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WIND TUNNEL TEST RESULTS FOR A MODEL SHIP PROPELLER BASED ON A MODIFIED WAGENINGEN B4.40

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SUMMARY

Freestream (Open Water) propeller tests were carried out in the University of Southampton's 11' x 8' low speed wind tunnel. The four-bladed ship propeller tested had an overall diameter of 800mm and maximum hub diameter of 200mm and profile and sections based on the Wageningen B4.40 series. The ability to vary pitch setting was incorporated in the design. The performance tests were conducted at a range of windspeeds between 5m/s and 20m/s and propeller revolutions between 600 and 3,000rpm. Results are presented in terms of Thrust coefficient(K_T), Torque coefficient(K_Q) and Efficiency (η) against advance ratio J. A good comparison was found with published data for the four propeller pitch ratio settings tested. Leading edge roughness was applied at a pitch ratio of 0.95 and this was found not to affect significantly the thrust characteristics of the propeller.

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NOMENCLATURE

D	-	Propeller Diameter (mm)
Nc	-	Corrected rpm
Nm	-	Measured rpm
n	-	Revs per second
V	-	Wind speed (m/s)
Q	-	Torque (Nm)
T	-	Thrust (N)
V_Q	-	Torque balance output voltage (μv)
V_{Qo}	-	Torque dynamic zero voltage (μv)
V_{Qs}	-	Torque Supply Voltage (v)
V_T	-	Thrust balance output voltage (μv)
V_{To}	-	Thrust dynamic zero voltage (μv)
V_{Ts}	-	Thrust supply voltage (v)
C_Q	-	Torque calibration slope (Nm/μv)
C_T	-	Thrust calibration slope (N/μv)
K_T	-	Thrust Coefficient ($T/\rho n^2 D^4$)
K_Q	-	Torque Coefficient ($Q/\rho n^2 D^5$)
η	-	Efficiency ($J.\ K_T/2\pi K_Q$)
J	-	Advance Ratio (V/nD)
ρ	-	Air Density (Kg/m^3)

1. INTRODUCTION

This report describes the freestream wind tunnel performance tests carried out on a four-bladed ship propeller. The propeller design was based on a modified Wageningen B4.40 series and had been developed as part of a test rig for investigating interactions between ship propellers and rudders. The test rig was designed to allow propellers to be tested independently as well as upstream of a ship rudder. A detailed description of the overall test rig is given in Turnock[1]. A 30kw 3-phase electric motor mounted beneath the tunnel floor drives the propeller through a system of toothed belts and pulleys. The propeller speed of revolution can be continuously varied between 0 and 3,000rpm.

The tests used the 11' x 8' closed return low speed wind tunnel at the University of Southampton and the results presented in this report were part of a 2 week period of testing carried out in August 1990.

The main reasons for carrying out the freestream(open water) tests on the propeller were to verify the modified propeller design against published data and to provide a bench mark performance for the study of the influence of a ship rudder on propeller performance.

2. PROPELLER DESIGN

The propeller had a diameter of 800mm and a hub diameter (max) of 200mm. The design was modelled on a Wageningen series B4.40 propeller whose known characteristics would enable validation of the new propeller to take place.

The use of air rather than water as a working fluid for the ship rudder/propeller interaction study necessitated some alteration to the basis Wageningen design and these are detailed in Turnock [2]. The principal reason for this was the far higher revolution speed of the propeller when working in air leading to the propeller stress regime being dominated by centripetal loading rather than aerodynamic forces. The original propeller shape was modified with the aim of keeping the final performance as similar as possible to that of the original design. Also, variable pitch settings were required to extend the range of thrust loadings on the rudder due to the propeller and this required the modification of the root section of the blades to allow for pitch rotation and attachment to the split hub.

Figure 1 shows a comparison of the original propeller shape with the final design. The principal design modifications to the propeller were:

1: Increase in the hub/diameter ratio from 0.167 to 0.25. This required a widening of the blade sections to maintain a blade area ratio of 0.4.

2: Increase in root thickness and reduction in root chord to allow the blades to have a variable pitch ratio setting.

3: Modification to rake to reduce centripetal bending moments.

4: Removal of sweep at inner sections to reduce centripetal bending moments.

Overall particulars of the propeller and, where relevant, the basis B4.40 propeller are summarised in Table 1.

The high centripetal loading led to the decision to manufacture the four blades from hybrid carbon/glass fibre composite. The manufacturing process is detailed in Molland and Turnock[3]. The blades were directly laid up in a female split mould which had been N.C. (Numerically Controlled) machined from aluminium alloy. As each blade was manufactured using the same mould, four identical blades were produced. Figure 2 shows a view of the four blades and also of the blades fixed in the split hub. The split hub is used to clamp the blades at the desired pitch ratio setting.

3. PROPELLER RIG INSTALLATION AND OPERATION

Figure 3. shows a side view of the propeller rig installed in the 11' x 8' wind tunnel. The installation process is described in Turnock[1]. The tests detailed in this report were carried out with the propeller's axis of rotation 600mm above the wind tunnel floor and in the flow direction. The propeller rotates anti-clockwise when viewed from aft (looking upstream). The aerofoil fairing around the propeller sting support tubes and drive belt has a NACA630040 profile with a chord of 550mm and 25% maximum thickness. The trailing edge of the fairing is located 0.5 of the propeller diameter (400mm) upstream of the propeller's plane of rotation. The fairing around the propeller sting has a diameter equal to the minimum hub diameter(180mm). The hub cone and nose cone have an identical profile, the dimensions of which are given in Turnock[1].

An in-line strain gauge dynamometer mounted close to the propeller was used to measure the delivered thrust and torque. The design and static calibration of this dynamometer is detailed in Molland and Turnock[4]. The two measurement components of the dynamometer are connected via a slip-ring assembly to Fylde Bridge balance units with a built in stabilised power supply. The bridge balance output voltage is measured directly (without amplification) using a Schlumberger Minate Digital Voltmeter. Data acquisition is controlled by a Research Machines personal computer and results stored on a 3.5" floppy disk for subsequent analysis.

A Fuji Variable Frequency Inverter is used to control the 30kw electric motor. The propeller rpm can be continuously varied in small discrete steps between 0 and 3000 rpm. The controller has a voltage output proportional to its output supply frequency and hence propeller rpm. This voltage is recorded to give the propeller rpm for a given measurement of thrust and torque.

Tests were carried out at four windspeeds of 5m/s, 10m/s, 15m/s, and 20m/s. This speed was set using the wind tunnel speed controller and measured using a betz manometer. For given propeller revolutions the wind speed controller had to be varied to compensate for the windspeed imparted by the propeller.

4. EXPERIMENTS CONDUCTED

Four propeller pitch ratios (P/D) were tested which corresponded to mean pitch ratios of 0.54, 0.69, 0.95, and 1.36. For each case the four windspeeds (5m/s, 10m/s, 15m/s, and 20m/s) were used. The propeller revolutions were varied between 600 and 3,000rpm. Bollard pull (zero windspeed) values of thrust and torque were also measured. The tests gave complete coverage of propeller performance in terms of Advance Ratio (J) for all pitch ratios tested.

For a mean pitch ratio of 0.95, a roughness strip was placed at the leading edge (L.E.) of each blade and extended around the nose to 5% of blade chord aft of the L.E. on the face and 10% aft of the L.E. on the back. The roughness strip consisted of double sided tape stretching from blade root to tip, densely covered with 100 Grade carborundum grit. The complete range of advance ratios was tested.

5. DATA ANALYSIS

Data analysis was carried out using a specifically written computer program to extract the information from the relevant test data file and then process the information. Manual checks on propeller rpm were carried out using a handheld optical tachometer and compared with the value measured from the Motor controller. Using a regression analysis the following correction to measured rpm was obtained:

$$Nc = 1.04\ Nm - 6.8 \times 10^{-6}\ Nm^2$$

where Nc and Nm are the corrected and measured rpm respectively. This expression was used to modify all the measured revolution speeds.

The static calibration carried out on the Torque-Thrust dynamometer gave a linear response to loading of both thrust and torque with negligible interactions (Molland and Turnock[4]). The calibration for both channels was carried out with a supply volage of 7 volts. The slope constant (C_T) for the thrust channel was 0.0903 N/μv and for the torque channel (C_Q) of 0.01284 Nm/μv. The propeller is separated from the dynamometer by a short shaft supported on two axially unconstrained roller bearings. When the propeller is rotating these give minimal torque and thrust losses. However, when stationary, frictional resistance in these bearings is enough to produce spurious no-load voltages.

To overcome this problem a dynamic dynamometer zeroing procedure was developed. This method was based on the zero windspeed characteristic of the propeller where the Thrust (or Torque) is proportional to the square of the speed of revolution. At the beginning and end of each test run, the thrust and torque output voltages were measured for three rpm; typically 350, 650, and 1000. Figure 4 shows these output voltages (μv) plotted against rpm^2. using a least-squares linear regression (Kreyszig[5]) the true dynamometer 'zero' voltage at 0 rpm is found. The method was found to give good, repeatable data.

