model and full-scale) [1999, pg.25]

$$For: 1.5\times10^6 < Rn < 20\times10^6$$
$$C_F = \left[0.9335+0.147(\log_{10} Rn-6.3)^2-0.071(\log_{10} Rn-6.3)^3\right]\cdot C_{F-ITTC1957}$$

$$For: \quad 20\times10^6 \le Rn < 6\times10^9$$
$$C_F = \begin{bmatrix} 1.0096+0.0456(\log_{10} Rn-7.3)-0.013944(\log_{10} Rn-7.3)^2+ \\ 0.0019444(\log_{10} Rn-7.3)^3 \end{bmatrix}\cdot C_{F-ITTC1957}$$

Using analysis of the turbulent boundary layer of a flat plate, Schlichting developed the following formula for the frictional coefficient [Schlichting, 1987, pg. 641].

Equation 26: Frictional coefficient - Schlichting

$$C_F = \frac{0.455}{(\log_{10} Rn)^{2.58}}$$

The delivered power of the ship is compared for the three different frictional formulations in Figure 17. There is only a very small difference between the predicted values using C_{F1957} and Schlichting's equation. However, Grigson's coefficient results in a trend that appears to follow the trials data more effectively. Using a different C_A value would raise the curve to align more closely to the trials data. The effect of the other correction factors, and in particular the exact value of the correlation allowance to be used is identified in a later section. It appears from this data and Grigson's extensive analysis [Grigson, 1993], that the more representative frictional coefficient would be that from Grigson.

Additional plots of the shaft speed, torque and thrust are found in Appendix A.

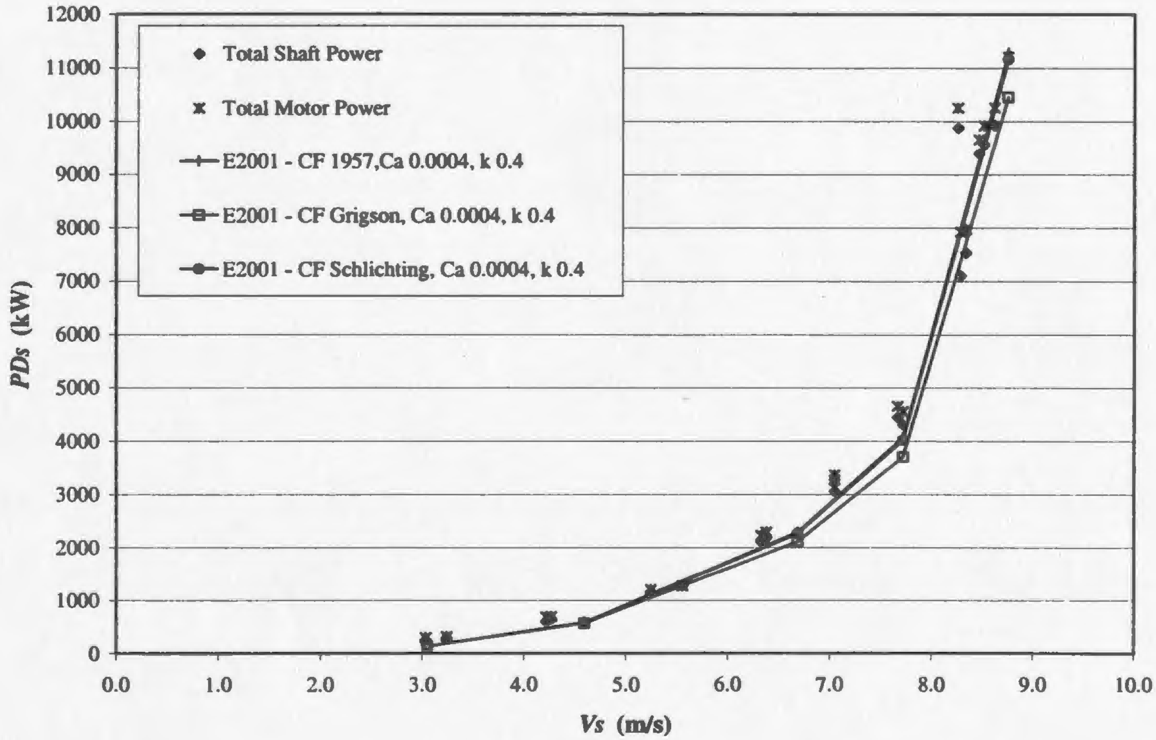


Figure 17: Predicted delivered power for *R-Class* data using three different C_F formulations

Chapter 6

6 Form Factor

In the ITTC 1978 method the form factor, the value that accounts for the effect of the shape of the vessel on the flat plate frictional resistance, is determined using Prohaska's method as mentioned in section 3.1. However E2001 does not use a resistance test so an alternate method is used. Holtrop [2000], and also the testing facility MARIN, use a method outlined in Equation 27 below, which is plotted on similar axes as Prohaska's method but which uses data from the lower Froude number self-propulsion tests.

At low Froude numbers, when wave-making is very small, the resistance as determined above ($R_M = F_{T=0}$) is approximately equal to the frictional resistance (R_F) times one plus the form factor ($1+k$) [Holtrop, 2000].

Equation 27: Form Factor - Holtrop

$$R_M = F - \frac{T}{\left(\partial T / \partial F\right)} = F + T(1-t)$$

$$R_M \approx R_F(1+k) \qquad Fn \to 0$$

$$(1+k) \approx \lim_{Fn \to 0}\left[\frac{R_M}{R_F}\right]$$

Strictly, since $F_{T=0}$ is somewhat greater than the resistance found from a resistance test, the value of 1+k is also greater by a similar factor. However no adjustment to the k value found here was made.

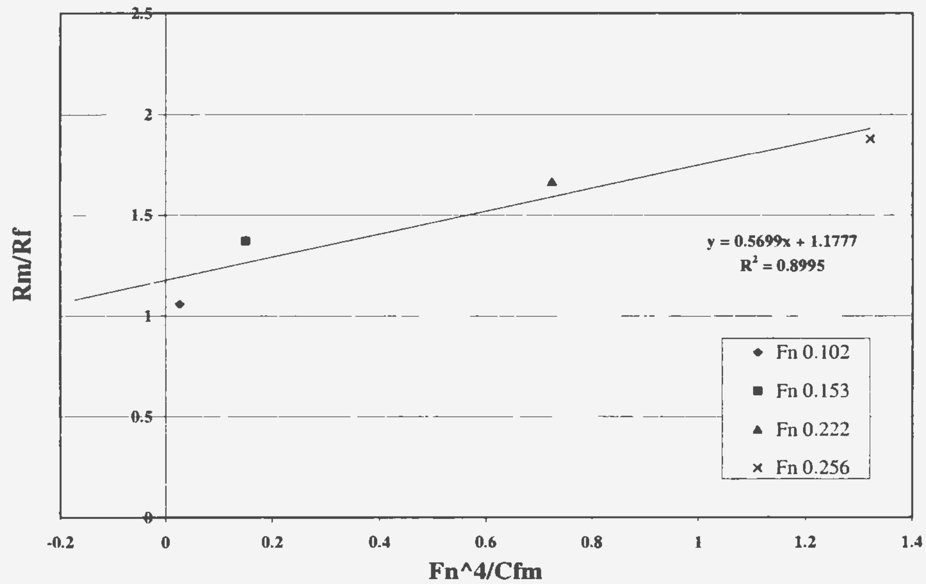


Figure 18: Form factor determination using Froude numbers from 0.102 to 0.256

While Prohaska recommends that data is used from tests conducted in the range $0.1<Fn<0.22$, the following charts are for:

Figure 18: 0.102<Fn<0.256, which proved to be strongly affected by the values at a Froude number of 0.102 (which is considered to be an unreliable data point due to uncertainty in the data and scatter) giving a form factor of $k = 0.1777$

Figure 19: 0.153<Fn<0.256, which gave $k = 0.3233$.

Figure 20: 0.153<Fn<0.222, which gave $k = 0.2964$.

Ideally these plots should indicate a trend as the Froude number is reduced, but very low Froude numbers can results in precision errors in the test results due to the low values of the forces being measured. There may also be laminar flow on the model at these low speeds. In subsequent analysis the value of the form factor was taken to be 0.3.

