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Powering for Medium Speed Wave-Piercing Catamarans comparing Waterjet and Screw Propeller Performance using Model Testing

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ABSTRACT

A comparative study of the powering performance of waterjet and screw propeller propulsion for medium speed wave-piercing catamarans using model testing is presented and discussed. The self-propulsion tests for both screw and waterjet propulsion were carried out to determine the ship's power at various speeds. The testing conditions for both propulsion system consisted of a speed range of 20 to 30 knots and two displacements, i.e. light and heavy displacements, at level static trim. The main comparison parameters are the estimated overall propulsive efficiency as well as the delivered power estimates at model scale.

Keywords

Catamaran, Powering, Self-propulsion test, Waterjet, Screw Propeller.

1 INTRODUCTION

Transport accounts for 26% of global CO_2 emissions, according to Chapman (2007) and is one of the few industrial sectors where emissions are still growing. Shipping, car use, road freight and aviation are the principal contributors to greenhouse gas emissions from the transport sector. As a result of changes in environmental protection laws regarding marine pollution, as defined by the International Convention for the Prevention of Pollution from Ships (MARPOL), and the steady increase of fuel costs the focus for new vessel designs must be on reducing fuel consumption and to reduce gas emissions (Psaraftis et al., 2009). As a consequence, the market for medium speed, fuel-efficient, vessels is likely to increase.

Tasmanian based shipbuilder Incat, which is renowned as a pioneer in wave-piercing catamaran technology, wishes to develop the next generation of energy efficient medium speed catamarans which includes the development of new hull forms and an investigation into feasible propulsion systems for efficient operation at medium speeds. At medium speed, screw propellers become progressively more efficient as waterjets are used for high-speed vessel due to high efficiency when operating at speeds over 30 knots, however their performance at medium speeds are less defined and need to be investigated. Davidson et al. (2011) stated that as the high speed requirement is reduced, in combination with a higher deadweight target for medium speed vessels, propellers will become progressively more competitive over waterjets. Defining the appropriate changeover point between using waterjets and propellers for large medium-speed catamarans is a challenge. Therefore the main investigative approach to answer the question on which propulsion system is more efficient was the experimental study of a self-propelled catamaran by calm water self-propulsion tests using the Australian Maritime College (AMC) towing tank. Self-propulsion tests for both screw propeller and waterjet propulsion were carried out to determine the powering requirement at various ship speeds.

This project brings together world-leaders in the design (Revolution Design Pty Ltd) and construction (Incat) of large lightweight catamarans with Australia's national centre for maritime engineering and hydrodynamics research (at AMC, a special insititute at the University of Tasmania). The project is strengthened by the participation of world-leading propeller and waterjet designers and manufacturers (Wartsila) and one of the world's foremost hydrodynamic research facilities (Marin).

2 METHODOLOGY

An experimental program was undertaken to study the powering performance of both a propeller driven catamaran and a waterjet driven catamaran. Two test programs were conducted, one for the propeller driven catamaran, and the other one for the waterjet driven catamaran, with the 130m propeller driven catamaran tested at two displacements, 2500 tonnes and 3640 tonnes, and the 98m waterjet driven catamaran was tested at only one displacement, which was at 1500 tonnes. See Table 1 for the main particulars of the two catamarans.

Table 1: Main particulars of the 130m propeller driven and the 98m waterjet driven wave piercing catamaran where FS stands for full scale and MS for model scale particulars. **Note: s/2 is half of the separation distance between the demihull centreline and the vessel centreline.*

	130m Propeller driven WPC (2500 tonnes)		130m Propeller driven WPC (3640 tonnes)		98m Waterjet driven WPC (1500 tonnes)	
Particular	**FS**	**MS**	**FS**	**MS**	**FS**	**MS**
L_{WL} (m)	124.8	4.30	122.6	4.23	92.9	4.30
$B_{WL,\ DH}$ (m)	6.35	0.219	6.40	0.221	4.50	0.208
T (m)	3.23	0.111	4.10	0.141	2.87	0.133
WSA (m^2)	995.8	1.2	1216.9	1.5	704.5	1.5
$\triangle$ (t, Kg)	2,500	100	3,640	146	1,500	145
∇ (m^3)	2439	0.100	3551	0.146	1463	0.145
$s/2$* (m)	12.3	0.424	12.3	0.424	11.05	0.511
$B_{WL,\ DH}/T$	1.97		1.56		1.56	
$L_{WL}/\nabla^{1/3}$	9.27		8.04		8.18	
s/L (-)	0.197		0.200		0.238	
C_B (-)	0.476		0.552		0.610	
Scale ratio	**29**		**29**		**21.6**	

2.1 Experimental Facility

The experiments were performed in the 100m long, 3.5m wide and 1.5m deep towing tank of the Australian Maritime College, as shown in Figure 2.

The standard bare hull resistance tests as well as the self-propulsion tests have been carried out using a single demihull in close proximity to the towing tank wall. Resistance tests carried out by Rovere (1997) demonstrated that the wave-making resistance can be accurately predicted with a single catamaran demihull using a towing tank wall as the symmetry plane, which reflects the waves and thereby provides the correct wave interference and blockage effect from the second, non-existing, hull. A schematic representation of the single demihull testing method is shown in Figure 1.

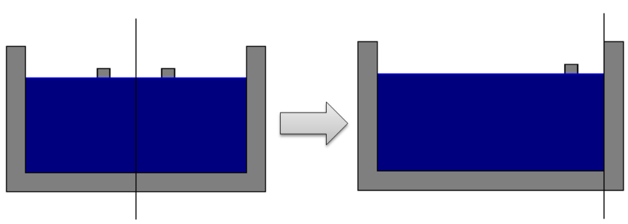

Figure 1: Schematic catamaran and equivalent demihull arrangement in towing tank.