For each individual torque and thrust measurement both the balance output voltages, V_Q and V_T (v), as well as the balance supply voltage, V_{Qs} and V_{Ts} (v), were recorded. This gives the measured thrust T (N) and torque Q (Nm) as:

$$T = (V_T - V_{To})*(V_{Ts}/7.0)*C_T$$

$$Q = (V_Q - V_{Qo})*(V_{Qs}/7.0)*C_Q$$

where V_{To} and V_{Qo} are the relevant dynamic zero voltages, the 7.0 is the value of calibration supply voltage and C_T, C_Q are the calibration slopes.

Using the relevant windspeed V (m/s) and n (revs/sec) the advance ratio J is calculated as:

$$J = V/(nD)$$

where D is propeller diameter. The non-dimensional thrust coefficient (K_T) and torque coefficient (K_Q) are given by

$$K_T = \frac{T}{\rho n^2 D^4}$$

$$K_Q = \frac{Q}{\rho n^2 D^5}$$

where ρ is the air density. The propeller efficiency η is:

$$\eta = \left(\frac{J}{2\pi}\right) x \left(\frac{K_T}{K_Q}\right)$$

Appendix 1 tabulates the data obtained in this investigation of the propeller freestream performance.

6. PROPELLER FREESTREAM PERFORMANCE

6.1 Variation With Windspeed

Figures 5, 6, and 7 show respectively the variation in K_T, K_Q, and η when plotted against J for the four different pitch ratios tested. It is seen that the results for 5m/s deviate from the values obtained at the higher speeds of 10m/s, 15m/s, and 20m/s, suggesting that some scale effect is present at 5m/s.

6.2 Comparison With Published Data

Figures 5, 6, and 7 include solid lines interpolated from [6] which gives published performance data for the basis Wageningen B4.40 propeller. Except at P/D=0.54 the overall comparison between the modified propeller design and the published data is good, especially for the thrust coefficient K_T. This provides an experimental verification that the thrust loading produced by the modified propeller design is representative of that produced by a typical ship propeller. The reasons for the very low K_T and K_Q values at P/D=0.54 are not at present clear, but include the possibility of an incorrect pitch setting.

The power absorbed (K_Q) for the modified design is greater than the standard B4.40. This was to be expected because of the modification in blade root thickness, increase in the hub/diameter ratio and test Reynold's numbers. Ref 7 indicates that the increase in hub/diameter ratio (0.167 to 0.25) will typically lead to a decrease in K_T and increase in K_Q of up to about 1%, and a decrease in maximum efficiency of about 2%. Ref 8 indicates that the increase in thickness ratio (0.045 to 0.050) will typically lead to an increase in K_Q (loss in efficiency) of about 1%. The largest increase in K_Q is due to the effect of Reynolds Number which, for example, based on blade chord at 0.7 radius and 10m/s varies from $0.2x10^6$ at 500 rpm up to $1.0x10^6$ at 3000 rpm. It is estimated that at these test Reynolds Numbers there will be a very small change in K_T whilst K_Q will be increased (hence efficiency reduced) by between 6% and 10%. These influences due to hub diameter, blade thickness and Reynolds Number are broadly reflected in the deviation of the measured test data from the published data for the basis B4.40 propeller shown in figures 5, 6 and 7.

6.3 Effect of Leading Edge Roughness

The effect of the leading edge roughness on the propeller's thrust performance for a pitch ratio of 0.95 can be seen in Figure 8. Overall there does not appear to be much variation over the whole range of advance coefficients. This gives confidence that the thrust loading is not affected by scale effects.

The large drag penalty caused by the L.E. roughness strips can be seen in the K_Q vs. J and η vs. J plots given as figures 9 and 10. As expected the propeller efficiency is significantly less than that for the tests without roughness.

7. CONCLUSIONS

The primary conclusions from the freestream performance tests of the modified Wageningen B4.40 are that:

1. The overall thrust characteristics produced by the modified design are similar to those of a standard Wageningen B4.40 propeller.

2. Scale effects do not alter significantly the thrust loading produced by the modified propeller except at very low wind speeds and low rpm.

3. Increases in K_Q (and decrease in η) compared with the basis B4.40 propeller were apparent in the modified design. This was due to increases in hub diameter and blade

thickness and the lower Reynolds Numbers resulting from the test conditions.

4. Overall the modified propeller's performance for K_T, K_Q, and η exhibited broadly similar characteristics to the basis Wageningen B4.40 design for the pitch ratios tested.

A general conclusion to be drawn from the tests was that the propeller dynamometer and test rig had performed satisfactorily indicating the suitability of the rig for testing propellers independently.

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APPENDIX TABULATED TEST RESULTS

Modified Wageningen B4.40 Open Water Results

Windspeed of 5m/s

P	V	RPM	J	Kt	Kq	n	Kt/J^2	Kq/J^2
0.54	5.00	597.20	0.6300	-0.138	-0.002	8.389	-0.3510	-0.0042
0.54	5.00	1067.78	0.3500	0.015	0.008	0.110	0.1234	0.0630
0.54	5.00	1529.91	0.2500	0.076	0.010	0.303	1.2610	0.1621
0.54	5.00	2055.13	0.1800	0.096	0.011	0.245	2.8684	0.3398
0.54	5.00	2518.16	0.1500	0.104	0.011	0.214	4.6737	0.5183
0.54	5.00	2954.71	0.1300	0.103	0.012	0.176	6.4193	0.7387
0.69	5.00	740.84	0.5100	0.184	0.021	0.698	0.7188	0.0830
0.69	5.00	1067.37	0.3500	0.203	0.023	0.483	1.6453	0.1904
0.69	5.00	1464.31	0.2600	0.229	0.025	0.372	3.4845	0.3813
0.69	5.00	1727.40	0.2200	0.226	0.025	0.310	4.8029	0.5346
0.69	5.00	2186.47	0.1700	0.226	0.026	0.237	7.6793	0.8846
0.69	5.00	2377.41	0.1600	0.240	0.027	0.225	9.6291	1.0731
0.95	5.00	1066.45	0.3500	-0.131	-0.002	3.525	-1.0555	-0.0168
0.95	5.00	667.35	0.5600	0.195	0.041	0.427	0.6187	0.1297
0.95	5.00	873.33	0.4300	0.254	0.043	0.405	1.3780	0.2328
0.95	5.00	1066.04	0.3500	0.278	0.043	0.358	2.2505	0.3514
0.95	5.00	1264.00	0.3000	0.306	0.048	0.302	3.4720	0.5429
0.95	5.00	1529.51	0.2500	0.326	0.048	0.263	5.4151	0.8047
0.95	5.00	1661.05	0.2300	0.356	0.050	0.258	6.9903	0.9749
0.95	5.00	1529.71	0.2500	0.340	0.050	0.265	5.6651	0.8350
0.95	5.00	1198.89	0.3100	0.324	0.049	0.331	3.3164	0.4987
0.95	5.00	808.20	0.4600	0.251	0.047	0.398	1.1658	0.2164
0.95	5.00	597.61	0.6300	0.203	0.043	0.471	0.5150	0.1092

Windspeed of 10m/s

0.54	10.00	667.87	1.1200	-0.493	-0.022	3.959	-0.3906	-0.0176
0.54	10.00	1199.50	0.6300	-0.100	0.000	-43.145	-0.2570	0.0006
0.54	10.00	1530.63	0.4900	-0.024	0.005	-0.399	-0.1016	0.0198
0.54	10.00	1858.80	0.4000	0.025	0.007	0.232	0.1506	0.0417
0.54	10.00	2119.62	0.3500	0.043	0.008	0.306	0.3452	0.0634
0.54	10.00	2519.46	0.3000	0.061	0.009	0.311	0.6872	0.1046
0.54	10.00	2765.65	0.2700	0.063	0.010	0.280	0.8530	0.1312
0.54	10.00	2972.12	0.2500	0.067	0.010	0.269	1.0591	0.1578
0.69	10.00	868.49	0.8600	0.015	0.004	0.490	0.0207	0.0058
0.69	10.00	1200.73	0.6200	0.089	0.015	0.576	0.2270	0.0392
0.69	10.00	1596.17	0.4700	0.146	0.018	0.596	0.6614	0.0830
0.69	10.00	1858.60	0.4000	0.159	0.020	0.517	0.9772	0.1214
0.69	10.00	2185.76	0.3400	0.177	0.022	0.432	1.4992	0.1894
0.69	10.00	2520.37	0.3000	0.195	0.023	0.395	2.1987	0.2636
0.69	10.00	2892.65	0.2600	0.190	0.024	0.323	2.8244	0.3603
0.95	10.00	596.89	1.2600	-0.126	-0.008	3.193	-0.0800	-0.0050
0.95	10.00	808.20	0.9300	0.055	0.017	0.468	0.0639	0.0202
0.95	10.00	1066.24	0.7000	0.157	0.030	0.584	0.3174	0.0609
0.95	10.00	1264.82	0.5900	0.197	0.036	0.521	0.5615	0.1018
0.95	10.00	1463.09	0.5100	0.226	0.038	0.488	0.8598	0.1437
0.95	10.00	1660.34	0.4500	0.264	0.040	0.470	1.2960	0.1983
0.95	10.00	2119.11	0.3500	0.283	0.043	0.369	2.2593	0.3454
0.95	10.00	2314.76	0.3200	0.304	0.045	0.347	2.8936	0.4296
0.95	10.00	2515.64	0.3000	0.310	0.046	0.318	3.4879	0.5211

