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DESCRIPTION OF PROPELLER OPEN WATER EXPERIMENTS CARRIED OUT ON STOCK PROPELLERS 321R AND 321L

TR-2010-04

C. Muselet
R. Pallard

March 2010

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LIST OF ABBREVIATIONS

A_0	propeller disk area
A_E	expanded area of all propeller blades, outside hub
cm	centimetre(s)
DC	direct current
deg.	degree(s)
deg. C, °C	degree(s) Centigrade
DC	direct current
GDAC	General Data Acquisition and Control
GEDAP	General Data Analysis Package
Hz	Hertz
IOT	Institute for Ocean Technology
ITTC	International Towing Tank Conference
kg	kilogram(s)
K&R	Kempf & Remmers
kW	kiloWatt(s)
m	metre(s)
mm	millimetre(s)
N	Newton(s)
OCC	Oceanic Consulting Corporation
QA	quality assurance
rps	revolution(s) per second
s	second(s)

LIST OF SYMBOLS – PROPELLER OPEN WATER EXPERIMENTS¹

<u>Symbol</u>	<u>Definition</u>
ν_M	kinematic viscosity of the water in the test facility, m ² /s
ρ_M	density of the water in the test facility, kg/m ³
η_O	open efficiency
$c_{0.7}$	model propeller blade chord at 0.7 radius, m
D	model propeller diameter, m
Fr	Froude number for the ship and model
g	gravitational acceleration (standard IOT value 9.808 m/s ²)
J_O	advance coefficient in propeller open water test
K_{QO}	propeller torque coefficient in open water test
K_{TO}	propeller thrust coefficient in open water test
K_{TDO}	duct thrust coefficient in open water test
n_O	propeller rate of rotation in open water test, rps
P/D	Pitch/diameter ratio
Q_O	propeller torque in open water test, Nm
R_{nco}	propeller Reynolds number
T_O	propeller thrust in open water test, N
T_{DO}	duct thrust in open water test, N
V_A	propeller speed of advance in open water test, m/s

¹ Note IOT uses ITTC Symbols Version 2002.

DESCRIPTION OF PROPELLER OPEN WATER EXPERIMENTS CARRIED OUT ON STOCK PROPELLERS 321R AND 321L

1.0 INTRODUCTION

This report describes propeller open water experiments carried out on a pair of four bladed adjustable-pitch stock propellers, designated 321R and 321L, owned by Oceanic Consulting Corporation (OCC), in the Institute for Ocean Technology (IOT) Towing Tank, February 11 to 12, 2010.

The experiments shall provide the open water characteristics of each propeller set at the same pitch/diameter ratio as used during the self-propulsion tests of CCG/DFO 25m Inshore Fisheries Science Vessel model IOT872 (Reference 1) in the IOT Ice Tank February 1 to 8, 2010. The propellers were fitted inside a stock 19A nozzle, equipped with 6-arm stators.

The open water characteristics of one propeller inside a stock 19A nozzle but without stator were also measured.

2.0 DESCRIPTION OF THE IOT TOWING TANK

The IOT Towing Tank has dimensions of 200 m by 12 m by 7 m with a dual-flap wavemaker fitted at one end capable of generating uni-directional regular waves up to 1 m in height or irregular waves up to a 0.5 m significant wave height. A wave absorber consisting of a parabolic beach is fitted at the opposite end. Flexible side absorbers can also be deployed along the entire length of the tank to minimize the time between runs. The 80 t tow carriage capable of speeds up to 10 m/s is used to accommodate models for a wide range of test types carried out in calm water or waves. A 4,000 kg lift capacity moveable overhead crane is available over most of the tank length. Additional information on the Towing Tank is provided in Appendix A.

3.0 DESCRIPTION OF IOT PROPELLER OPEN WATER DYNAMOMETER

The IOT Propeller Open Water Dynamometer is used to determine the characteristics of model propellers in a homogeneous flow field and can be mounted in either the 200 m Towing Tank or Cavitation Tunnel. The IOT unit is a Kempf & Remmers model H-39, fabricated by Cussons Technology Ltd. Torque and thrust of the propeller are measured using separate full-bridge strain gage transducers in a streamlined body, which is an extension of the propeller shaft. The strain gages are temperature compensated and an effort has been made to minimize crosstalk. A Kempf & Remmers Electric 1-Component Balance R35-I is mounted to the dynamometer, and attached to the nozzle through a faired strut, to measure the duct thrust.

A schematic of the dynamometer is presented in Figure 1 while a generic photograph of the dynamometer (fitted with a ducted propeller) is given in Figure 2. Primary specifications of IOT propeller open water dynamometer:

Rated Torque = ± 55 N-m

Rated Thrust = 1000 N

Maximum Shaft Speed = 50 rps

Power of the Drive Motor for Rated Torque @ 50 rps = 18 kW

1-Component Balance Maximum Load = ± 200 N

4.0 DESCRIPTION OF PROPELLERS 321R AND 321L

The propellers are 4 bladed, adjustable pitch brass propellers, respectively right hand rotation (321R) and left hand rotation (321L), with an average nominal propeller diameter of 152.4 mm.

Propeller description:

Kaplan Series

Diameter: 152.4 mm

4 blades

Expanded-Area Ratio: $A_E/A_0 = 0.7$

Propeller blade thickness at $0.7R = 3.09$ mm

Propeller blade chord at $0.7R = 55.6$ mm

These propellers are adjustable pitch units that can be set to four nominal pitch/diameter ratios ranging from 1 to 1.3. For this and the self-propulsion test, the propellers were set to $P/D=1.2$. However, the initial self-propulsion test and a subsequent quick check of the “stack height” of each blade of the propellers indicated that the pitch of each propeller was slightly different. Their open water characteristics were determined for the same setup as that tested in the self-propulsion experiments.

A photograph of the propellers IOT321R and 321L along with their friction hubs is given in Figure 3.

5.0 DESCRIPTION OF THE PROPELLER ASSEMBLY

The propellers were used inside stock 19A nozzles, equipped with 6-arm stators.

In the model self-propulsion tests, the nozzles had been attached to the hull by tapered mounts protruding from the hull about 20mm at the aft end and flush with the hull at the forward inboard end. The mounts had been considered to be appendages and had been left in place for the appended resistance tests.

For the propeller open water experiments, a nozzle mount was made, identical to the part of the mount that had been protruding from the hull. A faired strut connected this mount to the 1-component duct thrust balance.

A photograph of the assembly of the 1-component balance, faired strut, nozzle mount, nozzle, stator and propeller opens cone (no propeller), is given in Figure 4.

In addition, the open water characteristics of propeller 321R inside the 19A nozzle but without stator were also measured. This allowed investigating the open water effect of the stator, as the model stator design differed from the ship stator design.

All propeller open water experiments were conducted with the model propeller mounted on the horizontal shaft of the Propeller Open Water Dynamometer. The shaft was set at a depth of

immersion equal to 1.5 propeller diameters (23 cm). The nozzle was in the same relative position to the propeller as it had been during the model self propulsion tests.

6.0 DESCRIPTION OF INSTRUMENTATION AND DATA ACQUISITION SYSTEM

The experiments were carried out using the standard IOT propeller open water dynamometer equipped with the 1-component duct thrust balance, and fitted to the tow carriage in the IOT Towing Tank.

All acquired analog DC signals were low pass filtered at 10 Hz, amplified as required and digitized at 50 Hz using IOT standard data acquisition system and software described in Reference 2.

The signals measured and recorded during the propeller open water experiments are listed in the Table 1.

7.0 INSTRUMENTATION CALIBRATION PROCEDURE

The procedure used to calibrate each individual signal is described as follows using the standard IOT sign convention described in Reference 3.

Tow Carriage Speed: A tacho-generator mounted on a wheel of the towing carriage was used for carriage speed measurement. The output of this device was calibrated against carriage set speed. The accuracy of the tacho-generator carriage speed measurement has last been verified in May 2009 against the tank rail marker system, a set of 32 markers carefully surveyed at a known spacing (4202mm). An optical switch on the carriage, sampled at 1000 Hz, outputs a voltage drop as it passes by a marker. The tacho-generator speed measurement has shown to be 0.13% too high, when compared to speed derived from the tank rail marker system. In the present tests, the carriage speed is reported from the tacho-generator output with no correction to reflect this.

Dynamometer Shaft Speed: Shaft speed was acquired as the signal from the tacho-generator that governs the shaft motor speed control. The electronic pulse generator connected to the digital display of motor speed on the control desk provided physical values for calibration of shaft speed.

The shaft speed was calibrated over a range of 0 to 23 rps.

Dynamometer Shaft Thrust, Torque: The propeller open water dynamometer was calibrated in-situ with the dynamometer horizontal using the calibration procedures outlined in Reference 4. The shaft is clamped and an adaptor is fitted on the end of the dynamometer with a lever arm and tape roller to apply torque and thrust load. A series of static weights are added to a weight tray to calibrate thrust and torque in turn. See Figure 5. The thrust was calibrated over a range of 0 to 200 N, while the torque was calibrated over a range of ± 4.9 Nm.

1-Component Balance (Duct Thrust Balance): The balance was calibrated using the procedure outlined in Reference 4. The 1-component balance is mounted in a vertical axis onto a dedicated

calibration stand. The stand is levelled, and a weight pan is hung from a hanger attached to the balance.

The 1-component balance was calibrated over a range of thrust of 0 to 100 N.

Instrumentation calibration results are presented in Appendix B.

8.0 TEST PROGRAM AND PROCEDURES

The propeller open water experiments were carried out as per the IOT Standard Propeller Open Water Test Procedure (Reference 5). The test program is provided in Appendix C.

First, runs were carried out with only the faired strut and nozzle mount, over the planned range of carriage speeds, to obtain the thrust (resistance) of that assembly.

Then, three propellers (or propeller configurations) were tested: propeller 321R, propeller 321L, and propeller 321R without stator in the nozzle. For each of these three tests, shaft friction values were acquired with dummy hub fitted at the beginning and end of the test, at 10, 13, 14, 15, 17, 18, 19, 20, 21 rps, with the shaft rotating clockwise (as viewed from the aft) for the tests with the right hand propeller (321R), and counter-clockwise for the test with the left hand propeller (321L).

The tests were conducted at the following two shaft speeds:

For $n_o = 14$ rps – R_{nco} corresponds to 2.36×10^5 .

For $n_o = 19$ rps – R_{nco} corresponds to 3.21×10^5 .

Multiple speeds of advance were tested in one run.

The Test Log is provided in Appendix D.

9.0 DATA ANALYSIS PROCEDURE

The data were acquired in GDAC format (*.DAC files) described in References 6, 7. The data were converted to GEDAP format described in Reference 8 prior to carrying out an online data analysis on the Towing Tank carriage workstation during the test to verify the integrity of the acquired data. An offline analysis was carried out after completion of all tests to yield the final results of open water characteristics for each propeller.

9.1 Analysis Of The Faired Strut And Nozzle Mount Thrust Measurements

For each run, carriage speed and the thrust force measured by the 1-component balance were plotted in the time domain. Steady state segments were selected interactively. The mean values were computed for each data segment, and the mean values of the tare segment subtracted.

With all runs analyzed, a GEDAP file was generated describing measured thrust force against carriage speed. A spline curve of mean thrust vs. carriage speed was fitted through the data points, and output to a GEDAP file.

The spline curve file was used in the analysis of subsequent tests with the propellers: a correction value was interpolated from the curve at the test carriage speed, and subtracted from the 1-component balance force measurement to obtain duct thrust.

The measured thrust of the faired strut and nozzle mount assembly is presented in Table 2 and Figure 6.

9.2 Analysis Of The Shaft Friction Tests

For each friction test:

- Shaft torque and shaft speed were plotted in the time domain. Steady state segments were selected interactively.
- Basic statistics (minimum, maximum, mean, standard deviation) were computed for each data segment.
- A plot of mean shaft torque vs. shaft speed was displayed and a spline curve was fitted interactively through the data, and output to a GEDAP file.

After completion of the open water tests for one propeller, a routine was run to compute the average curve of shaft friction torque vs. shaft speed, from friction tests carried out before and after that propeller test. An average friction curve is generated for each propeller or propeller configuration.

In the analysis of the propeller tests, the friction associated with each propeller test run is obtained by interpolating the average friction curve for that propeller at the test shaft speed. This test friction is subtracted from the measured shaft torque to obtain propeller torque.

For the purpose of online checks, the friction measured immediately before the test was used to compute and plot propeller torque.

The results of friction tests for the test of each propeller are presented in Figures 7, 8, 9. The magnitude of shaft friction, and variation before and after the test, is presented in Table 3.

Note that the shaft friction results are presented with the usual sign convention that a right hand propeller has positive shaft speed and negative torque, and a left hand propeller negative shaft speed and positive torque.

But all results for the propeller open water tests will subsequently be presented as positive shaft speed and torque for normal operation of each propeller.

For the 321R tests, both with and without stator, shaft friction torques were of the order of 0.2 Nm, and correspond to approximately 20% of the maximum measured torque coefficient. Shaft friction torques for the 321L tests were half as much.

9.3 Analysis Of Propeller Open Water Runs

The analysis extracts from the measurements the mean values of propeller rate of rotation (n_O), propeller thrust (T_O), duct thrust (T_{DO}), torque (Q_O) and speed of advance (V_A), and calculate the non-dimensional coefficients J_O , K_{TO} , K_{TDO} , K_{QO} , R_{nco} (propeller Reynolds number at 0.7 of the propeller radius for each test):

$$J_O = \frac{V_A}{n_O D} \quad (1)$$

$$K_{QO} = \frac{Q_O}{\rho_M n_O^2 D^5} \quad (2)$$

$$K_{TO} = \frac{T_O}{\rho_M n_O^2 D^4} \quad (3)$$

$$K_{TDO} = \frac{T_{DO}}{\rho_M n_O^2 D^4} \quad (4)$$

$$R_{nco} = \frac{c_{0.7} \sqrt{V_A^2 + (0.7\pi n_O D)^2}}{v_M} = \frac{c_{0.7} n_O D \sqrt{J_O^2 + (0.7\pi)^2}}{v_M} \quad (5)$$

In the online analysis:

- The measured shaft torque, shaft thrust, duct thrust, shaft speed and carriage speed were plotted in the time domain. Steady state segments were selected interactively.
- Basic statistics (minimum, maximum, mean, standard deviation) were computed for each data segment. The mean values of the tare segments were subtracted from the mean thrust values and carriage speed values. The corrections for torque and for duct thrust were computed.
- The non-dimensional propeller coefficients: advance coefficient, J_O , torque coefficient, K_{QO} , propeller thrust coefficient, K_{TO} , duct thrust coefficient, K_{TDO} , and propeller Reynolds number R_{nco} were computed using the corrected averaged values of each relevant parameter. These dimensionless coefficients were calculated using equations 1 to 5.
- The computed non-dimensional propeller coefficients points (K_{TO} vs. J_O) and ($10K_{QO}$ vs. J_O) were displayed along with comparison curves. The comparison curves represented results provided by OCC of previous open water tests for these propellers and nozzles (without stator) at a pitch/diameter ratio of 1.2.
- Carriage Speed (m/s), Shaft Speed (rps), Shaft Thrust (N), Duct Thrust (N), Total Thrust (N), Shaft Torque (N-m) mean values and Reynolds Number data as well as dimensionless coefficients were output to ASCII files.

After completion of the open water experiment for each propeller, offline data analysis was carried out:

- The propeller open water data were re-computed taking into consideration the average shaft friction curve for that propeller;
- Fourth order polynomials were fitted to the K_{QO} vs. J_O data and to the total thrust coefficient ($K_{TO} + K_{TDO}$) vs. J_O data;
- The propeller efficiency in open water (η_o) was calculated with the data interpolated from the fitted curves:

$$\eta_o = \frac{J_o(K_{TO} + K_{TDO})}{2\pi K_{QO}} \quad (6)$$

- The polynomial coefficients to the fitted lines for K_{TO} , K_{TDO} , ($K_{TO} + K_{TDO}$) and $10K_{QO}$ where:

$$f(J_o) = \sum_{i=0}^4 B(i)J_o^i \quad (7)$$

and the values for the fitted lines for J_O , K_{TO} , K_{TDO} , ($K_{TO} + K_{TDO}$), $10K_{QO}$ and η_o in J_O increments of 0.05 were stored.

10.0 RESULTS

The results for each propeller in each configuration are presented in Appendix E. The results for 321R and 321L with stator are to be used for ship power prediction in conjunction with the self-propulsion test results.

A comparison of the results with propeller open water data provided by OCC for pitch/diameter ratios $P/D=1.1$ and $P/D=1.2$, is presented in appendix F.

Comparisons of propeller open water data for 321L and 321R, and for 321R with and without stator, are presented in Appendix G.

11.0 DATA QUALITY CONTROL

The following measures were taken to ensure the integrity of the acquired data:

TEST PROCEDURES: The test equipment, experiment techniques and analysis methods used at IOT follow well-established methodologies.

ONLINE DATA ANALYSIS: The data were analyzed during the test as described in Section 9.0. Using the technique of plotting the acquired data against a comparison curve, it is possible to detect anomalies, and if necessary a run would be repeated or the test equipment checked.

REPEATS AT $J_O=0$: At the beginning of each run, the shaft speed was brought to the test value, before the carriage was brought to speed. Therefore multiple measurement points at $J_O = 0$ are available for each propeller at each shaft speed. At $J_O = 0$, thrust and torque values are maximum.