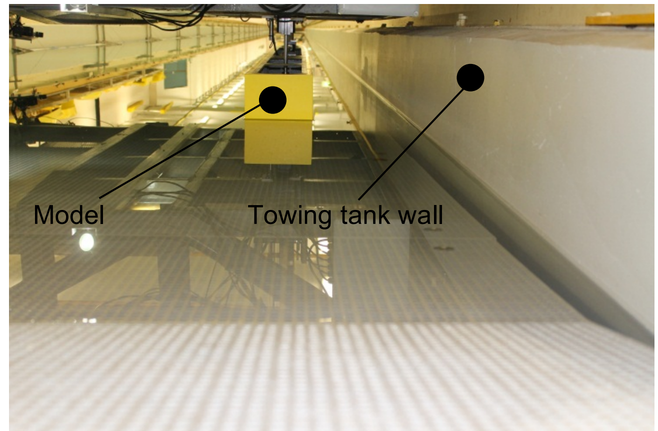

Figure 2: The single demihull model of the catamaran in the towing tank in close proximity with the towing tank wall.

2.2 Experimentation of Propeller Driven Catamaran

The powering performance of the propeller driven catamaran was assessed by conducting three separate tests. The three discrete tests were: the bare hull resistance tests; an open water propeller test; and a self-propulsion test, as described in the 1978 International Towing Tank Conference performance prediction method (Lindgren et al., 1978). In the bare hull resistance test; the resistance of the model, R_{TM}, was measured at a number of different carriage velocities, V_M, without the propeller installed.

In the propeller open water test, the test was performed with the model propeller operating in uniform flow without the model hull. The propeller torque, Q_O and thrust, T_O were measured using a propeller dynamometer. The shaft speed, n_O was measured using a proximity sensor. In the self-propulsion test, a model complete with appendages and an operating propeller was used, where the propeller torque, Q_P, the propeller thrust, T_P, the towing force, F_M and the carriage speed, V_M were measured.

The self-propelled model of the single demihull catamaran was assembled with one Cussons R-31 propeller dynamometer, one AMTI load cell for measuring the towing force, one brushless electric motor to drive the propulsion system, a one meter stainless steel shaft, one five bladed 120mm diameter, Wageningen B-series propeller, and a rectangular spade rudder with NACA 0015 section profile as shown in Figure 3.

Figure 3: The propeller arrangement (with a support bracket and a rudder) of the 130m propeller driven catamaran model

Figure 4: The 3D printed waterjet propulsion unit attachment. Note the nozzles and the tunnels of the waterjet unit of the 98m waterjet driven catamaran model.

Seven channels of data acquisition were used as shown in Figure 6. In addition to the instrumentation mentioned above, the forward and aft post connecting the model to the towing tank carriage was fitted with two Linear Variable Differential Transformers, LVDT, for heave and trim measurements of the models.

2.3 Experimentation of Waterjet Driven Catamaran

The full scale vessel selected for the waterjet propulsion testing is an Incat Tasmania designed and built vessel named HSV-2 Swift (hull 061). As presented in Table 1, the model to full scale ratio of the tested single demihull is 21.6 and the model length is 4.3m at the waterline.

The waterjet and the propeller performance estimation were both carried out using the load varied ("British" method) model self-propulsion testing where the model speed was put constant and a series of runs were carried out at different shaft speeds at the over- and underloaded conditions relative to the self-propulsion point.

The waterjet propulsion for the waterjet driven catamaran consists of two model waterjets which have been scaled geometrically from full scale waterjet units (model: LIPS Jet LJ120E) using manufacturer supplied dimensions. The waterjet pump was designed to allow the required thrust for the self-propulsion points. The model waterjets were incorporated into a special, 3D printed hull section, which is attached to the model demihull as shown in Figure 4.

A schematic representation of the demihull model with the two model waterjets and self-propulsion testing data acquisition system is shown in Figure 7 as given by the ITTC (2011) 'ITTC – Recommended Procedures and Guidelines – Propulsive Performance Prediction', ITTC 7.5-02-05-03.1. The data acquisition system and sensors for the model waterjet were employed based on recommended ITTC propulsive performance prediction procedures for waterjet propelled vessels. ITTC recommends Laser Doppler Velocimetry (LDV) measurements for determining waterjet flow rate. But due to the lack of LDV equipment, a separate static flow rate measurement test was conducted at the AMC Model Test Basin to relate total flow rate to jet velocity measured at a single point using a Kiel probe (Zürcher, 2013). The flow rates measured in the flow rate measurement test and the waterjet self-propulsion test were connected by using a reference measurement in both tests which was derived from a pressure measurement at the ITTC momentum flux station 6 (Figure 5), that was at the waterjet nozzle outlet. The reference measurement was recorded using a Kiel probe at each nozzle in combination with a Differential Pressure Transducer which was connected to the data acquisition system.

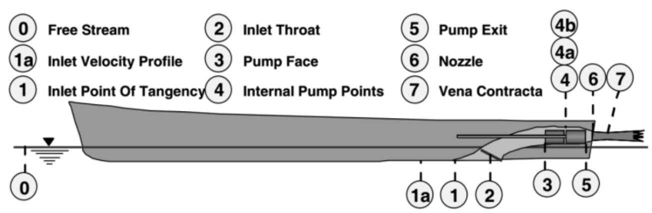

Figure 5: Momentum flux method reference stations as defined Final Report and Recommendations to the 23rd ITTC.