P	V	RPM	J	Kt	Kq	n	Kt/J^2	Kq/J^2
0.95	10.00	2765.75	0.2700	0.331	0.048	0.297	4.4959	0.6538
1.36	10.00	668.69	1.1200	0.118	0.035	0.606	0.0936	0.0276
1.36	10.00	668.69	1.1200	0.116	0.039	0.528	0.0924	0.0312
1.36	10.00	1067.78	0.7000	0.314	0.074	0.475	0.6373	0.1500
1.36	10.00	1464.93	0.5100	0.405	0.089	0.372	1.5451	0.3387
1.36	10.00	1728.21	0.4300	0.418	0.091	0.317	2.2202	0.4841
1.36	10.00	2055.64	0.3600	0.468	0.098	0.276	3.5152	0.7389
1.36	10.00	2381.14	0.3100	0.450	0.096	0.235	4.5405	0.9699

Windspeed of 15m/s

0.54	15.00	670.96	1.6800	-1.140	-0.066	4.606	-0.4054	-0.0235
0.54	15.00	1530.32	0.7400	-0.165	-0.004	4.950	-0.3046	-0.0072
0.54	15.00	2315.37	0.4900	-0.013	0.005	-0.215	-0.0559	0.0201
0.54	15.00	2641.25	0.4300	0.007	0.007	0.071	0.0378	0.0358
0.54	15.00	2971.72	0.3800	0.022	0.008	0.175	0.1560	0.0539
0.69	15.00	1067.47	1.0500	-0.144	-0.013	1.869	-0.1296	-0.0116
0.69	15.00	1530.22	0.7400	0.036	0.007	0.632	0.0660	0.0122
0.69	15.00	2119.92	0.5300	0.092	0.015	0.507	0.3257	0.0542
0.69	15.00	2519.36	0.4500	0.122	0.019	0.462	0.6125	0.0942
0.69	15.00	2970.62	0.3800	0.147	0.021	0.423	1.0223	0.1457
0.95	15.00	598.02	1.8800	-0.740	-0.095	2.321	-0.2090	-0.0270
0.95	15.00	1066.04	1.0600	-0.007	0.006	-0.195	-0.0062	0.0053
0.95	15.00	1330.49	0.8500	0.087	0.020	0.596	0.1222	0.0276
0.95	15.00	1527.98	0.7400	0.166	0.029	0.675	0.3061	0.0531
0.95	15.00	2184.15	0.5200	0.235	0.037	0.524	0.8847	0.1384
0.95	15.00	2517.25	0.4500	0.251	0.039	0.452	1.2557	0.1974
0.95	15.00	2766.35	0.4100	0.262	0.042	0.408	1.5853	0.2516
0.95	15.00	2970.62	0.3800	0.280	0.044	0.388	1.9516	0.3035
1.36	15.00	669.31	1.6800	-0.169	-0.031	1.447	-0.0598	-0.0111
1.36	15.00	875.59	1.2800	0.056	0.027	0.424	0.0339	0.0163
1.36	15.00	1265.84	0.8900	0.250	0.061	0.576	0.3165	0.0778
1.36	15.00	1596.99	0.7000	0.326	0.072	0.506	0.6575	0.1458
1.36	15.00	2120.02	0.5300	0.392	0.083	0.398	1.3923	0.2952
1.36	15.00	2380.84	0.4700	0.400	0.087	0.347	1.7922	0.3888
1.36	15.00	2580.73	0.4400	0.438	0.092	0.329	2.3037	0.4864

Wind Speed of 20m/s

0.54	20.00	2118.30	0.7100	-0.142	-0.002	6.993	-0.2830	-0.0046
0.54	20.00	2970.42	0.5000	-0.032	0.004	-0.618	-0.1270	0.0165
0.69	20.00	2182.43	0.6900	0.033	0.009	0.393	0.0703	0.0196
0.69	20.00	1854.94	0.8100	-0.040	0.002	-2.057	-0.0608	0.0038
0.69	20.00	2517.25	0.6000	0.061	0.013	0.444	0.1708	0.0365
0.69	20.00	2971.42	0.5000	0.095	0.017	0.446	0.3711	0.0668
0.95	20.00	1198.27	1.2500	-0.147	-0.014	2.116	-0.0937	-0.0088
0.95	20.00	1527.36	0.9800	0.023	0.010	0.344	0.0239	0.0109
0.95	20.00	1790.03	0.8400	0.108	0.022	0.651	0.1539	0.0315
0.95	20.00	2182.63	0.6900	0.162	0.030	0.587	0.3438	0.0641
0.95	20.00	2515.94	0.6000	0.186	0.033	0.527	0.5227	0.0941
0.95	20.00	2769.06	0.5400	0.217	0.036	0.519	0.7384	0.1226
0.95	20.00	2970.22	0.5100	0.234	0.038	0.495	0.9168	0.1488
1.36	20.00	1068.29	1.4000	0.011	0.013	0.194	0.0055	0.0064
1.36	20.00	1333.04	1.1300	0.154	0.039	0.697	0.1213	0.0312
1.36	20.00	1596.68	0.9400	0.229	0.057	0.602	0.2593	0.0644

P	V	RPM	J	Kt	Kq	n	Kt/J^2	Kq/J^2
1.36	20.00	2121.03	0.7100	0.307	0.071	0.490	0.6144	0.1411
1.36	20.00	2450.28	0.6100	0.357	0.078	0.446	0.9519	0.2081
1.36	20.00	2769.76	0.5400	0.379	0.083	0.392	1.2912	0.2835

Modified Wageningen B4.40 Open Water Results with Transition Strip

Wind Speed of 5 m/s

0.95	5.00	607.52	0.6200	0.174	0.048	0.358	0.4565	0.1254
0.95	5.00	817.97	0.4600	0.250	0.050	0.365	1.1898	0.2377
0.95	5.00	1083.68	0.3500	0.287	0.051	0.311	2.3980	0.4246
0.95	5.00	1413.47	0.2700	0.334	0.055	0.258	4.7499	0.7763

Wind Speed of 10m/s

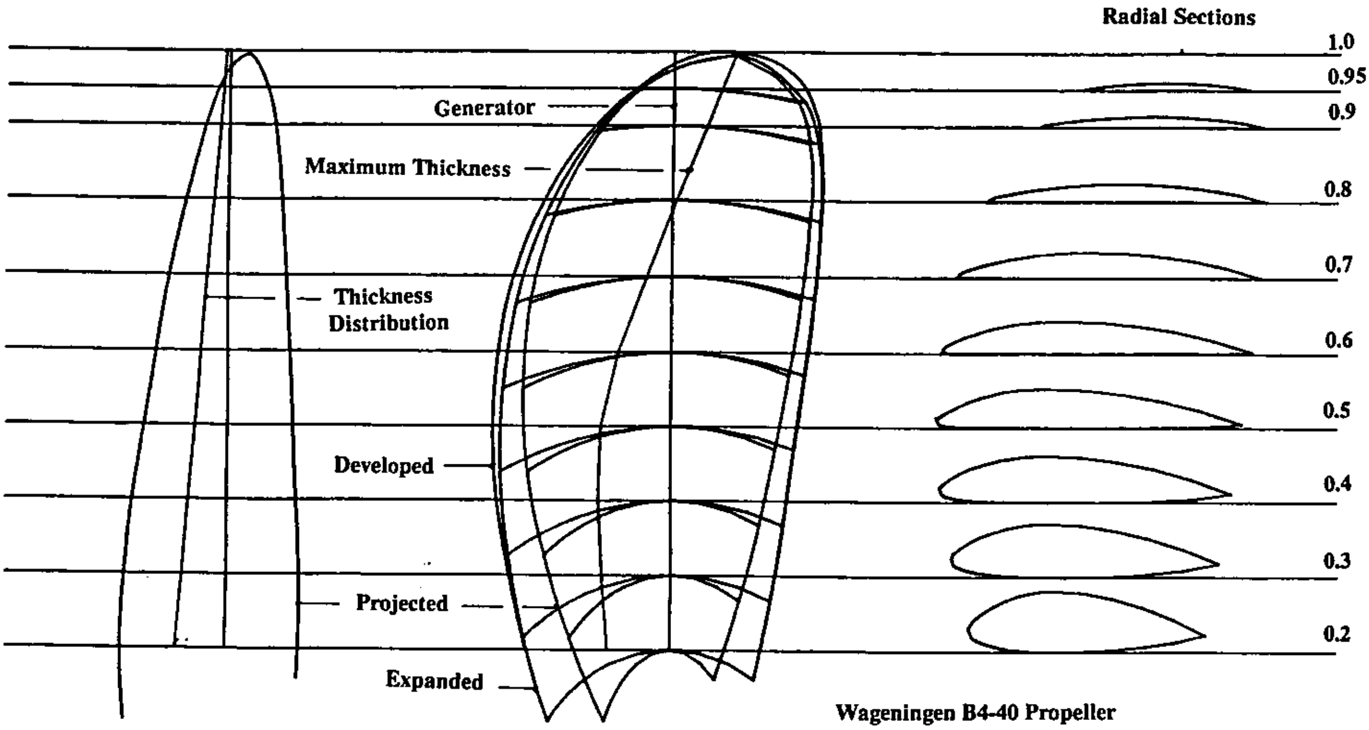
0.95	10.00	823.22	0.9100	0.037	0.019	0.284	0.0450	0.0230
0.95	10.00	1083.58	0.6900	0.131	0.032	0.453	0.2732	0.0664
0.95	10.00	1479.62	0.5100	0.228	0.040	0.456	0.8877	0.1570
0.95	10.00	2457.54	0.3100	0.298	0.051	0.287	3.2039	0.5428