Statistics for these measurement points are presented in Table 4. The maximum difference between repeat run values of shaft torque and thrust is less than 1.9%.

12.0 DISCUSSION

For the right rotation propeller 321R with or without stator, we observe a small Reynolds number effect on the open water coefficients, and especially on the torque coefficient. Table 4 shows the differences in the coefficients for the two shaft speeds tested. Over all advance coefficients, $10K_{QO}$ increases by 0.015 on average when the propeller is run at a shaft speed of 19 rather than 14 rps. The difference represents about 2.3% of the maximum torque coefficient. This is perhaps within the error of the measurement. But the increase is present at all advance speeds, and it is also observed consistently for both tests of 321R with and without stator, done on different days. The fourth order polynomials represent the average of the measured coefficients for both shaft speeds, for use in self-propulsion analysis.

The open water torque, shaft thrust and total thrust coefficient curves measured for propellers 321R and 321L are in between the curves for pitch/diameter ratios of 1.1 and 1.2 provided by OCC (cf. Appendix F). This is consistent with the quick survey of the propellers, that had indicated that on each propeller some of the blades may have been set for 1.1 and others for 1.2. The duct thrust coefficient decreases less with advance speed than expected from the existing curves.

Comparison between the left rotation propeller 321L and right rotation propeller 321R (cf. Appendix G) shows that the thrust coefficients are practically identical. Only the measured torque coefficients of these two propellers differ significantly, but only due to the right rotation propeller having less torque coefficient at 14 rps than at 19 rps. At 19 rps, the torque coefficients are practically the same. At 14 rps, $10K_{QO}$ is 0.021 higher on average for the 321L propeller than for the 321R propeller. The difference represents 3% of the maximum torque coefficient.

Comparison of the tests with and without stator (cf. Appendix G) show that the presence of the stator lowers duct thrust but increases shaft thrust by a similar amount. The torque coefficient is increased (by 0.01, or 1.7% of maximum torque coefficient), resulting overall in a lower efficiency.

13.0 ACKNOWLEDGEMENTS

The authors would like to thank all IOT technical staff that assisted with acquiring this propeller open water data.

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TABLES

PROJECT NUMBER: 42-2412-16
 PROJECT TITLE: CCG 25m Inshore Science Vessel
 PROJECT PHASE: Propeller Open Water Experiments, IOT Tow Tank, Feb 11-12, 2010
 PROJECT MANAGER: Rob Pallard

Description	Units	Range	Sample Rate (Hz)	Critical Level	Device	Excitation volts	Filter Hz	Gain
Carriage Speed (Tacho-Generator)	m/s	-1 to 3.7	50	1	Hubner TDP 0,09 LT-4	10	10	
Shaft Thrust	N	0 to 100	50	1	K&R H-39 Opens Dyno	6	10	500, PG4
Shaft Torque	N-m	-4 to +4	50	1	K&R H-39 Opens Dyno	6	10	500, PG4
Shaft Speed	rps	0 to 23	50	1	K&R H-39 Opens Dyno	10	10	PG2
Duct Force	N	0 to 100	50	1	K&R R35 1-Component Balance	6	10	500, PG2

Water Temperature was measured periodically, using the cable array of thermistors located at one fixed location in the tank.

Table 1: List of Signals

Vm m/s	Thrust N	Drag Area Coefficient m ²
0	0	
0.150	-0.03	0.00258
0.345	-0.14	0.00237
0.539	-0.36	0.00249
0.734	-1.10	0.00409
0.734	-1.07	0.00396
1.025	-2.22	0.00423
1.316	-2.60	0.00300
1.608	-3.12	0.00242
1.899	-4.09	0.00227
2.483	-6.83	0.00222
3.066	-10.60	0.00226
3.648	-15.17	0.00228

Table 2: Measured Force on Faired Strut and Nozzle Mount

		Shaft Friction Torque expressed as 10KQO	
		Shaft Speed	
		14 rps	19 rps
321R Test	friction_cw_002	-0.136	-0.074
	friction_cw_003	-0.148	-0.085
	friction_cw_004	-0.130	-0.075
	range	0.019	0.011
321L Test	friction_ccw_001	0.071	0.045
	friction_ccw_002	0.064	0.041
	range	0.007	0.004
321R no stator Test	friction_cw_005	-0.125	-0.071
	friction_cw_006	-0.122	-0.070
	range	0.003	0.001

Table 3: Magnitude and Range of Shaft Friction

		Shaft Thrust	Duct Thrust	Total Thrust	Torque
		N	N	N	Nm
321R, 14 rps 4 data points	average	35.23	31.41	66.64	1.033
	stdev	0.13	0.21	0.31	0.005
	min	35.05	31.17	66.21	1.029
	max	35.32	31.65	66.95	1.040
	range/mean	0.8%	1.5%	1.1%	1.1%
	stdev/mean	0.4%	0.7%	0.5%	0.5%
321R, 19 rps 6 data points	average	65.32	58.80	124.12	1.944
	stdev	0.11	0.11	0.18	0.013
	min	65.18	58.67	123.97	1.925
	max	65.43	58.93	124.30	1.956
	range/mean	0.4%	0.4%	0.3%	1.6%
	stdev/mean	0.2%	0.2%	0.1%	0.7%
321L, 14 rps 4 data points	average	35.37	31.49	66.86	1.065
	stdev	0.12	0.19	0.31	0.009
	min	35.24	31.29	66.53	1.052
	max	35.50	31.71	67.21	1.072
	range/mean	0.7%	1.3%	1.0%	1.9%
	stdev/mean	0.3%	0.6%	0.5%	0.9%
321L, 19 rps 6 data points	average	65.31	58.61	123.92	1.948
	stdev	0.19	0.13	0.31	0.006
	min	65.04	58.48	123.52	1.941
	max	65.45	58.78	124.23	1.955
	range/mean	0.6%	0.5%	0.6%	0.7%
	stdev/mean	0.3%	0.2%	0.2%	0.3%
321R, 14 rps (no stator) 4 data points	average	34.11	33.20	67.31	1.022
	stdev	0.25	0.25	0.45	0.006
	min	33.90	32.93	66.83	1.013
	max	34.43	33.51	67.70	1.026
	range/mean	1.6%	1.8%	1.3%	1.3%
	stdev/mean	0.7%	0.7%	0.7%	0.6%
321R, 19 rps (no stator) 6 data points	average	63.97	62.35	126.32	1.916
	stdev	0.22	0.12	0.33	0.004
	min	63.75	62.22	126.05	1.910
	max	64.28	62.50	126.78	1.920
	range/mean	0.8%	0.5%	0.6%	0.5%
	stdev/mean	0.3%	0.2%	0.3%	0.2%

Table 4: Repeat Run Statistics at Jo=0

	321R				321L				321R no stator			
	coefficient at 19 rps minus coefficient at 14 rps											
Jo	10KQO	KTO	KTDO	KTO+KTDO	10KQO	KTO	KTDO	KTO+KTDO	10KQO	KTO	KTDO	KTO+KTDO
0.00	0.014	0.002	0.004	0.006	-0.004	0.002	0.003	0.005	0.009	0.005	0.005	0.010
0.07	0.014	0.001	0.003	0.003	-0.006	0.002	0.002	0.003	0.014	0.003	0.001	0.004
0.15	0.020	0.001	0.004	0.005	-0.006	0.002	0.003	0.005	0.013	0.004	0.004	0.008
0.22	0.020	0.000	0.001	0.001	-0.006	0.002	0.003	0.004	0.017	0.003	0.001	0.004
0.30	0.013	0.002	0.005	0.006	-0.005	0.002	0.005	0.008	0.020	0.004	0.006	0.010
0.37	0.014	0.000	0.002	0.002	-0.007	0.001	0.003	0.004	0.009	0.004	0.002	0.007
0.45	0.012	0.002	0.002	0.004	-0.004	0.002	0.002	0.004	0.011	0.005	0.003	0.007
0.52	0.014	0.001	-0.001	0.000	-0.006	0.002	0.000	0.002	0.010	0.005	0.000	0.005
0.60	0.011	0.002	0.002	0.004	0.001	0.004	0.002	0.006	0.011	0.005	0.002	0.007
0.67	0.016	0.001	0.001	0.001	-0.005	0.003	0.002	0.005	0.011	0.005	0.003	0.008
0.75	0.014	0.004	0.003	0.006	0.003	0.005	0.004	0.008	0.012	0.005	0.003	0.008
0.82	0.010	-0.001	0.000	-0.002	-0.008	0.001	0.002	0.002	0.012	0.005	0.003	0.008
0.90	0.020	0.008	0.008	0.015	-0.003	0.006	0.005	0.011	0.014	0.010	0.009	0.019
0.97	0.027	0.008	0.008	0.016	0.007	0.011	0.011	0.022	0.024	0.015	0.016	0.031
1.05	0.041	0.019	0.013	0.032	0.025	0.018	0.007	0.025	0.018	0.013	0.013	0.026
1.12	0.029	0.009	0.009	0.018	0.003	0.008	0.009	0.017	0.020	0.013	0.007	0.020
mean difference	0.015	0.002	0.003	0.004	-0.004	0.002	0.003	0.005	0.013	0.005	0.003	0.008
mean difference / max coefficient	2.3%	0.4%	0.8%	0.6%	-0.6%	0.7%	0.9%	0.8%	2.0%	1.5%	1.0%	1.2%

Table 5: Reynolds Number Effect: Difference Between Propeller Coefficients At 14 and 19 rps

FIGURES

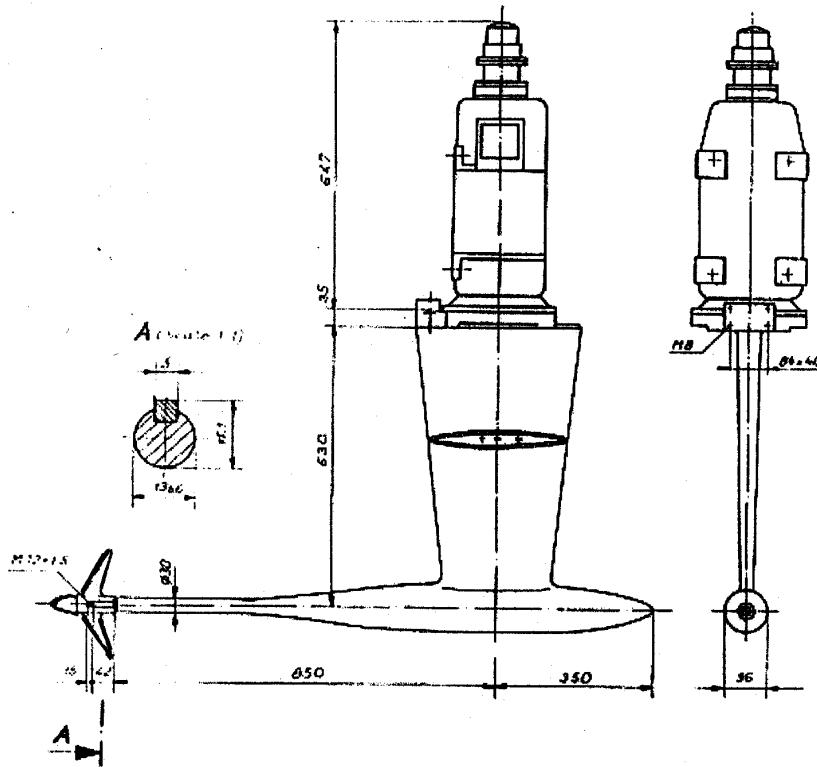


Figure 1: Schematic of IOT Propeller Open Water Dynamometer



Figure 2: IOT Propeller Open Water Dynamometer



Figure 3: 321L (top) and 321R (bottom) Propellers and Friction Hubs



Figure 4: Nozzle and Stator Assembly on 1-Component Balance

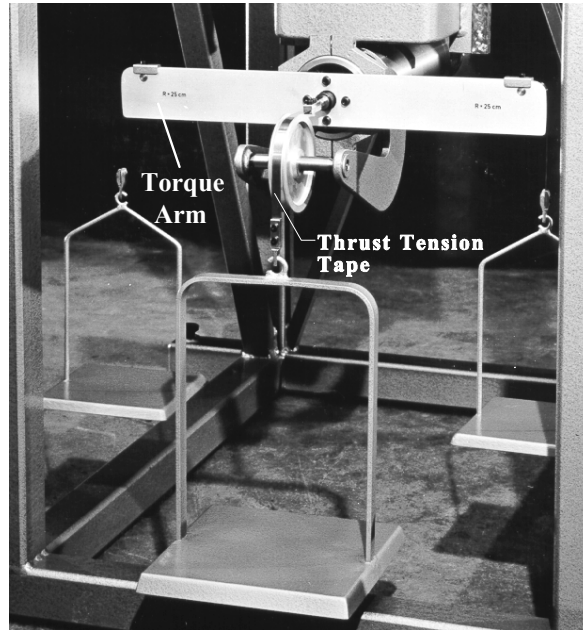


Figure 5: Propeller Open Water Dynamometer Calibration Arrangement

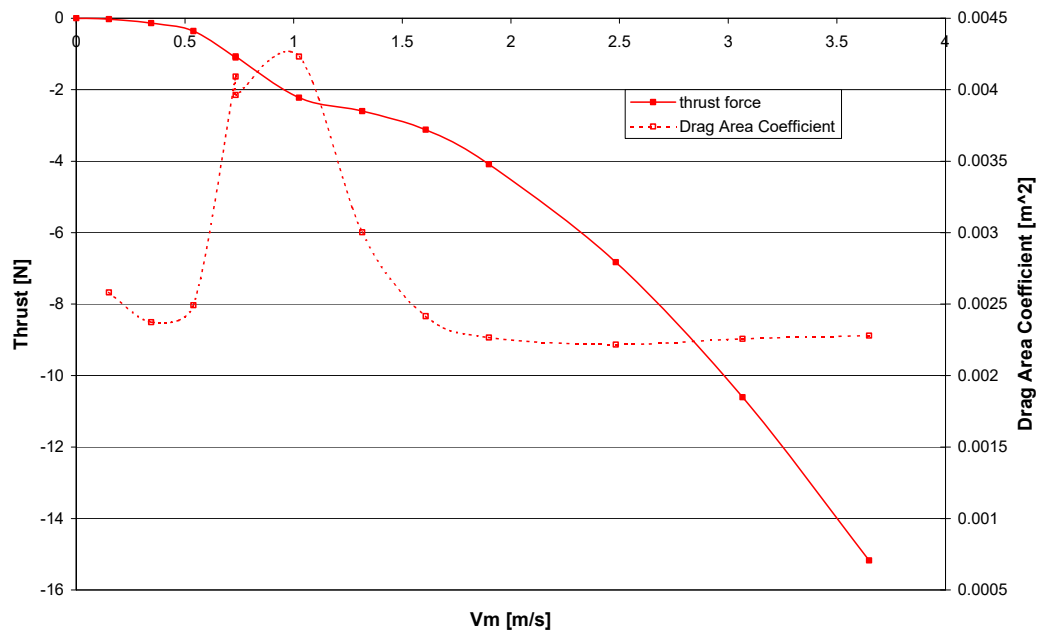
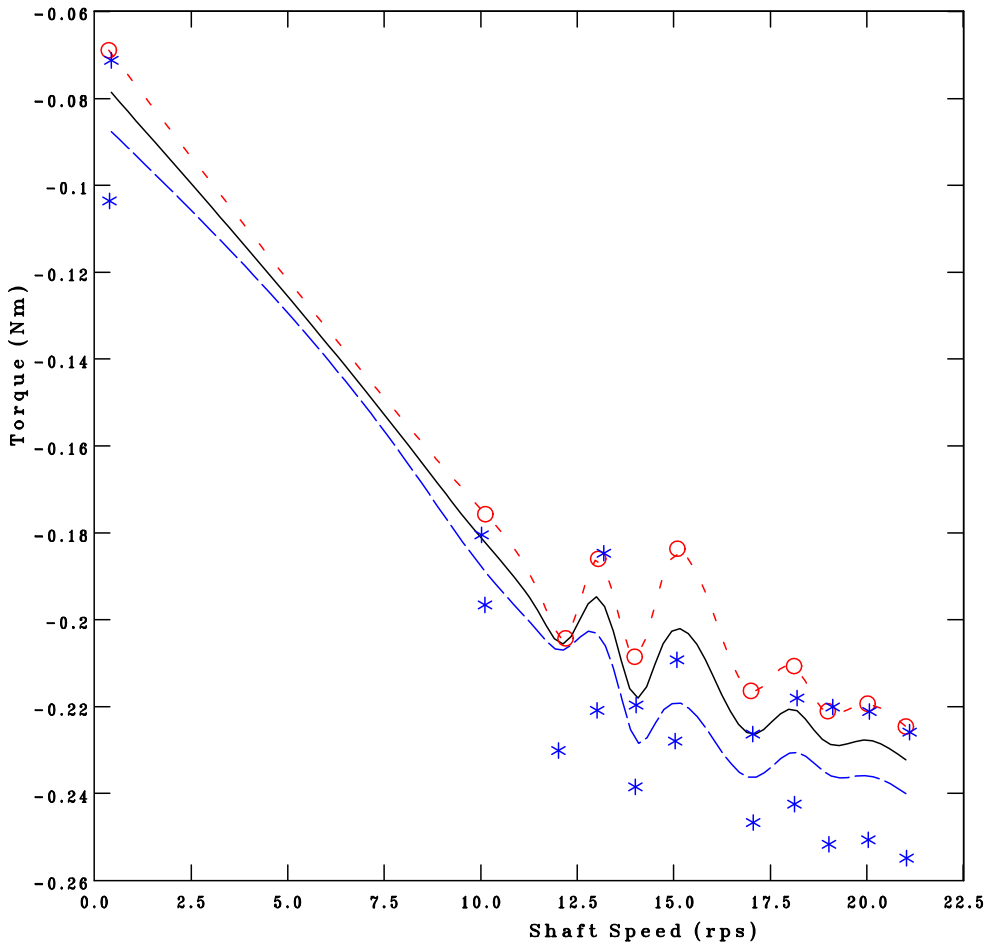