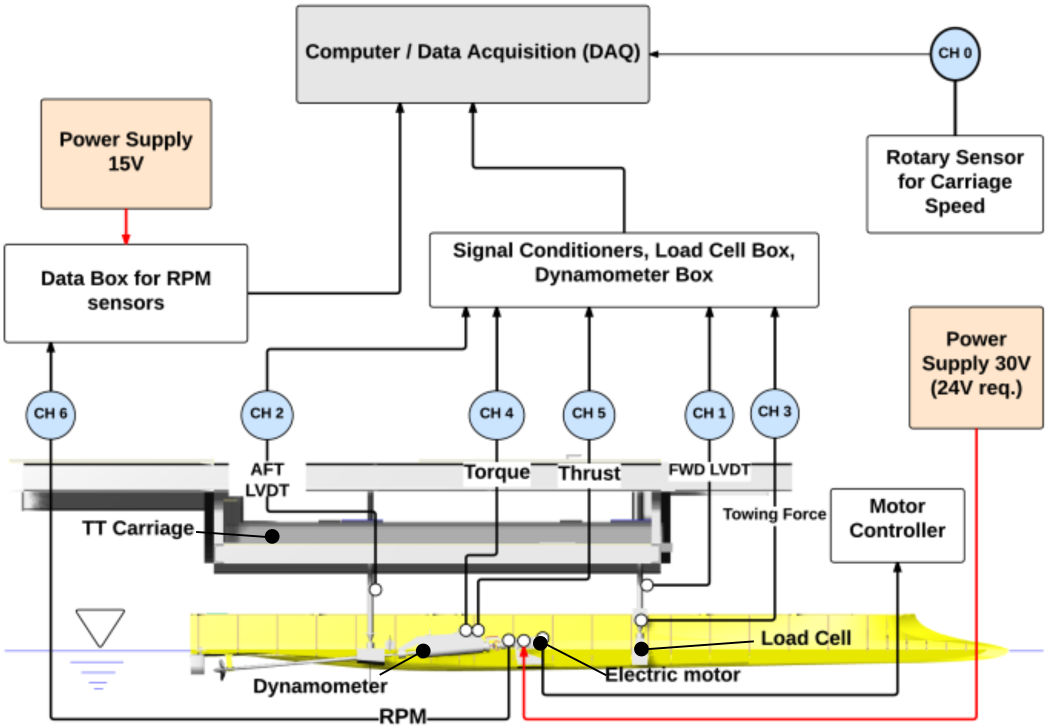

Figure 6: Data acquisition setup for the propeller driven self-propulsion test.

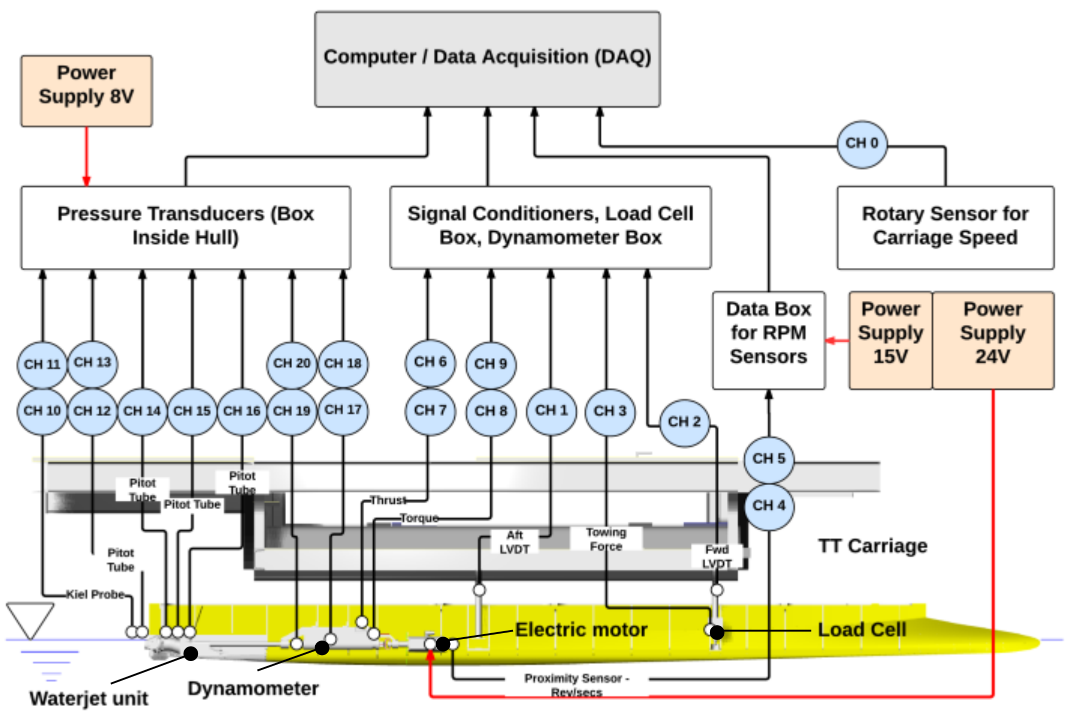

Figure 7: Data acquisition setup for the waterjet driven self-propulsion test.

2.4 Propeller Propulsion Extrapolation Procedures

The ITTC 1978 method was used to extrapolate the results of three physical model tests, i.e. bare hull resistance test, propeller open water test, self-propulsion test, to full-scale power. In the self-propulsion test, the British method was applied, where the model was towed at a number of tow force values and at the intersection of the non-dimensional K_{FD} curve using Equation 1 and the curve of the required towing force coefficient by using Equation 2, the towing force at the self-propulsion point was obtained (Bose, 2008). The non-dimensional form of the K_{FD} curve is given by:

$$K_{FD} = \frac{F_D}{\rho_M n^2 D_M^4} \tag{1}$$

where F_D is the towing force; ρ_M is the specific density of fresh water; and n_M is the model propeller revolution and D_M is the the diameter of the model propeller.