Wind Speed of 15 m/s

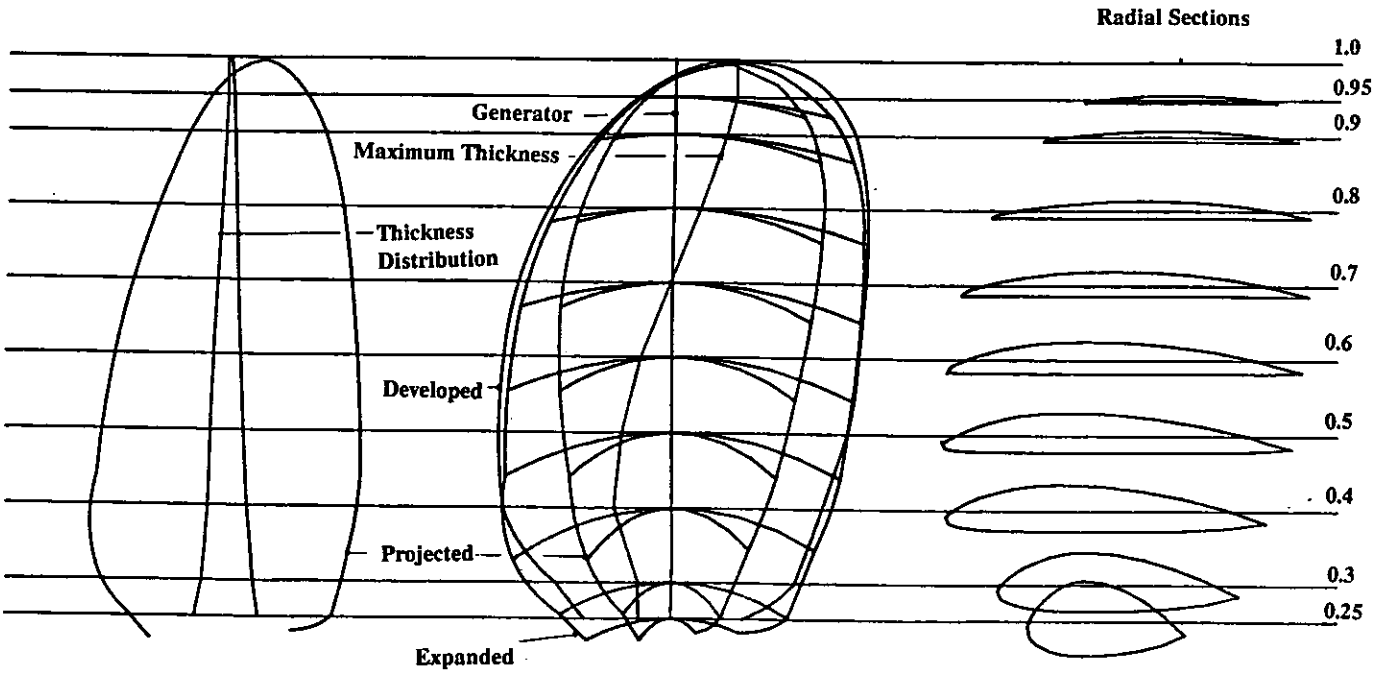
0.95	15.00	608.03	1.8500	-0.765	-0.094	2.400	-0.2234	-0.0274
0.95	15.00	888.96	1.2700	-0.171	-0.011	3.061	-0.1066	-0.0070
0.95	15.00	1082.96	1.0400	-0.010	0.012	-0.138	-0.0092	0.0110
0.95	15.00	1414.08	0.8000	0.115	0.027	0.535	0.1824	0.0432
0.95	15.00	2135.50	0.5300	0.228	0.040	0.478	0.8229	0.1445
0.95	15.00	2962.81	0.3800	0.262	0.047	0.336	1.8154	0.3265

Table I Summary of Propeller Particulars

	Modified Design	Original Wageningen B4.40
Diameter (D) (mm)	800	800
Hub Diameter (mm)	200	134
Hub Diameter/D	0.25	0.167
Blade Area Ratio	0.40	0.40
t/D	0.050	0.045
Rake	Nom. 0°	15°
Blade Profile/Skew	See Figure 1	



