FURTHER COMPUTER-ANALYZED DATA OF THE WAGENINGEN B-SCREW SERIES

by

M.W.C. OOSTERVELD and P. VAN OOSSANEN *)

Summary

In this paper the open-water characteristics of the Wageningen B-series propellers are given in polynomials for use in preliminary ship design studies by means of a computer. These polynomials were obtained with the aid of a multiple regression analysis of the original open-water test data of the 120 propeller models comprising the B-series. All test data was corrected for Reynolds effects by means of an 'equivalent profile' method developed by Lerbs. For this Reynolds number effect additional polynomials are given. Criteria are included to facilitate the choice of expanded blade area and blade thickness. Finally, a number of new type of diagrams are given with which the optimum diameter and optimum RPM can easily be determined.

1. Introduction

In preliminary ship design studies in which the ship size, speed, principal dimensions and proportions are to be determined, the application of computers is rapidly increasing. Here, the hydrodynamic aspects, including resistance data, wake and thrust deduction data and the propeller characteristics are of importance.

In this paper the characteristics of screw propellers are given in a form suitable for use in preliminary design problems. These characteristics are obtained from open-water test results with the Wageningen B-screw series [1]**). B-series propellers are frequently used in practice and possess satisfactory efficiency and adequate cavitation properties. At present about 120 screw models of the B-series have been tested.

Some years ago the fairing of the B-screw series test results was started by means of a regression analysis. In addition, the test results were corrected for Reynolds number effects by using a method developed by Lerbs [2]. Preliminary results of these investigations were given by Van Lammeren et al [3] and by Oosterveld and Van Oossanen [4].

The fairing of the B-screw series test results has now been completed. The thrust and torque coefficients K_T and K_Q of the screws are expressed as polynomials in the advance ratio J, the pitch ratio P/D, the blade-area ratio A_E/A_O, and the blade number Z. In addition, the effect of Reynolds number and of the thickness of the blade profile at a characteristic radius is taken into account in the polynomials. As such the following relations have been determined:

$$K_T = f_1(J, P/D, A_E/A_O, Z, R_n, t/c)$$
$$K_Q = f_2(J, P/D, A_E/A_O, Z, R_n, t/c) \quad (1)$$

2. Geometry of B-series screws

A systematic screw series is formed by a number of screw models of which only the pitch ratio P/D is varied. All other characteristic screw dimensions such as the diameter D, the number of blades Z, the blade-area ratio A_E/A_O, the blade outline, the shape of blade sections, the blade thicknesses and the hub-diameter ratio d/D are the same. These screw series now comprises models with blade numbers ranging from 2 to 7, blade area ratios ranging from 0.30 to 1.05 and pitch ratios ranging from 0.5 to 1.4.

Table 1 gives the overall geometric properties of the original Wageningen B-series. The required coordinates of the profiles can be calculated by means of formulas, analogous to the formulas given by Van Gent and Van Oossanen [5] and Van Oossanen [6], viz:

$$\left.\begin{aligned} y_{face} &= V_1(t_{max} - t_{t.e.}) \\ y_{back} &= (V_1 + V_2)(t_{max} - t_{t.e.}) + t_{t.e.} \end{aligned}\right\} \text{for } P \leq 0 \quad (2)$$

and

*) Netherlands Ship Model Basin, Wageningen, the Netherlands.

**) Numbers in brackets refer to the list of references at the end of this paper.

Table 1
Dimensions of Wageningen B-propeller series.

Dimensions of four-, five-, six- and seven bladed B-screw series.					
r/R	$\frac{c_r}{D} \cdot \frac{Z}{A_E/A_O}$	a_r/c_r	b_r/c_r	$s_r/D=A_r-B_rZ$	
				A_r	B_r
0.2	1.662	0.617	0.350	0.0526	0.0040
0.3	1.882	0.613	0.350	0.0464	0.0035
0.4	2.050	0.601	0.351	0.0402	0.0030
0.5	2.152	0.586	0.355	0.0340	0.0025
0.6	2.187	0.561	0.389	0.0278	0.0020
0.7	2.144	0.524	0.443	0.0216	0.0015
0.8	1.970	0.463	0.479	0.0154	0.0010
0.9	1.582	0.351	0.500	0.0092	0.0005
1.0	0.000	0.000	0.000	0.0030	0.0000
Dimensions of three-bladed B-screw series.					
r/R	$\frac{c_r}{D} \cdot \frac{Z}{A_E/A_O}$	a_r/c_r	b_r/c_r	$s_r/D=A_r-B_rZ$	
				A_r	B_r
0.2	1.633	0.616	0.350	0.0526	0.0040
0.3	1.832	0.611	0.350	0.0464	0.0035
0.4	2.000	0.599	0.350	0.0402	0.0030
0.5	2.120	0.583	0.355	0.0340	0.0025
0.6	2.186	0.558	0.389	0.0278	0.0020
0.7	2.168	0.526	0.442	0.0216	0.0015
0.8	2.127	0.481	0.478	0.0154	0.0010
0.9	1.657	0.400	0.500	0.0092	0.0005
1.0	0.000	0.000	0.000	0.0030	0.0000

$A_r\ B_r$ = constants in equation for S_r/D

a_r = distance between leading edge and generator line at r

b_r = distance between leading edge and location of maximum thickness

c_r = chord length of blade section at radius r

s_r = maximum blade section thickness at radius r

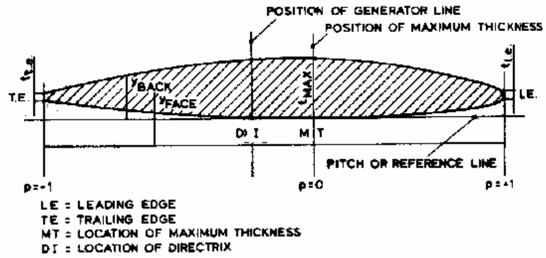

Figure 1. Definition of geometric blade section parameters of Wageningen B- and BB-series propellers.

$$\left.\begin{aligned} y_{face} &= V_1(t_{max} - t_{l.e.}) \\ y_{back} &= (V_1 + V_2)(t_{max} - t_{l.e.}) + t_{l.e.} \end{aligned}\right\} \text{for } P > 0 \qquad (3)$$

From Figure 1 it follows that:

y_{face}, y_{back} = vertical ordinate of a point on a blade section on the face and on the back with respect to the pitch line,

t_{max} = maximum thickness of blade section,

$t_{t.e.}$, $t_{l.e.}$ = extrapolated blade section thickness at the trailing and leading edges,

V_1, V_2 = tabulated functions dependent on r/R and P,

P = non-dimensional coordinate along pitch line from position of maximum thickness to leading edge (where P=1), and from position of maximum thickness to trailing edge (where P = -1).