The required towing force at the self-propulsion point is given by:

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

where C_{FD} = required towing force coefficient; S_S = wetted surface area of the ship; D_S = the diameter of the ship propeller and J_P = advance coefficient at the self-propulsion point.

The outline of the ITTC1978 method is described in detail by Bose (2008), where once the advance coefficient, J_P, at the model self-propulsion point is obtained using the curve of K_{FD} and K_{FD}/J_P^2, the values of the propeller coefficients, in the behind condition, K_{TP} and K_{QP}, can be found from the results of the self-propulsion test. Then, using the "thrust identity" method, the value of K_{TP} is used to find the value of advance coefficient, J_O in the results from the open water test of the propeller.

Some corrections have to be made to the model open water thrust and torque coefficients, K_{TO} and K_{QO}, to obtain the full-scale open water propeller thrust and torque coefficients, K_{TOS} and K_{QOS}. The operating point of the full-scale propeller can be found from the intersection of the curves of K_{TOS}, K_{QOS} and the requirement for thrust given in the form of $K_T/J^2 = S_S.C_{TS}/2D_S^2(1-t)(1-w_{TS})^2$ (Bose, 2008). This intersection leads to the operating values of K_{TS}, K_{QS} and $J_{TS,}$ of the ship propeller. Then it is possible to calculate the delivered power, P_{DS}.

Another method that was used in this study to extrapolate the towing tank results to full scale was is the self-propulsion test only method. Bose (2008) has described this powering procedure prediction. In this method the resistance test and the propeller open water test are not required. The method uses the results from a load varied self-propulsion test alone. The first step of this method is to plot the propeller thrust against the towing force for every speed tested. From the plot of the towing force versus thrust, the thrust deduction fraction, t, can be obtained from a linear regression line fitted through the points, where the line can be described by $F_M = F_{T=0} - T_M\ (1- t)$. The full scale thrust then can be calculated from:

$$T_S = T_M \lambda^3 \frac{\rho_S}{\rho_M} = \left(\frac{F_{T=0} - F_M}{1-t} \right) \lambda^3 \frac{\rho_S}{\rho_M} \tag{3}$$

where λ is the scale factor, ρ is the density and T and F are any coordinates on the line. The next step is to determine the ship propeller operating point. The operating point is interpolated from the intersection of the full scale thrust and torque coefficients. A wake scaling is needed, to take into account wake scale effects. These can be done by adjusting the advance coefficients of the plot by:

$$J_S = J \frac{1-w_M}{1-w_S} \tag{4}$$

where J is the advance coefficients and the wake fraction, w, are for the model and ship, respectively. The interpolation equation $K_{TS} = J^2.\ T_S/\ 2\ \rho D_S^2 V_S^2$ intersect with the ship thrust coefficient, K_{TS}. Once the full scale thrust and the ship propeller operating point are determined, then these can be used to calculate the shaft speed, the full scale torque and the delivered power.

2.5 Waterjet Extrapolation Procedures

Waterjet performance extrapolation is partially based on standard ITTC waterjet extrapolation procedures but deviates from the common method by not carrying out a waterjet system test. As the thrust is the main component of the waterjet performance extrapolation, mass flow rate established using flow rate measurements test results and the waterjet self-propulsion test is the most important measured quantity which can be converted to thrust by:

$$T_G = \rho Q_J \left(V_j - V_i \right) \tag{5}$$

where ρQ_J is the mass flow rate, V_J is the jet velocity (i.e. where $V_j=Q_j/A_n$), and V_i is the inlet velocity (i.e. $V_i=(1-w)V$). The inlet wake fraction w was determined by carrying out boundary layer measurements at ITTC momentum flux station 1a (ahead of the inlet).

Waterjet self-propulsion test results were used to establish self-propulsion points for each tested speed. Model self-propulsion points were corrected for frictional differences between model and full scale vessels using the towing force F_G (Equation 6).

$$F_G = \frac{1}{2} \rho_M V_M^2 S_M \left[(1+k)(C_{FM} - C_{FS}) - C_A \right] \tag{6}$$

Self-propulsion points result in thrust, mass flow rate, torque and shaft revolution values for each of the tested speeds. Thrust was extrapolated to full scale by:

$$T_S = T_M \lambda^3 \frac{\rho_S}{\rho_M} \quad (7)$$

where T_S is full scale thrust, T_M model thrust, ρ_S sea water fluid density, and ρ_M towing tank fluid density.

The momentum flux energy method is then used to calculate delivered power P_D by:

$$P_D = \frac{P_{PE}}{\eta_{pump}} \quad (8)$$

where P_{PE} is the effective pump power and η_{pump} is pump efficiency. Effective pump power can be established using $P_{PE}=(E_7/\eta_n)-\eta_i E_1$ where E_7 and E_1 are the momentum based energies at ITTC momentum flux stations 7 and 1, η_n is nozzle efficiency, and η_i is inlet efficiency. Pump efficiency was established using a set of manufacturer supplied waterjet unit benchmark data.

Overall propulsive efficiency η_D can be calculated by:

$$\eta_D = \frac{P_E}{P_D} = \frac{\Delta MV}{P_{PE}} \eta_{pump} \eta_{inst} \quad (9)$$

where P_E is effective power ($P_E=R_T V$), P_{PE} pump effective power, η_{pump} pump efficiency, and η_{Inst} installation efficiency (assumed to be 1 due to the absence of more detailed data).

Extrapolated delivered power from model tests has been validated using sea trials performance data for the full scale vessel.

3 RESULTS AND DISCUSSION

3.1 The towing force versus thrust plots

As the self-propulsion tests for both propeller and waterjet driven catamarans were done using the 'British' method, the towing force variation can be plotted with respect to the propeller thrust as shown in Figures 8, 9 and 10. The tests were done by varying the propeller thrust so that the catamaran models operate at both under and overloaded conditions relative to the self-propulsion point of the ship. These tests were repeated again for different sets of Froude numbers.