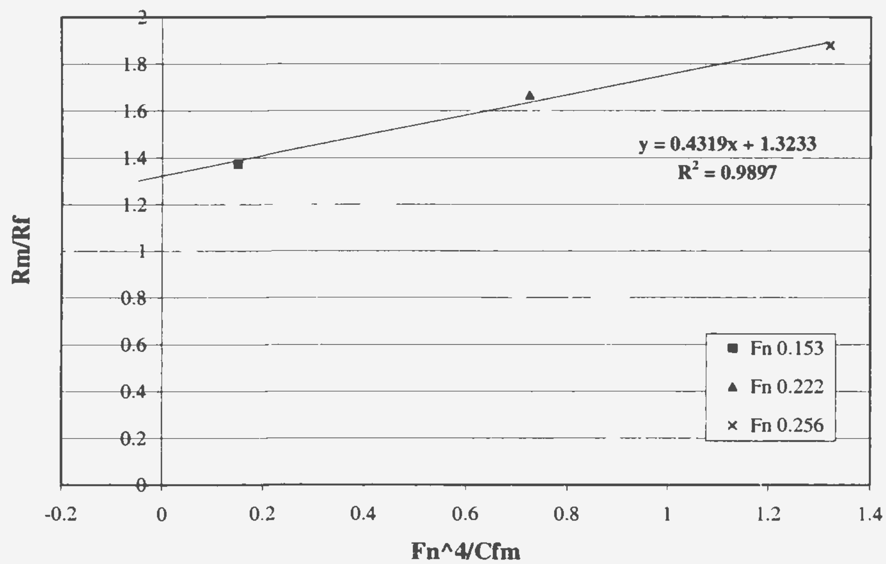


Figure 19: Form factor determination using Froude numbers from 0.153 to 0.256

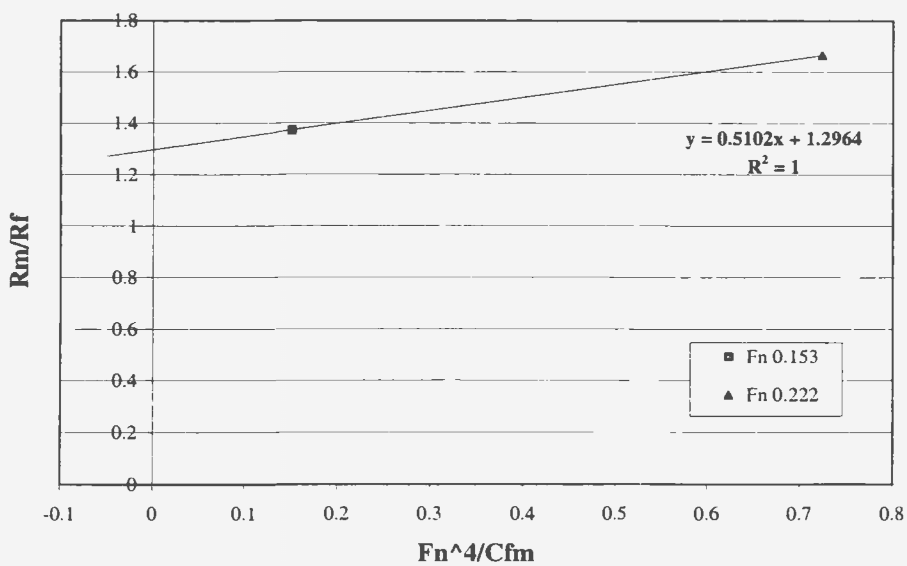


Figure 20: Form factor determination using Froude numbers from 0.153 to 0.222

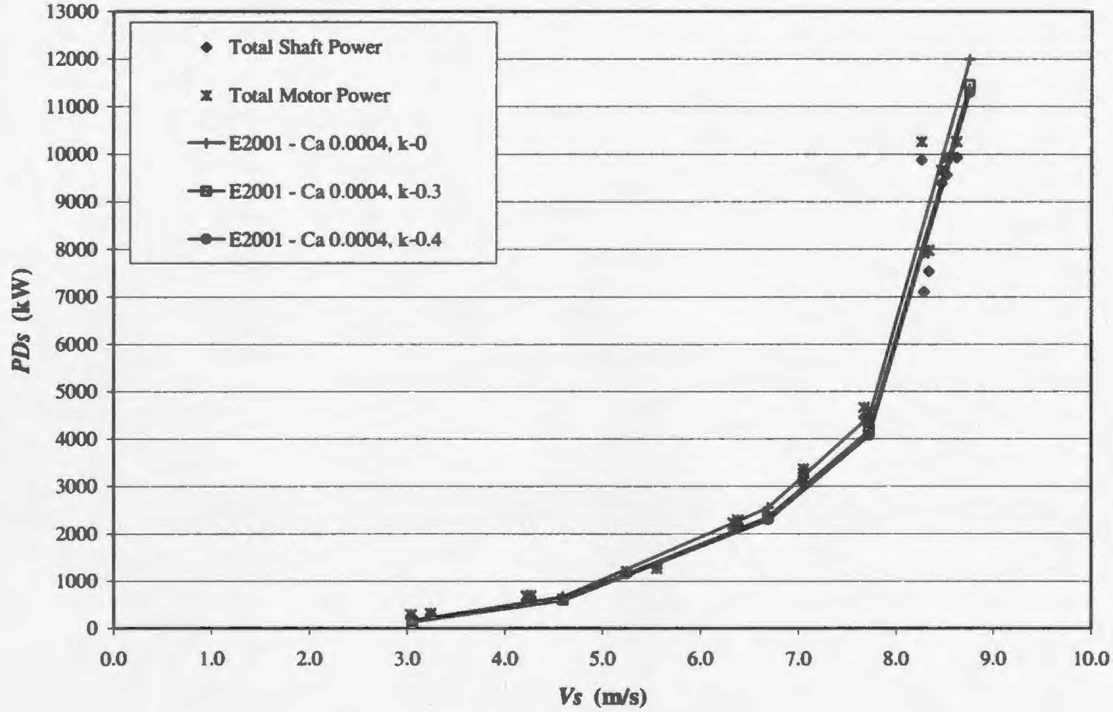


Figure 21: Predicted Full-scale delivered power for *k*= 0, 0.3, 0.4

This approach to obtaining the form factor was first used with C_{F1957} then when the method was performed using $C_{FGrigson}$ in place of the C_{F1957} the value of 0.3 remained an appropriate value for the *R-Class* data.

As C_A has been shown to simply shift the curves (Figure 16) the comparison of the form factor was made using a C_A of 0.0004 in order to illustrate how the power is affected. A later chapter evaluates the best combination of values.

Table 6 gives a comparison of the predicted delivered power using E2001 for two of the speeds from the *R-Class* data and the average power of the average of these speeds with the full-scale trials. The values of the full-scale trials came from a polynomial approximation of the data (Figure 23). Taking into consideration the fact that the full-scale data is approximated, the k=0.3 gives results that are on par with those obtained using the result of Prohaska's method, k=0.4. It can be seen then, that for this data set the Holtrop method provides a promising method of obtaining the form factor using solely self-propulsion tests.

Additional plots showing the shaft speed, torque and thrust are found in (Appendix B)

Table 6: Comparison of delivered power using different form factors with full-scale trials, C_A 0.0004

$C_A = 0.0004$, $w_{scaling} = 1.0$					
Vs		*E2001*	*E2001*	*E2001*	*Full scale*
Knots	*(m/s)*	$k = 0$	$k = 0.3$	$k = 0.4$	*Trials (kW)*
12.996	6.686	2545.445	2352.986	2289.550	2405.211
% difference with full scale trials		5.51%	-2.22%	-5.05%	
15.004	7.719	4467.275	4168.788	4067.304	4970.316
% difference with full scale trials		-11.26%	-19.23%	-22.20%	
Average Values					
14.000	7.202	3506	3260	3178	3687
% difference of averages with full scale trials		-4.92%	-11.58%	-13.81%	

Use of this method within the computer program involved externally evaluating the data and adding the chosen form factor to the input file. The trend of the form factors needed to be clearly identified and this could not be accomplished within the program. If, upon evaluation of the data while determining the thrust deduction fraction, the points were deemed reliable, the factor could be determined using values at pre-determined Froude numbers within the body of the program. For the purpose of evaluation of the data and method here however, it was most useful to observe the data within an EXCEL™ spreadsheet.

Chapter 7

7 Wake Scaling

The wake scaling is included to account for the change in the wake from model to full-scale and is shown in Equation 28 [Holtrop, 2000]. The correction, $w_{scaling}$, is included in the equations that evaluate the full-scale thrust and torque coefficients (K_{TS} and K_{QS}).

Equation 28: Wake scaling

$$w_{scaling} = \frac{\left(V_A / V \right)_S}{\left(V_A / V \right)_M}$$

Equation 29: Full-scale thrust coefficient with wake scaling

$$K_{TS} = a_1 \left(w_{scaling} J \right)^2 + b_1 \left(w_{scaling} J \right) + c_1 - \Delta K_T$$

Equation 30: Full-scale torque coefficient with wake scaling

$$K_{QS} = a_2 \left(w_{scaling} J \right)^2 + b_2 \left(w_{scaling} J \right) + c_2 - \Delta K_Q$$

The wake scaling cannot be determined from the model data. The most appropriate value for this model is found from a comparison with the full-scale trials results, the scaling is varied from 0.95 to 1.0. In order for this to be a useful tool, a database of values needs to be determined that is based on comparisons between model and full-scale test results and will match hull-propeller configurations with appropriate wake scaling. These can be partly determined by comparison of propeller thrust and torque coefficients in the behind condition between model tests and full-scale trials.

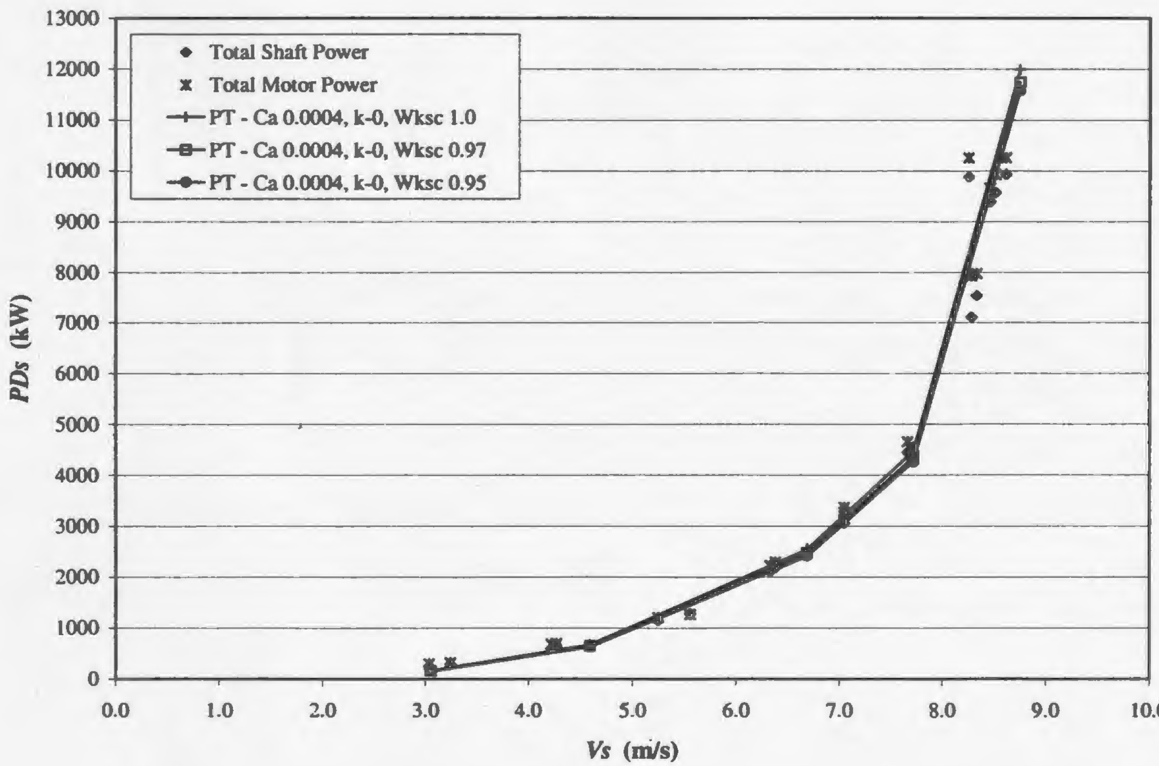


Figure 22: Full-scale predicted delivered power using a wake scaling of 1.0, 0.97, 0.95, $C_A = 0.0006$, $k = 0.3$

For this data Figure 22 shows there is very little difference in the predicted power for each of the wake scaling values with a C_A = 0.0004 in the lower and higher speed regions. Table 7 shows that overall the predicted power varies less than 6% from a datum of $w_{scaling}$ = 1.0 using the form factor of 0.3 and C_A = 0.0004. For a form factor of 0.3 and a C_A = 0.0006, Table 8 shows similar power variation. A low wake scaling is expected with a twin-screw, center-rudder vessel.