Figure 6: Measured Thrust of Faired Strut and Nozzle Mount

Shaft Friction Analysis (Opens)			
Propeller:	P321R	Test Date:	11-Feb-2010
Description:	Kaplan BAR 0.70	Analysis Date:	26-Feb-2010
Condition:	Used with Nozzle 19A and 6 arm stator	Project Number:	2412
Rotation:	Right		
Tank:	Towing Tank		



○	Initial friction data	*	Final friction data
- - -	Initial friction curve	- - -	Final friction curve
—	Average friction curve		


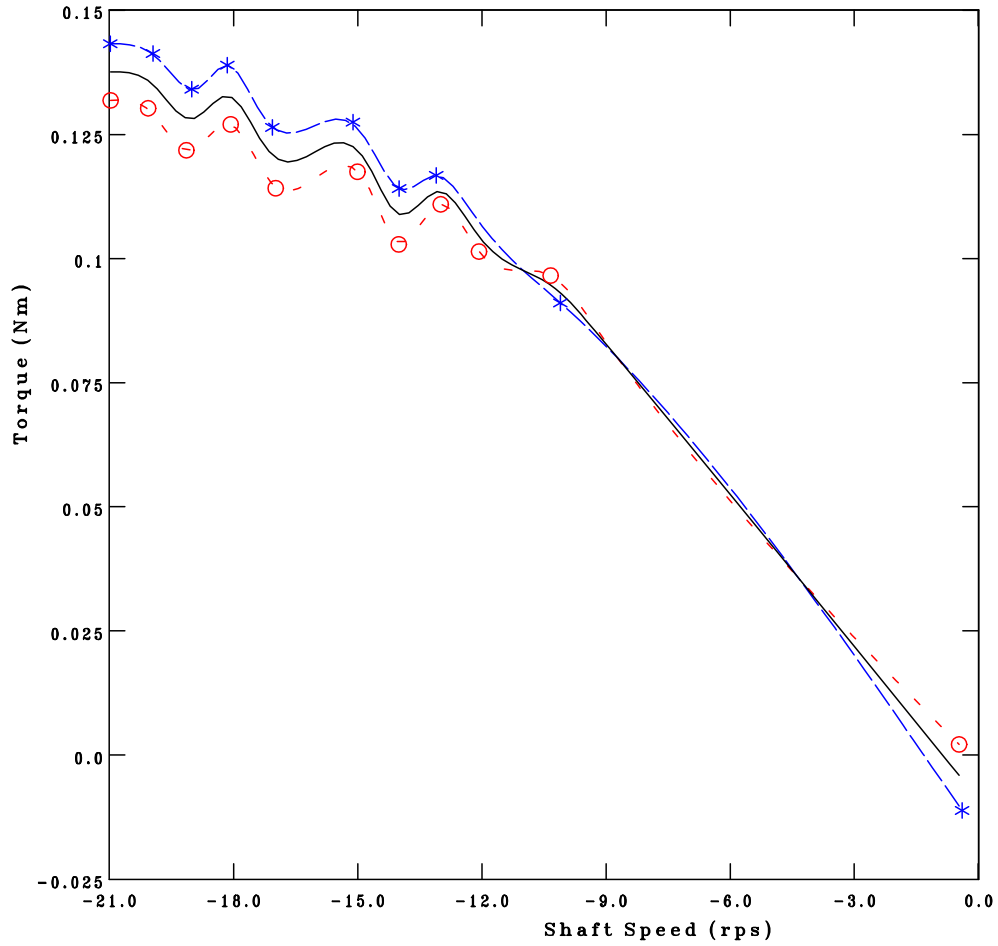
 National Research Council Canada
Institute for Ocean Technology

Figure 7: Shaft Friction For 321R Test

Shaft Friction Analysis (Opens)		
Propeller:	P321L	Test Date: 11-Feb-2010
Description:	Kaplan BAR 0.70	Analysis Date: 26-Feb-2010
Condition:	Used with Nozzle 19A and 6 arm stator	Project Number: 2412
Rotation:	Left	
Tank:	Towing Tank	



○	Initial friction data	*	Final friction data
- - -	Initial friction curve	- - -	Final friction curve
—	Average friction curve		

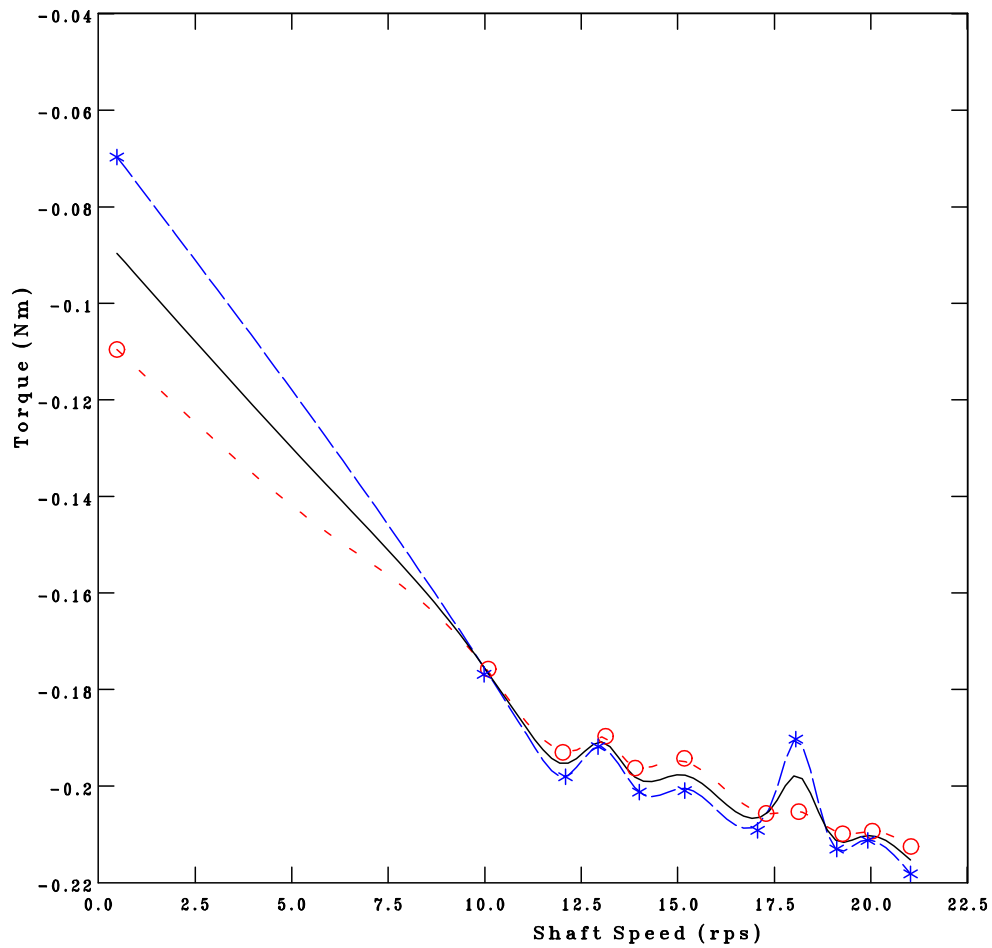
	<p>National Research Council Canada Institute for Ocean Technology</p>
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Figure 8: Shaft Friction For 321L Test

Shaft Friction Analysis (Opens)

Propeller: P321R
Description: Kaplan BAR 0.70
Condition: Used with Nozzle 19A
Rotation: Right
Tank: Towing Tank

Test Date: 12-Feb-2010
Analysis Date: 26-Feb-2010
Project Number: 2412



○ Initial friction data * Final friction data
- - - Initial friction curve - - - Final friction curve
— Average friction curve

 National Research Council Canada
Institute for Ocean Technology

Figure 9: Shaft Friction For 321R Test Without Stator

APPENDIX A
Description of IOT Towing Tank

IOT Towing Tank

Description: rectangular tank 200m (656 ft) in length, 12m (39 ft) in width and 7m (23 ft) in depth, models are towed through still water or waves by a carriage spanning the width of the tank, model rigging is facilitated by two trim docks and a moveable overhead crane (4000 kg).

Carriage: single manned carriage with 8 wheel synchronous motor drive, test frame adjustable for model size, 80,000 kg mass, 746 kW power, speed range .001 m/s - 10.0 m/s, manual service carriage for wind and current generation.

Wave Generator: dual flap hydraulic wave board with digital computer control, regular or irregular waves program controlled, maximum wave height 1m (regular) or 0.5m significant (irregular).

Wave Absorber: parabolic corrugated surface beach with transverse slats, 20m long with 10.5 slope at water line, flexible side absorbers.

Current Generation: maximum surface current speed 0.3 m/s @ 10m from nozzles.

Wind Generation: 12 fan bank with gusting capability, maximum wind speed 12 m/s @ 10m from fans.

Model Size Range: ships models up to 12m in length, floating structures 0.5m - 4m diameter.

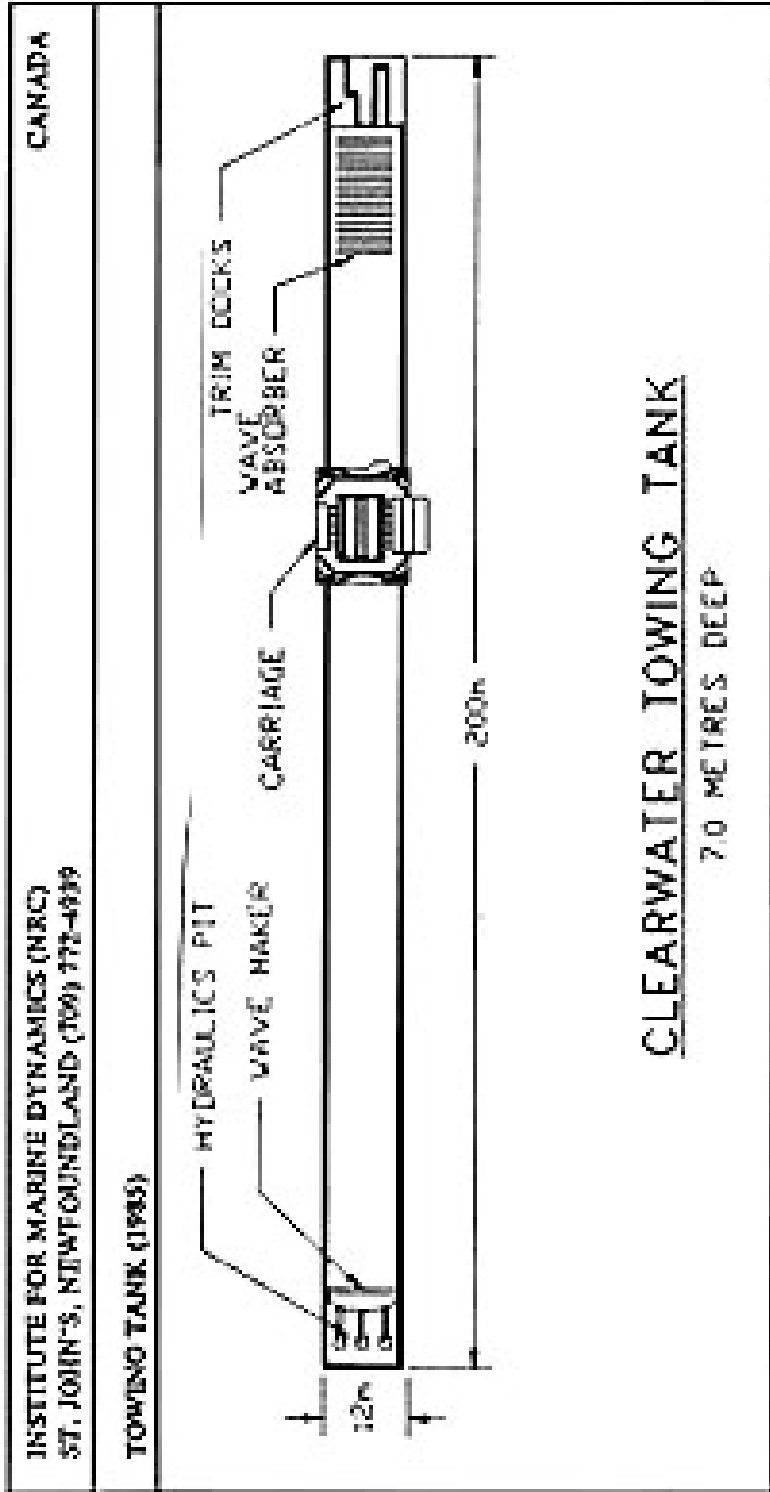
Instrumentation: force measurement, strain gauge load cells, capacitance and sonic wave probes, model position, Qualisys optical tracking, accelerometer arrays and motions package for model motions, propeller characteristics, open water propeller dynamometer, propulsion and control system for free-running models, under and above water video, transient recorders, and flow measurement.

Data Acquisition: A VMS and Windows NT based distributed client/server system using one or more IOtech DaqBoards, each with 256 channel capability at 100kHz aggregate.

Tests Performed:

- (1) resistance and propulsion
- (2) wake survey
- (3) flow visualization
- (4) propeller open water
- (5) seakeeping
- (6) floating and moored structures
- (7) loads due to wind and current
- (8) lift and drag
- (9) dynamics of underwater vehicles

INTERNATIONAL TOWING TANK CONFERENCE CATALOGUE OF FACILITIES
TOWING TANKS, SEAKEEPING AND MANOEUVRING BASINS

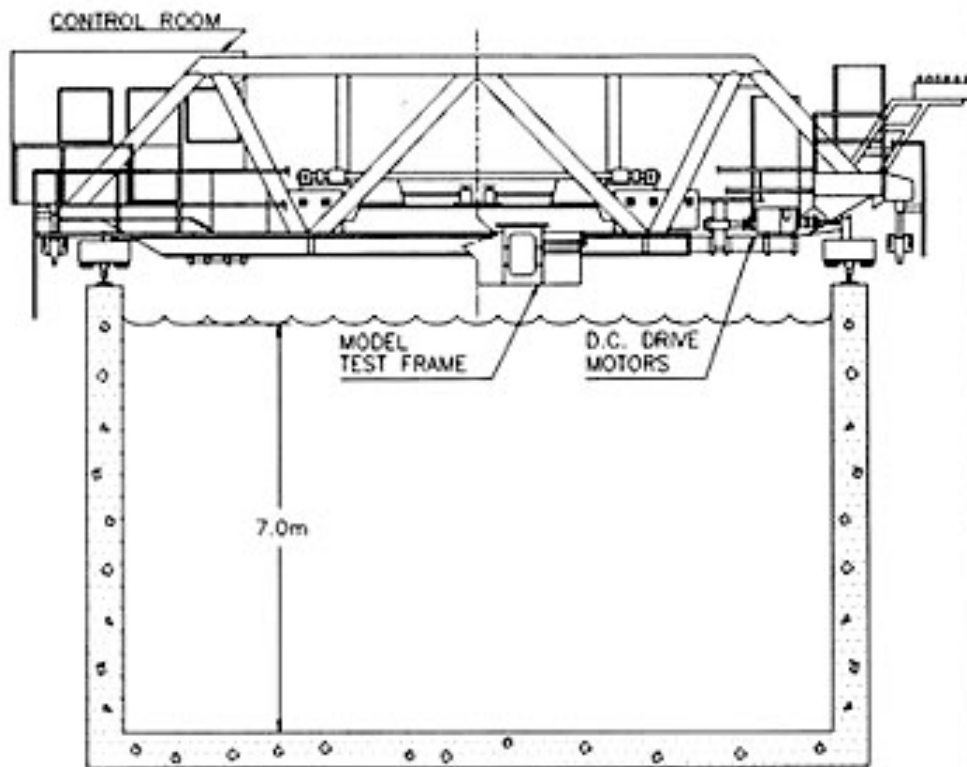


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CANADA

TOWING TANK (1985)