Wageningen B4-40 Propeller



Final Modified Wageningen B4-40 Propeller Design

Figure 1 Comparison of original Wageningen B4.40 Propeller with modified shape

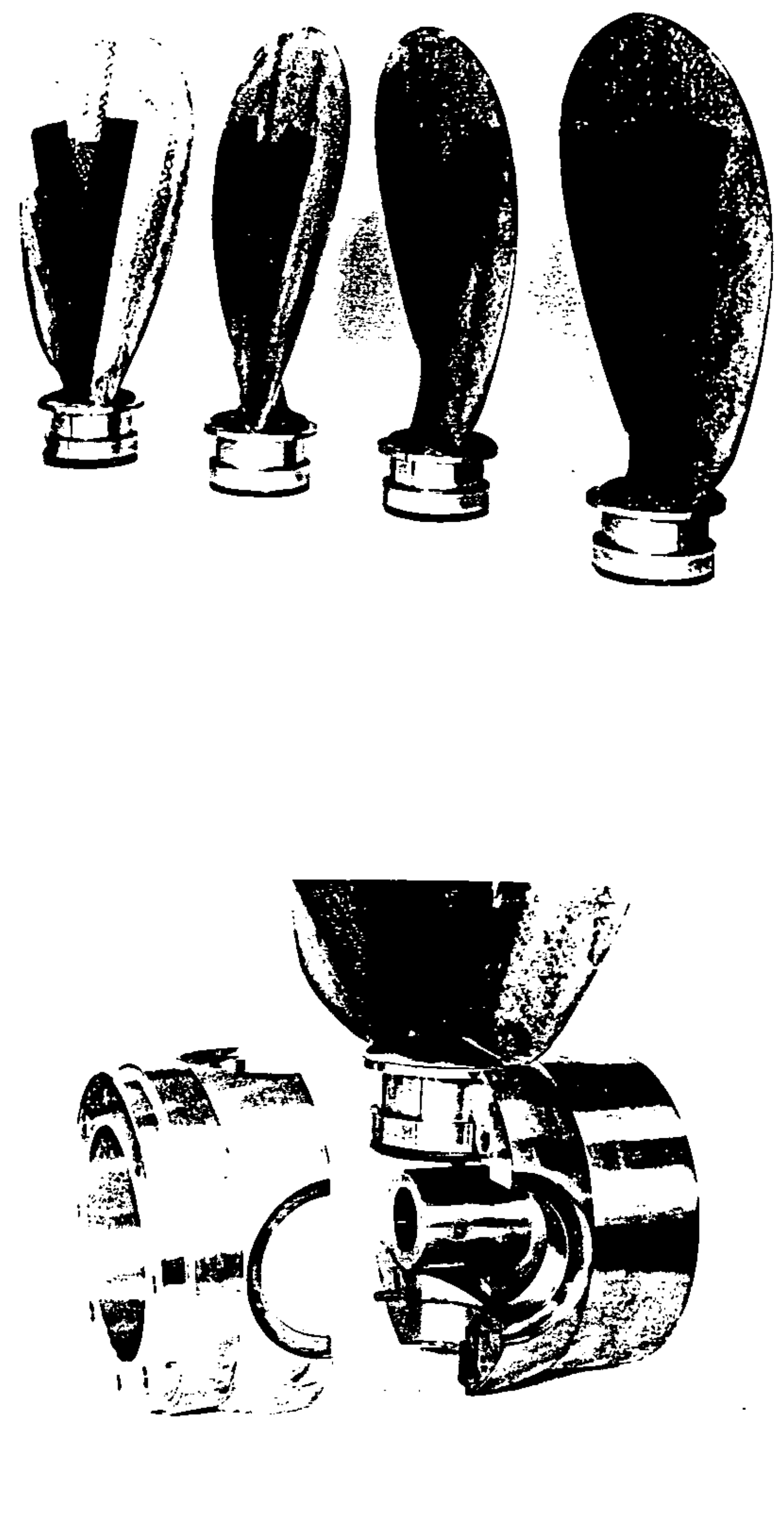


Figure 2 View of Propeller Blades and Overall propeller Hub assembly

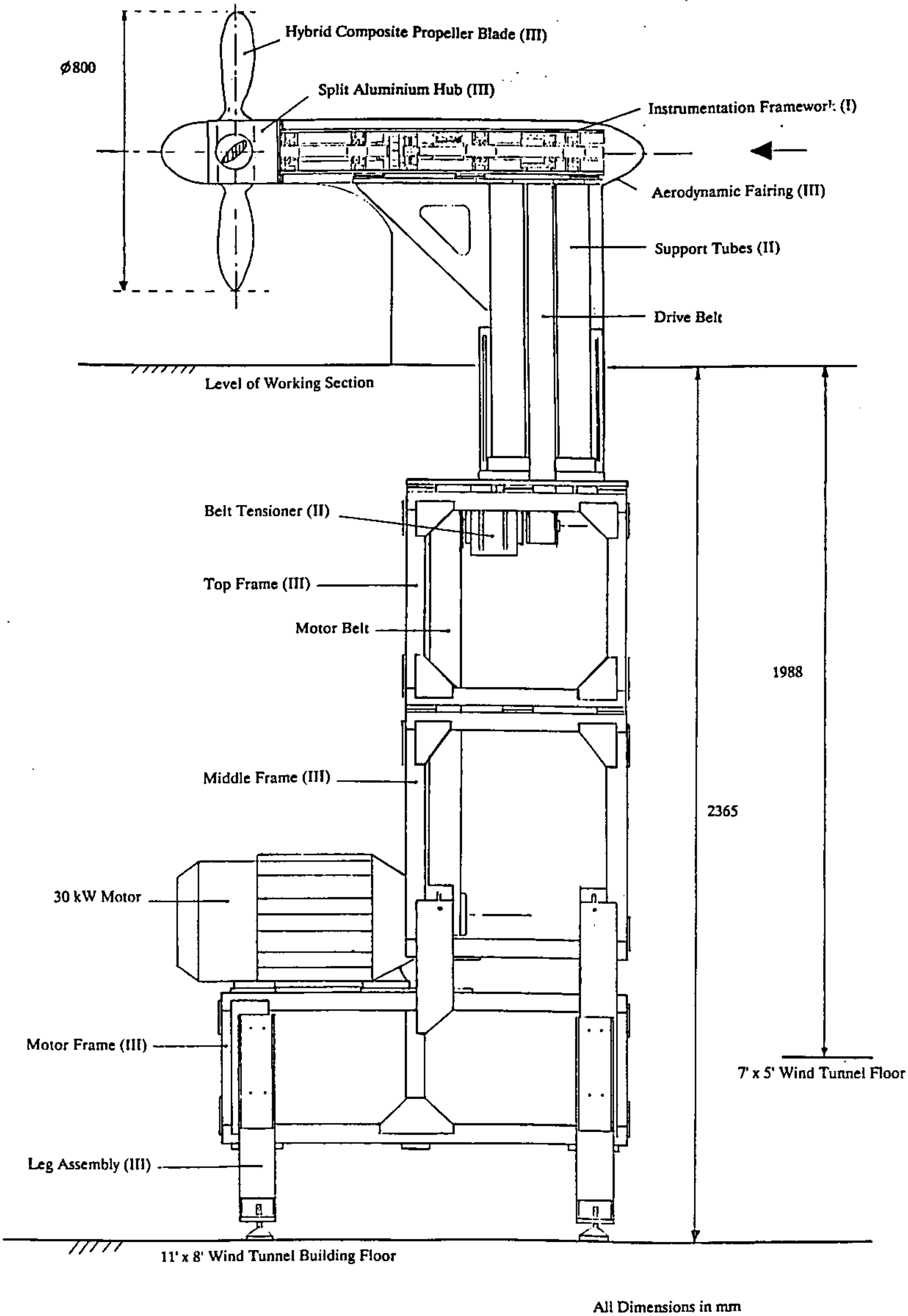
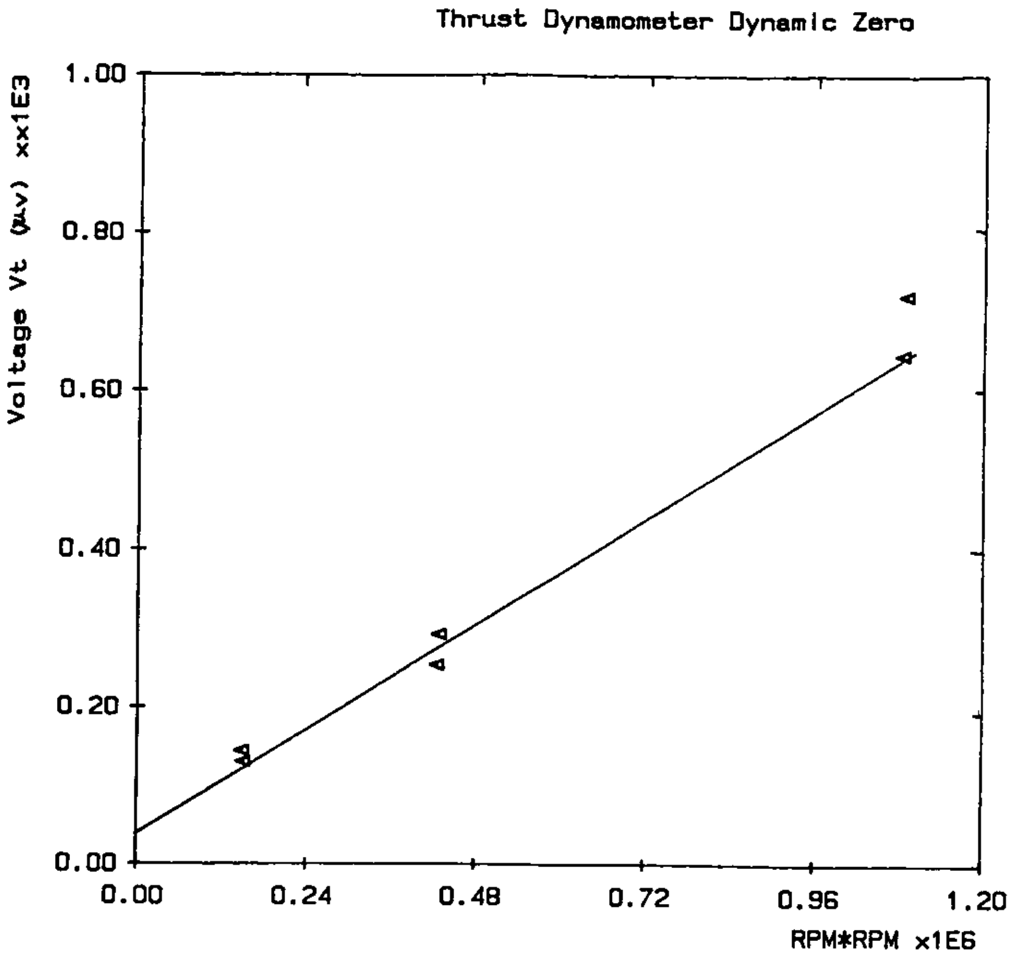