Table 7: Comparison of delivered power using $w_{scaling}$ =1.0 with power using different wake scaling values, C_A = 0.0004

CA=0.0004, k=0.3				
Vs		*E2001*		
knots	*m/s*	*$w_{scaling}$ = 1.0*	*$w_{scaling}$ = 0.97*	*$w_{scaling}$ = 0.95*
12.996	6.686			
Predicted Power		2352	2276	2226
% difference with power @ $w_{scaling}$ =1.0			-3.25%	-5.37%
15.004	7.719			
Predicted Power		4168	4048	3970
% difference with power @ $w_{scaling}$ =1.0			-2.89%	-4.76%
Average Values				
14.000	7.202			
Average Predicted Power		3260	3162	3098
% difference of averages with $w_{scaling}$ =1.0			-3.02%	-4.98%

The variation from wake scaling at 1.0 is significant; ~ 2-6% and the percentage change from the full-scale trials showed a variation from ~ 0.5 to 20% over the range of speeds. A wake scale of 1.0 was chosen for the E2001 extrapolation method of this data as an initial value used for comparative purposes.

Additional plots showing the shaft speed, torque and thrust are found in Appendix C.

Table 8: Comparison of delivered power using $w_{scaling}$ =1.0 with power using different wake scaling values, C_A = 0.0006

CA=0.0006, k=0.3				
Vs		*E2001*		
knots	*m/s*	$w_{scaling}$ = *1.0*	$w_{scaling}$ = *0.97*	$w_{scaling}$ = *0.95*
12.996	6.686			
Predicted Power		2500	2421	2369
% difference with power @ $w_{scaling}$ =1.0			-3.27%	-5.23%
15.004	7.719			
Predicted Power		4410	4287	4206
% difference with power @ $w_{scaling}$ =1.0			-2.80%	-4.62%
Average Values				
14.000	7.202			
Average Predicted Power		3455	3354	3288
% difference of averages with $w_{scaling}$ =1.0			-2.93%	-4.84%

Chapter 8

8 Comparison of the E2001 method with the ITTC 1978 Method and Full Scale Trials

The version of the method proposed for further analysis and validation included the use of Grigson's formulations for turbulent flat plate friction and the Holtrop/MARIN method to determine the form factor from self-propulsion tests. For this *R-Class* model/ship the value of the form factor evaluated was 0.3 and a correlation allowance of 0.0006 was used.

A 4^{th} order polynomial from the selection of EXCEL™ software functions was used to determine the full-scale trials power at specific speeds that corresponded with those extrapolated, Figure 23. Only a small number of the actual trials speeds were close to those speeds tested at model scale. The rise in the curve from 5.0 m/s was. The curve was a more reliable approximation at the lower and higher speeds and slightly under-predicted at the ship operating speeds. If this caused concern in an analysis, it was noted in the text.

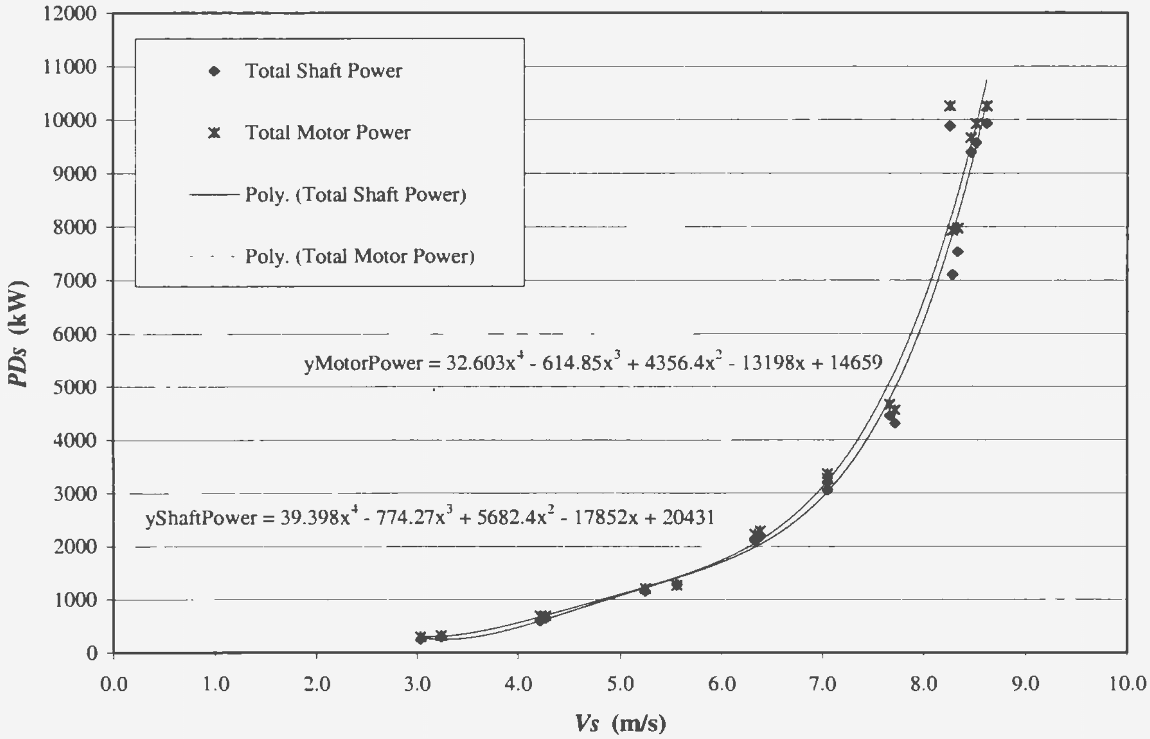


Figure 23: 4th order regression curves fit to full-scale trials data

While the C_A value of 0.0006 was found to give the best correlation with both the full-scale trials data and the ITTC 1978 method in this and previous chapters, correlation allowances of 0.0004 and 0.0008 are included in the final comparison in order to illustrate the variation and appropriateness of the choice. Table 9 is a summary of the comparison of the E2001 method and the ITTC 1978 method with the full-scale trials results. The results are given first for the two speeds that are close to the operating speed and then the operating speed of 14 knots which is an average of the two given speeds.

Table 9: Comparison of the complete E2001 method (k=0.3, $w_{scaling}$ = 1.0, $C_{FGrigson}$) with the ITTC 1978 method and full-scale trials

Vs		*E2001*	*E2001*	*E2001*	*E2001*	*ITTC 1978*	*Full- scale*
knots	*m/s*	$C_A = 0.0004$	$C_A = 0.0005$	$C_A = 0.0006$	$C_A = 0.0008$	$C_A = 0.0004$ $k = 0.4$	*Trials (kW)*
12.996	6.686	2260.016	2332.940	2406.351	2554.583	2365.202	2405.211
% difference with full scale trials		-6.04%	-3.00%	0.05%	5.85%	-1.66%	
15.004	7.719	3935.424	4053.849	4173.270	4415.016	4348.383	4970.316
% difference with full scale trials		-20.82%	-18.44%	-16.04%	-11.17%	-12.51%	
Average Values							
14.000	7.202	3097.720	3193.395	3289.810	3484.799	3356.792	3687.763
% difference with full scale trials		-16.00%	-13.41%	-10.79%	-5.50%	-8.97%	

Table 10 shows the variation over the range of speeds extrapolated to full-scale and also includes a comparison between the results of the E2001 at two C_A values with the results obtained using the ITTC 1978 method. Table 9 indicates that the delivered power with a C_A of 0.0008 has the smallest percentage difference with the polynomial approximation of the full-scale trials, Figure 23. Overall the percentage differences in predicted power of the ITTC 1978 and E2001 methods (at both C_A = 0.0006 and C_A = 0.0008) only differ a small amount. Table 10 shows that the E2001 results with a C_A of 0.0006 are closer to the ITTC 1978 results.

Further analysis that will correspond correlation allowances with specific ship types is needed in order to be confident in the choice of C_A when extrapolating data for which full-scale trials results are not yet available. As stated before, post-construction ship trials would "close the loop" and provide valuable verification of the E2001 method.

Table 10: Percentage difference of predicted values from the E2001 method (k=0.3, $w_{scaling}$ = 1.0, $C_{FGrigson}$) and the ITTC 1978 method and full-scale trials power at each speed

% Difference with full scale trials							% Difference with the ITTC method & E2001	
Vs		E2001	E2001	E2001	E2001	ITTC 1978	ITTC 1978 vs E2001	ITTC 1978 vs E2001
knots	m/s	C_A=0.0004	C_A=0.0005	C_A=0.0006	C_A=0.0008	C =0.0004 k = 0.4	C_A=0.0006	C_A=0.0008
4.593	8.928	25.52%	22.93%	20.32%	15.03%	20.88%	-0.71%	-7.40%
6.686	12.996	6.04%	3.00%	-0.05%	-6.21%	1.66%	-1.74%	-8.01%
7.719	15.004	20.82%	18.44%	16.04%	11.17%	12.51%	4.03%	-1.53%
8.752	17.012	5.52%	3.63%	1.74%	-2.09%	1.19%	0.56%	-3.31%

Figure 24 shows the predicted delivered power of E2001 with a C_A of 0.0006, the ITTC 1978 method with C_A of 0.0004 and the full-scale trials results. The E2001 and ITTC 1978 methods correlated remarkably well for this data, the only very significant differences are between 7 and 8 m/s, which are also the speeds that showed the most difference between the predicted delivered power using different friction coefficients C_{F1957} and $C_{FGrigson}$, Figure 17. When compared to the trials, the E2001 method has a smaller percentage difference at 13 knots while the ITTC 1978 method is smaller at 15 knots.

The comparison between the E2001 and ITTC 1978 methods is most favourable using E2001 with a C_A of 0.0006. Figure 25, C_A of 0.0004, and Figure 26, C_A of 0.0008, indicate a less effective correlation at the upper and middle speeds (respectively).