Values of V_1 and V_2 are given in Tables 2 and 3. The values of $t_{l.e.}$ and $t_{t.e.}$ are usually chosen in accordance with rules laid down by classification societies or in accordance with manufacturing requirements. In conjunction with the geometry of this propeller series, it is remarked that at the Netherlands Ship Model Basin modified B-series propellers are now used and designed, which have a slightly wider blade contour near the blade tip. These propellers are denoted as 'BB' propellers. For the sake of completeness, Table 4 is included which gives the particulars of this series. The performance characteristics of these BB-series propellers may be considered identical with the original B-series propellers.

Table 2

Values of V_1 for use in equations 2 and 3.

r/R \ P	-1.0	-.95	-.9	-.8	-.7	-.6	-.5	-.4	-.2	0
.7-1.0	0	0	0	0	0	0	0	0	0	0
.6	0	0	0	0	0	0	0	0	0	0
.5	.0522	.0420	.0330	.0190	.0100	.0040	.0012	0	0	0
.4	.1467	.1200	.0972	.0630	.0395	.0214	.0116	.0044	0	0
.3	.2306	.2040	.1790	.1333	.0943	.0623	.0376	.0202	.0033	0
.25	.2598	.2372	.2115	.1651	.1246	.0899	.0579	.0350	.0084	0
.2	.2826	.2630	.2400	.1967	.1570	.1207	.0880	.0592	.0172	0
.15	.3000	.2824	.2650	.2300	.1950	.1610	.1280	.0955	.0365	0

r/R \ P	+1.0	+.95	+.9	+.85	+.8	+.7	+.6	+.5	+.4	+.2	0
.7-1.0	0	0	0	0	0	0	0	0	0	0	0
.6	.0382	.0169	.0067	.0022	.0006	0	0	0	0	0	0
.5	.1278	.0778	.0500	.0328	.0211	.0085	.0034	.0008	0	0	0
.4	.2181	.1467	.1088	.0833	.0637	.0357	.0189	.0090	.0033	0	0
.3	.2923	.2186	.1760	.1445	.1191	.0790	.0503	.0300	.0148	.0027	0
.25	.3256	.2513	.2068	.1747	.1465	.1008	.0669	.0417	.0224	.0031	0
.2	.3560	.2821	.2353	.2000	.1685	.1180	.0804	.0520	.0304	.0049	0
.15	.3860	.3150	.2642	.2230	.1870	.1320	.0920	.0615	.0384	.0096	0

Table 3

Values of V_2 for use in equations 2 and 3.

r/R \ P	-1.0	-.95	-.9	-.8	-.7	-.6	-.5	-.4	-.2	0
.9-1.0	0	.0975	.19	.36	.51	.64	.75	.84	.96	1
.85	0	.0975	.19	.36	.51	.64	.75	.84	.96	1
.8	0	.0975	.19	.36	.51	.64	.75	.84	.96	1
.7	0	.0975	.19	.36	.51	.64	.75	.84	.96	1
.6	0	.0965	.1885	.3585	.5110	.6415	.7530	.8426	.9613	1
.5	0	.0950	.1865	.3569	.5140	.6439	.7580	.8456	.9639	1
.4	0	.0905	.1810	.3500	.5040	.6353	.7525	.8415	.9645	1
.3	0	.0800	.1670	.3360	.4885	.6195	.7335	.8265	.9583	1
.25	0	.0725	.1567	.3228	.4740	.6050	.7184	.8139	.9519	1
.2	0	.0640	.1455	.3060	.4535	.5842	.6995	.7984	.9446	1
.15	0	.0540	.1325	.2870	.4280	.5585	.6770	.7805	.9360	1

r/R \ P	+1.0	+.95	+.9	+.85	+.8	+.7	+.6	+.5	+.4	+.2	0
.9-1.0	0	.0975	.1900	.2775	.3600	.51	.6400	.75	.8400	.9600	1
.85	0	.1000	.1950	.2830	.3660	.5160	.6455	.7550	.8450	.9615	1
.8	0	.1050	.2028	.2925	.3765	.5265	.6545	.7635	.8520	.9635	1
.7	0	.1240	.2337	.3300	.4140	.5615	.6840	.7850	.8660	.9675	1
.6	0	.1485	.2720	.3775	.4620	.6060	.7200	.8090	.8790	.9690	1
.5	0	.1750	.3056	.4135	.5039	.6430	.7478	.8275	.8880	.9710	1
.4	0	.1935	.3235	.4335	.5220	.6590	.7593	.8345	.8933	.9725	1
.3	0	.1890	.3197	.4265	.5130	.6505	.7520	.8315	.8920	.9750	1
.25	0	.1758	.3042	.4108	.4982	.6359	.7415	.8259	.8899	.9751	1
.2	0	.1560	.2840	.3905	.4777	.6190	.7277	.8170	.8875	.9750	1
.15	0	.1300	.2600	.3665	.4520	.5995	.7105	.8055	.8825	.9760	1

Table 4
Particulars of BB-series propellers.

r/R	$\frac{c_r}{D} \cdot \frac{Z}{A_E/A_O}$	a_r/c_r	b_r/c_r
0.200	1.600	0.581	0.350
0.300	1.832	0.584	0.350
0.400	2.023	0.580	0.351
0.500	2.163	0.570	0.355
0.600	2.243	0.552	0.389
0.700	2.247	0.524	0.443
0.800	2.132	0.480	0.486
0.850	2.005	0.448	0.498
0.900	1.798	0.402	0.500
0.950	1.434	0.318	0.500
0.975	1.122	0.227	0.500

a_r = distance between leading edge and generator line at r

b_r = distance between leading edge and location of maximum thickness at r

c_r = chord length at r

3. Analysis of model test data

The open-water test results of B-series propellers are given in the conventional way in the form of the thrust and torque coefficients K_T and K_Q, expressed as a function of J and the pitch ratio P/D, where:

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

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

$$J = \frac{V_A}{nD} \tag{6}$$

in which

T = propeller thrust,
Q = propeller torque,
ρ = fluid density,
n = revolutions of propeller per second,
D = propeller diameter,
V_A = velocity of advance.