As expected, these plots were observed to be linear. The linearity of these plots agreed with those reported by Bose (2008) and Kracht (1991). These curves were also found to be linear for the results from the self-propelled tests with the waterjet propelled model.

3.2 The Delivered Power Comparison

In Figure 11, the delivered power values were plotted against Froude length number for the catamaran with a displacement of 3640 and 2500 tonnes. The delivered power was extrapolated to full scale using the ITTC 1978 method and the self-propulsion test only method.

The results show that the delivered power obtained using the self-propulsion test only method were higher except at low Froude numbers. The extrapolated delivered power ranged from 6 to 25% higher using the self-propulsion test only method. The values used for the wake scaling (Equation 4) as mentioned earlier were defined to be 0.98. This wake scaling data was obtained from numerical simulation using OpenFOAM.

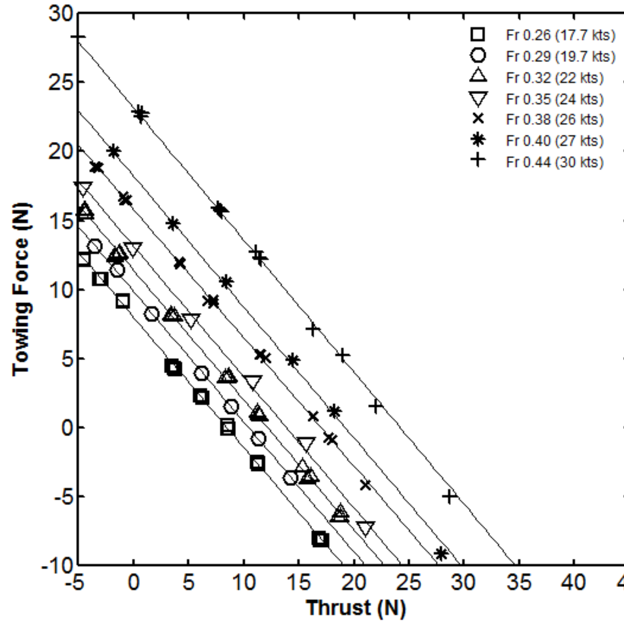

Figure 8: Towing force plotted against the propeller thrust for the 130m propeller driven catamaran with the displacement of 2,500 tonnes.

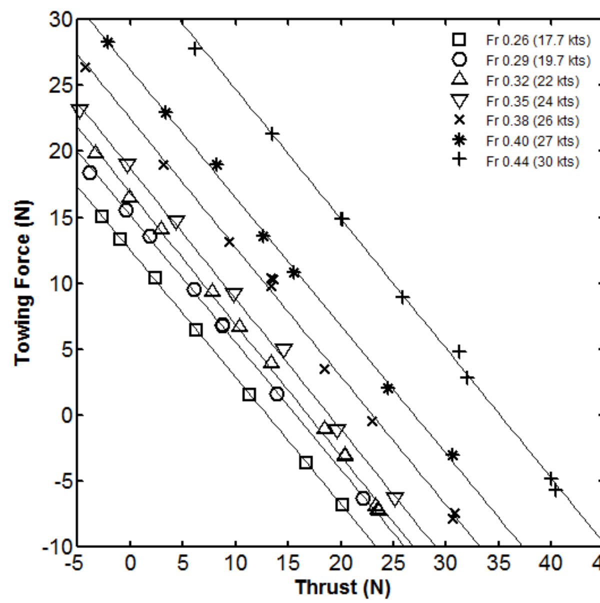

Figure 9: Towing force plotted against the propeller thrust for the 130m propeller driven catamaran with the displacement of 3,640 tonnes.

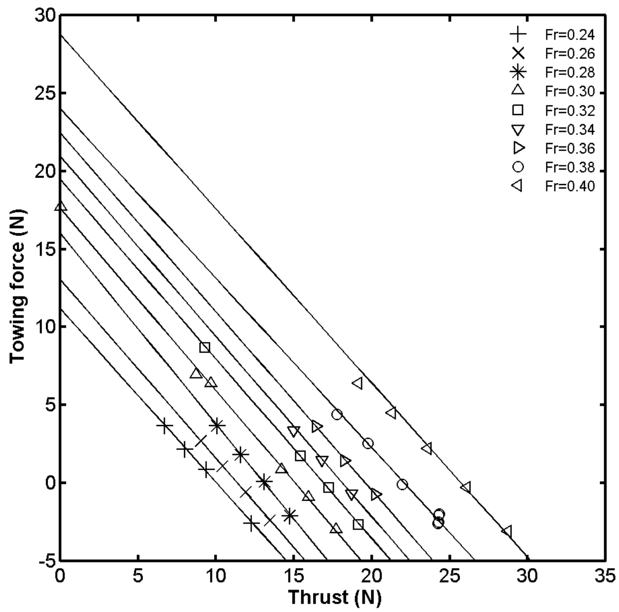

Figure 10: Towing force plotted against the propeller thrust for the 98m waterjet driven catamaran with the displacement of 1,500 tonnes.

3.3 The Overall Propulsive Efficiency

In Figure 12, the plot of the overall propulsive efficiency versus Froude length number for the propeller driven and waterjet driven catamaran are shown. The maximum efficiency of the propeller driven catamaran is at 76% at Froude number Fn = 0.35 which is equivalent to 24 knots at full scale. The maximum efficiency for the waterjet driven catamaran is at 69% at Froude number Fn = 0.36 which is equivalent to 21 knots in full scale.