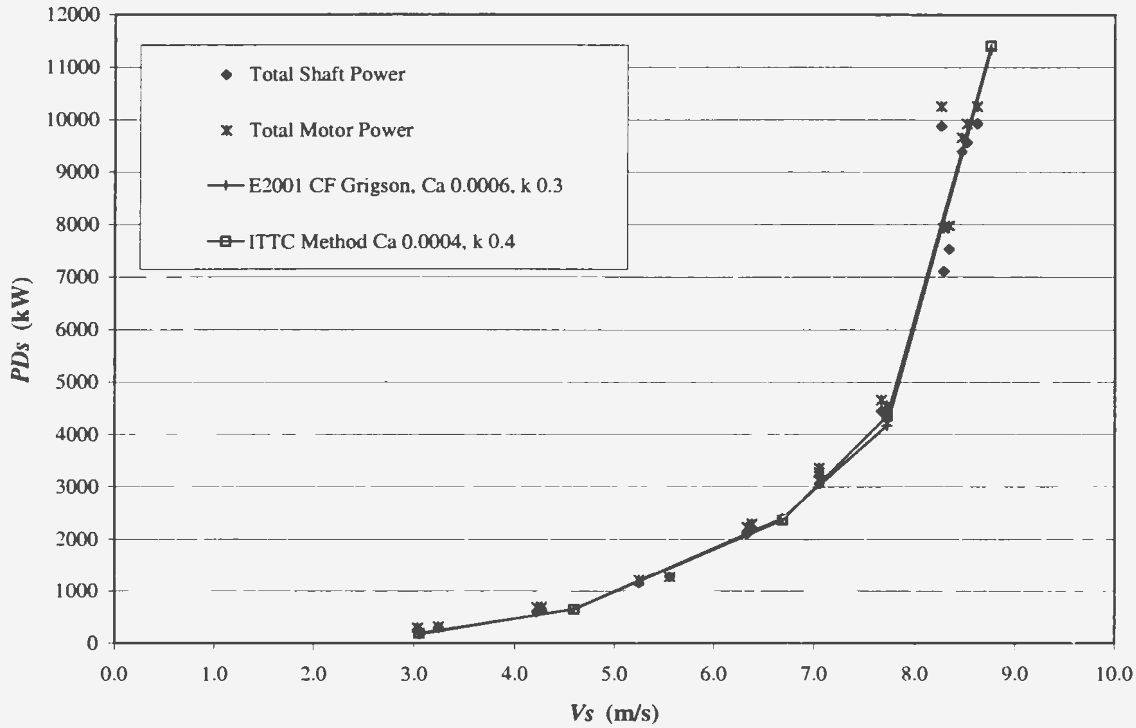


Figure 24: Delivered power for the E2001 method with C_A 0.0006, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

The E2001 method has been shown, with this data, to be an alternative extrapolation procedure. The form factor was determined using a self-propulsion test. When used in combination with Grigson's frictional coefficient [Grigson, 1999], an appropriate wake scaling and correlation allowance, the results correlated very closely with the ITTC 1978 method and also approximate the full-scale trials results.

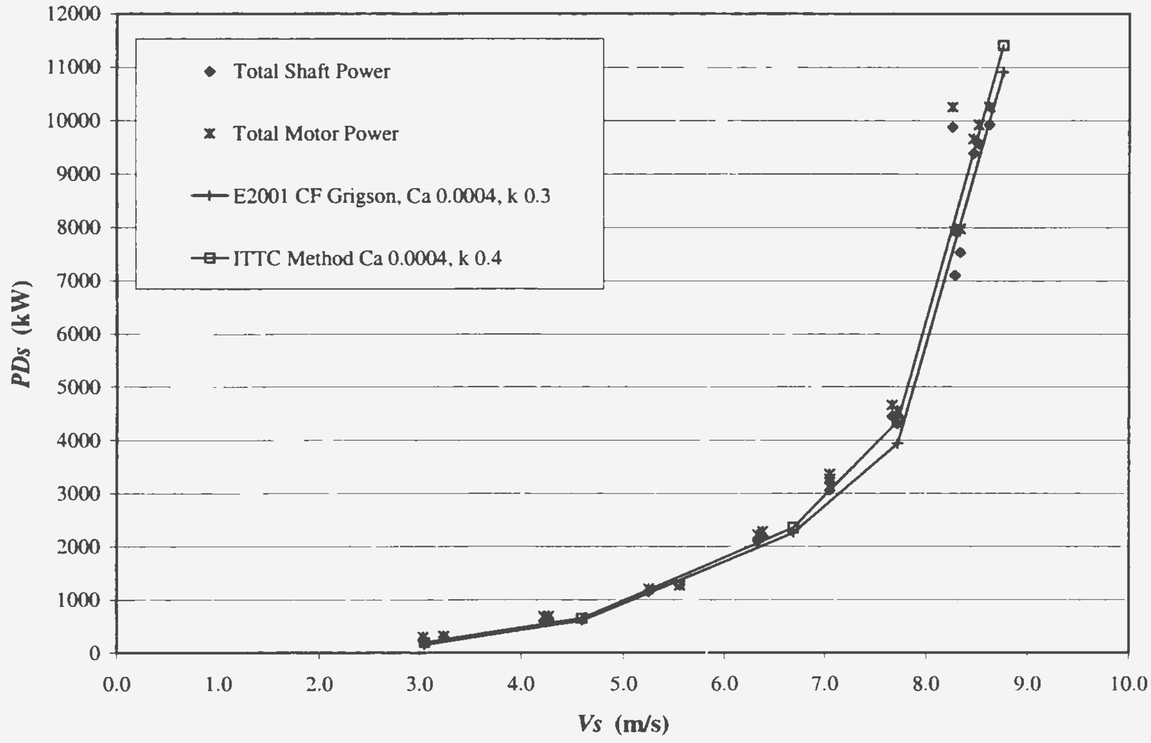


Figure 25: Delivered power for the E2001 method with C_A 0.0004, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

Additional plots that show the predicted full-scale shaft speed, torque and thrust are found in the appendices. Appendix D first shows the results for a C_A of 0.0006, followed by C_A of 0.0008 then C_A of 0.0004. In each case the E2001 method has a superior correlation with the full-scale data over the ITTC 1978 method.

The shaft speed, Figure 27, provides an interesting correlation; there was concern over the low-Froude number test when evaluating with ITTC 1978, but the E2001 method results match very neatly. The shaft speed and torque, Figure 28, correlated most closely with the full-scale data using a C_A of 0.0006 but the thrust is best represented by the C_A of 0.0004, Figure 29.

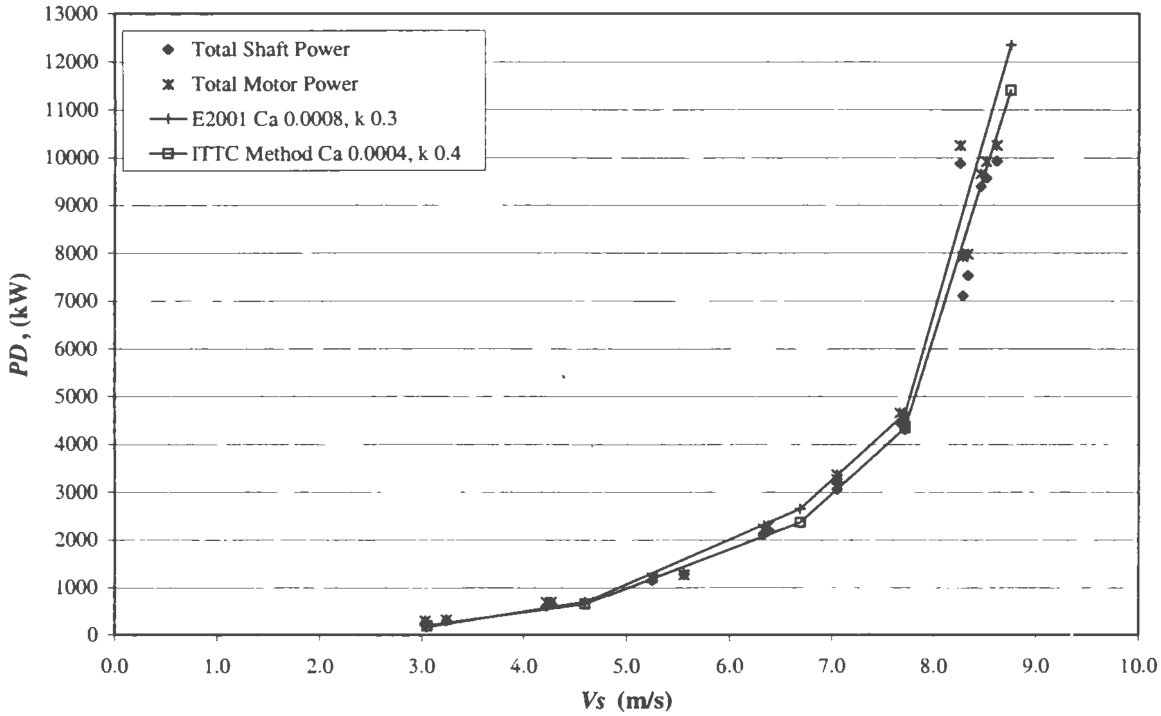


Figure 26: Delivered power for the E2001 method with C_A 0.0008, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

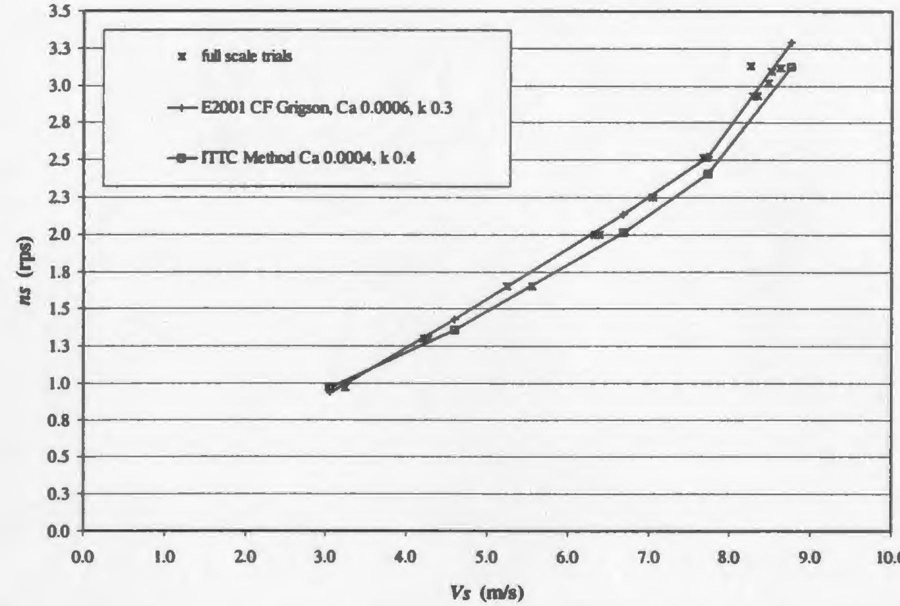


Figure 27: Shaft speed for final E2001 with C_A 0.0006, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