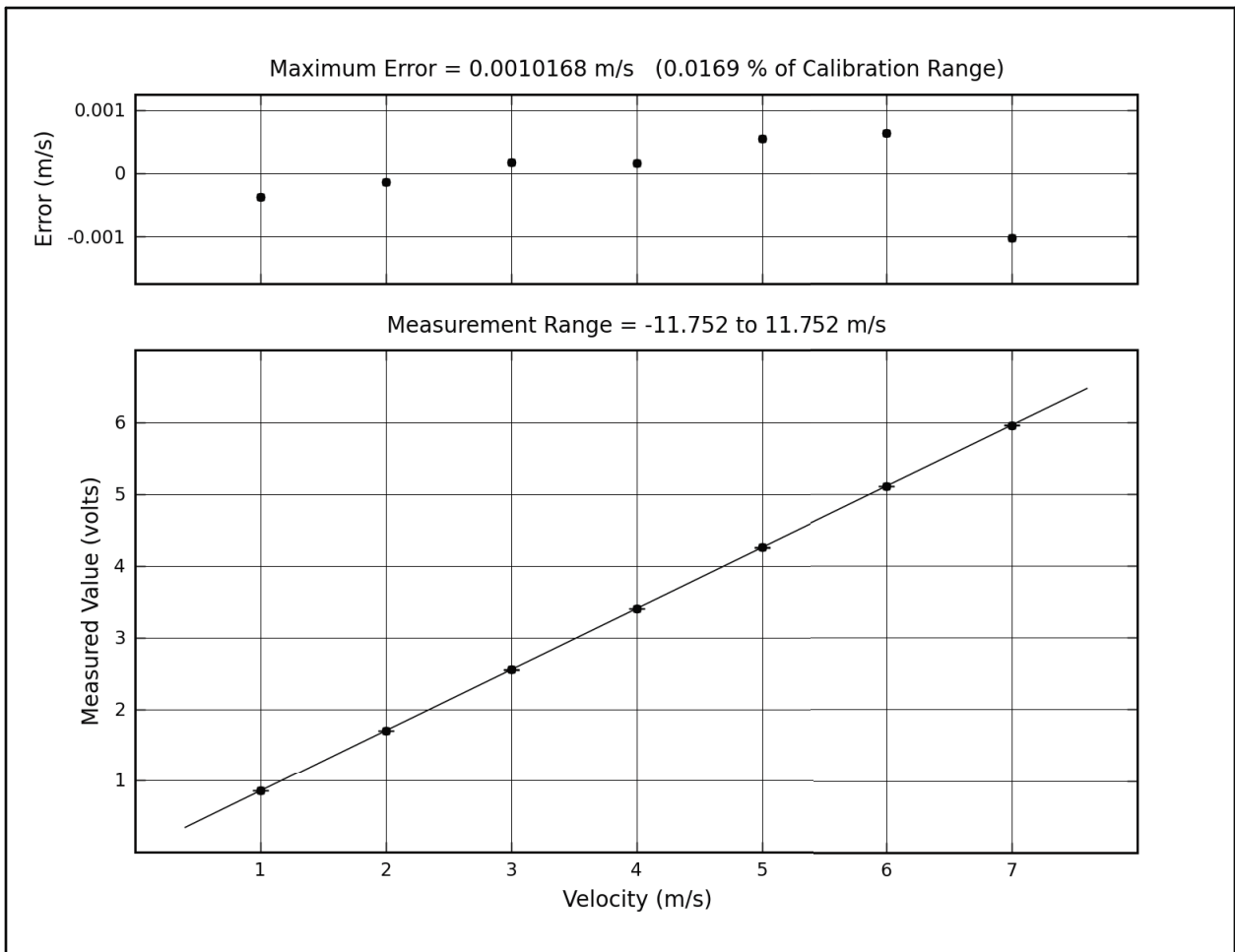
ELEVATION VIEW OF TOWING TANK
AND CARRIAGE

APPENDIX B
Instrumentation Calibration Results

**GGC 25m Inshore Science Vessel
Calibration of Tachogenerator
Calibrated 2009-05-15 15:24**

Test Facility: CWT	Serial #:	Filter Frequency: 10
Data Source: TOWDAS Channel 1	Programmable Gain:	Excitation Voltage: 10v
Sensor Model:	Plug-In Gain:	

Data Point #	Physical Value (m/s)	Measured Value (volts)	Fitted Curve Value (m/s)	Error (m/s)	Definition of Calibration Curve Polynomial Degree = 1 (Linear Fit) $Y = C_0 + C_1 \cdot V$ where $Y(t)$ = Velocity (m/s), $V(t)$ = measured value (volts), $C_0 = -0.00030294$ m/s, $C_1 = 1.1752$ m/s/volt.
1	1.0000	0.85085	0.99962	-0.00037991	
2	2.0000	1.7020	1.9999	-0.00013115	
3	3.0000	2.5532	3.0002	0.00017644	
4	4.0000	3.4041	4.0002	0.00016476	
5	5.0000	4.2553	5.0006	0.00055151	
6	6.0000	5.1063	6.0006	0.00063622	
7	7.0000	5.9558	6.9990	-0.0010168	

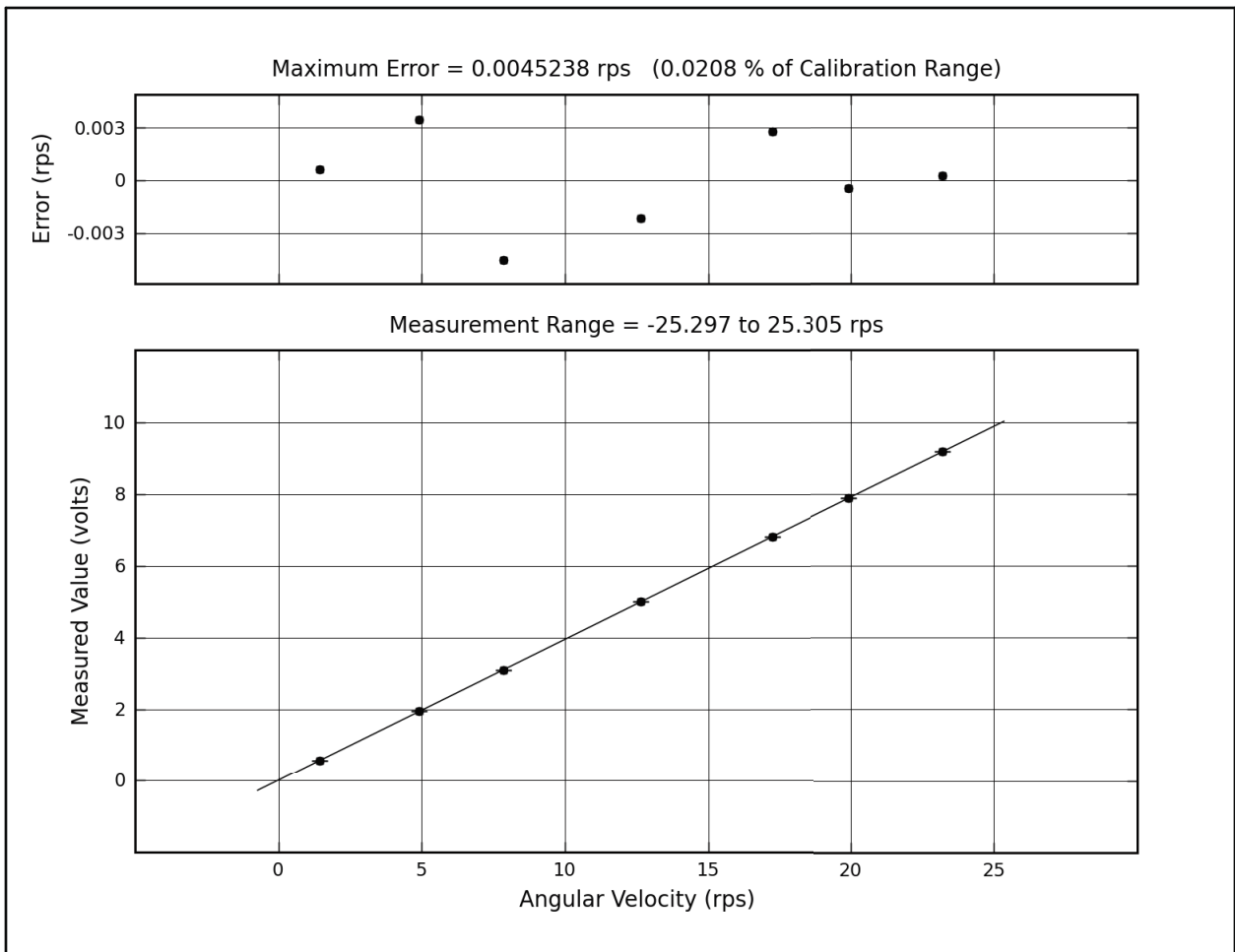


**GGC 25m Inshore Science Vessel
Calibration of Shaft Speed
Calibrated 2010-02-10 15:04**

Test Facility: CWT	Serial #:	Filter Frequency: 10
Data Source: TOWDAS Channel 4	Programmable Gain: 2	Excitation Voltage: 10v
Sensor Model: K&R H-39 Opensboat	Plug-In Gain:	

Data Point #	Physical Value (rps)	Measured Value (volts)	Fitted Curve Value (rps)	Error (rps)	Definition of Calibration Curve
1	1.4500	0.57176	1.4506	0.00063899	
2	4.9100	1.9404	4.9135	0.0034673	
3	7.8500	3.0993	7.8455	-0.0045238	
4	12.645	4.9954	12.643	-0.0021740	
5	17.230	6.8096	17.233	0.0027799	
6	19.940	7.8795	19.940	-0.00045825	
7	23.200	9.1683	23.200	0.00026751	

Polynomial Degree = 1 (Linear Fit)
 $Y = C_0 + C_1 \cdot V$
 where $Y(t)$ = Angular Velocity (rps),
 $V(t)$ = measured value (volts),
 $C_0 = 0.0040535$ rps,
 $C_1 = 2.5301$ rps/volt.

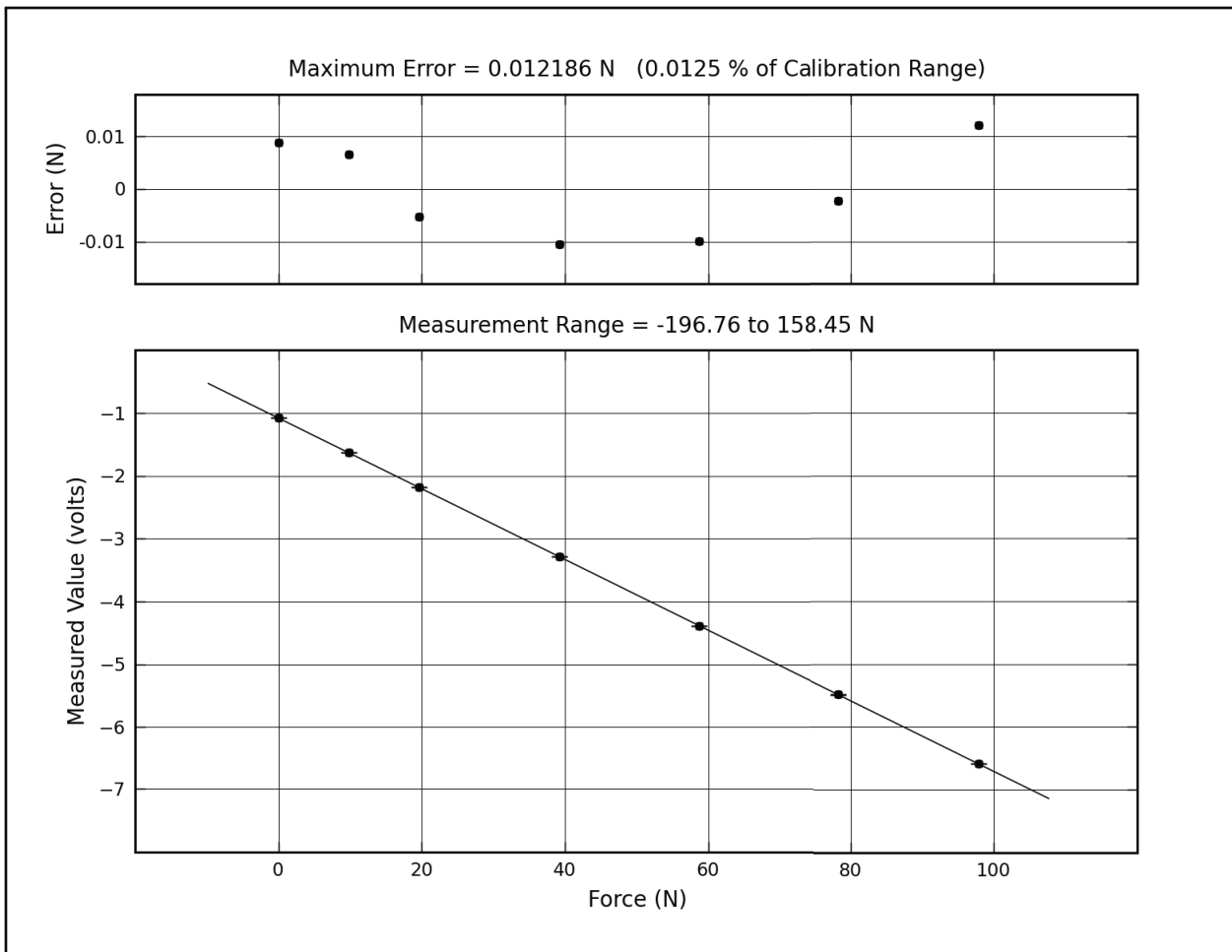


**GGC 25m Inshore Science Vessel
Calibration of Duct Force
Calibrated 2010-02-09 09:44**

Test Facility: CWT	Serial #:	Filter Frequency: 10
Data Source: TOWDAS Channel 13	Programmable Gain: 2	Excitation Voltage: 6v
Sensor Model: KSR R35 1-Component Balance	Plug-In Gain: 500	

Data Point #	Physical Value (N)	Measured Value (volts)	Fitted Curve Value (N)	Error (N)	Definition of Calibration Curve
1	0.00000	-1.0789	0.0088084	0.0088084	
2	9.8080	-1.6311	9.8146	0.0066242	
3	19.620	-2.1829	19.615	-0.0051934	
4	39.176	-3.2837	39.166	-0.010408	
5	58.704	-4.3833	58.694	-0.0098429	
6	78.265	-5.4851	78.263	-0.0021833	
7	97.839	-6.5880	97.851	0.012186	

Polynomial Degree = 1 (Linear Fit)
 $Y = C_0 + C_1 \cdot V$
 where $Y(t)$ = Force (N),
 $V(t)$ = measured value (volts),
 $C_0 = -19.154$ N,
 $C_1 = -17.76$ N/volt.

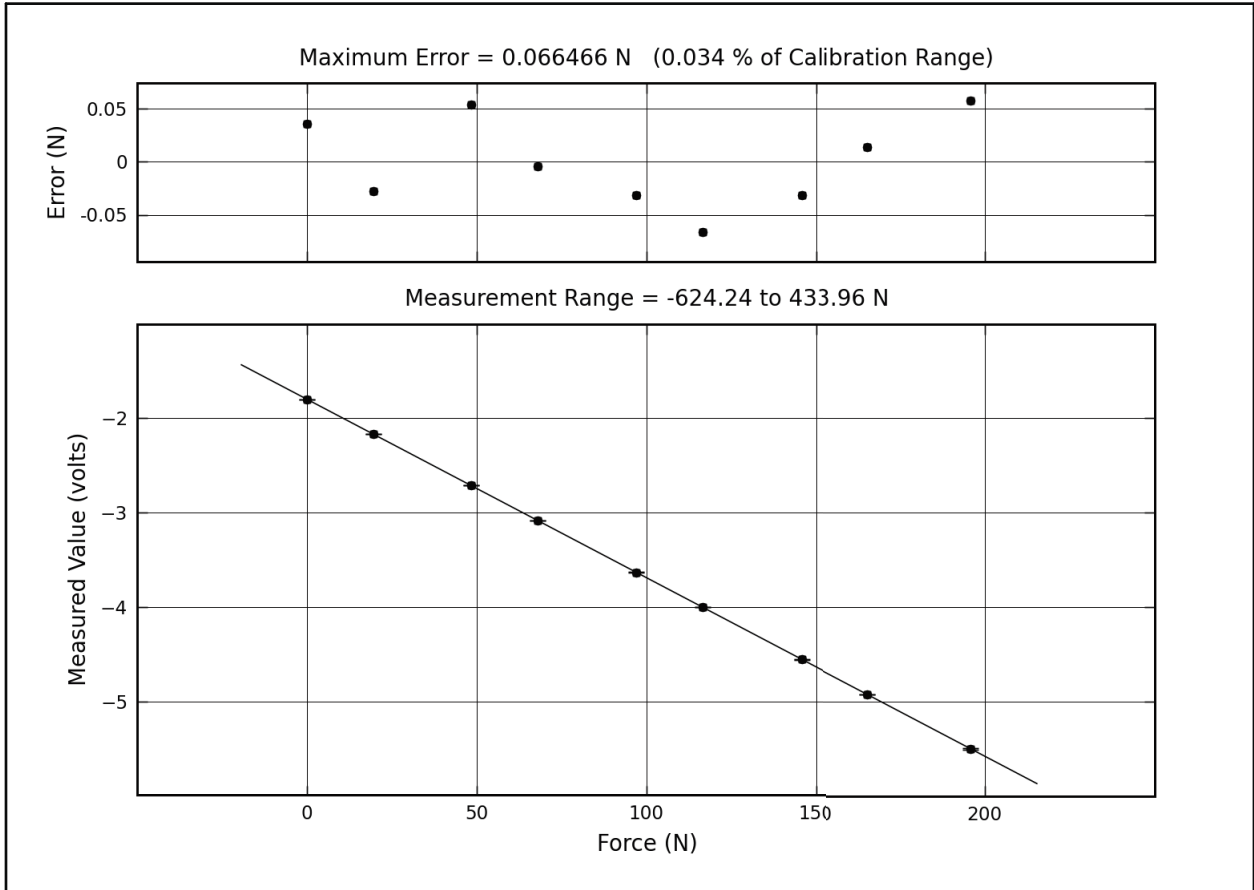


**GGC 25m Inshore Science Vessel
Calibration of Opens Thrust
Calibrated 2010-02-08 14:39**

Test Facility: CWT	Serial #:	Filter Frequency: 10
Data Source: TOWDAS Channel 14	Programmable Gain: 4	Excitation Voltage: 6v
Sensor Model: K&R H-39 Opensboat	Plug-In Gain: 500	