The open-water efficiency is defined as:

$$\eta_o = \frac{J}{2\pi} \frac{K_T}{K_Q} \tag{7}$$

The effect of a Reynolds number variation on the test results has been taken into account by using the method developed by Lerbs [2], from the characteristics of equivalent blade sections. This method has been followed also in References 7, 8, 9 and 10.

In the Lerbs equivalent profile method the blade section at 0.75R is assumed to be equivalent for the whole blade. At a specific value of the advance coefficient J, the lift and drag coefficient C_L and C_D and the corresponding angle of attack α, for the blade section, are deduced from the K_T- and K_Q -values from the open-water test.

Reynolds number effects are only considered to influence the drag coefficient of the equivalent profile. It is furthermore assumed that this influence is in accordance with a vertical shift of the C_D-curve, equal to the change in the minimum value of the drag coefficient. This minimum value is for thin profiles composed of mainly frictional resistance, the effect of the pressure gradient being small.

According to Hoerner [11], the minimum drag coefficient of a profile is:

$$C_{D_{min}} = 2C_f(1 + 2\frac{t}{c_{0.75R}}) \tag{8}$$

in which;

$$C_f = \frac{0.075}{[0.43429 \ln(R_{n_{0.75R}}) - 2]^2} \tag{9}$$

where

$$R_{n_{0.75R}} = \frac{c_{0.75R}\sqrt{V_A^2 + (0.75\pi nD)^2}}{\nu} \tag{10}$$

C_f is the drag coefficient of a flat plate in a turbulent flow and the term $1 + 2\frac{t}{c_{0.75R}}$ represents the effect of the pressure gradient; $c_{0.75R}$ is the chord length at 0.75R and ν the kinematical viscosity.

On setting out the minimum value of the drag coefficient as obtained from the polar curve for each propeller on a base of Reynolds number, a large scatter is apparent as shown in Figure 2. When this minimum value of the drag coefficient

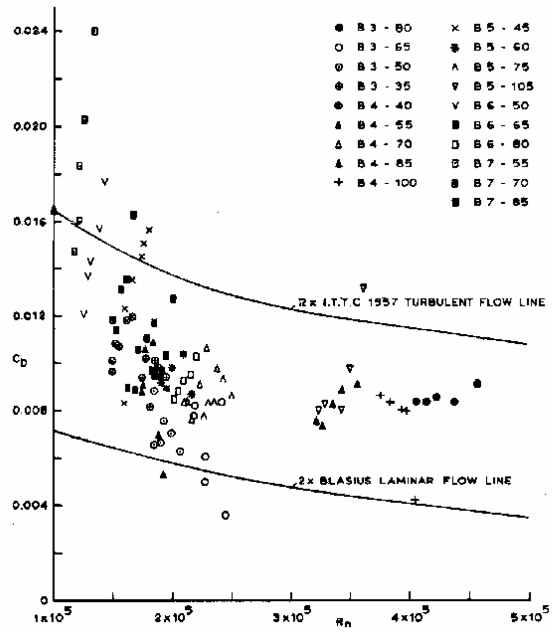

Figure 2. Uncorrected value of minimum drag coefficient of equivalent profile of B-series propellers.

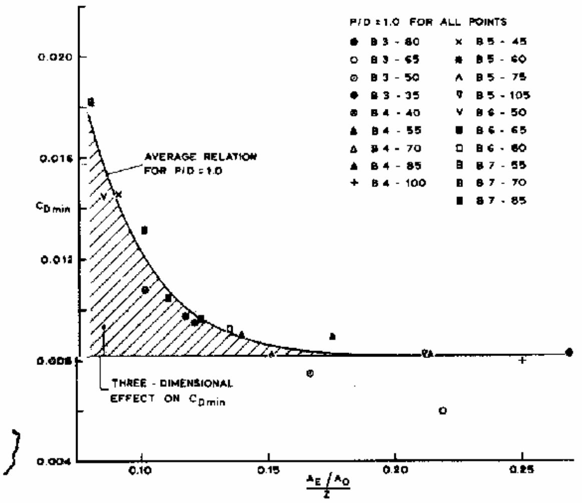

Figure 3. Three-dimensional effect on minimum drag coefficient of equivalent profile of B-series propellers.

is set out against $\frac{A_E/A_O}{Z}$ for each pitch-diameter ratio, it is seen that below a specific value of the blade area-blade number ratio an increase in the $C_{D_{min.}}$ value occurs. For a pitch-diameter ratio equal to 1.0, this is shown in Figure 3. The existence of such a correlation of the $C_{D_{min.}}$ value with propeller geometry points to the fact that the scatter in Figure 2 is not entirely due to Reynolds number effects and experimental errors. It is obvious that the drag coefficient is influenced by a three-dimensional effect. It is necessary, therefore, before correcting for Reynolds number according to the given equations, to subtract this three-dimensional effect from the $C_{D_{min.}}$ value. An estimation of this effect was obtained by applying regression analysis of which the results are given by Van Oossanen [6].

The thus obtained lift and drag coefficients were each expressed as a function of blade number, blade area ratio, pitch-diameter ratio and angle of attack in polynomials by means of a multiple regression analysis method. By applying this process in reverse, thrust and torque coefficient values were then calculated. The basis for this reverse process was formed by calculating C_L and C_D coefficients from the C_L and C_D polynomials for specific combinations of Z, A_E/A_O, P/D, α and R_n. The resulting values formed the input for the development of a thrust coefficient and a torque coefficient polynomial. The thrust and torque coefficients were then expressed as polynomials in the advance coefficient J, pitch ratio P/D, blade area ratio A_E/A_O and blade number Z and with the aid of a multiple regression analysis method the significant terms of the polynomials and the values of the corresponding coefficients were determined. For $R_n = 2x10^6$ the polynomials obtained in this way are given in Table 5. The choice of a Reynolds number value of $2x10^6$ for the characteristics on the model scale followed from the fact that the corresponding $C_{D_{min.}}$ values is an average of all model $C_{D_{min.}}$ values.

4. Reynolds number effect on propeller chararacteristics

In formulating the minimum value of the drag coefficient as a function of the Reynolds number (see equation 8), it is possible to calculate thrust and torque values valid for full-scale by correcting this C_D-value.