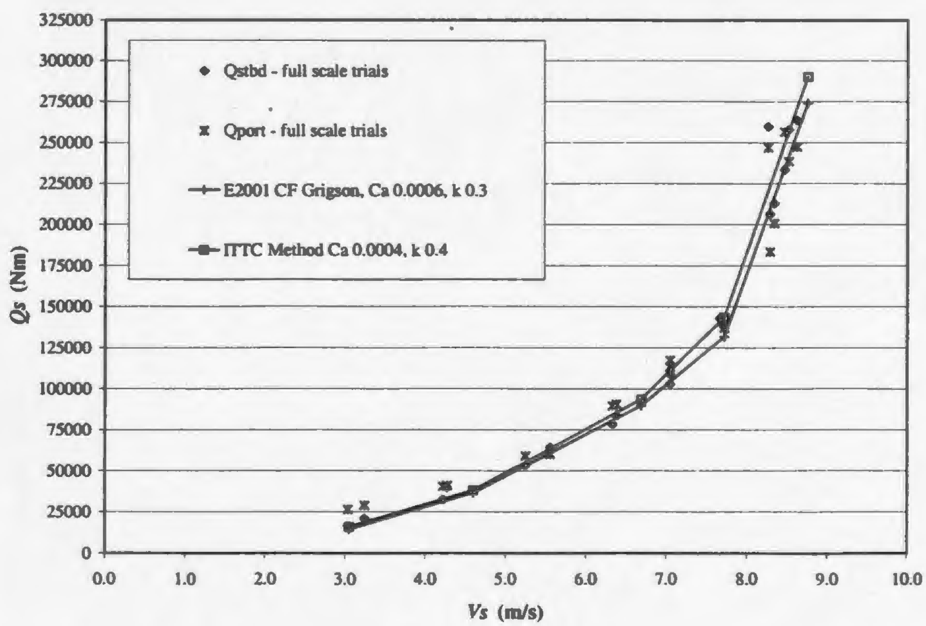


Figure 28: Torque for final E2001 with C_A 0.0006, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

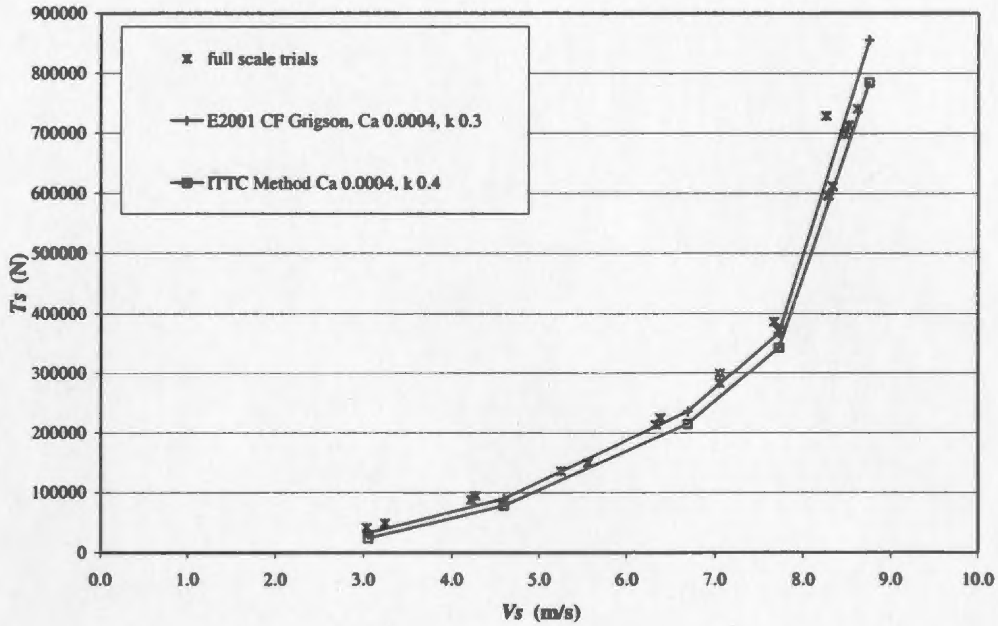


Figure 29: Thrust for final E2001 with CA 0.0004, *k* 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

Chapter 9

9 Discussion & Conclusion

The purpose of this thesis was to present E2001, a method that could be used in place of the ITTC 1978 method. It is a method that is less complicated and that requires only one tank test. The E2001 method was shown to be an effective extrapolation method and for this data set could be used as an alternative method of extrapolation. It is expected that with further model - full-scale trials comparisons E2001 could serve as a substitute for the ITTC 1978 method in the extrapolation of the powering prediction of ships fitted with unconventional and conventional propulsors.

The primary focus of the comparison was on the delivered power trends, but the shaft speed, torque and thrust (these plots are mainly found in the appendices) provided valuable information on the selection of the most appropriate overall correction factors. As previously mentioned, the power from the full-scale trials was the shaft power and although this is not the delivered power of the ship it is used in correlating the extrapolated delivered power. A correction factor can be used to accommodate for the difference in the shaft and delivered power of the ship, however, because IMD does not have a standard correction for tests that do not have a recommended value so the data was directly correlated. This difference in the shaft and delivered power (potentially up to 2.5% or 3%) could account for some of the differences between the extrapolation methods and the full-scale data, but will not have an affect on the comparison between the E2001 and ITTC 1978 methods.

There was considerable weight put on the differences between the results obtained using the E2001 and ITTC 1978 methods. The E2001 method was comparable in all plots when the appropriate correlation allowance was used. For this data (the *R-Class*) the allowance was a C_A of 0.0006. The full-scale trials were used to verify the results of the extrapolation methods and indicate which correction factors were the most appropriate.

The correlation allowance was used as a general correction but with some physical significance. The C_A incorporated the correction factors for the roughness and the still air effects. During the full-scale trials the vessel was very rough which accounts for the high correlation allowance that produced the most favourably comparable predictions when compared to the full-scale data in the final power plots (Figure 24).

Introduction of the frictional coefficient from Grigson was influenced by dissatisfaction in the industry with the 1957 frictional coefficient, "a law that does not obey the laws of fluid physics" [Grigson, 2000, pg. 29]. The results for this *R-Class* twin screw vessel showed that the E2001 extrapolation method using $C_{FGrigson}$ followed the predominant trend in the full-scale trials data more closely (Figure 17).

The form factor calculation from the self-propulsion test proved to be a valid alternate method of obtaining the form factor for this test data. Upon further analysis this could mean that the resistance test could potentially be eliminated for powering prediction and retained for ship hull research purposes. The form factor obtained from the self-propulsion test resistance, $F_{T=0}$, resulted in power predictions that were a close approximation of the trials data using a correlation allowance of 0.0004 (Figure 21). The results were an even closer fit using a correlation allowance of 0.0006 (Figure 24).

For this data set from the *R-Class* twin screw icebreaker, the wake scaling was small over the range of speeds (Figure 22). This was expected for a twin screw centre rudder configuration. Throughout the remaining extrapolations the wake scaling was taken as 1.0 or in other words, no wake scaling was accounted for. If a database of wake scaling for different ship and propulsion configurations can be developed through the post-construction correlation of trials, self-propulsion and open water tests; the open-water test in extrapolation of power can also be eliminated and open water tests only done to compare propulsors themselves and for research purposes.

The reduction of testing time reduces the cost of testing to the ship owner and could increase turnover time for the testing group. The testing can also be performed in one testing session. The ITTC 1978 method has three tests performed in different conditions at different times, which is a form of superposition that may not be entirely valid. Errors are also implicit in the re-calibration of testing instruments, changes in test-tank water temperatures, changes in model or changes in personnel. The change in model is important. For example; the *R-Class* report provided resistance test data that was performed a year prior to the self-propulsion test [Spencer *et al.*, 1992]. Without impeccable care the model could reasonably have had some of its characteristics affected (e.g. roughness, paint quality) from the time of the resistance test to when the self-propulsion test was performed.

If this method was used to extrapolate the results from such tests as podded propulsion systems the self-propulsion test would be done with a geometrically similar model of the fitted device. This is as close as possible to the full-scale, but the Reynolds number is different. One way to develop this is to increase the Reynolds number of the test to observe the wake scaling and thrust deduction variations with Reynolds number and determine appropriate correlation factors. Geometrically similar propellers are also required for the most reliable results and maximum flexibility in the tests that are performed, particularly in the testing of conventional propulsion systems. However, while the propulsion system is chosen by the testing stage, often the final design of the propeller is not available. The cost of fabricating the model propeller would increase the cost of the test but if the E2001 extrapolation method were used, the absence of resistance and open water tests would offset this cost.

This thesis gives an outline of the method and how it can compare with the ITTC 1978 method in the prediction of powering. Only one set of data was used because of the difficulties in acquiring model tests with corresponding full-scale trials. Further evaluation of the method using correlated data would assist in the long-term evaluation of the E2001 method and potentially show it to be a valid alternative to the ITTC 1978 method.

Further work

As said, additional data sets that could further validate the E2001 method would be valuable. In addition, if E2001 is to be considered for use with unconventional propulsors, development of the methods and extent of the self-propulsion test procedure is necessary, particularly Reynolds number variation as mentioned above.