Data Point #	Physical Value (N)	Measured Value (volts)	Fitted Curve Value (N)	Error (N)	Definition of Calibration Curve
1	0.00000	-1.7988	0.035961	0.035961	
2	19.594	-2.1679	19.566	-0.027999	
3	48.312	-2.7122	48.366	0.053997	
4	67.907	-3.0815	67.903	-0.0039209	
5	96.966	-3.6302	96.934	-0.031728	
6	116.56	-3.9999	116.49	-0.066466	
7	145.80	-4.5532	145.77	-0.031564	
8	165.40	-4.9244	165.41	0.013609	
9	195.68	-5.4975	195.73	0.058054	

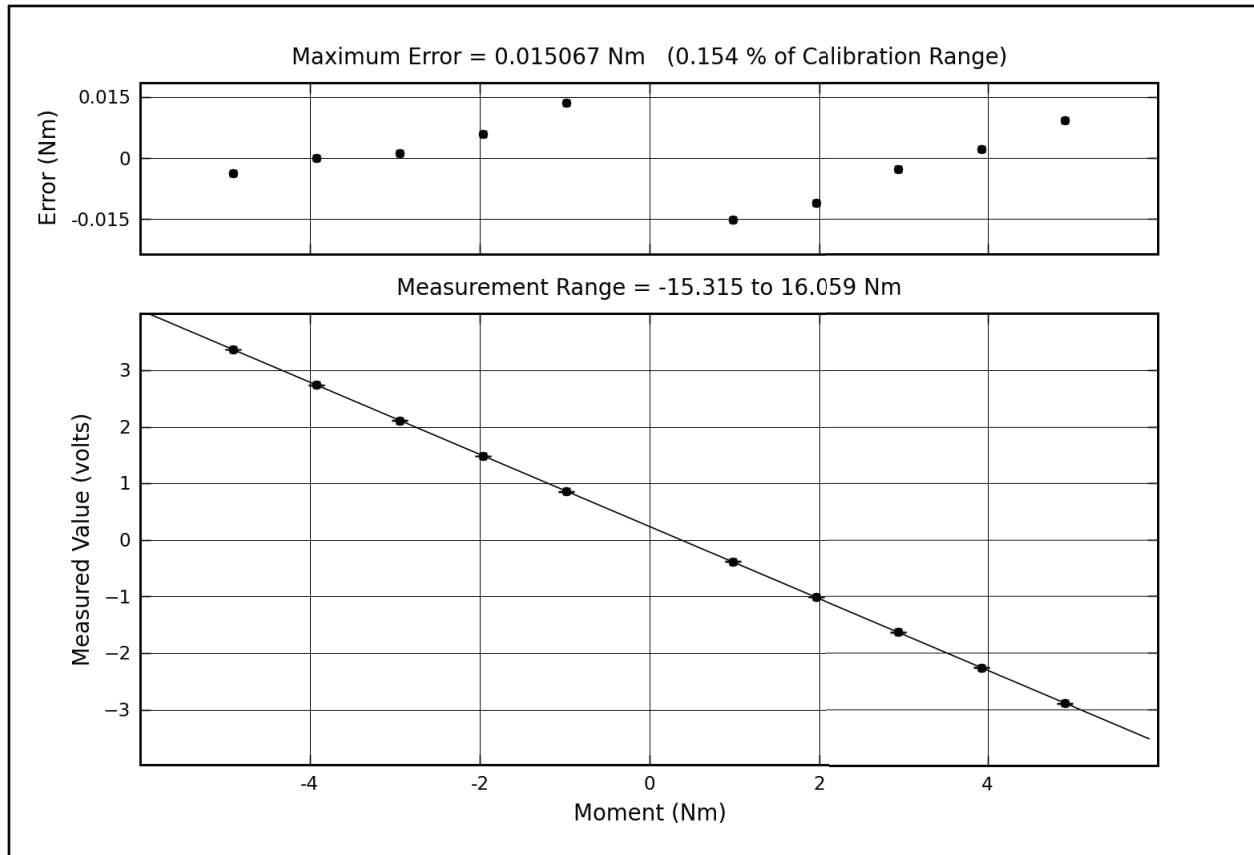
Polynomial Degree = 1 (Linear Fit)
 $Y = C_0 + C_1 \cdot V$
 where $Y(t)$ = Force (N),
 $V(t)$ = measured value (volts),
 $C_0 = -95.138$ N,
 $C_1 = -52.91$ N/volt.



**GGC 25m Inshore Science Vessel
Calibration of Opens Torque
Calibrated 2010-02-08 15:23**

Test Facility: CWT	Serial #:	Filter Frequency: 10
Data Source: TOWDAS Channel 15	Programmable Gain: 4	Excitation Voltage: 6v
Sensor Model: K&R H-39 Opensboat	Plug-In Gain: 500	

Data Point #	Physical Value (Nm)	Measured Value (volts)	Fitted Curve Value (Nm)	Error (Nm)	Definition of Calibration Curve
1	-4.9040	3.3658	-4.9077	-0.0036942	
2	-3.9232	2.7382	-3.9232	-2.8200e-005	
3	-2.9424	2.1121	-2.9411	0.0013283	
4	-1.9616	1.4839	-1.9557	0.0059142	
5	-0.98080	0.85373	-0.96709	0.013714	
6	0.98080	-0.37842	0.96573	-0.015067	
7	1.9616	-1.0062	1.9506	-0.011027	
8	2.9424	-1.6368	2.9397	-0.0026760	
9	3.9232	-2.2652	3.9255	0.0022786	
10	4.9040	-2.8949	4.9133	0.0092563	



APPENDIX C
Test Program

321 Propellers Opens Test Matrix

$c_{0.7}$ = 0.0556 m
 D = 0.1524 m
 Nu_M = 1.10E-06
 n = **14 rps** **19 rps**
 $Rnco$ = 2.36E+05 3.21E+05

Jo	V_A [m/s]	
0.001	0.002	0.003
0.075	0.160	0.217
0.15	0.320	0.434
0.225	0.480	0.652
0.3	0.640	0.869
0.375	0.800	1.086
0.45	0.960	1.303
0.525	1.120	1.520
0.6	1.280	1.737
0.675	1.440	1.955
0.75	1.600	2.172
0.825	1.760	2.389
0.9	1.920	2.606
0.975	2.080	2.823
1.05	2.240	3.040
1.125	2.400	3.258
1.2	2.560	3.475

321 Propellers Opens Test Plan

Set 1- Thrust of faired strut + nozzle mount		
	Shaft Speed rps	Carriage Speed m/s
roughup	0	1.900
run 2	0	0.152
	0	0.735
	0	1.317
	0	1.900
run 3	0	2.483
	0	3.066
run 4	0	3.648
	0	0.346
run 5	0	0.540
	0	0.735
	0	1.026
	0	1.609

Set 2- P321R		
	Shaft Speed rps	Carriage Speed m/s
friction test	10	0.000
	13	
	14	
	15	
	17	
	18	
	19	
run 1	14	20
		21
		0.160
		0.480
		0.800
run 2	14	1.120
		1.440
run 3	14	1.760
		2.080
run 4	14	2.400
		2.240
run 5	19	2.560
		0.320
		0.640
		0.960
		1.280
run 6	19	1.600
		1.920
		0.217
run 7	19	0.652
		1.086
run 8	19	1.520
		1.955
run 9	19	2.389
		2.823
run 10	19	3.258
		3.475
friction test	10	0.000
	13	
	14	
	15	
	17	
	18	
	19	
20		
21		

321 Propellers Opens Test Plan

Set 3- P321L		
	Shaft Speed rps	Carriage Speed m/s
friction test	10	0.000
	13	
	14	
	15	
	17	
	18	
	19	
run 1	14	0.160
		0.480
		0.800
		1.120
		1.440
		1.760
run 2	14	2.080
		2.400
run 3	14	2.240
		2.560
run 4	14	0.320
		0.640
		0.960
		1.280
		1.600
		1.920
run 5	19	0.217
		0.652
		1.086
		1.520
		1.955
run 6	19	2.389
		2.823
run 7	19	3.258
run 8	19	3.475
run 9	19	2.606
		3.040
run 10	19	0.434
		0.869
		1.303
		1.737
		2.172
friction test	10	0.000
	13	
	14	
	15	
	17	
	18	
	19	

Set 4- P321R without stator		
	Shaft Speed rps	Carriage Speed m/s
friction test	10	0.000
	13	
	14	
	15	
	17	
	18	
	19	
run 1	14	0.160
		0.480
		0.800
		1.120
		1.440
		1.760
run 2	14	2.080
		2.400
run 3	14	2.240
		2.560
run 4	14	0.320
		0.640
		0.960
		1.280
		1.600
		1.920
run 5	19	0.217
		0.652
		1.086
		1.520
		1.955
run 6	19	2.389
		2.823
run 7	19	3.258
run 8	19	3.475
run 9	19	2.606
		3.040
run 10	19	0.434
		0.869
		1.303
		1.737
		2.172
friction test	10	0.000
	13	
	14	
	15	
	17	
	18	
	19	

APPENDIX D
Test Log

DATE	TIME	WAIT TIME ACTUAL	Speed (m/s)	FILENAME(.DAC)	RUN DESCRIPTION	COMMENTS
08-Feb-10						Setup and install opens boat. Calibrate Torque and Thrust. Assemble opens boat.
09-Feb-10						Complete install. Calibrate single component balance. Align opens boat.
10-Feb-10	10:33		0.00	friction_CW_001	Fiction test	Friction test rotating clockwise (for STBD prop)
"						Install single component balance and nozzle
"	15:10			321R_14rps_001	Propeller opens test	

11-Feb-10						Puck is not on strut for this set of runs
"	8:18	0:08	1.90	strut_res_001		Roughup run, temperature @ 16.19 degrees
"	8:26	0:08	0.152, 0.735, 1.317, 1.900	strut_res_002		
"	8:34	0:07	2.483, 3.066	strut_res_003		
"	8:41	#####	3.648	strut_res_004		
"						Install puck on strut and repeat strut res runs
"	9:06	0:10	0.152, 0.735, 1.317, 1.900	strut_res_005		No tare segment
"	9:16	0:08	0.152, 0.735, 1.317, 1.900	strut_res_006		Repeat of strut_res_005
"	9:24	0:08	2.483, 3.066	strut_res_007		
"	9:32	0:11	3.648	strut_res_008		
"	9:43	0:16	0.346, .54, .735, 1.026, 1.609	strut_res_009		
"	9:59	0:17		Friction_CW_002		Acquisition timed out
"	10:16	1:03		Friction_CW_003		
"						Remove friction hub. Install propeller with nozzle. Kaplan 321R propeller
"	11:19	0:08	0.16, 0.48, 0.8, 1.12, 1.44, 1.76	321R_14rps_002		
"	11:27	0:08	2.08, 2.4	321R_14rps_003		
"	11:35	0:06	2.24, 2.56	321R_14rps_004		
"	11:41	0:13	0.32, 0.64,, 0.96, 1.28, 1.6, 1.92	321R_14rps_005		
"	11:54	0:09	0.217, 0.652, 1.086, 1.520, 1.955	321R_19rps_001		
"	12:03	0:08	2.389, 2.823	321R_19rps_002		
"	12:11	0:07	3.258	321R_19rps_003		
"	12:18	0:07	3.475	321R_19rps_004		
"	12:25	0:07	2.606, 3.040	321R_19rps_005		
"	12:32	0:40	0.434, 0.869, 1.303, 1.737, 2.172	321R_19rps_006		
"						Remove propeller and nozzle. Install friction hub
"	13:12			Friction_CW_004		
"						Warmup shaft in the CCW direction
"	14:04			Friction_CCW_001		
"						Install 321L propller and nozzle.
"	14:46	0:09	0.16, 0.48, 0.8, 1.12, 1.44, 1.76	321L_14rps_001		
"	14:55	0:07	2.08, 2.4	321L_14rps_002		
"	15:02	0:08	2.24, 2.56	321L_14rps_003		
"	15:10	0:09	0.32, 0.64,, 0.96, 1.28, 1.6, 1.92	321L_14rps_004		
"	15:19	0:08	0.217, 0.652, 1.086, 1.520, 1.955	321L_19rps_001		
"	15:27	0:07	2.389, 2.823	321L_19rps_002		
"	15:34	0:07	3.258	321L_19rps_003		
"	15:41	0:06	3.475	321L_19rps_004		
"	15:47	0:07	2.606, 3.040	321L_19rps_005		
"	15:54	0:26	0.434, 0.869, 1.303, 1.737, 2.172	321L_19rps_006		
"		16:20				Remove propellor and install friction hub

DATE	TIME	WAIT TIME ACTUAL	Speed (m/s)	FILENAME(.DAC)	RUN DESCRIPTION	COMMENTS
"	16:20			Friction_CW_002		

12-Feb-10						Remove stator from nozzle. Run in shaft CW
"	9:18			Friction_CW_005	Friction test clockwise direction	
"						Install propeller 321R w/o stator
"	10:00	0:08	0.16, 0.48, 0.8, 1.12, 1.44, 1.76	321R_NS_14rps_001	Propeller opens 321R w/o stator	water temp 16.23 deg
"	10:08	0:07	2.08, 2.4	321R_NS_14rps_002	Propeller opens 321R w/o stator	
"	10:15	0:08	2.24, 2.56	321R_NS_14rps_003	Propeller opens 321R w/o stator	
"	10:23	0:10	0.32, 0.64., 0.96, 1.28, 1.6, 1.92	321R_NS_14rps_004	Propeller opens 321R w/o stator	
"	10:33	0:09	0.217, 0.652, 1.086, 1.520, 1.955	321R_NS_19rps_001	Propeller opens 321R w/o stator	
"	10:42	0:07	2.389, 2.823	321R_NS_19rps_002	Propeller opens 321R w/o stator	
"	10:49	0:07	3.258	321R_NS_19rps_003	Propeller opens 321R w/o stator	
"	10:56	0:07	3.475	321R_NS_19rps_004	Propeller opens 321R w/o stator	
"	11:03	0:07	2.606, 3.040	321R_NS_19rps_005	Propeller opens 321R w/o stator	
"	11:10	0:18	0.434, 0.869, 1.303, 1.737, 2.172	321R_NS_19rps_006	Propeller opens 321R w/o stator	
"						Install friction hub
"	11:28			Friction_CW_006	Friction test clockwise direction	
						remove friction hub and propeller nozzle. Decommission setup