3.4 The Thrust Deduction Comparison

The thrust deduction fractions which were obtained from the slope $t - 1$, were plotted against Froude length number as shown in Figure 13. The results for the propeller driven catamaran were positive, as expected and range from 0.00 to 0.05. The results for the waterjet driven catamaran were negative and range from -0.34 to -0.10.

One reason for the negative values of the thrust deduction fractions may be due to the larger hull transom submergence for the waterjet case. Increasing the submergence of the dry transom increases its hull resistance, thus increasing the slope $t - 1$. As slope $t - 1$ increases, the thrust deduction fraction decreases.

It is also likely that the flow through the waterjet ducting leads to a net thrust that is not measured through the estimation of thrust from the experiments. Negative thrust deduction fractions have been found by van Terwisga (1996) and Eslamdoost (2012) when using a definition of thrust as defined here in Equation 5.

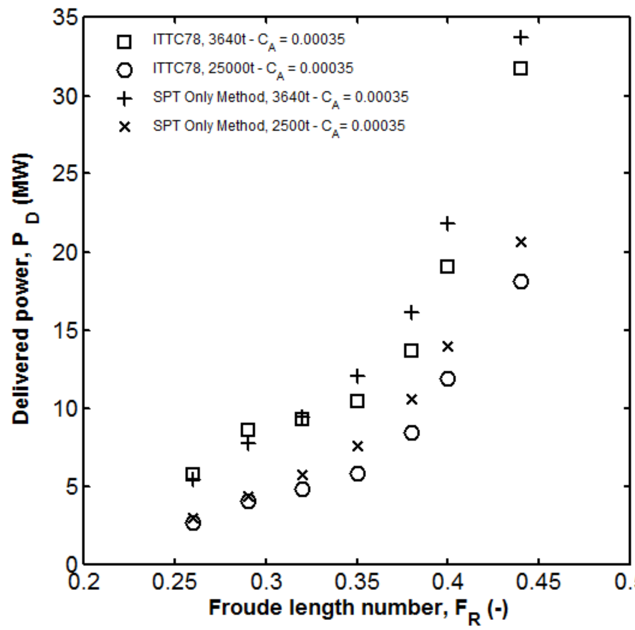

Figure 11: The delivered power versus Froude length number for the displacement of 3640 tonnes. The results were extrapolated using the ITTC 1978 method and the self-propulsion test (SPT) only method.

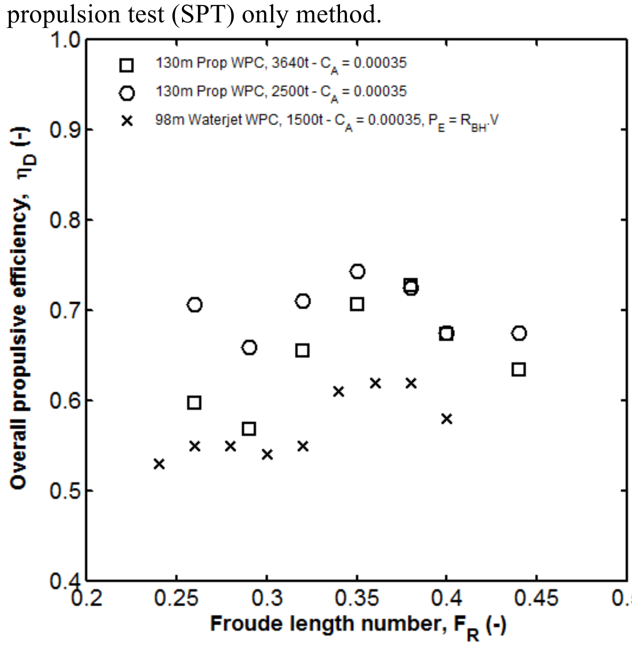

Figure 12: Overall propulsive efficiency versus Froude length number. This plot shows the results for the propeller driven and the waterjet driven catamaran.

3.5 The Transport Efficiency Comparison

The transport efficiency for both waterjet and propeller propelled vessels were also compared as shown in Figure 14. The transport efficiency was obtained using the similar approach used by Papanikolaou (2002) and was obtained from the formula for the reciprocal of the transport efficiency, E_I: $1/ E_I = P_D/ W_D V_S$, where P_D is the delivered power in kW, W_D is the displacement in tonnes and V_S in km/h. Although it is noted that the model tests were done for different sized vessels and the transport efficiency attempts to allow this, the results show that the propeller driven catamaran has a larger transport efficiency than the waterjet driven catamaran over the whole Froude number range tested.

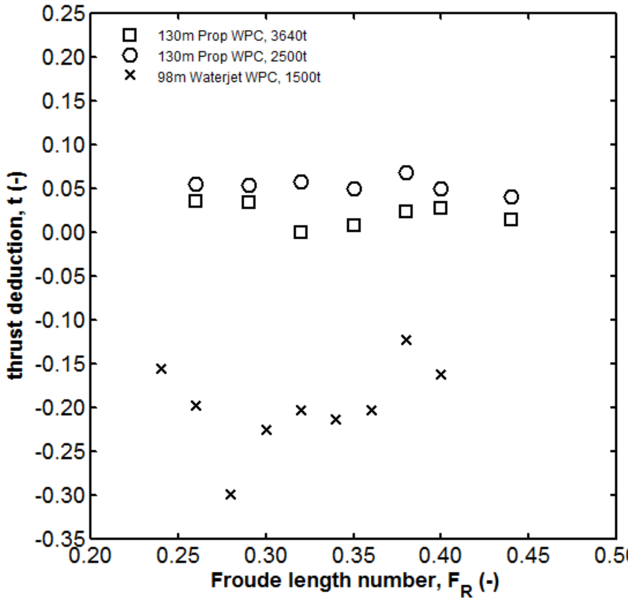

Figure 13: The thrust deduction fractions versus Froude length number.