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Appendix A Additional plots – Frictional coefficients

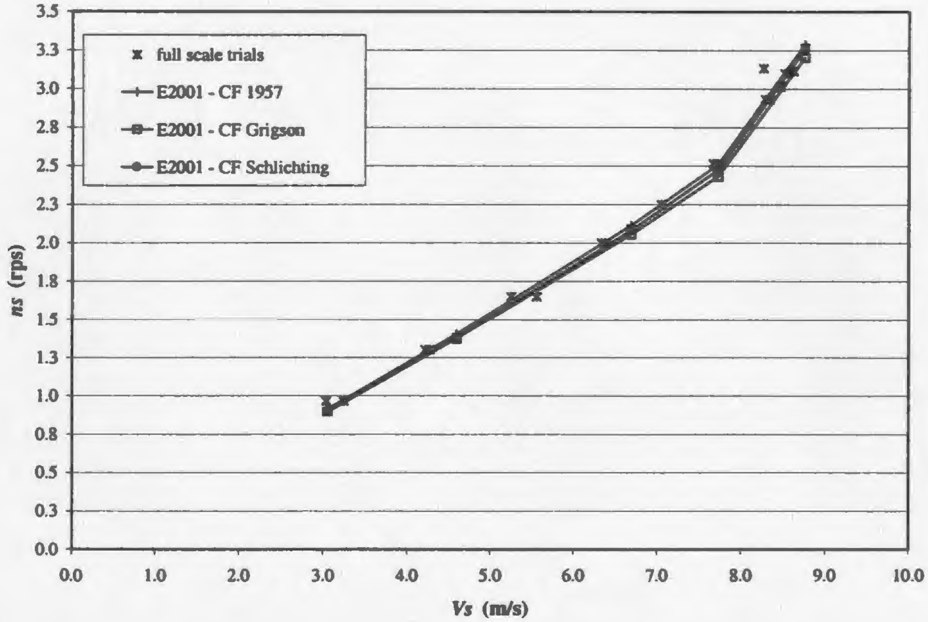

Figure 30: E2001 shaft speed predicted values for different C_Fs

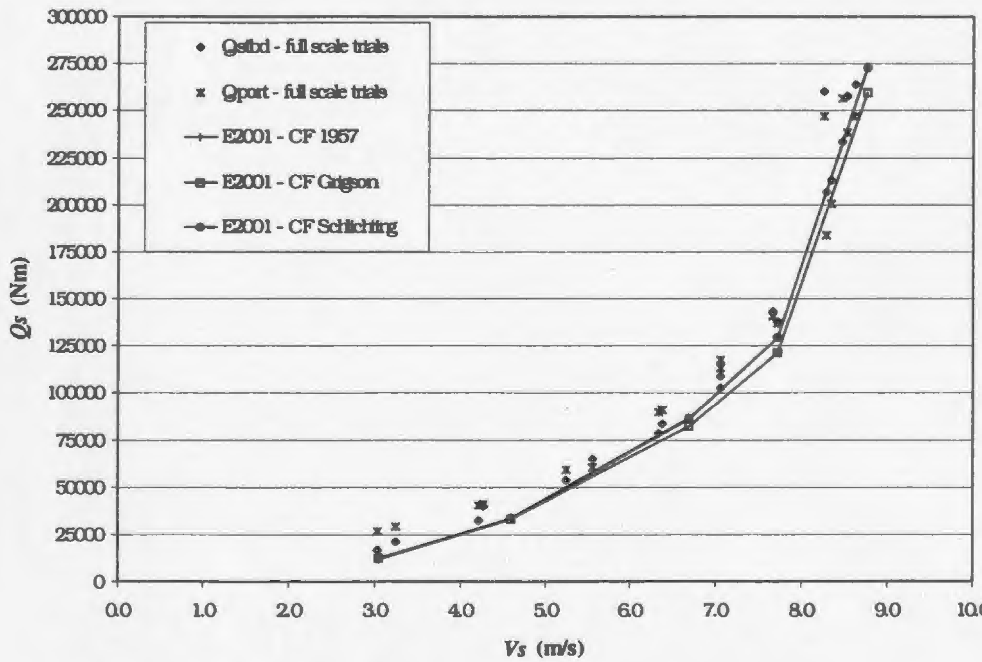

Figure 31: E2001 torque predicted values for different C_Fs

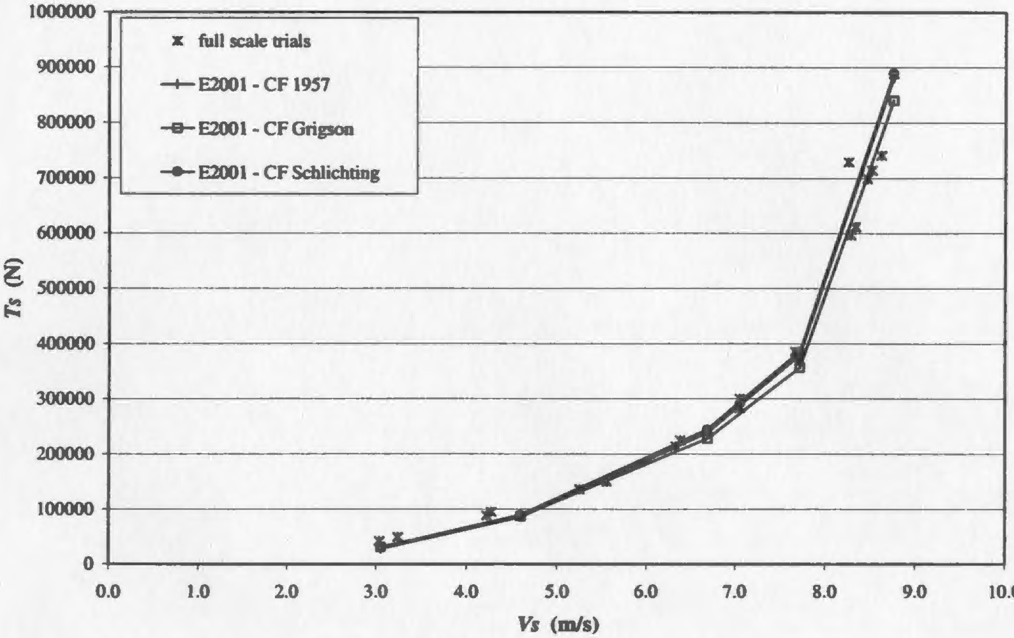

Figure 32: E2001 thrust predicted values for different C_Fs

Appendix B Additional plots – Form factors

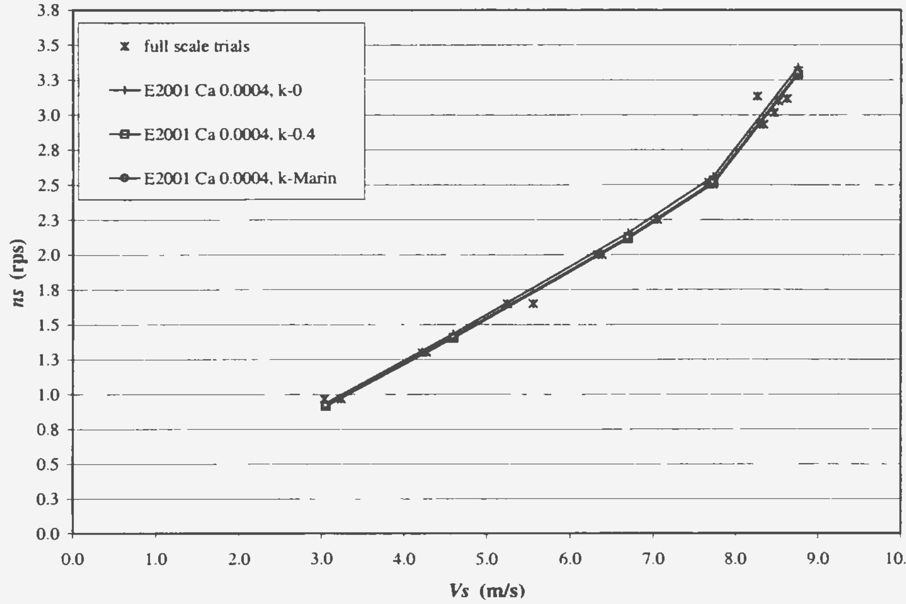

Figure 33: E2001 shaft speed predicted values for form factors *k*, of 0, 0.3 (Marin), 0.4

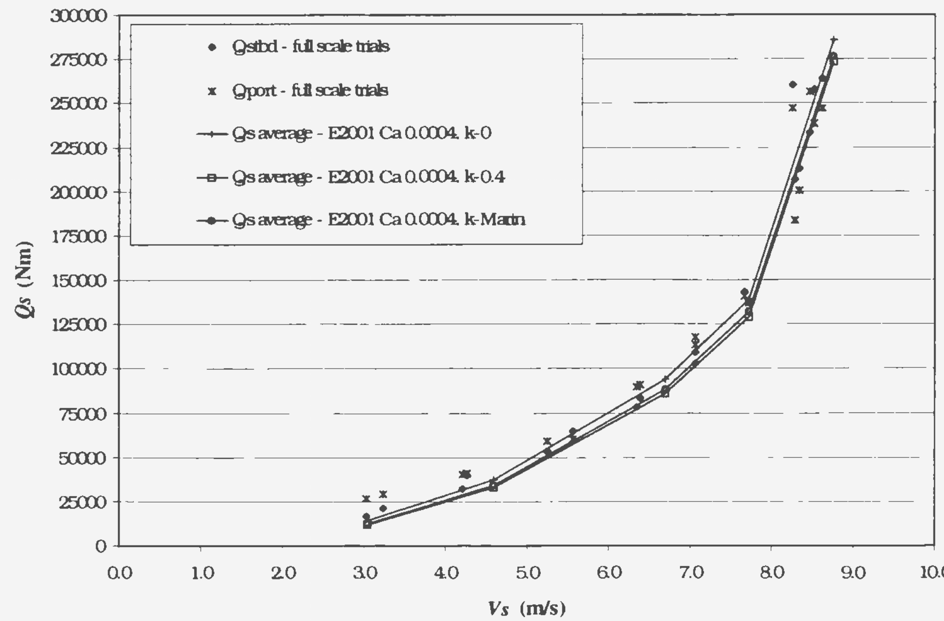

Figure 34: E2001 torque predicted values for form factors *k*, of 0, 0.3 (Marin), 0.4