APPENDIX E
Results

321L used with nozzle 19A and 6arm stator

Temperature 16.2 degC

Rho= 998.650 kg/m³Nu= 1.10E-06 m²/s

Carriage Speed m/s	Shaft Speed rps	Shaft Thrust N	Duct Thrust N	Total Thrust N	Torque Nm	Jo	KTo	KTD0	KTo+KTD0	10KQo	EtaO	RncO
0.000	13.99	35.24	31.29	66.53	1.067	0.0000	0.3340	0.2966	0.6306	0.6636	0.0000	2.36E+05
0.000	14.00	35.50	31.71	67.21	1.070	0.0000	0.3364	0.3005	0.6369	0.6656	0.0000	2.36E+05
0.000	13.99	35.30	31.38	66.68	1.052	0.0000	0.3346	0.2974	0.6321	0.6545	0.0000	2.36E+05
0.000	14.00	35.44	31.57	67.01	1.072	0.0000	0.3358	0.2992	0.6350	0.6667	0.0001	2.36E+05
0.159	14.00	34.53	27.25	61.78	1.040	0.0744	0.3272	0.2581	0.5853	0.6465	0.1071	2.36E+05
0.319	14.00	33.93	22.60	56.53	1.027	0.1493	0.3215	0.2142	0.5357	0.6386	0.1994	2.37E+05
0.479	14.00	33.13	18.62	51.74	1.004	0.2244	0.3138	0.1764	0.4902	0.6243	0.2805	2.38E+05
0.638	14.00	31.95	14.87	46.83	0.978	0.2993	0.3028	0.1409	0.4437	0.6081	0.3476	2.38E+05
0.799	14.00	30.66	11.79	42.44	0.946	0.3744	0.2904	0.1117	0.4021	0.5881	0.4073	2.40E+05
0.959	14.00	28.88	9.05	37.94	0.907	0.4495	0.2737	0.0858	0.3595	0.5638	0.4561	2.41E+05
1.119	14.00	26.74	6.49	33.23	0.854	0.5245	0.2533	0.0615	0.3148	0.5311	0.4948	2.43E+05
1.280	14.00	24.25	3.98	28.24	0.796	0.5999	0.2298	0.0378	0.2676	0.4951	0.5160	2.45E+05
1.439	14.00	21.51	1.41	22.91	0.729	0.6747	0.2037	0.0133	0.2171	0.4534	0.5141	2.47E+05
1.599	14.00	18.27	-1.39	16.88	0.652	0.7497	0.1731	-0.0132	0.1599	0.4052	0.4709	2.50E+05
1.759	14.00	14.57	-4.52	10.05	0.563	0.8246	0.1380	-0.0429	0.0952	0.3498	0.3570	2.52E+05
1.919	14.00	10.10	-7.89	2.21	0.454	0.8997	0.0957	-0.0748	0.0210	0.2823	0.1063	2.55E+05
2.080	13.99	4.55	-11.78	-7.23	0.316	0.9751	0.0431	-0.1117	-0.0686	0.1965	-0.5414	2.58E+05
2.239	13.99	-1.21	-15.35	-16.56	0.161	1.0500	-0.0114	-0.1455	-0.1569	0.1004		2.62E+05
2.399	13.99	-6.61	-18.33	-24.95	0.036	1.1251	-0.0627	-0.1738	-0.2365	0.0222		2.65E+05
2.560	13.99	-12.83	-22.12	-34.95	-0.131	1.2002	-0.1216	-0.2096	-0.3312	-0.0816		2.69E+05
0.000	18.99	65.45	58.78	124.23	1.955	0.0000	0.3370	0.3027	0.6397	0.6605	0.0000	3.20E+05
0.000	18.99	65.42	58.65	124.07	1.952	0.0000	0.3368	0.3019	0.6387	0.6592	0.0000	3.21E+05
0.000	18.99	65.04	58.48	123.52	1.941	0.0000	0.3349	0.3012	0.6361	0.6559	0.0000	3.20E+05
0.000	18.99	65.34	58.54	123.88	1.945	0.0000	0.3364	0.3014	0.6378	0.6571	0.0000	3.21E+05
0.000	18.99	65.39	58.55	123.94	1.949	0.0000	0.3367	0.3015	0.6382	0.6586	0.0000	3.20E+05
0.000	18.99	65.88	58.80	124.69	1.958	0.0000	0.3391	0.3026	0.6417	0.6613	0.0000	3.21E+05
0.216	18.99	63.87	50.47	114.34	1.897	0.0745	0.3287	0.2597	0.5884	0.6406	0.1090	3.21E+05
0.433	18.99	62.77	42.27	105.04	1.873	0.1495	0.3231	0.2176	0.5407	0.6326	0.2034	3.21E+05
0.651	18.99	61.29	34.79	96.08	1.830	0.2247	0.3154	0.1790	0.4944	0.6179	0.2862	3.22E+05
0.868	18.99	59.31	28.38	87.69	1.787	0.2999	0.3053	0.1461	0.4514	0.6035	0.3570	3.24E+05
1.085	18.99	56.66	22.34	79.00	1.722	0.3749	0.2916	0.1150	0.4066	0.5813	0.4173	3.25E+05
1.302	18.99	53.55	17.04	70.59	1.658	0.4499	0.2756	0.0877	0.3633	0.5601	0.4646	3.27E+05
1.519	18.99	49.59	11.95	61.54	1.556	0.5249	0.2552	0.0615	0.3167	0.5255	0.5035	3.30E+05
1.736	18.99	45.46	7.77	53.23	1.468	0.5999	0.2340	0.0400	0.2740	0.4958	0.5276	3.32E+05
1.954	18.99	40.12	2.96	43.08	1.329	0.6752	0.2065	0.0152	0.2217	0.4487	0.5308	3.35E+05
2.172	18.99	34.55	-1.87	32.68	1.207	0.7503	0.1778	-0.0096	0.1682	0.4077	0.4925	3.39E+05
2.389	18.99	26.91	-7.99	18.92	1.012	0.8254	0.1386	-0.0411	0.0974	0.3418	0.3745	3.42E+05
2.606	18.99	19.70	-13.58	6.12	0.828	0.9006	0.1014	-0.0699	0.0315	0.2796	0.1614	3.46E+05
2.823	18.99	10.45	-19.57	-9.12	0.604	0.9756	0.0538	-0.1008	-0.0470	0.2040	-0.3574	3.51E+05
3.040	18.99	1.32	-26.97	-25.66	0.371	1.0503	0.0068	-0.1389	-0.1321	0.1252		3.55E+05
3.258	18.99	-10.57	-31.99	-42.56	0.074	1.1259	-0.0544	-0.1647	-0.2191	0.0248		3.60E+05
3.475	18.99	-21.50	-38.31	-59.81	-0.204	1.2009	-0.1107	-0.1972	-0.3079	-0.0689		3.65E+05

321R used with nozzle 19A and 6arm stator

Temperature 16.2 degC

Rho= 998.650 kg/m³Nu= 1.10E-06 m²/s

Carriage Speed m/s	Shaft Speed rps	Shaft Thrust N	Duct Thrust N	Total Thrust N	Torque Nm	Jo	K _{TO}	K _{TDO}	K _{TO} +K _{TDO}	10K _{QO}	EtaO	RncO
0.000	14.00	35.30	31.65	66.95	1.030	0.0000	0.3346	0.3000	0.6345	0.6408	0.0000	2.36E+05
0.000	13.99	35.26	31.50	66.75	1.030	0.0000	0.3341	0.2985	0.6327	0.6407	0.0000	2.36E+05
0.000	13.99	35.05	31.17	66.21	1.029	0.0000	0.3322	0.2954	0.6275	0.6401	0.0000	2.36E+05
0.000	14.00	35.32	31.33	66.65	1.040	0.0000	0.3347	0.2969	0.6316	0.6468	0.0001	2.36E+05
0.158	14.00	34.45	27.23	61.69	0.999	0.0742	0.3265	0.2581	0.5846	0.6210	0.1112	2.36E+05
0.318	14.00	33.82	22.54	56.36	0.981	0.1493	0.3205	0.2136	0.5341	0.6101	0.2081	2.37E+05
0.479	14.00	33.10	18.74	51.84	0.955	0.2244	0.3137	0.1776	0.4912	0.5939	0.2954	2.37E+05
0.639	14.00	31.87	14.85	46.71	0.945	0.2994	0.3020	0.1407	0.4427	0.5878	0.3588	2.38E+05
0.799	14.00	30.60	11.96	42.56	0.909	0.3744	0.2900	0.1134	0.4034	0.5651	0.4254	2.40E+05
0.959	14.00	28.73	9.00	37.72	0.875	0.4495	0.2722	0.0852	0.3575	0.5441	0.4701	2.41E+05
1.119	14.00	26.72	6.63	33.35	0.821	0.5245	0.2532	0.0629	0.3161	0.5106	0.5168	2.43E+05
1.279	14.00	24.22	4.08	28.30	0.770	0.5996	0.2295	0.0386	0.2681	0.4790	0.5343	2.45E+05
1.439	14.00	21.50	1.58	23.08	0.698	0.6747	0.2038	0.0150	0.2188	0.4343	0.5408	2.47E+05
1.599	14.00	18.21	-1.26	16.96	0.624	0.7496	0.1726	-0.0119	0.1607	0.3883	0.4937	2.50E+05
1.759	14.00	14.62	-4.30	10.31	0.531	0.8248	0.1385	-0.0408	0.0977	0.3303	0.3883	2.52E+05
1.919	14.00	10.10	-7.86	2.24	0.428	0.8997	0.0957	-0.0745	0.0212	0.2660	0.1142	2.55E+05
2.079	14.00	4.83	-11.70	-6.86	0.288	0.9749	0.0458	-0.1108	-0.0651	0.1788	-0.5646	2.58E+05
2.239	14.00	-1.15	-15.27	-16.42	0.140	1.0497	-0.0109	-0.1446	-0.1556	0.0870		2.62E+05
2.400	14.00	-6.44	-18.40	-24.84	0.000	1.1250	-0.0610	-0.1744	-0.2354	0.0000		2.65E+05
2.560	14.00	-12.34	-21.81	-34.15	-0.147	1.1997	-0.1169	-0.2066	-0.3235	-0.0911		2.69E+05
0.000	19.00	65.37	58.93	124.30	1.925	0.0000	0.3361	0.3029	0.6390	0.6494	0.0000	3.21E+05
0.000	19.01	65.43	58.82	124.25	1.950	0.0000	0.3362	0.3022	0.6384	0.6574	0.0000	3.21E+05
0.000	19.00	65.18	58.79	123.97	1.944	0.0000	0.3351	0.3022	0.6373	0.6558	0.0000	3.21E+05
0.000	19.00	65.30	58.67	123.97	1.956	0.0000	0.3356	0.3016	0.6372	0.6598	0.0000	3.21E+05
0.000	19.00	65.46	58.77	124.23	1.957	0.0000	0.3365	0.3021	0.6385	0.6600	0.0000	3.21E+05
0.000	19.00	64.88	58.63	123.51	1.934	0.0000	0.3335	0.3014	0.6349	0.6522	0.0000	3.21E+05
0.216	19.00	63.62	50.73	114.35	1.882	0.0744	0.3271	0.2608	0.5879	0.6349	0.1097	3.21E+05
0.433	19.00	62.56	42.34	104.90	1.867	0.1494	0.3216	0.2176	0.5392	0.6296	0.2036	3.22E+05
0.651	19.00	60.95	34.83	95.78	1.820	0.2247	0.3133	0.1791	0.4924	0.6140	0.2868	3.22E+05
0.868	19.00	59.06	28.33	87.39	1.783	0.2996	0.3035	0.1456	0.4492	0.6012	0.3562	3.24E+05
1.085	19.00	56.38	22.40	78.78	1.717	0.3746	0.2898	0.1152	0.4050	0.5791	0.4169	3.25E+05
1.302	19.00	53.28	16.99	70.28	1.649	0.4495	0.2739	0.0873	0.3612	0.5560	0.4648	3.27E+05
1.519	19.00	49.37	12.09	61.46	1.556	0.5246	0.2538	0.0622	0.3159	0.5249	0.5025	3.30E+05
1.736	19.00	45.13	7.82	52.94	1.454	0.5994	0.2319	0.0402	0.2721	0.4903	0.5294	3.33E+05
1.954	19.00	39.77	3.06	42.83	1.335	0.6748	0.2044	0.0158	0.2202	0.4501	0.5253	3.36E+05
2.171	19.01	34.27	-1.83	32.44	1.194	0.7497	0.1761	-0.0094	0.1667	0.4028	0.4939	3.39E+05
2.389	19.00	26.71	-8.00	18.71	1.010	0.8247	0.1373	-0.0411	0.0961	0.3405	0.3706	3.43E+05
2.606	19.01	20.16	-13.03	7.13	0.848	0.8994	0.1036	-0.0669	0.0366	0.2858	0.1836	3.47E+05
2.823	19.00	10.52	-20.09	-9.57	0.609	0.9746	0.0541	-0.1032	-0.0492	0.2053	-0.3714	3.51E+05
3.040	19.01	1.51	-25.56	-24.05	0.378	1.0491	0.0078	-0.1313	-0.1235	0.1275		3.56E+05
3.258	19.01	-10.16	-32.09	-42.25	0.087	1.1247	-0.0522	-0.1649	-0.2171	0.0294		3.60E+05
3.475	19.01	-21.40	-38.52	-59.91	-0.205	1.1997	-0.1099	-0.1979	-0.3079	-0.0690		3.65E+05

321R no stator

321R used with nozzle 19A

(no stator)

Temperature 16.2 degC

Rho= 998.650 kg/m³Nu= 1.10E-06 m²/s

Carriage Speed m/s	Shaft Speed rps	Shaft Thrust N	Duct Thrust N	Total Thrust N	Torque Nm	Jo	KTo	KTD0	KTo+KTD0	10Kqo	EtaO	RncO
0.000	14.00	33.93	33.11	67.04	1.025	0.0000	0.3212	0.3135	0.6347	0.6366	0.0000	2.36E+05
0.000	14.00	34.43	33.26	67.69	1.023	0.0000	0.3259	0.3148	0.6407	0.6353	0.0000	2.36E+05
0.000	14.01	34.19	33.51	67.70	1.026	0.0000	0.3234	0.3171	0.6405	0.6367	0.0000	2.36E+05
0.000	14.01	33.90	32.93	66.83	1.013	0.0000	0.3208	0.3116	0.6324	0.6289	0.0000	2.36E+05
0.159	14.01	33.46	29.20	62.66	0.986	0.0743	0.3165	0.2763	0.5928	0.6120	0.1146	2.37E+05
0.318	14.00	32.78	24.26	57.04	0.977	0.1492	0.3104	0.2296	0.5400	0.6069	0.2112	2.37E+05
0.479	14.01	32.09	20.34	52.43	0.947	0.2242	0.3036	0.1924	0.4960	0.5881	0.3009	2.38E+05
0.638	14.00	30.96	16.36	47.32	0.921	0.2991	0.2931	0.1549	0.4480	0.5723	0.3726	2.39E+05
0.798	14.01	29.58	13.32	42.90	0.901	0.3739	0.2799	0.1260	0.4059	0.5594	0.4318	2.40E+05
0.959	14.00	27.82	10.31	38.13	0.861	0.4492	0.2633	0.0976	0.3609	0.5348	0.4824	2.41E+05
1.119	14.01	25.74	7.88	33.61	0.809	0.5240	0.2435	0.0745	0.3180	0.5020	0.5283	2.43E+05
1.279	14.00	23.28	5.24	28.52	0.755	0.5991	0.2204	0.0496	0.2700	0.4686	0.5493	2.45E+05
1.438	14.01	20.44	2.68	23.12	0.681	0.6738	0.1934	0.0254	0.2188	0.4229	0.5547	2.47E+05
1.599	14.00	17.21	-0.24	16.97	0.608	0.7490	0.1629	-0.0023	0.1606	0.3778	0.5069	2.50E+05
1.758	14.01	13.33	-3.51	9.82	0.509	0.8237	0.1261	-0.0332	0.0929	0.3162	0.3851	2.52E+05
1.918	14.00	9.04	-6.88	2.16	0.413	0.8989	0.0856	-0.0651	0.0205	0.2566	0.1141	2.55E+05
2.079	14.01	3.80	-10.90	-7.11	0.283	0.9740	0.0359	-0.1032	-0.0673	0.1759	-0.5928	2.59E+05
2.239	14.01	-2.22	-14.86	-17.08	0.133	1.0490	-0.0210	-0.1406	-0.1616	0.0824		2.62E+05
2.399	14.01	-7.98	-17.70	-25.68	-0.012	1.1238	-0.0755	-0.1675	-0.2430	-0.0076		2.66E+05
2.559	14.01	-14.34	-21.37	-35.70	-0.174	1.1989	-0.1357	-0.2022	-0.3379	-0.1081		2.69E+05
0.000	19.03	63.91	62.22	126.12	1.918	0.0000	0.3274	0.3188	0.6462	0.6448	0.0000	3.21E+05
0.000	19.03	63.75	62.30	126.05	1.910	0.0000	0.3269	0.3194	0.6463	0.6425	0.0000	3.21E+05
0.000	19.03	64.28	62.50	126.78	1.920	0.0000	0.3295	0.3204	0.6499	0.6457	0.0000	3.21E+05
0.000	19.03	63.95	62.40	126.35	1.917	0.0000	0.3277	0.3198	0.6475	0.6448	0.0000	3.21E+05
0.000	19.03	63.79	62.39	126.18	1.915	0.0000	0.3268	0.3196	0.6465	0.6438	0.0000	3.21E+05
0.000	19.03	63.89	62.47	126.37	1.907	0.0000	0.3274	0.3201	0.6475	0.6411	0.0000	3.21E+05
0.215	19.03	62.38	54.05	116.43	1.863	0.0742	0.3196	0.2769	0.5965	0.6263	0.1125	3.21E+05
0.432	19.03	61.39	45.48	106.87	1.842	0.1491	0.3147	0.2332	0.5479	0.6198	0.2098	3.22E+05
0.650	19.03	59.91	37.76	97.67	1.800	0.2241	0.3069	0.1935	0.5004	0.6051	0.2950	3.23E+05
0.867	19.03	58.04	31.30	89.34	1.761	0.2991	0.2976	0.1605	0.4580	0.5923	0.3680	3.24E+05
1.085	19.03	55.48	25.07	80.55	1.692	0.3739	0.2842	0.1284	0.4127	0.5688	0.4317	3.26E+05
1.302	19.03	52.26	19.54	71.80	1.622	0.4488	0.2680	0.1002	0.3681	0.5455	0.4820	3.28E+05
1.519	19.03	48.48	14.59	63.07	1.524	0.5236	0.2484	0.0748	0.3232	0.5122	0.5257	3.30E+05
1.736	19.03	43.91	10.16	54.07	1.425	0.5985	0.2251	0.0521	0.2772	0.4793	0.5509	3.33E+05
1.954	19.03	38.75	5.46	44.21	1.289	0.6735	0.1985	0.0280	0.2265	0.4334	0.5602	3.36E+05
2.171	19.03	32.80	0.09	32.88	1.158	0.7487	0.1681	0.0004	0.1686	0.3896	0.5156	3.39E+05
2.388	19.04	25.58	-5.88	19.70	0.977	0.8232	0.1310	-0.0301	0.1009	0.3284	0.4027	3.43E+05
2.606	19.03	18.65	-10.99	7.66	0.805	0.8984	0.0956	-0.0563	0.0393	0.2708	0.2073	3.47E+05
2.822	19.04	9.95	-17.05	-7.10	0.595	0.9729	0.0510	-0.0873	-0.0364	0.2000	-0.2816	3.51E+05
3.039	19.03	-1.48	-24.93	-26.41	0.298	1.0479	-0.0076	-0.1277	-0.1353	0.1001		3.56E+05
3.257	19.04	-12.13	-31.30	-43.44	0.036	1.1227	-0.0622	-0.1603	-0.2225	0.0122		3.61E+05
3.475	19.03	-24.74	-38.77	-63.50	-0.293	1.1978	-0.1267	-0.1986	-0.3254	-0.0983		3.66E+05