Figure 3 Side View of Propeller Rig



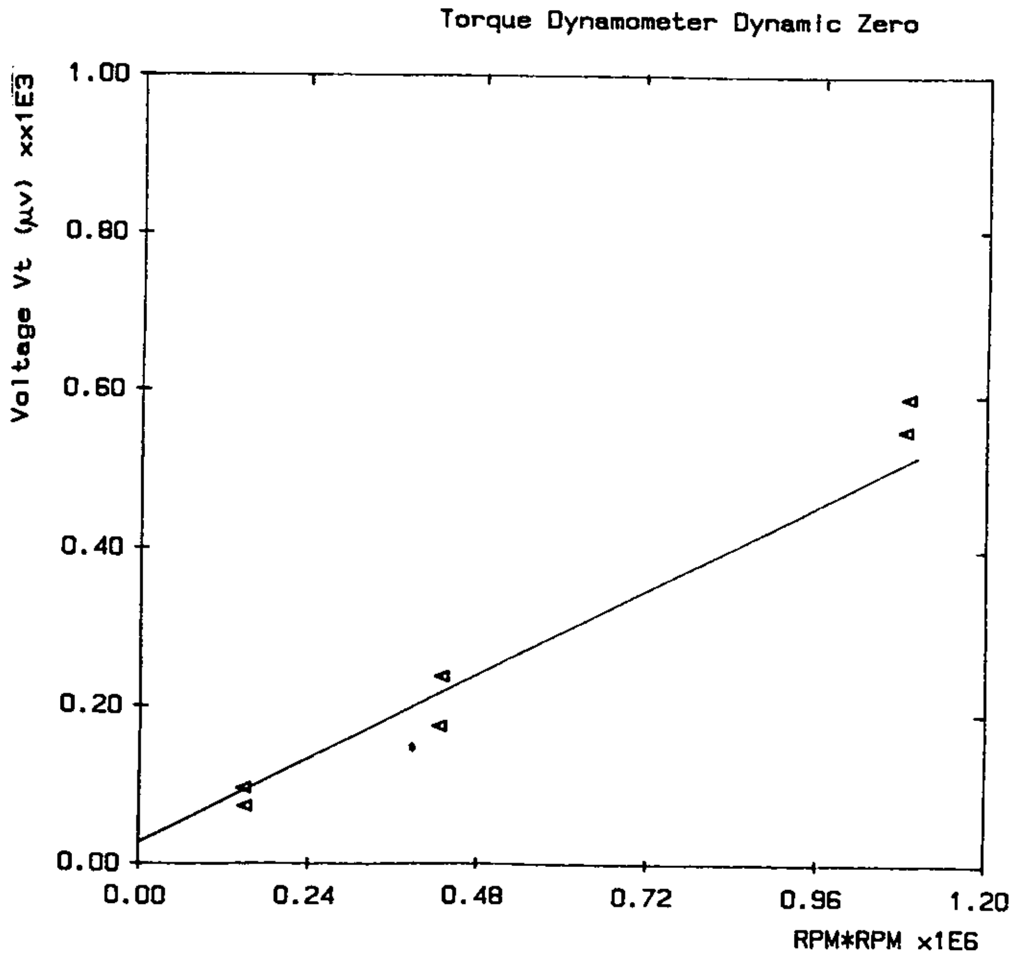


Figure 4 Derivation of Thrust and Torques Zeros

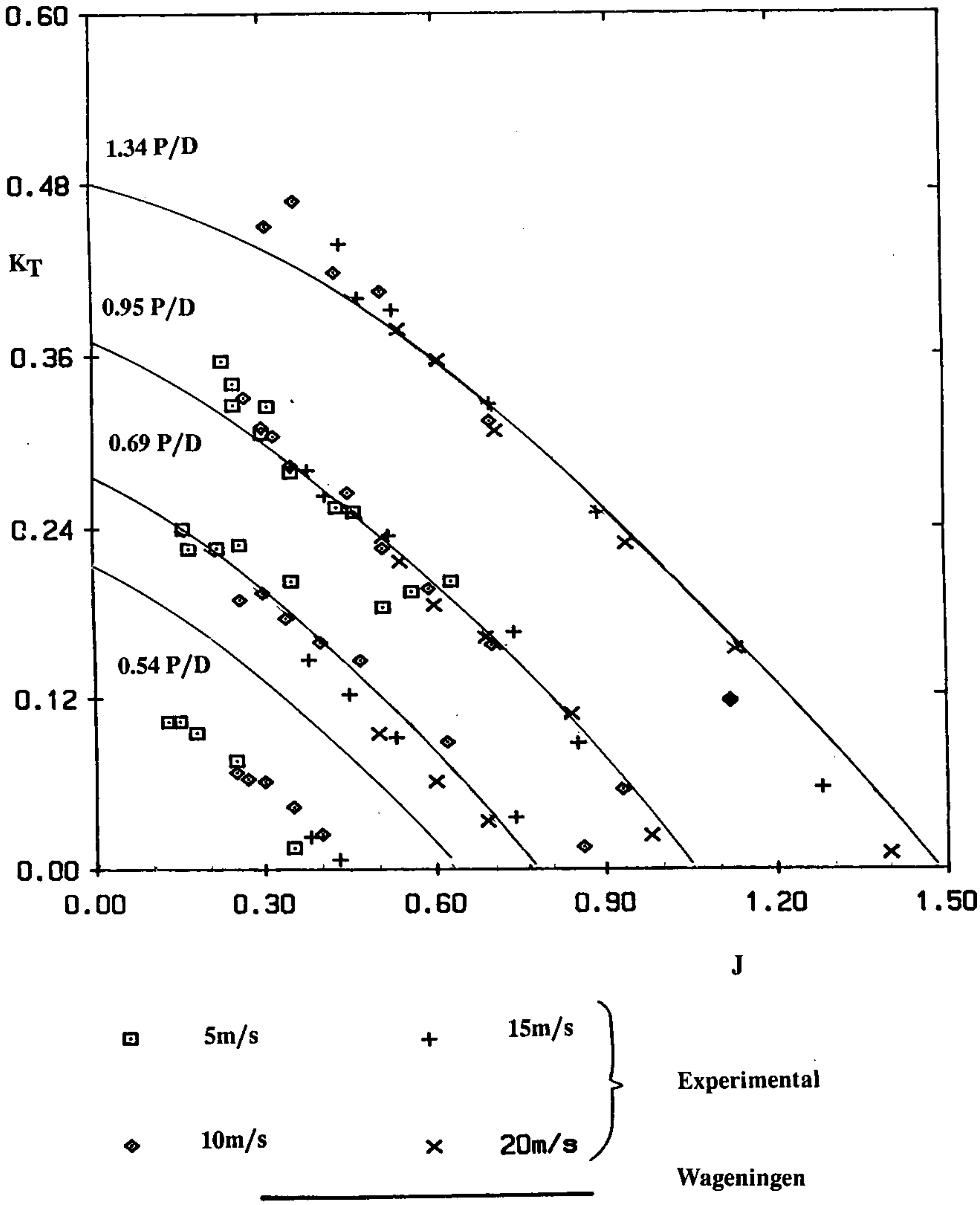


Figure 5 Modified Wageningen B4.40 Propeller Freestream (Open Water) K_T - J curves