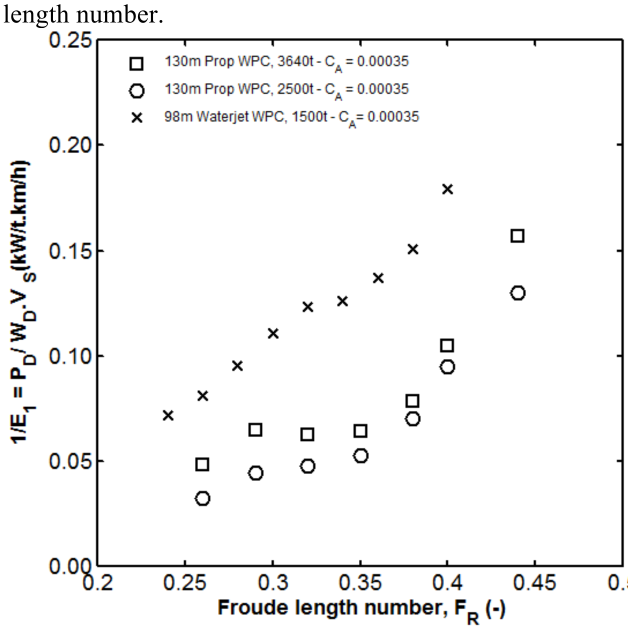

Figure 14: The transport efficiency versus Froude length number. The results for the propeller driven catamaran were extrapolated using the ITTC 1978 method.

4 CONCLUSIONS

In this paper, a comparison between the powering performance and transport efficiency of a waterjet driven catamaran and a propeller driven catamaran are presented. From the study the following was concluded:

- For the propeller driven catamaran the delivered power extrapolated using the self-propulsion test (SPT) only method were higher than the extrapolated values using the ITTC 1978 method except at low Froude numbers. The extrapolated delivered power ranged from 6 to 25% higher using the self-propulsion test only method.
- The thrust deduction fraction values were found to be negative for the waterjet propelled model when using the definition of thrust given by Equation 5 of the paper.
- The propeller driven catamaran has a larger transport efficiency than the waterjet driven catamaran over the whole Froude number range tested.

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SMP'15 Paper: Discussion & Comments

Comment #1 (by Mehmet Atlar):

"Have the authors compared the bare hull resistance & hull was characteristics of the hull forms for the waterjet & propeller driven hulls?"

Answer to comment #1 (Mehmet Atlar) by authors:

The tested models for waterjet and propeller propulsion performance estimations were of the same length (i.e. 4.3 m), but were using a different scale factor. The full scale waterjet driven vessel is 98 m while the propeller driven vessel is 135 m long. The displacements for both vessels were also different (1,500 and 1,800 tonnes for waterjet propelled vessel and 2,500 and 3,640 tonnes for propeller propelled vessel) so that a direct comparison of the resistance was not feasible. When scaling the resistance results from one model to the other, resistance can be compared and the results showed that the resistance was within 10% of each other, depending on speed. Resistance of the waterjet driven hull was higher than the propeller driven one up to a length Froude number (F_r) of 0.38 but was lower up to the maximum tested length Froude number of 0.45.

As for the wash, a direct comparison of the wash for the waterjet and propeller propelled models has not been carried out. An extensive investigation has been carried out regarding the wash and transom stern ventilation process for the waterjet propelled vessel comparing model testing results with results established using Computation Fluid Dynamics (CFD). Results of this research are available in a 2016 paper published by Max Haase at the Australian Maritime College (see *Haase, M., Binns, J., Thomas, G., Bose, N.: Wave-Piercing Catamaran Transom Stern Ventilation Process, Ship Technology Research / Schiffstechnik, in press, 2016*).

Comment #2 (by Mehmet Atlar):

"Why do the authors prefer to use transport efficiency to compare which is reciprocal of specific power coefficient?"

Answer to comment #2 (Mehmet Atlar) by authors:

As in comment #1, the base vessel used for the waterjet and propeller testing were not of the same length and displacement which did not allow for direct comparison of the full scale power estimates scaled from model scale results. Therefore, another path was selected to compare powering results which was based on comparisons of non-dimensional values and one set of values selected for comparison was the transport efficiency. A more in-depth analysis comparing waterjet and propeller performance estimations is available in a 2016 PhD thesis authored by Iwan Mustaffa Kamal at the Australian Maritime College (see *Kamal, I. M. (2016). "An insight into the powering performance of large medium-speed waterjet and propeller driven catamarans through model testing". PhD Thesis. University of Tasmania*). Results published in this PhD thesis also compares powering coefficients of results which were not available in time to be included in the SMP'15 paper.

Comment #3 (by Arash Eslamdoost):

"The measured thrust deduction fraction of the waterjet driven hull in this paper seems to have a rather large negative value in comparison to the collected thrust deduction values available from different hull types (e.g. see van Terwisga PhD thesis, 1996). The under-prediction of the jet flow rate may result in such a low thrust deduction fraction. Another parameter, which may influence the thrust deduction fraction, is the rope force magnitude during the self-propulsion test."

Answer to comment #3 (Arash Eslamdoost) by authors:

The low thrust deduction is partially based on errors in the estimation of the flow rate. As discussed in the paper, the jet flow rate was based on a combination of the static flow measurement test and the self-propulsion test. The two tests were combined using a reference measurement utilising Kiel probes at the nozzle outlet. Estimated errors (based on an uncertainty analysis not shown in the paper) resulted in errors of 4% at low shaft RPM and 2% at high RPM values. Calculations were done using two types of thrust deduction calculations based on the following two equations:

$$t = 1 - \frac{F_{T=0} - F_M}{T_M} \qquad \text{(Equation 1)}$$

where the force at zero thrust ($F_{T=0}$), towing force (F_M), and thrust at model self-propulsion (T_M) were found using results of the self-propulsion test only, and

$$t = 1 - \frac{R_{BH}}{T_G} \qquad \text{(Equation 2)}$$

where the bare-hull resistance (R_{BH}) and gross thrust (T_G) were found using results from the bare-hull resistance test as well as the self-propulsion test.