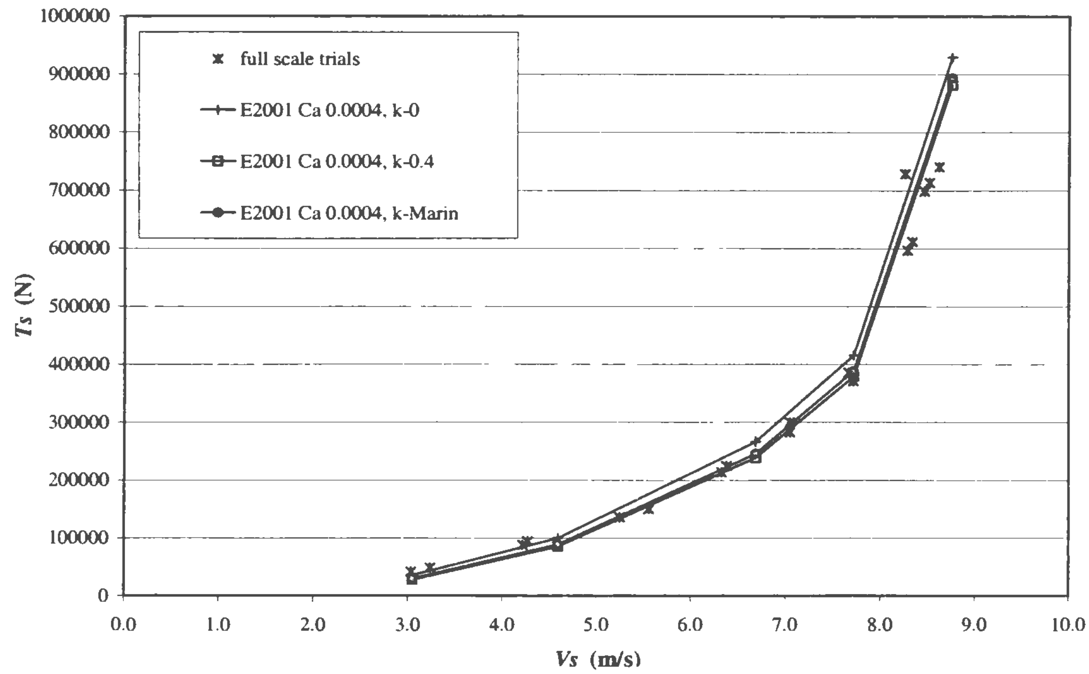

Figure 35: E2001 thrust predicted values for form factors *k*, of 0, 0.3 (Marin), 0.4

Appendix C Additional plots – Wake scales

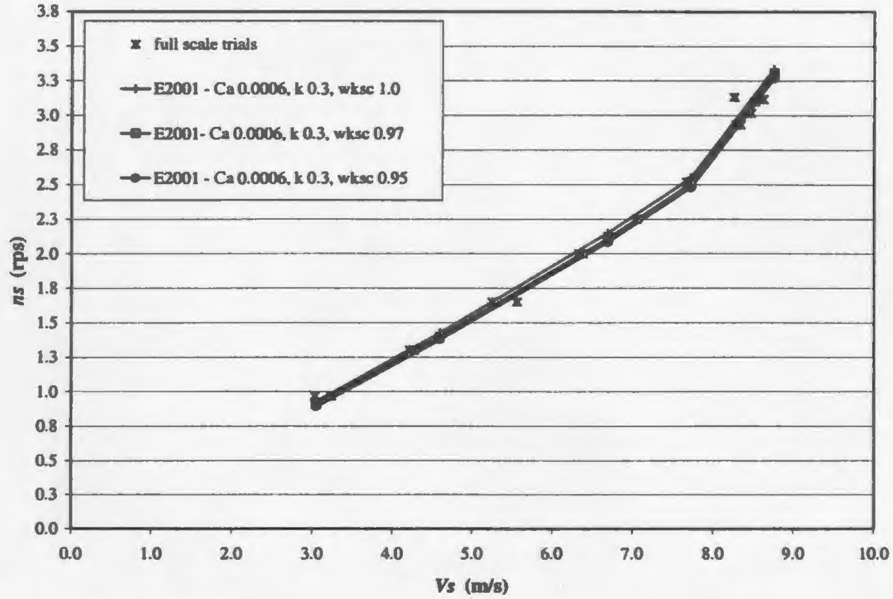

Figure 36: E2001 shaft speed predicted values for wake scale factors of 1.0, 0.97, 0.95, C_A 0.0006

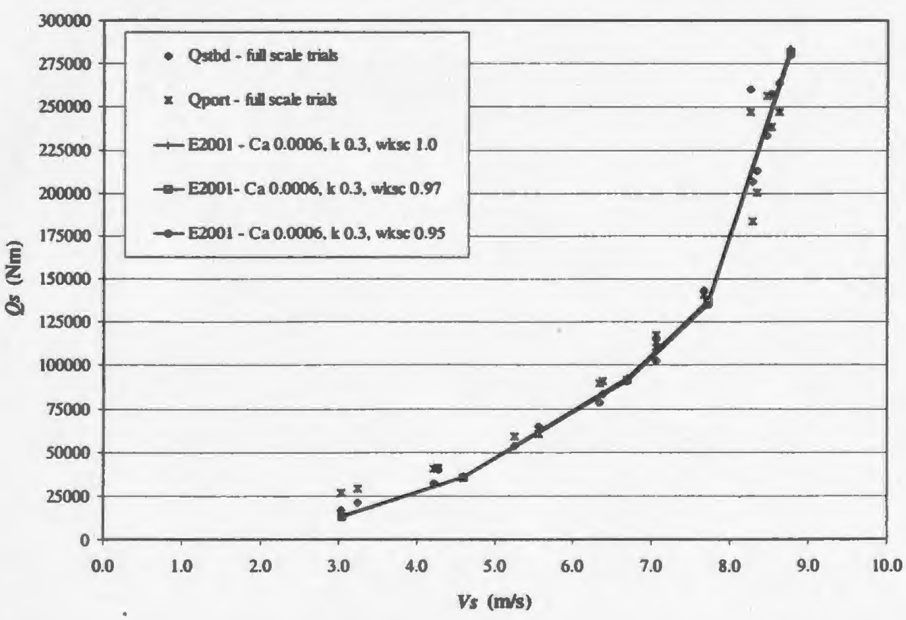

Figure 37: E2001 torque predicted values for wake scale factors of 1.0, 0.97, 0.95, C_A 0.0006

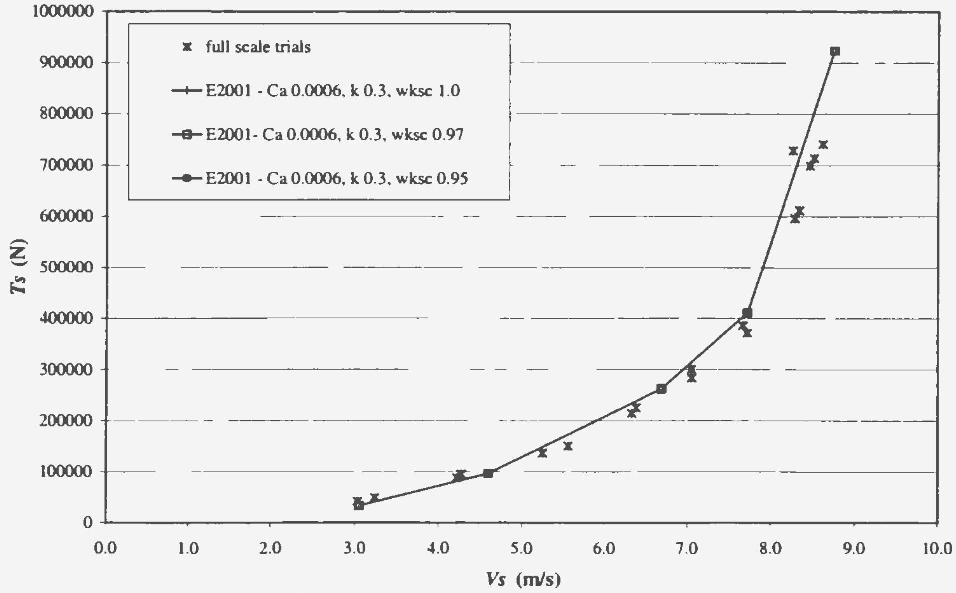

Figure 38: E2001 thrust predicted values for wake scale factors of 1.0, 0.97, 0.95, C_A 0.0006

Appendix D Additional plots – Comparison of final results

(a)CA of 0.0006

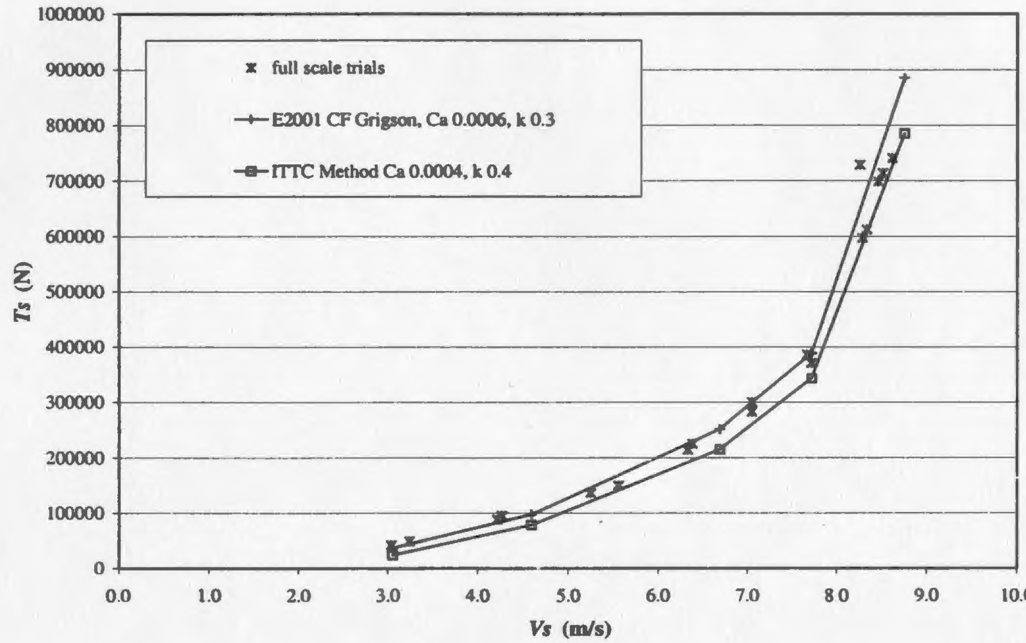

Figure 39: Thrust for final E2001 with C_A 0.0006, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