This was performed for Reynolds numbers equal to $2x10^7$, $2x10^8$ and $2x10^9$ for a selected grid of J, P/D, A_E/A_O and Z-values. Together with the values for $R_n = 2x10^6$, these K_T and K_Q values formed the input for the determination of a K_T and K_Q polynomial for the additional Reynolds number effect above $2x10^6$. These polynomials are given in Table 6. The actual value to be substituted into these polynomials is the common logarithm of the actual Reynolds number. Thus if $R_n = 2x10^7$, the value to be substituted is 7.3010.

To demonstrate how the Reynolds number effect is dependent on the number of propeller blades, the blade area ratio, the pitch-diameter ratio and the advance coefficient, diagrams have been prepared each of which gives the effect of one of these parameters on K_T and K_Q with increasing Reynolds number. The effect of the number of blades is shown in Figure 4 while the effect of the expanded blade area ratio is shown in Figure 5. Figure 6 gives the effect of the pitch-diameter ratio and Figure 7 shows the effect of the advance coefficient J. The results shown are for the propellers grouped around the B5-75 ($Z = 5$, $A_E/A_O = 0.75$) propeller with a pitch-diameter ratio of 1.0, working at an advance coefficient equal to 0.5.

Table 5

Coefficients and terms of the K_T and K_Q polynomials for the Wageningen B-screw Series for $R_n = 2x10^6$.

$$K_T = \sum_{s,t,u,v} \left[C_{s,t,u,v} \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_O)^u \cdot (Z)^v \right]$$
$$K_Q = \sum_{s,t,u,v} \left[C_{s,t,u,v} \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_O)^u \cdot (Z)^v \right]$$

K_T: $C_{s,t,u,v}$	s (J)	t (P/D)	u (A_E/A_O)	v (Z)	K_Q: $C_{s,t,u,v}$	s (J)	t (P/D)	u (A_E/A_O)	v (Z)
0.00880496	0	0	0	0	0.00379368	0	0	0	0
0.204554	1	0	0	0	0.00886523	2	0	0	0
0.166351	0	1	0	0	0.032241	1	1	0	0
0.158114	0	2	0	0	0.00344778	0	2	0	0
0.147581	2	0	1	0	0.0408811	0	1	1	0
0.481497	1	1	1	0	0.108009	1	1	1	0
0.415437	0	2	1	0	0.0885381	2	1	1	0
0.0144043	0	0	0	1	-0.188561	0	2	1	0
0.0530054	2	0	0	1	0.00370871	1	0	0	1
0.0143481	0	1	0	1	0.00513696	0	1	0	1
0.0606826	1	1	0	1	0.0209449	1	1	0	1
0.0125894	0	0	1	1	0.00474319	2	1	0	1
0.0109689	1	0	1	1	0.00723408	2	0	1	1
0.133698	0	3	0	0	0.00438388	1	1	1	1
0.00638407	0	6	0	0	0.0269403	0	2	1	1
0.00132718	2	6	0	0	0.0558082	3	0	1	0
0.168496	3	0	1	0	-0.0161886	0	3	1	0
0.0507214	0	0	2	0	0.00318086	1	3	1	0
0.0854559	2	0	2	0	-0.015896	0	0	2	0
0.0504475	3	0	2	0	0.0471729	1	0	2	0
0.010465	1	6	2	0	0.0196283	3	0	2	0
0.00648272	2	6	2	0	0.0502782	0	1	2	0
0.00841728	0	3	0	1	0.030055	3	1	2	0
0.0168424	1	3	0	1	0.0417122	2	2	2	0
0.00102296	3	3	0	1	0.0397722	0	3	2	0
0.0317791	0	3	1	1	0.00350024	0	6	2	0
0.018604	1	0	2	1	0.0106854	3	0	0	1
0.00410798	0	2	2	1	0.00110903	3	3	0	1
0.000606848	0	0	0	2	0.000313912	0	6	0	1
0.0049819	1	0	0	2	0.0035985	3	0	1	1
0.0025983	2	0	0	2	0.00142121	0	6	1	1
0.000560528	3	0	0	2	0.00383637	1	0	2	1
0.00163652	1	2	0	2	0.0126803	0	2	2	1
0.000328787	1	6	0	2	0.00318278	2	3	2	1
0.000116502	2	6	0	2	0.00334268	0	6	2	1
0.000690904	0	0	1	2	0.00183491	1	1	0	2
0.00421749	0	3	1	2	0.000112451	3	2	0	2
0.0000565229	3	6	1	2	0.0000297228	3	6	0	2
0.00146564	0	3	2	2	0.000269551	1	0	1	2
					0.00083265	2	0	1	2
					0.00155334	0	2	1	2
					0.000302683	0	6	1	2
					0.0001843	0	0	2	2
					0.000425399	0	3	2	2
					0.0000869243	3	3	2	2
					0.0004659	0	6	2	2
					0.0000554194	1	6	2	2

$R_n = 2 \cdot 10^6$

Table 6

Polynomials for Reynolds number effect (above $R_n = 2x10^6$) on K_T and K_Q.

$$
\begin{aligned}
\Delta K_T = \; & 0.000353485 \\
& -0.00333758(A_E/A_O)J^2 \\
& -0.00478125(A_E/A_O)(P/D)J \\
& +0.000257792(\log R_n-0.301)^2 \cdot (A_E/A_O)J^2 \\
& +0.0000643192(\log R_n-301)(P/D)^6 \cdot J^2 \\
& -0.0000110636(\log R_n-0.301)^2 (P/D)^6 J^2 \\
& -0.0000276305(\log R_n-0.301)^2 z(A_E/A_O)J^2 \\
& +0.0000954(\log R_n-0.301) z(A_E/A_O)(P/D)J \\
& +0.0000032049(\log R_n-0.301) z^2(A_E/A_O)(P/D)^3 J
\end{aligned}
$$

$$
\begin{aligned}
\Delta K_Q = \; & -0.000591412 \\
& +0.00696898(P/D) \\
& -0.0000666654\, z(P/D)^6 \\
& +0.0160818(A_E/A_O)^2 \\
& -0.000938091(\log R_n-0.301)(P/D) \\
& -0.00059593(\log R_n-0.301)(P/D)^2 \\
& +0.0000782099(\log R_n-0.301)^2 (P/D)^2 \\
& +0.0000052199(\log R_n-0.301) z(A_E/A_O)J^2 \\
& -0.00000088528(\log R_n-0.301)^2 z(A_E/A_O)(P/D)J \\
& +0.0000230171(\log R_n-0.301) z(P/D)^6 \\
& -0.00000184341(\log R_n-0.301)^2 z(P/D)^6 \\
& -0.00400252(\log R_n-0.301)(A_E/A_O)^2 \\
& +0.000220915(\log R_n-0.301)^2 (A_E/A_O)^2
\end{aligned}
$$