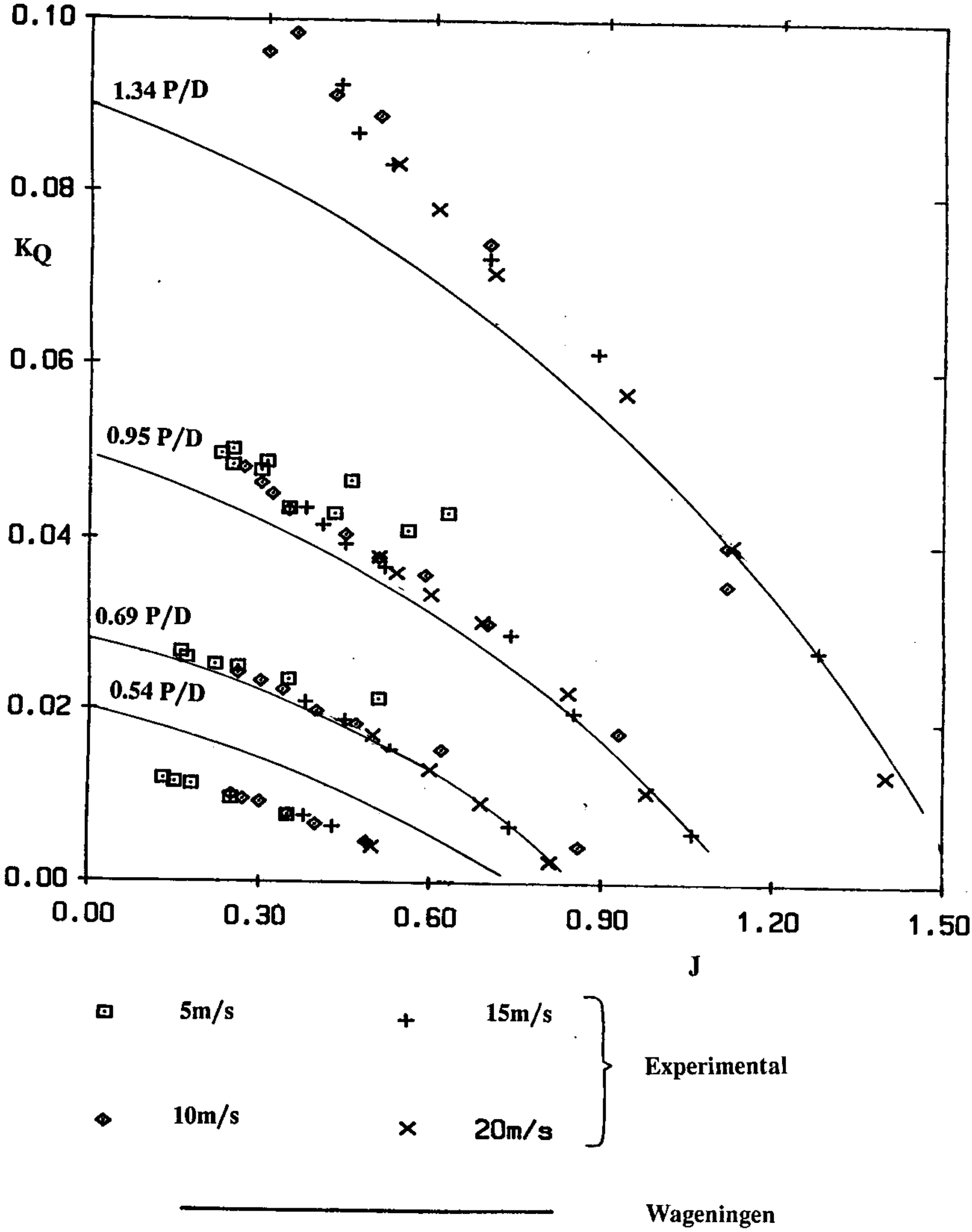


Figure 6 Modified Wageningen B4.40 Propeller Freestream (Open Water) K_Q - J curves

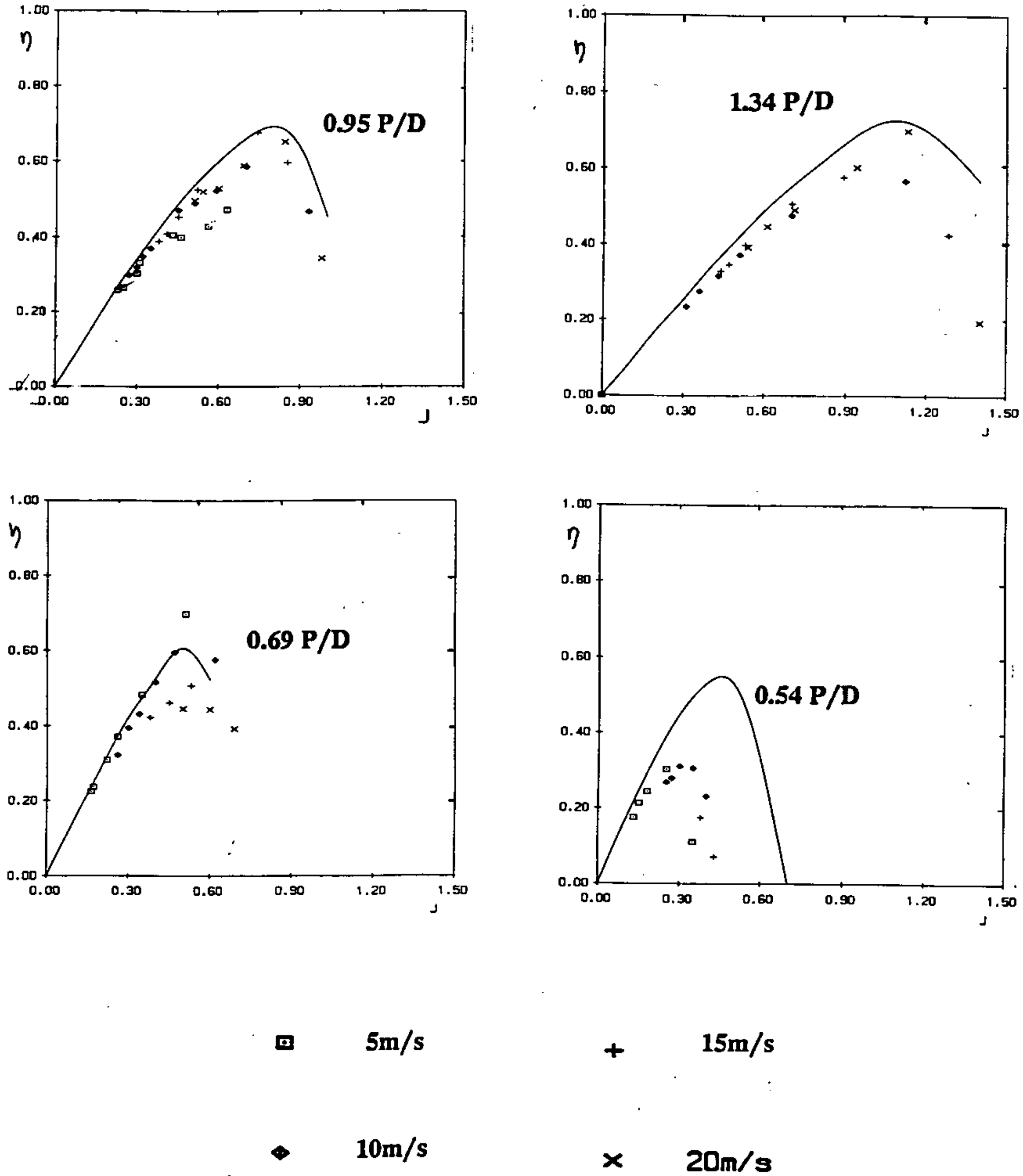


Figure 7 Modified Wageningen B4.40 Propeller Freestream (Open Water) η - J curves

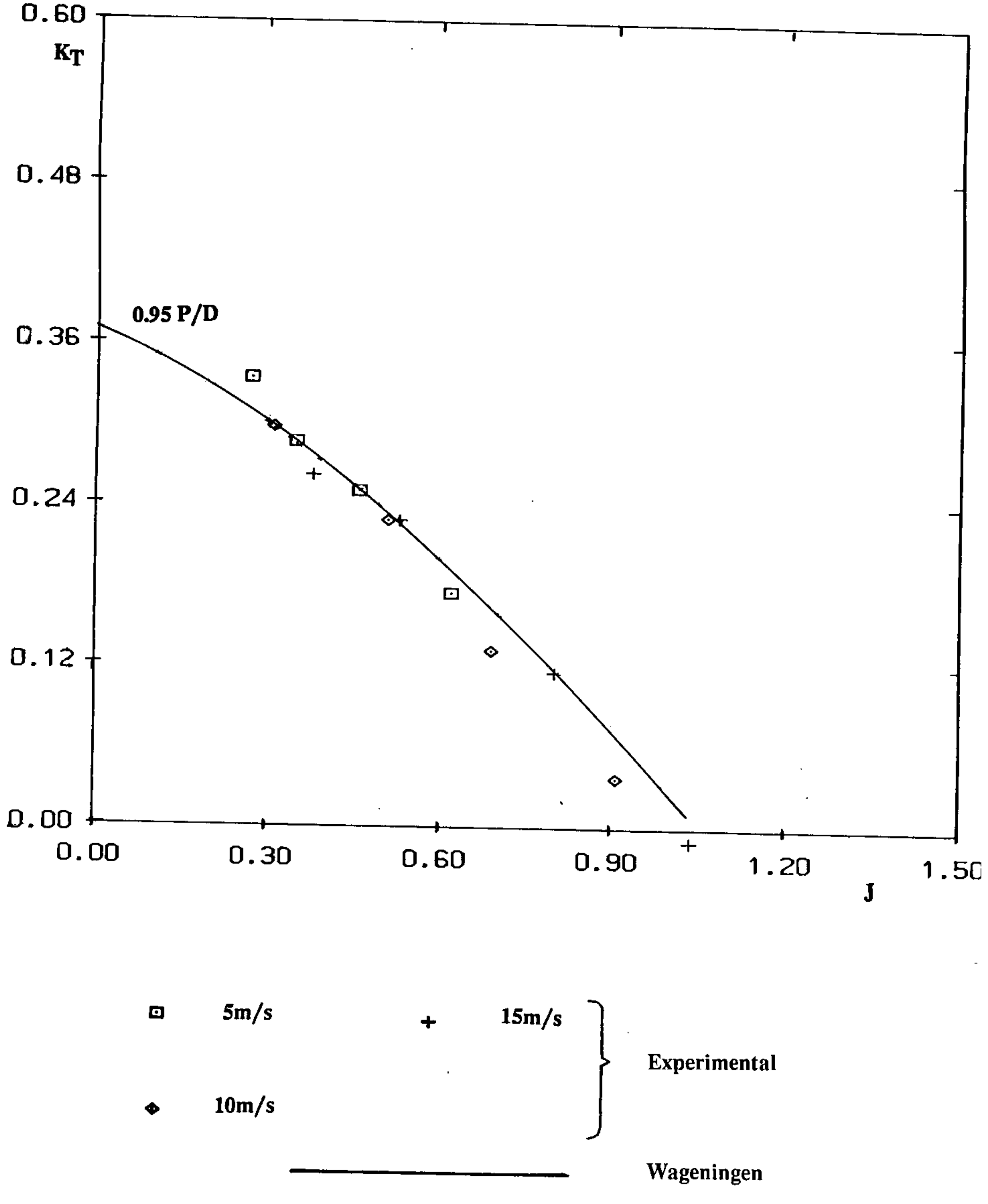


Figure 8 Modified Wageningen B4.40 Propeller Freestream (Open Water) with transition strip K_T - J curve

