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PROPULSION CHARACTERISTICS OF A SUBMERGED MODEL AS AFFECTED BY REYNOLDS NUMBER

by

John L. Beveridge

[redacted]

HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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NOTATION

Symbol	Description
$b_{0.7}$	Propeller Section Length at 0.7 Radius
D	Propeller Tip Diameter
L	Length of Body of Revolution
n	Propeller Revolutions per unit time
Q	Propeller Torque
R_t	Resistance
S	Wetted Surface
T	Propeller Thrust
V	Body Speed
V_a	Propeller Speed of Advance $= V(1-W)$
ν	Kinematic Viscosity
ρ	Mass Density

COEFFICIENTS AND RATIOS

Symbol	Formula	Description
C_t	$\frac{R_t}{1/2\,\rho S V^2}$	Total Resistance Coefficient
J	$\frac{V(1-W)}{nD}$	Propeller Speed Coefficient
J_a	$\frac{V}{nD}$	Propeller Speed Coefficient
K_q	$\frac{Q}{\rho n^2 D^5}$	Propeller Torque Coefficient
K_t	$\frac{T}{\rho n^2 D^4}$	Propeller Thrust Coefficient

Symbol	Formula	Description
R_e	$\frac{b_{0.7}}{\nu}\sqrt{V_a^2 + (0.7\pi nD)^2}$	Propeller Reynolds Number
$(1 - t)$	$\frac{R_t}{T}$	Thrust Deduction Factor
W	$1 - \frac{V_a}{V}$	Taylor Wake Fraction

ABSTRACT

The results of an experimental investigation on the effect of Reynolds number on model propulsion tests of a submerged body are presented. A propeller was characterized in open-water and behind a 15-foot submerged body of revolution. The influence of test Reynolds number on propeller thrust and torque is determined and the results obtained are discussed.

INTRODUCTION

As a part of the Bureau of Ships Fundamental Hydromechanics Research Program, experiments were conducted at the David Taylor Model Basin to determine the influence of Reynolds number on certain propulsion quantities which are obtained from model open-water and submerged propulsion tests. The present work was limited to experiments with a smooth model (equipped with a turbulence stimulating sand strip) at Reynolds numbers which are usually encountered in the model range. The problem of "scale effect" as related to extrapolation to a relatively higher range of Reynolds number, for the prediction of prototype performance, is not treated. The problem studied here is basically one of establishing the degree of correspondence between model propulsion data obtained at different test speeds. The necessity for such information lies in the need for fixing the allowable lower limit of Reynolds number for a propeller during submerged propulsion tests.

The problem of scale effect in model propulsion experiments has been well recognized.[1,2,3] Past efforts have been directed primarily toward work on propelled surface ship models and planks. This report deals with the results of open-water and propulsion tests of a single-screw submerged body of revolution which was propelled at different speeds.

DESCRIPTION OF BODY AND PROPELLER

All tests were conducted with Model 4198 which is a 15-foot mahogany body of revolution[4] of TMB Series 58 with a ten-to-one fineness ratio. A photograph of Model 4198 and a table of offsets are shown in Figure 1 and Table 1, respectively. The model was fitted with a single propeller shaft along the axis of symmetry. A 4-bladed, white metal, TMB stock propeller 3085A was used for all tests. The propeller hub and fairwater retain the original Series 58 body geometry; i.e. the stock hub was built up with wax to conform to the body shape. A photograph of Propeller 3085A is shown in Figure 2 and a propeller drawing is included in Appendix A.

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[1] References are listed on page 9.