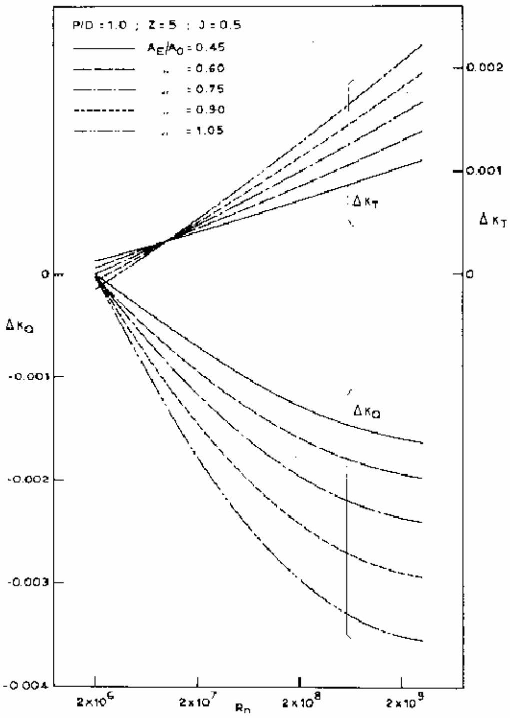

Figure 5. Influence of blade area ratio on Reynolds number effect on thrust and torque coefficients.

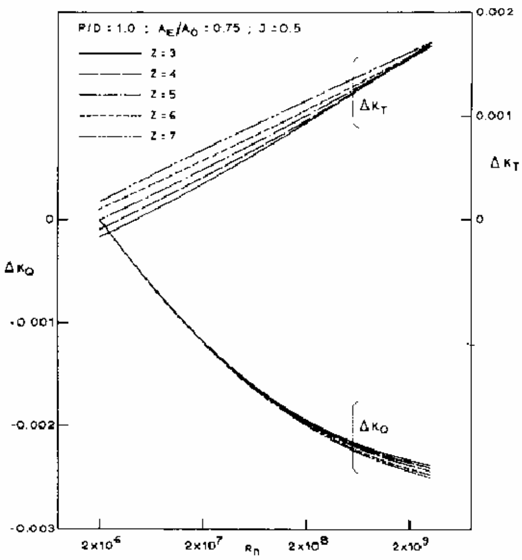

Figure 4. Influence of number of blades on Reynolds number effect on thrust and torque coefficients.

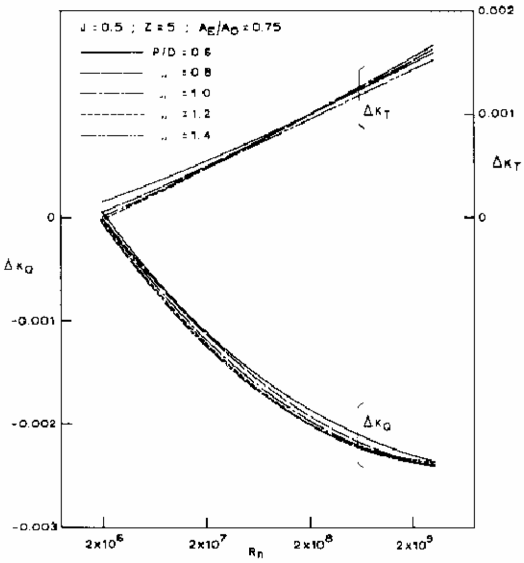

Figure 6. Influence of pitch-diameter ratio on Reynolds number effect on thrust and torque coefficients.

It should be noticed that the increment in K_T (ΔK_T) and the increment in K_Q (ΔK_Q) presented in Figures 4 to 7 are relative to a Reynolds number value of 2×10^6. The value of the Reynolds number is determined by equation 10. Strictly, therefore, the ΔK_T and ΔK_Q values for a Reynolds number equal to 2×10^6 should equal zero. As shown in Figures 4 to 7, this is not the case. This is due to the difficulty in multiple regression analysis methods to prescribe that the resulting relation must have a specific value for a particular combination of values for the independent variables.

5. Effect of variation in blade thickness on propeller characteristics

The effect of blade thickness on the thrust and torque coefficients can be determined in an analogous manner as used to determine the effect of Reynolds number as described in section 4. A change in the t/c-value of the equivalent propeller blade section at 0.75R is again only considered to influence the value of the minimum drag coefficient. Thus, as was the case in analysing the effect of Reynolds number, the drag coefficient of the equivalent blade section as a function of angle of attack (or advance ratio) is shifted vertically upwards or downwards in accordance with the change in the value of the minimum drag coefficient $C_{D_{min}}$. This situation, therefore, leads to the idea that the effect of a specific change in the t/c-value at 0.75R can be represented by a specific change in Reynolds number.

The polynomials given in Tables 5 and 6 are for a blade thickness-chord length ratio equal to:

$$t/c_{0.75R} = \frac{(0.0185 - 0.00125Z)Z}{2.073\, A_E/A_O} \qquad (11)$$

By rearranging equation 8, 9 and 10 a change in this value of t/c can be shown to correspond to a new value of the Reynolds number given by:

$$R^1_{n0.75R} = \exp\left[4.6052 + \sqrt{\frac{1+2(t/c)_{0.75R}}{1+2(t/c)^1_{0.75R}}}\,(\ln R_{n0.75R} - 4.6052)\right] \qquad (12)$$