polynomial fitted lines

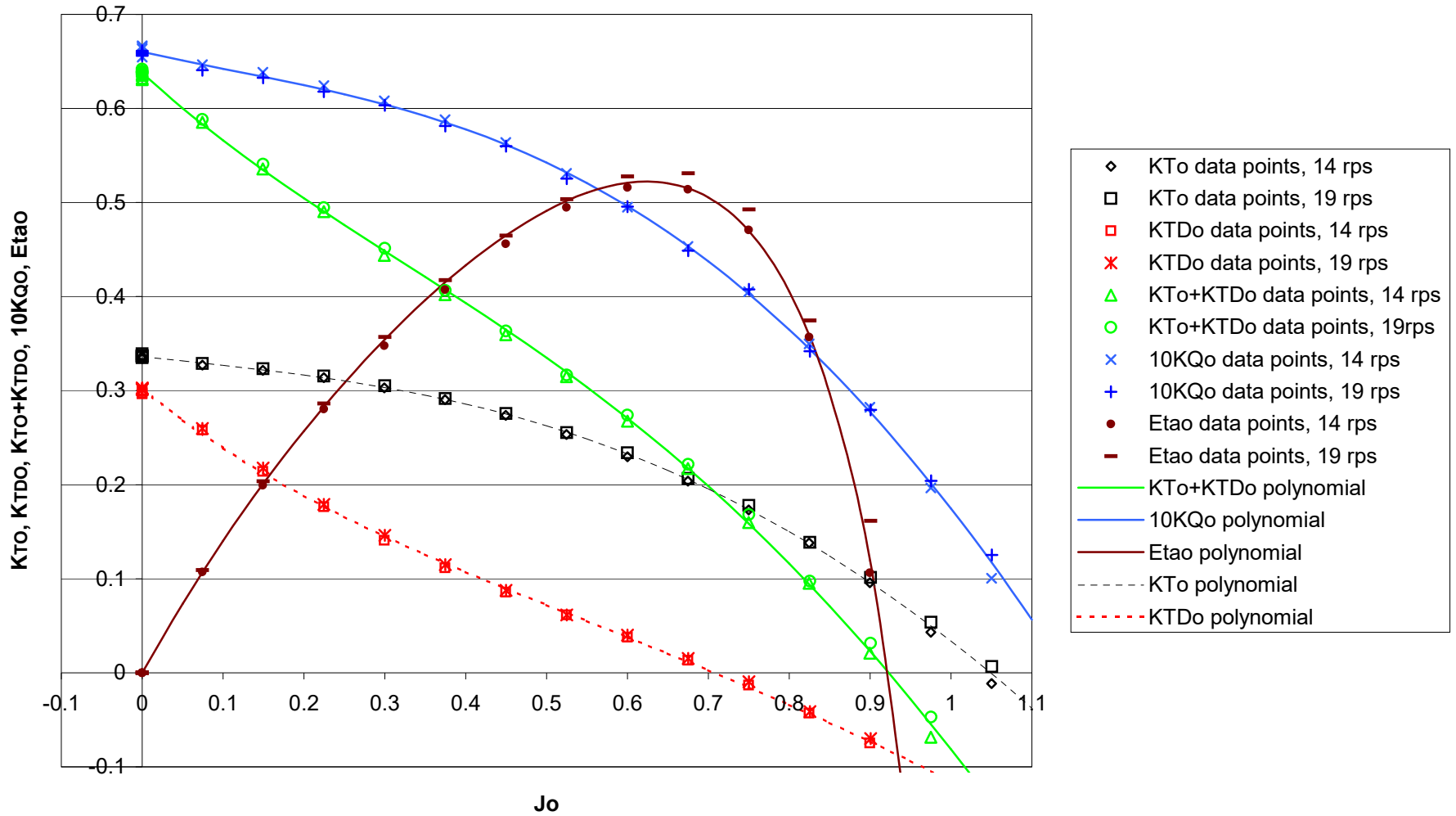
321L used with nozzle 19A and 6arm stator

321R used with nozzle 19A and 6arm stator

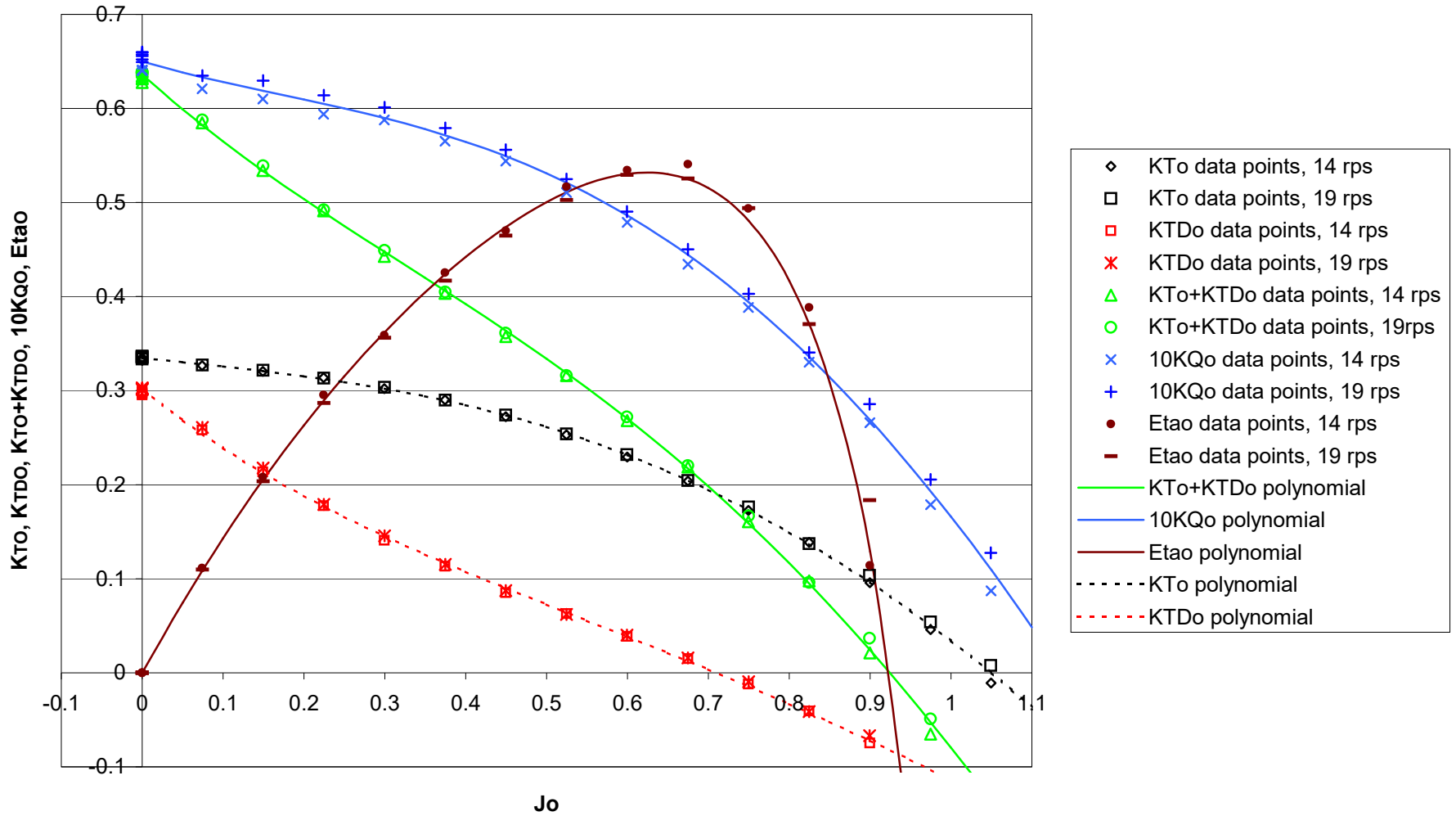
321R used with nozzle 19A (no stator)

Jo	321L used with nozzle 19A and 6arm stator					321R used with nozzle 19A and 6arm stator					321R used with nozzle 19A (no stator)				
	$\kappa\tau_0 + \kappa\tau_{D0}$ polynomial	$10\kappa\tau_{Q0}$ polynomial	$\kappa\tau_0$ polynomial	$\kappa\tau_{D0}$ polynomial	Etao from polynomial	$\kappa\tau_0 + \kappa\tau_{D0}$ polynomial	$10\kappa\tau_{Q0}$ polynomial	$\kappa\tau_0$ polynomial	$\kappa\tau_{D0}$ polynomial	Etao from polynomial	$\kappa\tau_0 + \kappa\tau_{D0}$ polynomial	$10\kappa\tau_{Q0}$ polynomial	$\kappa\tau_0$ polynomial	$\kappa\tau_{D0}$ polynomial	Etao from polynomial
0	0.6375	0.6602	0.3361	0.3014	0.0000	0.6360	0.6498	0.3348	0.3012	0.0000	0.6438	0.6393	0.3255	0.3185	0.0000
0.05	0.6001	0.6509	0.3315	0.2686	0.0734	0.5989	0.6382	0.3303	0.2686	0.0747	0.6078	0.6300	0.3217	0.2855	0.0768
0.1	0.5660	0.6422	0.3268	0.2391	0.1403	0.5649	0.6281	0.3257	0.2392	0.1431	0.5741	0.6209	0.3175	0.2556	0.1472
0.15	0.5343	0.6336	0.3219	0.2124	0.2013	0.5333	0.6187	0.3207	0.2125	0.2058	0.5422	0.6118	0.3128	0.2284	0.2116
0.2	0.5046	0.6247	0.3165	0.1881	0.2571	0.5036	0.6095	0.3153	0.1883	0.2630	0.5117	0.6023	0.3075	0.2035	0.2704
0.25	0.4761	0.6150	0.3103	0.1658	0.3080	0.4751	0.6000	0.3091	0.1660	0.3151	0.4822	0.5921	0.3013	0.1805	0.3240
0.3	0.4484	0.6042	0.3033	0.1451	0.3543	0.4474	0.5896	0.3020	0.1453	0.3623	0.4533	0.5808	0.2941	0.1592	0.3726
0.35	0.4209	0.5918	0.2952	0.1257	0.3961	0.4198	0.5780	0.2939	0.1259	0.4046	0.4247	0.5681	0.2859	0.1392	0.4164
0.4	0.3930	0.5776	0.2858	0.1072	0.4332	0.3920	0.5645	0.2845	0.1075	0.4421	0.3959	0.5537	0.2763	0.1203	0.4551
0.45	0.3645	0.5612	0.2750	0.0895	0.4651	0.3635	0.5490	0.2737	0.0898	0.4742	0.3666	0.5373	0.2655	0.1020	0.4886
0.5	0.3348	0.5423	0.2627	0.0721	0.4913	0.3339	0.5309	0.2614	0.0725	0.5004	0.3364	0.5187	0.2531	0.0843	0.5161
0.55	0.3037	0.5208	0.2487	0.0550	0.5104	0.3028	0.5101	0.2474	0.0554	0.5197	0.3051	0.4974	0.2391	0.0669	0.5368
0.6	0.2707	0.4962	0.2329	0.0378	0.5210	0.2701	0.4862	0.2317	0.0384	0.5304	0.2722	0.4734	0.2233	0.0494	0.5490
0.65	0.2357	0.4685	0.2152	0.0205	0.5205	0.2353	0.4590	0.2141	0.0211	0.5302	0.2375	0.4463	0.2058	0.0319	0.5504
0.7	0.1984	0.4374	0.1955	0.0028	0.5053	0.1982	0.4284	0.1947	0.0036	0.5155	0.2006	0.4160	0.1863	0.0141	0.5372
0.75	0.1586	0.4029	0.1739	-0.0153	0.4699	0.1587	0.3941	0.1732	-0.0145	0.4807	0.1612	0.3822	0.1647	-0.0042	0.5036
0.8	0.1162	0.3647	0.1501	-0.0339	0.4055	0.1166	0.3561	0.1496	-0.0330	0.4169	0.1191	0.3446	0.1411	-0.0231	0.4402
0.85	0.0710	0.3229	0.1242	-0.0532	0.2975	0.0718	0.3143	0.1240	-0.0522	0.3089	0.0740	0.3032	0.1152	-0.0426	0.3302
0.9	0.0230	0.2773	0.0961	-0.0731	0.1190	0.0242	0.2686	0.0962	-0.0721	0.1288	0.0256	0.2577	0.0871	-0.0630	0.1422
0.95	-0.0277	0.2278	0.0659	-0.0937	-0.1842	-0.0263	0.2192	0.0663	-0.0926	-0.1813	-0.0264	0.2080	0.0565	-0.0841	-0.1919
1	-0.0813	0.1745	0.0335	-0.1149	-0.7417	-0.0796	0.1659	0.0343	-0.1138	-0.7631	-0.0822	0.1539	0.0236	-0.1062	-0.8500
1.05	-0.1377	0.1174	-0.0010	-0.1367	-1.9591	-0.1356	0.1090	0.0001	-0.1357	-2.0794	-0.1421	0.0953	-0.0118	-0.1291	-2.4913
1.1	-0.1966	0.0566	-0.0376	-0.1590	-6.0865	-0.1944	0.0485	-0.0363	-0.1581	-7.0172	-0.2062	0.0320	-0.0498	-0.1530	-11.2724
B(0)	0.63752	0.66015	0.33612	0.3014		0.63602	0.6498	0.33478	0.30124		0.64377	0.63933	0.32553	0.31847	
B(1)	-0.785	-0.1945	-0.09417	-0.69083		-0.77886	-0.24979	-0.09079	-0.68807		-0.74424	-0.19337	-0.07402	-0.69338	
B(2)	0.79141	0.2174	0.04531	0.7461		0.76548	0.4141	0.02831	0.73718		0.53313	0.14312	-0.03737	0.70026	
B(3)	-1.00377	-0.68994	-0.34929	-0.65449		-0.96312	-0.91215	-0.32355	-0.63957		-0.58158	-0.52111	-0.22724	-0.569	
B(4)	0.2785	0.18142	0.09556	0.18294		0.26092	0.26397	0.08551	0.17541		0.06672	0.08594	0.0367	0.13747	

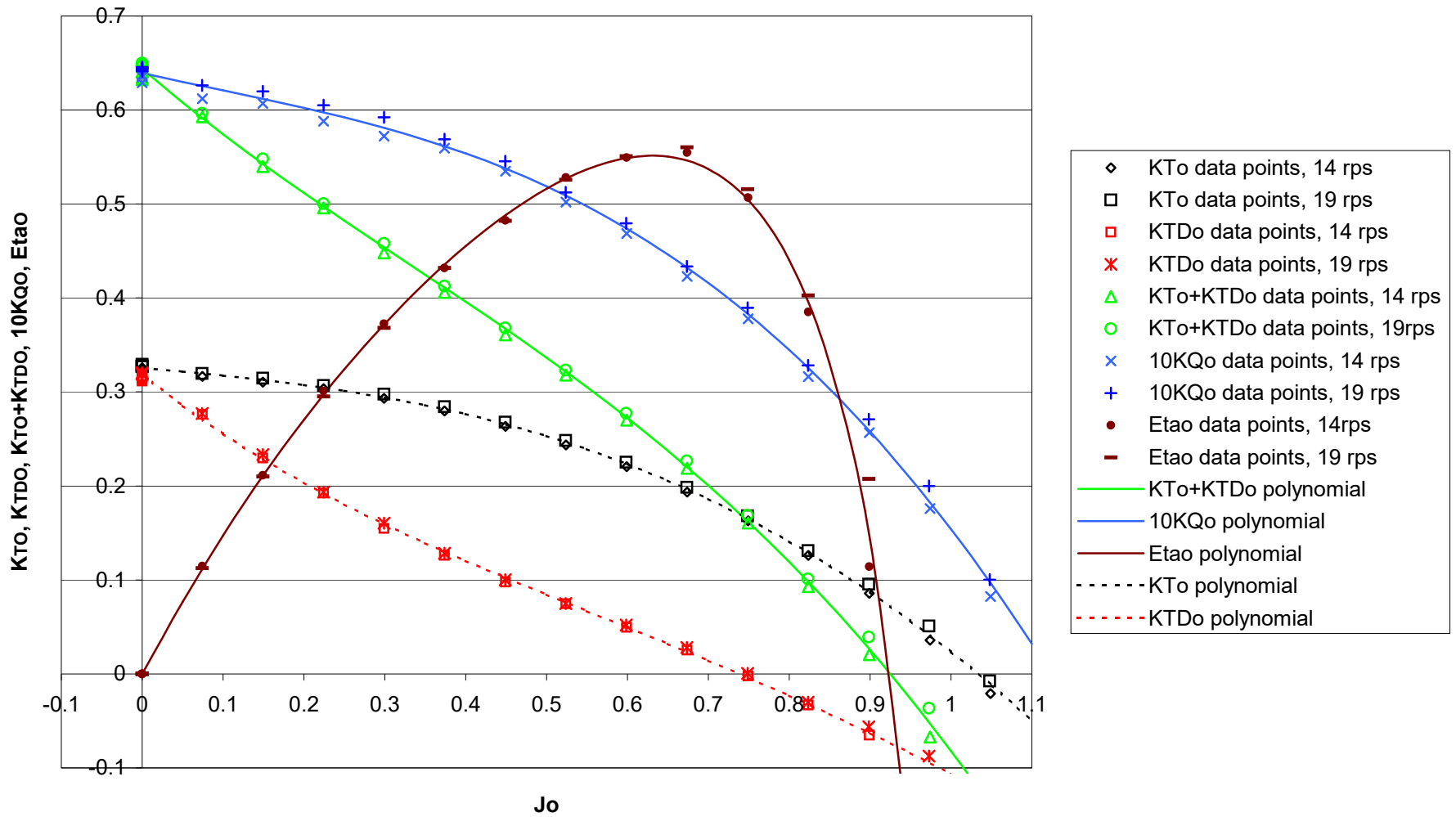
Propeller Open Water Coefficients
321L
(Kaplan BAR 0.70, left rotation, used with Nozzle 19A and 6arm stator)