Results obtained using the discussed equations showed that the thrust deduction using Equation 1 was lower than the thrust deduction based on Equation 2 as shown in Figure 1.

A recommendation of this for future waterjet performance tests is that the flow rate should be measured even more accurately for example using the T-junction and a momentum flux balance equation method as suggested by the author of the comments (see *Eslamdoost, A. (2014). "The Hydrodynamics of Waterjet/Hull interactions". PhD Thesis. Chalmers University of Technology, Gothenburg, Sweden*) to minimise errors in measured flow rates.

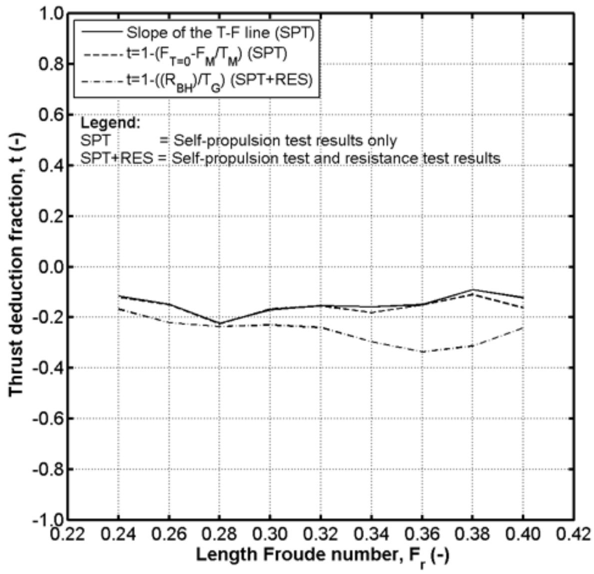

Figure 1 Comparison of thrust deduction results calculated using bare-hull resistance test results together with waterjet self-propulsion test results and thrust deduction calculated using only waterjet self-propulsion test results.

The towing force was calculated using Equation 3, where ρ_m is the water density from the model test, V_m is the model speed, S_m is the wetted surface area of the model, *1+k* is the form factor, C_{Fm} and C_{Fs} are the model scale and full scale frictional resistance coefficients, and C_A is the correlation allowance.

$$F_D = \frac{1}{2}\rho_m V_m^2 S_m\big((1+k)(C_{Fm} - C_{Fs}) - C_A\big) \quad \text{(Equation 3)}$$

The form factor *(1+k)* was established using a Prohaska low speed resistance test and the correlation factor used was $C_A=0.00035$ based on testing of a similar hull form by MARIN (see *MARIN (2008). "Calm Water Tests for the JHSV Wave Piercing Catamaran". Final Report 22162-3-DT. Maritime Research Institute Netherlands (MARIN)*).

<u>Comment #4 (by Arash Eslamdoost):</u>

"In this paper, the gross thrust of the waterjet unit is scaled only using the scale factor. The in-flow to the waterjet unit is not the same in the model scale and the full scale and therefore this needs to be considered during the scaling procedure."

<u>Answer to comment #4 (Arash Eslamdoost) by authors:</u>

This has been looked at. The in-flow velocity (i.e. inlet speed) of the waterjet for model scale and full scale was adjusted based on model scale measurements of the boundary layer. The model scale flow rate was known as measured using a flow rate measurement test and combined with the self-propulsion test using a reference measurement as mentioned in answer to comment #1 but full scale flow rates were only available in the form of scaled flow rates based on model waterjet benchmark test results supplied by the waterjet unit manufacturer. Therefore, as an approximation the gross thrust was only scaled using the scale factor.

<u>Comment #5 (by Arash Eslamdoost):</u>

"The thrust deduction fractions for the propeller driven hulls and the waterjet propelled hull are plotted in Figure 13 and compared with each other. Since the thrust used in the thrust deduction formula is not the same for these hulls (i.e. net thrust for the propeller driven hull and it is gross thrust for the waterjet propelled hull), the direct comparison of these values can be misleading."

<u>Answer to comment #5 (Arash Eslamdoost) by authors:</u>

This is a valid point. Additional to this, the thrust for a propeller system can be measured directly while the thrust for the waterjet driven hull can only be measured indirectly which will add more uncertainty to this comparison of propeller and waterjet thrust deduction results. When investigating thrust deduction for propeller propulsion, there is a physical explanation and this can also be indirectly measured through the bare-hull resistance, from bare-hull resistance test, and thrust of propeller (thrust measured in propeller self-propulsion test using a self-propulsion propeller dynamometer). In the case of the waterjet propelled vessel, there is no physical explanation for thrust deduction since waterjet thrust cannot be measured directly and thrust deduction also cannot be measured through bare-hull resistance of vessel and impeller thrust of waterjet.

Sources for deviation for thrust deduction in relation to waterjet propulsion are:

- effect of inlet opening on vessel resistance;
- effect of transom ventilation and transom resistance;
- neglected friction and pressure related stresses in momentum balance;
- new, partially developed boundary layer aft of inlet lip;
- boundary layer model.

Considering the non-physical nature of the thrust deduction for waterjet propelled vessels and all the deviations possible in the calculation of thrust deduction, thrust deduction for waterjet propulsion is not as meaningful as for propeller propelled vessels and should be considered more as a correlation factor. The thrust deduction (i.e. correlation factor) for waterjet propulsion also depends, on a big part, on the accuracy of the thrust measurements using direct or indirect thrust measurements.