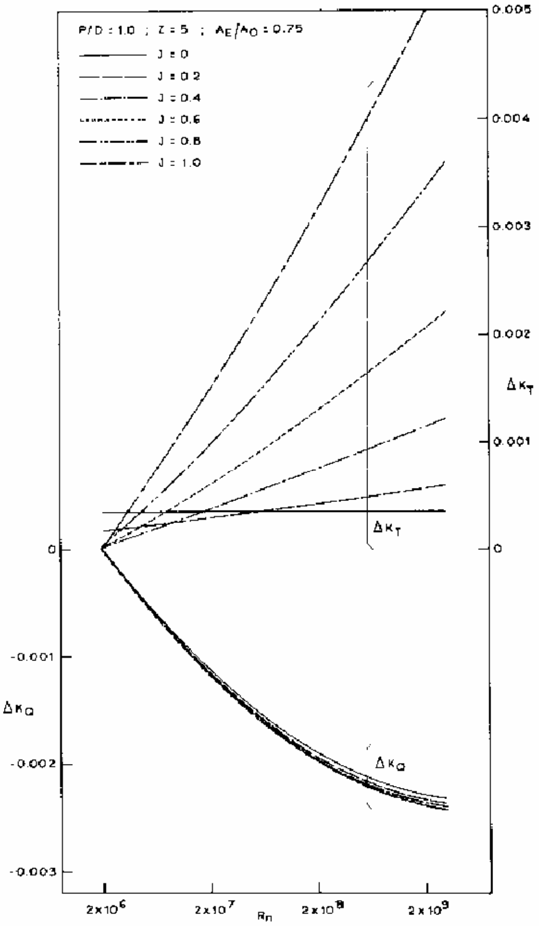

Figure 7. Influence of advance ratio on Reynolds number effect on thrust and torque coefficients.

where

$R^1_{n0.75R}$ = effective Reynolds number for a change in $(t/c)_{0.75R}$

and

$(t/c)^1_{0.75R}$ = new t/c value at 0.75R.

Thus, when it is assumed that an increase or decrease in blade section thickness (relative to equation 11) does not influence the effective camber and pitch, the effect on thrust and torque can be ascertained by calculating an effective new value for the Reynolds number according to equation 12 and then determining, by means of the polynomials presented in Table 5 and Table 6, the associated values of K_T and K_Q.

6. Choice of blade area ratio based on cavitation criteria

A reasonable indication as to the required blade area ratio of fixed pitch propellers can be obtained by means of a formula given by Keller [12], viz:

$$\frac{A_E}{A_O}=\frac{(1.3+0.3Z)T}{(P_o-P_V)\cdot D^2}+K \qquad (13)$$

where

$\frac{A_E}{A_O}$ = expanded blade area ratio,
Z = number of blades,
T = propeller thrust in kg,
P_o = static pressure at centre line of propeller shaft in kg/m^2,
P_V = vapour pressure in kg/m^2,
K = constant which can be put equal to 0 for fast twin-screw ships,
K = 0.10 for other twin-screw ships,
K = 0.20 for single-screw ships.

7. Choice of characteristic thickness chord length ratio based on cavitation criteria and strength

In a number of previous studies [13, 5], it is shown that the minimum allowable blade section thickness based on strength criteria does not give the largest margin against cavitation when operating in a non-uniform velocity field. In a propeller design the proper compromise between the conflicting characters of thick blade sections (having a large cavitation-free angle of attack range) and thin blade sections (being free of cavitation at low cavitation numbers at shock-free entry of the flow) must be made.

For every type of thickness and camber distribution used, there is only one optimum t/c-value for a specific value of the cavitation number. For propeller blade sections with an elliptic type of thickness distribution the optimum t/c-value, giving the largest cavitation-free lift coefficient range, can be approximately given by:

$$(t/c)_{opt}=0.3\sigma-0.012 \qquad (14)$$

where

σ = cavitation number of the blade section in the vertical upright blade position.

Relation 14 is only valid for small blade section cambers and values of the cavitation number between 0.1 and 0.6. A handy formula for the value of the cavitation number of the blade section at 0.75R in the vertical upright blade position is:

$$\sigma=\frac{200+20(h-0.375D)}{V_A^2+(0.04ND)^2} \qquad (15)$$

in which

h = distance in meter of propeller shaft to effective water surface,
V_A = velocity of advance of propeller in m/sec.,
N = revolutions per minute,
D = propeller diameter in meter.

The resulting thickness-chord length ratio of the equivalent blade section at 0.75R must also possess satisfactory strength properties. Many methods have been devised to determine the minimum acceptable value of the blade thickness at various propeller radii. However, in this preliminary design stage, in which the only interest of the naval architect is focussed on a parametric study to determine overall propeller parameters, it is quite sufficient to use a very simple formula to ensure that the chosen t/c-value is not too small. In this regard it should be noticed that for normal merchant ships equation 14 always leads to larger t/c-values than, e.g., the t/c-value for the B-series according to equation 11.

A simple formula for the minimum blade thickness at 0.75R can be derived from Saunders [14], viz:

$$t_{min_{0.75R}}=D\left[0.0028+0.21\sqrt[3]{\frac{(2375-1125P/D)P_S}{4.123ND^3\left(S_c+\frac{D^2N^2}{12.788}\right)}}\right] \qquad (16)$$

where

$t_{min_{0.75R}}$ = minimum blade thickness at 0.75R in feet,
D = propeller diameter in feet,
P_S = shaft horsepower per blade,
N = revolutions per minute,
S_c = maximum allowable stress in pounds per square inch (psi).

In this formula the bending moment due to the centrifugal force effect is neglected, which is correct only for propellers with zero rake. The additional formula for the chord length for determining the minimum value of t/c at 0.75R is:

$$C_{0.75R} = \frac{2.073 A_E/A_O \cdot D}{Z} \qquad (17)$$

8. Diagrammatical representation of polynomials: determination of optimum diameter and optimum propeller revolutions

For many purposes, it is still useful to have at one's disposal diagrams giving the characteristics of open-water tests. It was, therefore, decided to make a new set of diagrams for the B-series based on the K_T and K_Q polynomials given in Tables 5 and 6.

Figure 8 gives the K_T K_Q-J diagram of the B5-75 propeller for a Reynolds number of $2x10^6$. For the case that the optimum propeller diameter is to be calculated when the power, the rotative propeller speed and the advance velocity is specified, use is generally made of the variables B_{p_1}, and δ defined as:

$$B_{p_1} = N \cdot P^{1/2} \cdot V_A^{-5/2} \qquad (18)$$
$$\delta = N \cdot D \cdot V_A^{-1}$$

in which

N = number of propeller revolutions per minute.
P = shaft horsepower in british units (1HP = 76kgm/sec.)
D = propeller diameter in feet,
V_A = advance velocity of propeller in knots.