Propeller Open Water Coefficients
321R
(Kaplan BAR 0.70, right rotation, used with Nozzle 19A and 6arm stator)



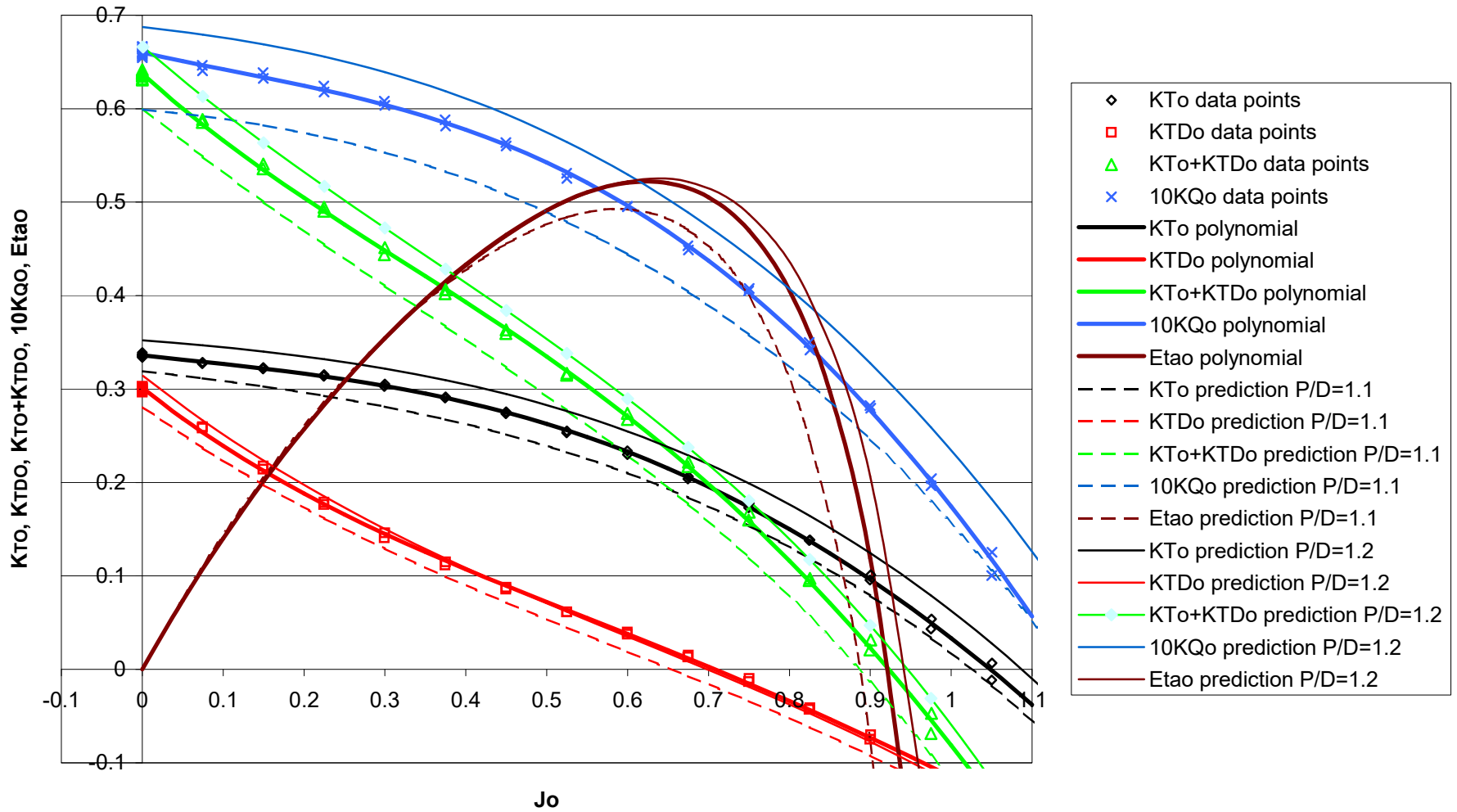
Propeller Open Water Coefficients
321R (no stator)
(Kaplan BAR 0.70, right rotation, used with Nozzle 19A)



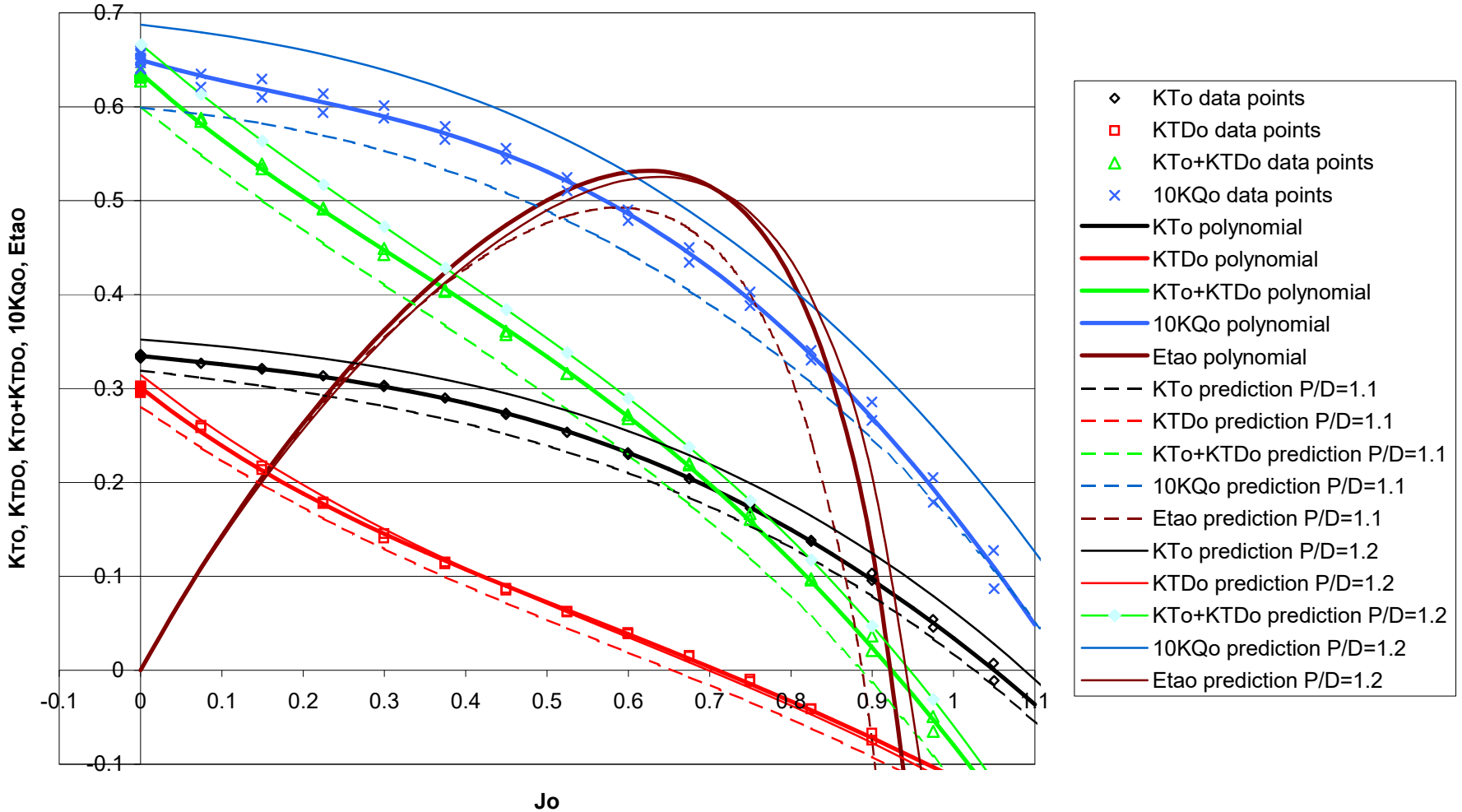
APPENDIX F
Comparison With Existing Data

Propeller Open Water Coefficients

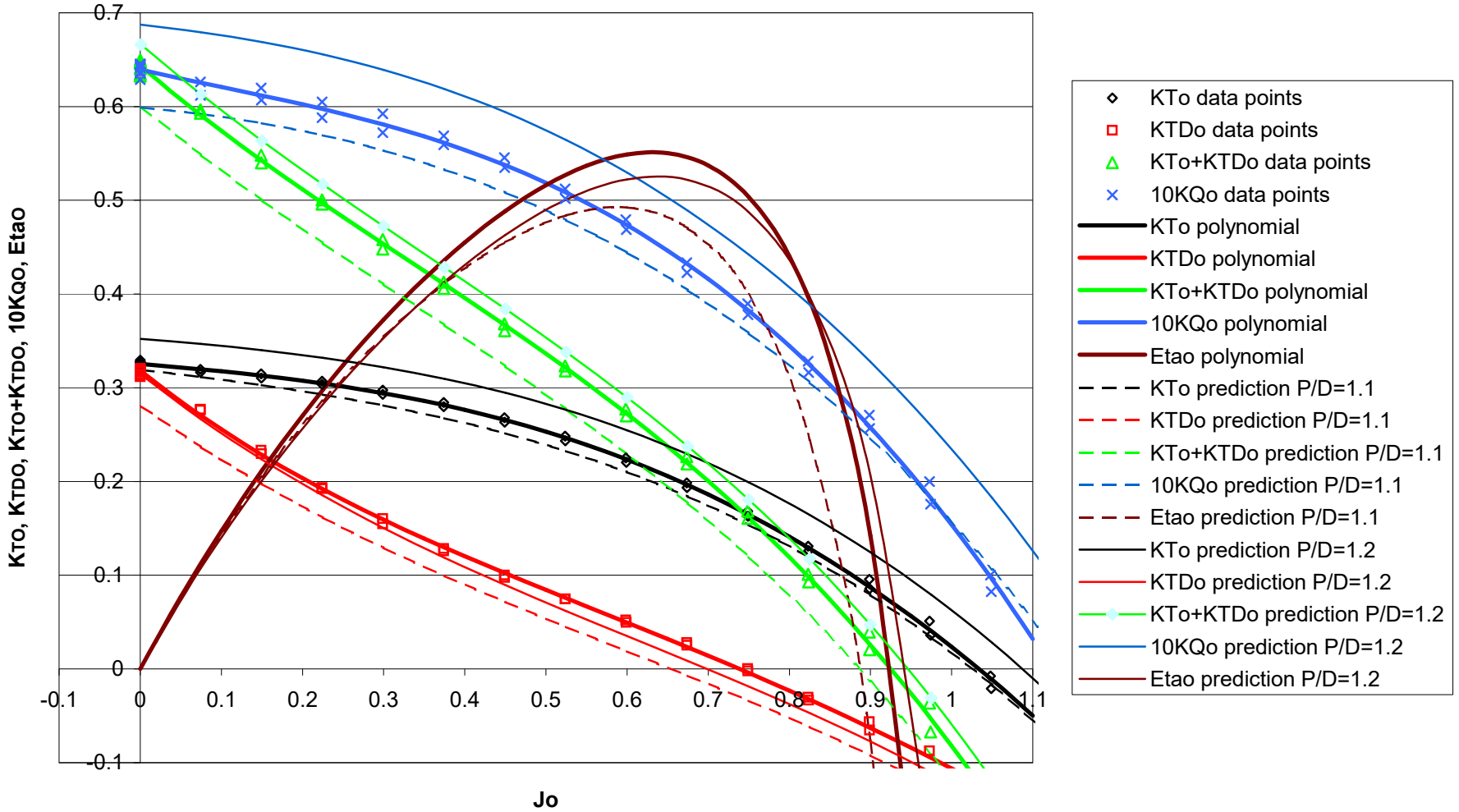
321L (Kaplan BAR 0.70, left rotation, used with Nozzle 19A and 6arm stator)
 Compared to Existing Open Water Data at P/D=1.1 and P/D=1.2



Propeller Open Water Coefficients
321R (Kaplan BAR 0.70, right rotation, used with Nozzle 19A and 6arm stator)
 Compared to Existing Open Water Data at P/D=1.1 and P/D=1.2

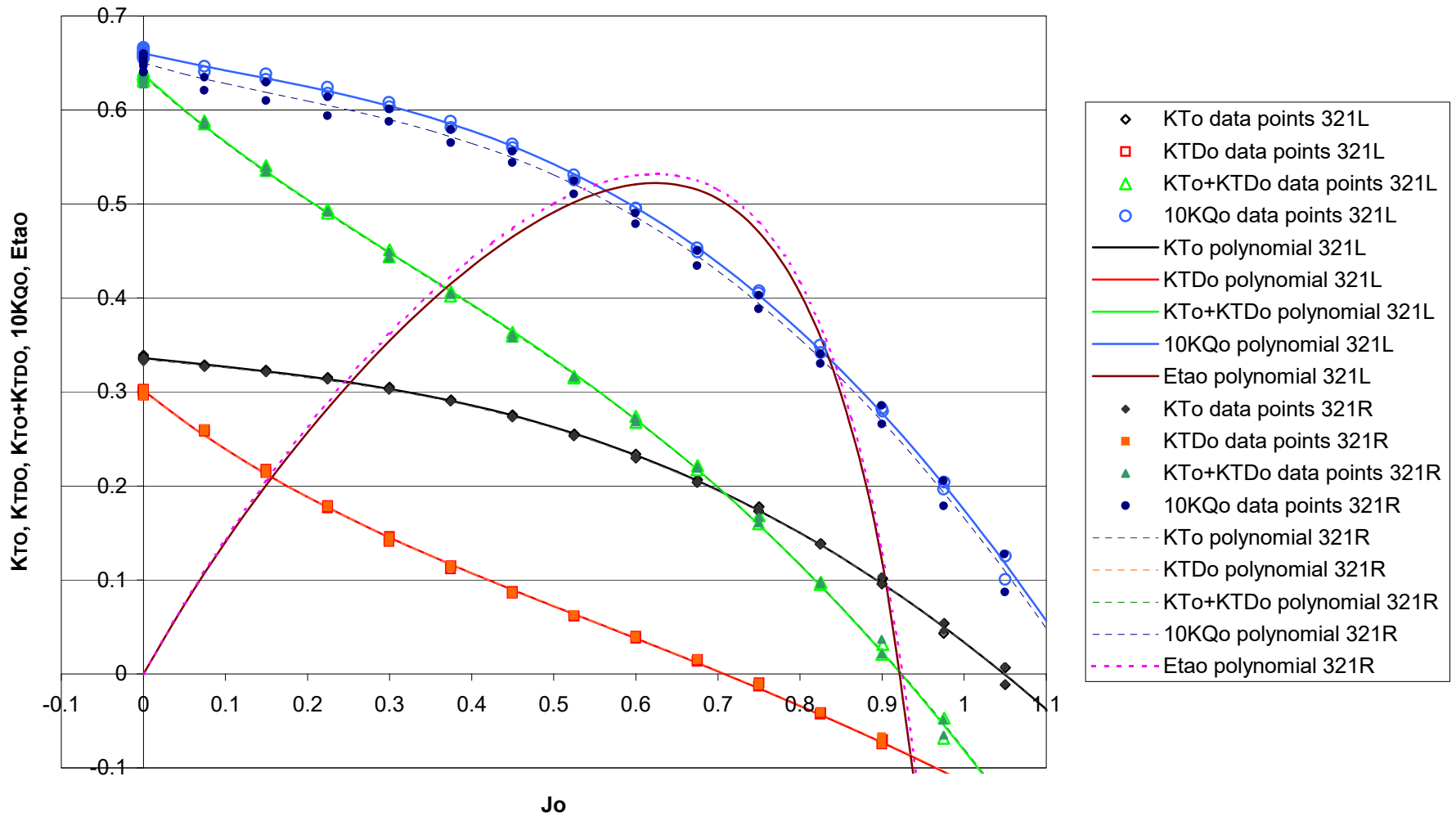


Propeller Open Water Coefficients
321R (no stator) (Kaplan BAR 0.70, right rotation, used with Nozzle 19A)
 Compared to Existing Open Water Data at P/D=1.1 and P/D=1.2



APPENDIX G
Comparison of Propellers and Configurations Tested

**Propeller Open Water Coefficients
comparison of 321R and 321L**
(Kaplan BAR 0.70, used with Nozzle 19A and 6arm stator)



Propeller Open Water Coefficients
321R with and without stator
(Kaplan BAR 0.70, right rotation, used with Nozzle 19A)