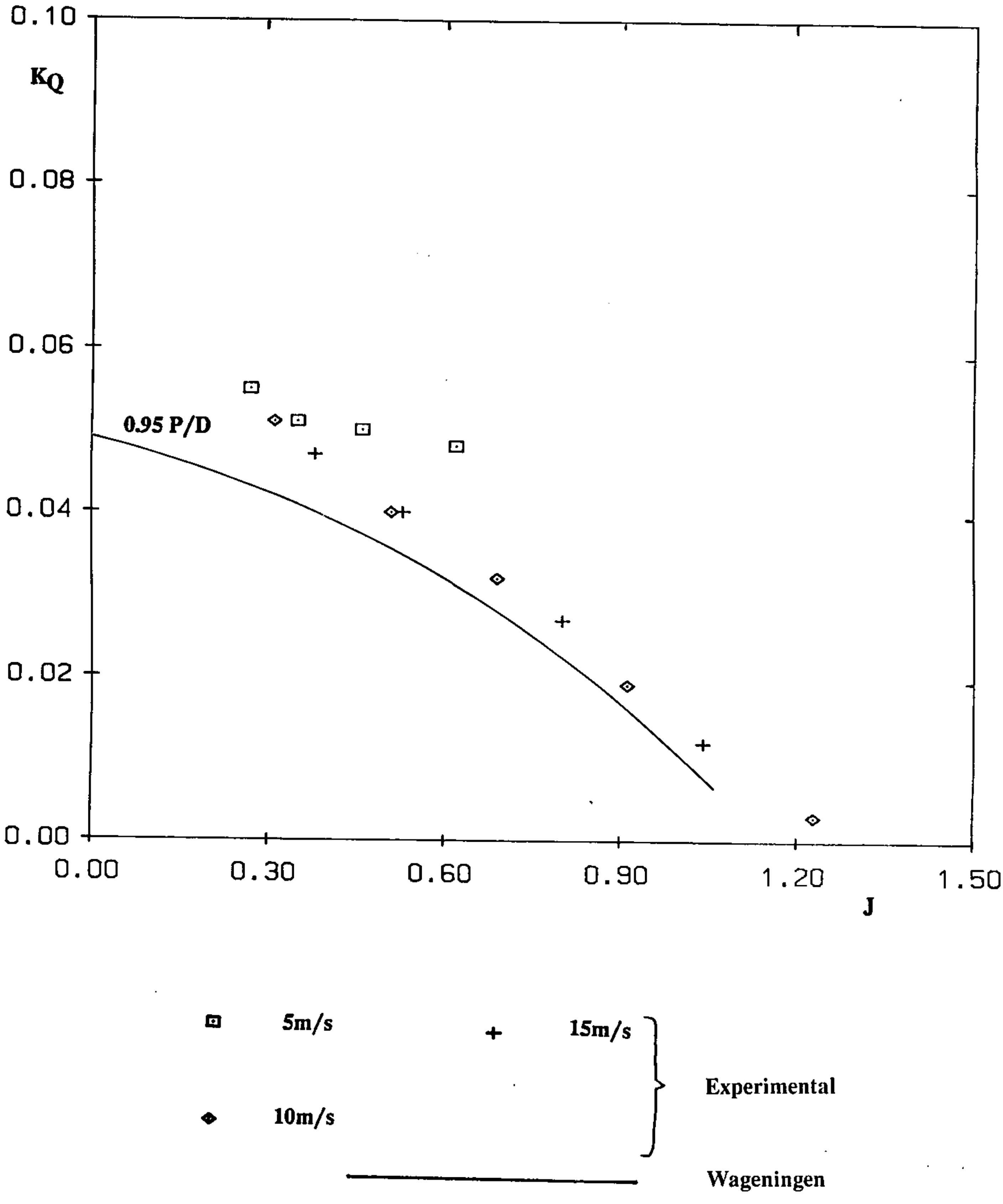


Figure 9 Modified Wageningen B4.40 Propeller Freestream (Open Water) with transition strip K_Q - J curve

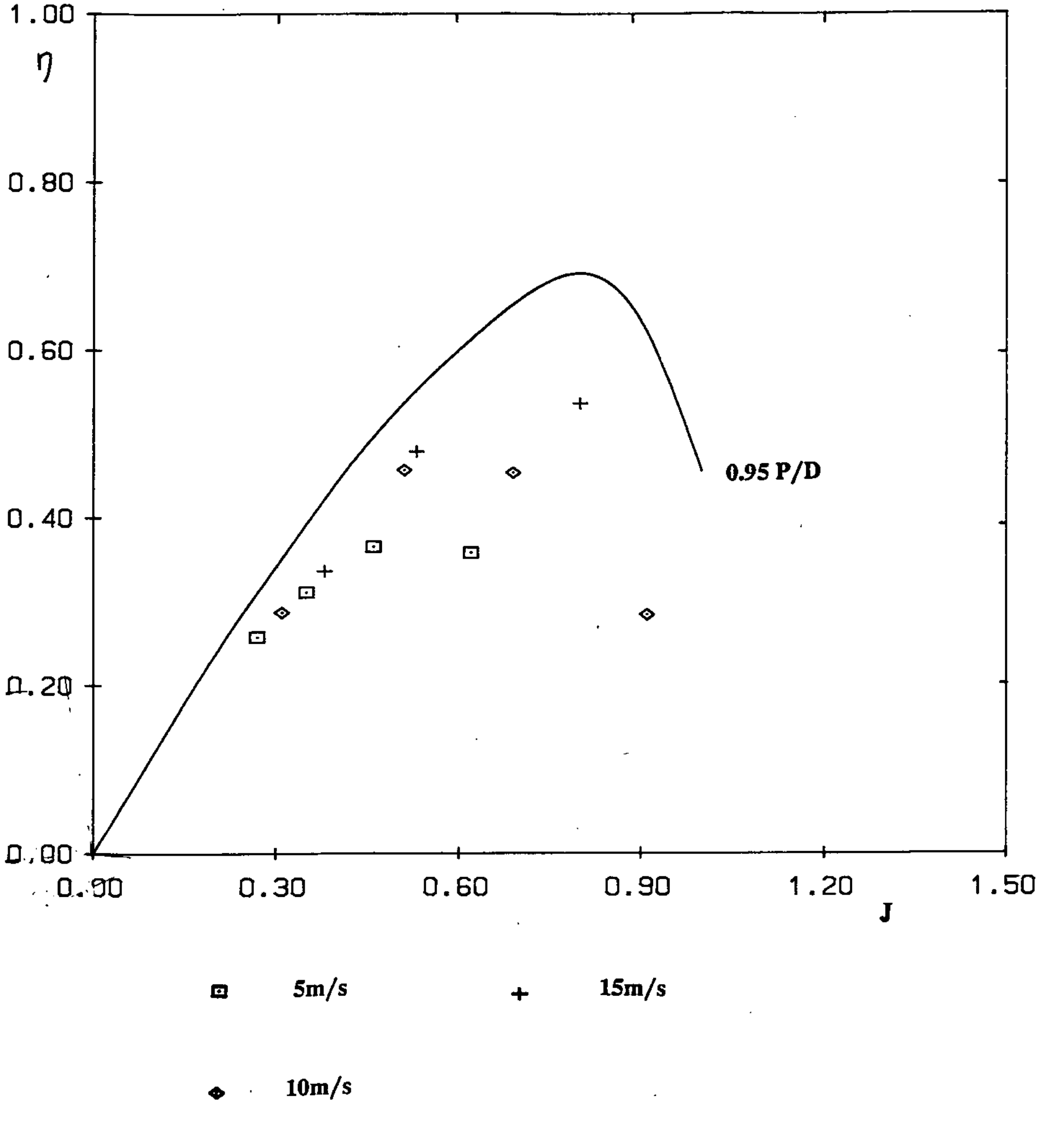


Figure 10 Modified Wageningen B4.40 Propeller Freestream (Open Water) with transition strip η - J curve