Since the value of B_{p_1} and δ are dependent on the system of units used, it is appropriate to replace these variable by the non-dimensional variables $K_Q^{1/4} \cdot J^{-5/4}$ and J^{-1} respectively, such that:

$$0.1739\sqrt{B_{p_1}} = K_Q^{1/4} \cdot J^{-5/4}$$

and (19)

$$0.009875\,\delta = J^{-1}$$

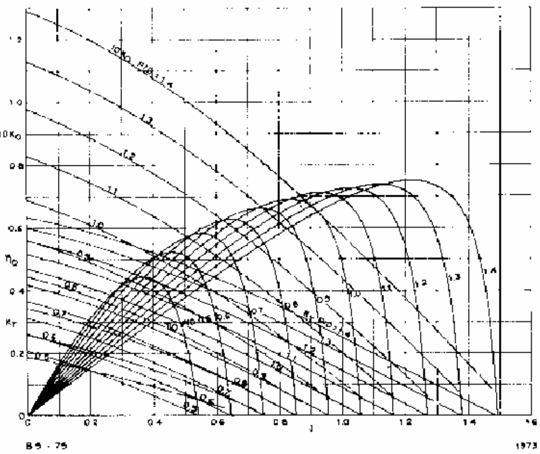

Figure 8. K_T-K_Q-J diagram of B5-75 propeller according to polynomials given in Table 5 ($R_n = 2 \times 10^6$).

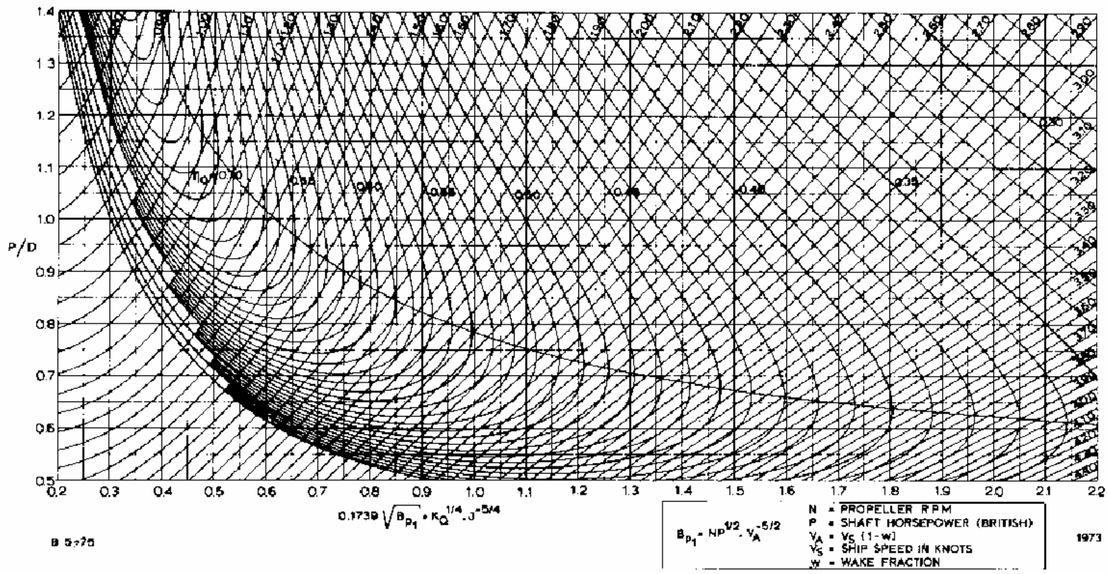

Figure 9. $K_Q^{1/4} \cdot J^{-5/4} - J^{-1}$ diagram of B5-75 propeller according to polynomials given in Table 5 ($R_n = 2 \times 10^6$) for determination of optimum diameter.

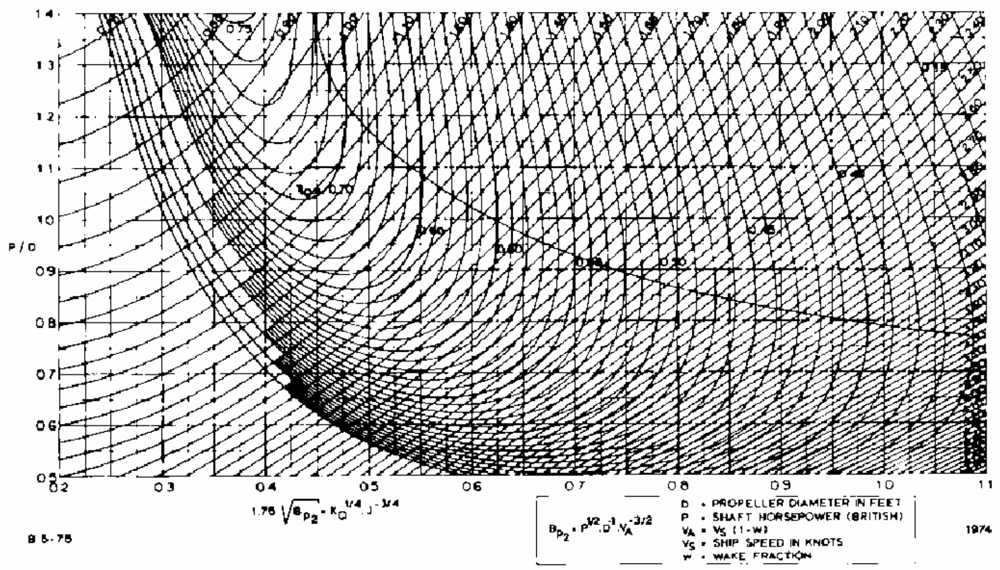

Figure 10. $K_Q^{1/4} \cdot J^{-3/4}$ - J^{-1} diagram of B5-75 propeller according to polynomials given in Table 5 ($R_n = 2 \times 10^6$) for determination of optimum diameter.