(b)CA of 0.0008

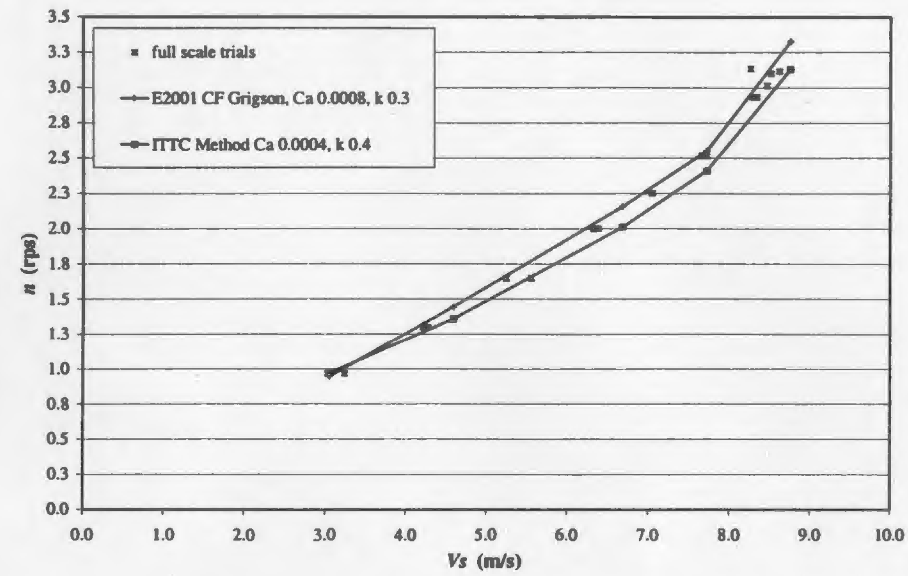

Figure 40: Shaft speed for final E2001 with C_A 0.0008, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

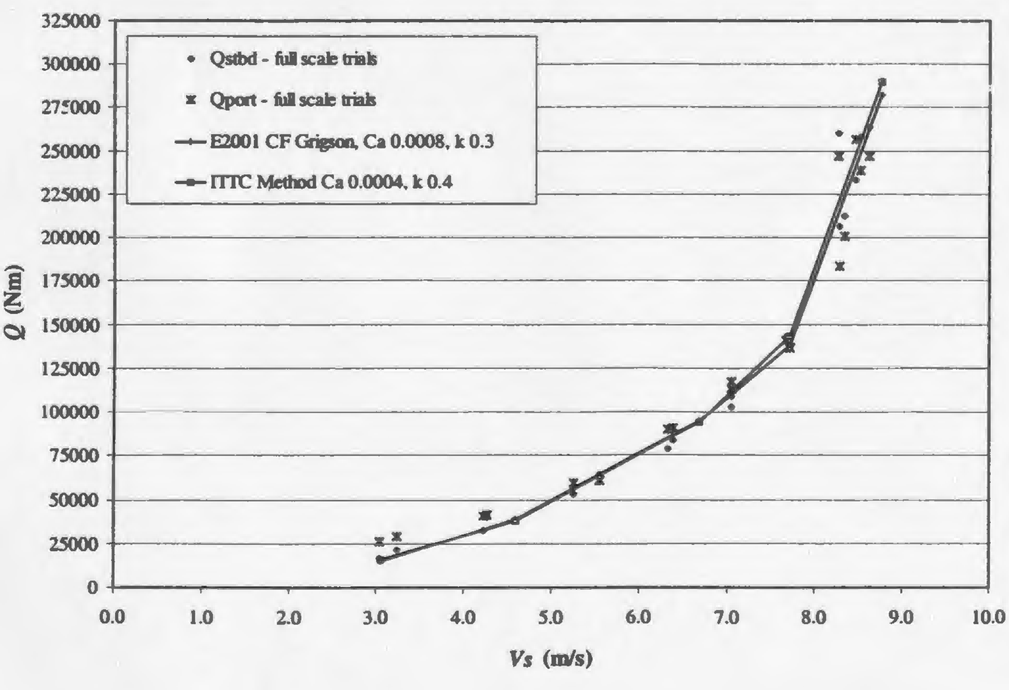

Figure 41: Torque for final E2001 with C_A 0.0008, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

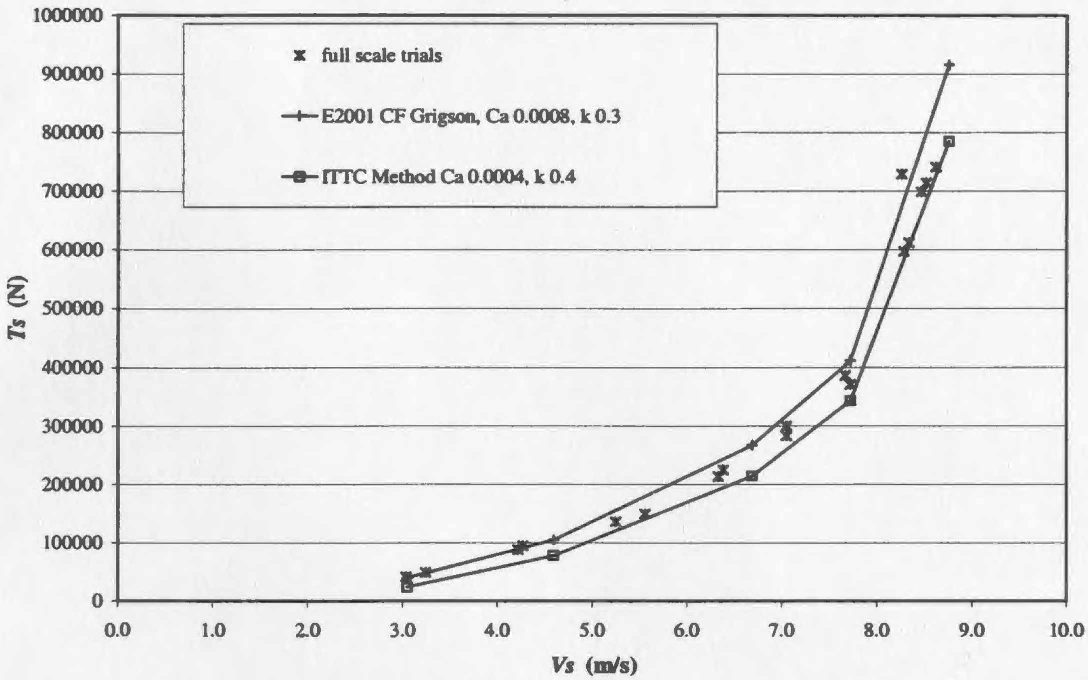

Figure 42: Thrust for final E2001 with C_A 0.0008, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

(c)CA of 0.0004

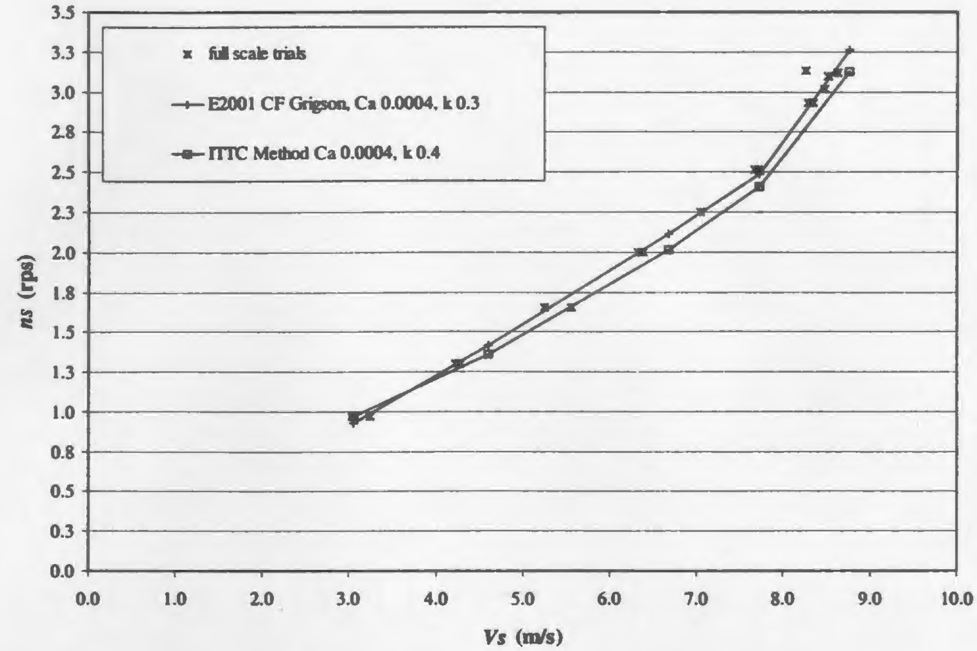

Figure 43: Shaft speed for final E2001 with C_A 0.0004, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials

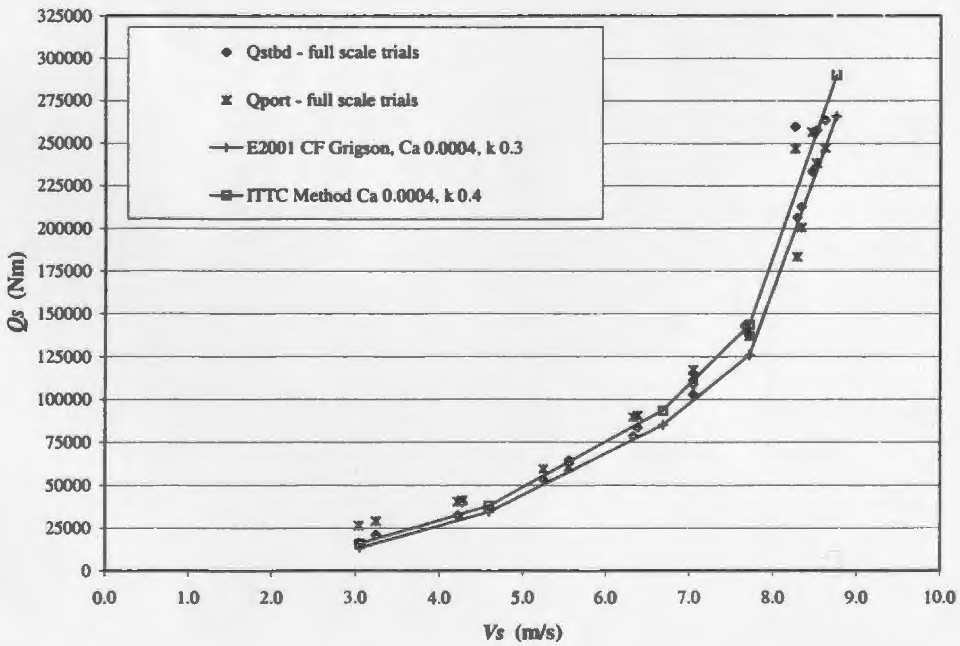

Figure 44: Torque for final E2001 with CA 0.0004, k 0.3, $w_{scaling}$ 1.0, $C_{FGrigson}$ compared with the ITTC 1978 method and full-scale trials