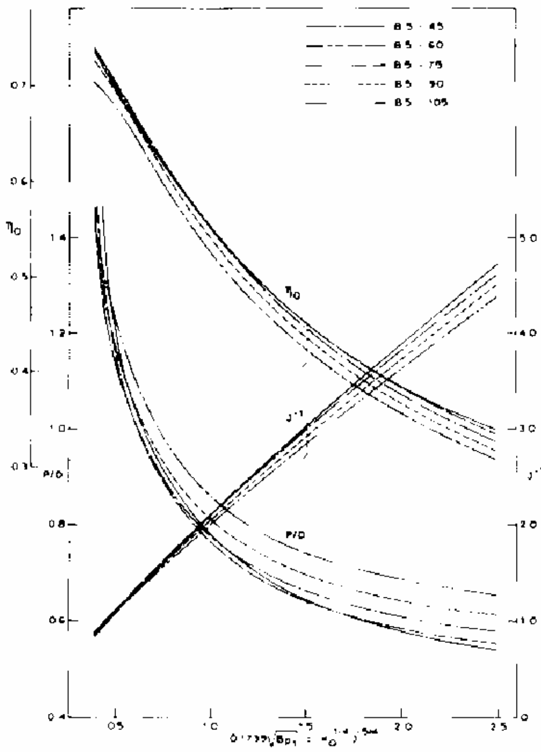

Figure 11. Values of pitch diameter ratio and J^{-1} corresponding to optimum diameter (based on $K_Q^{1/4} \cdot J^{-5/4}$)

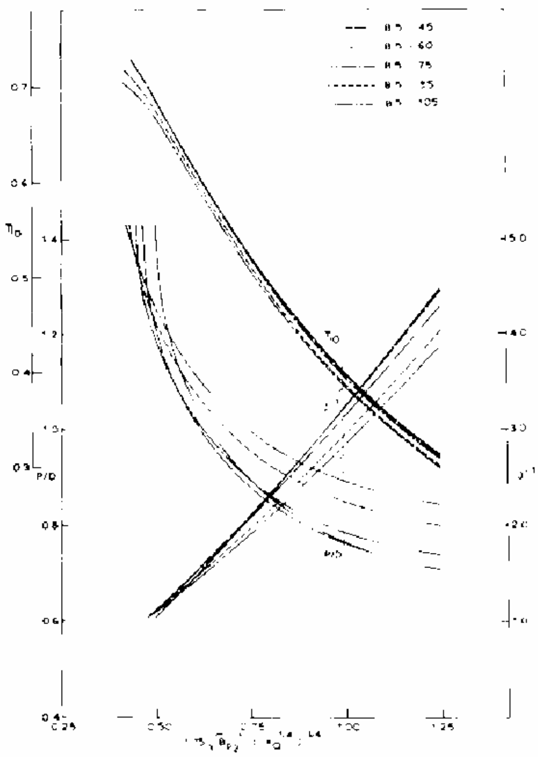

Figure 12. Values of pitch diameter ratio and J^{-1} corresponding to optimum RPM (based on $K_Q^{1/4} \cdot J^{-3/4}$).

The square root of B_{p_1} is adopted since then a linear scale can be used in the resulting diagrams for this variable. Figure 9 shows the result for the B5-75 propeller for a Reynolds number of $2x10^6$.

In the case that the optimum propeller speed is to be determined when the power, the propeller diameter and the advance velocity is specified, use can be made of the power constant B_{p_2}, defined as:

$$B_{p_2} = P^{1/2} \cdot D^{-1} \cdot V_A{}^{-3/2} \qquad (20)$$

in which the variables P, D and V_A are defined as in equations 18. This power constant can be replaced by the non-dimensional expression $K_Q{}^{1/4} \cdot J^{-3/4}$ as follows:

$$1.75\sqrt{B_{p_2}} = K_Q{}^{1/4} \cdot J^{-3/4} \qquad (21)$$

Here also the square root of B_{p_2} is adopted since then a linear scale on the horizontal axis can be used in the resulting diagram. Figure 10 shows the result for the B5-75 propeller for a Reynolds number of $2x10^6$. At the Netherlands Ship Model Basin, diagrams of the type shown in Figures 9 and 10 have been prepared for all B-series propellers for a Reynolds number value of $2x10^6$.

A diagram giving the values of the pitch-diameter ratio P/D, the open-water efficiency η_0 and J^{-1}, corresponding to the value of the optimum diameter, based on $K_Q{}^{1/4} \cdot J^{-5/4}$, is given in Figure 11. Figure 12 gives the analogous diagram for the value of the optimum number of revolutions. Both diagrams are for the 5-bladed B-series propellers.

9. References

1. Troost, L., 'Open-water tests with modern propeller forms', Trans. NECI, 1938, 1940 and 1951.
2. Lerbs, H.W., 'On the effect of scale and roughness on free running propellers', Journal ASME, 1951.
3. Lammeren, W.P.A. van, Manen, J.D. van and Oosterveld, M.W.C., The Wageningen B-screw series', Trans. SNAME, 1969.
4. Oosterveld, M.W.C. and Oossanen, P. van, 'Recent developments in marine propeller hydrodynamics', Jubilee Meeting of NSMB, 1972.
5. Gent, W. van and Oossanen, P. van, 'Influence of wake on propeller loading and cavitation', Paper presented at 2nd Lips Propeller Symposium; May 1973. International Shipbuilding Progress, 1973.
6. Oossanen, P. van, 'Calculation of performance and cavitation characteristics of propellers including effects of non-uniform flow and viscosity'. Doctor's thesis, Delft University of Technology, 1974: Netherlands Ship Model Basin, Publication No. 457, 1974.
7. Lindgren, H., 'Model tests with a family of three and five bladed propellers', Publication No. 47, SSPA, 1961.
8. Lindgren, H. and Bjarne, E., 'The SSPA standard propeller family open-water characteristics', Publication No. 60, SSPA, 1967.
9. Newton, R.N. and Rader, H.P., 'Performance data of propellers for high-speed craft', Trans. RINA, 1961.
10. Schmidt, D., 'Einfluss der Reynoldzahl und der Rauhigkeit auf die propeller-characteristik, berechnet nach der Methode des äquivalenten Profils', Schiffbauforschung 11, 1972.
11. Hoerner, S.F., 'Fluid dynamic drag', Published by the author, 1971.
12. Keller, J. auf'm, 'Enige aspecten bij het ontwerpen van scheepsschroeven', Schip en Werf, No. 24, 1966.
13. Oossanen, P. van, 'A method for minimizing the occurrence of cavitation on propellers in a wake', International Shipbuilding Progress, Vol. 18, No. 205, 1971.
14. Saunders, H.E., 'Hydrodynamics in ship design', Vol. 2, page 620, published by the Society of Naval Architects and Marine Engineers, 1957.