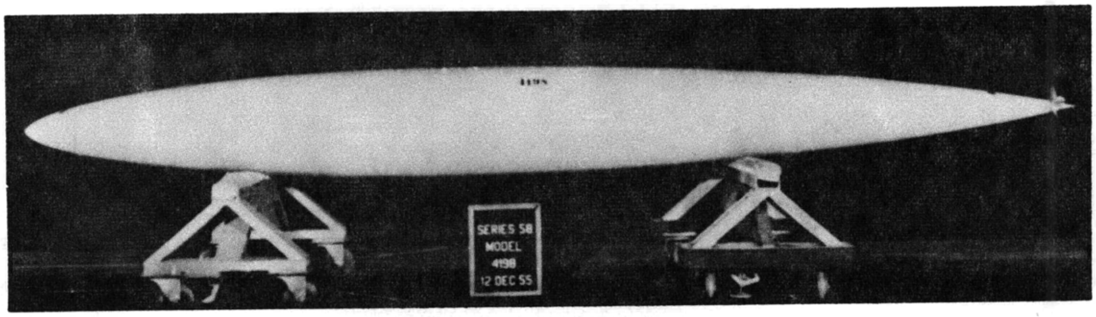

Figure 1 – Series 58 Form, TMB Model 4198 Equipped for Propulsion Test

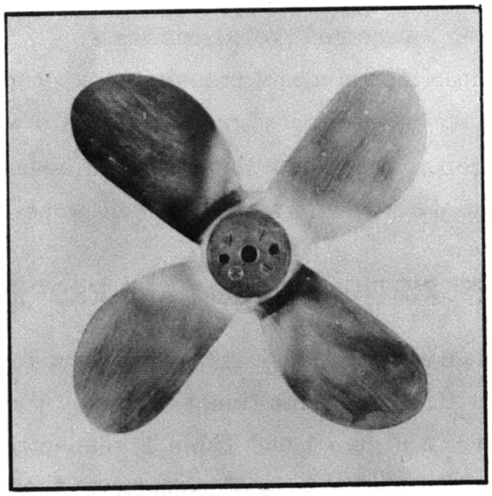

Figure 2 – TMB Stock Propeller 3085A

TEST PROCEDURE

The model was provided with a turbulence stimulating sand strip which was fitted around the girth of a section located at 1/20 of the body length. The resistance and propulsion tests were conducted at approximately a 10-foot depth of submergence measured to the body axis. At this submergence there were no observed free-surface effects. Towing was accomplished with a single strut and internal resistance dynamometer arrangement. The tow-point was about 30 percent of the body length aft of the bow. The arrangement of the dynamometers and ballast within the model and the installation of propeller shafting are basically standard for most submerged propulsion tests conducted at the Model Basin. With the model still rigged on the single strut, propulsion tests were made immediately following the resistance test using a submersible motor and propulsion dynamometer. This procedure insured the same orientation and condition of the model for the two tests.

It was stated earlier that Propeller 3085A was manufactured of white metal (50 percent tin and 50 percent bismuth). This propeller was used for all propulsion tests. At a later date when the open-water tests were to be scheduled, the question arose as to whether or not there might be a load deflection problem. In order to eliminate this question an aluminum propeller was made from the plans for Propeller 3085A, and both propellers were subsequently characterized in open water. The performance of these two propellers was identical, within test accuracy, over the appropriate range of loading. In view of this fact, the open-water results are presented only for Propeller 3085A; the propulsion tests with this propeller are considered entirely reliable.

Two test procedures were used to obtain propulsion data. In the first procedure the propeller thrust, torque, and revolutions were measured at the propulsion condition (e.g. the condition where the propeller thrust balances the resistance which is experienced by the model at the selected test speed). The other propulsion method was the so called "overload and underload" test which is currently used at the Model Basin for submerged body propulsion work. In this constant carriage speed procedure a number of propulsion conditions are simulated by varying the propeller revolutions to cover a range of propeller loading.

The test procedure for conducting open-water propeller experiments is well known, and therefore, will not be discussed.

DISCUSSION OF TEST RESULTS

For purposes of analysis the results obtained from the various tests will be discussed primarily in terms of the thrust deduction factor $(1-t)$ and wake factor $(1-W)$. These factors are considered descriptive, in part, of the flow. Other derived propulsion quantities such as the propulsive coefficient, relative rotative efficiency, etc. can be calculated from the data presented. However, their calculation does not add additional information regarding the influence of Reynolds number. The results of five submerged propulsion tests at speeds from

2 knots to 10 knots are summarized in Table 2. Where the basic coefficients K_t, K_q, and J_a are tabulated for the propulsion condition and for overload and underload values of $C_t \times 10^3$ equal to 1.0, 2.0, 3.0, and 4.0. The open-water test results are presented in Figure 3. These curves were obtained from the propeller characteristic curves given in Appendix A.

The factors $(1-W)$ and $(1-t)$ for the propulsion and for overload and underload conditions are presented as a function of propeller Reynolds number in Figures 4 and 5, respectively. The thrust deduction factor $(1-t)$ was calculated from the relation

$$(1-t) = \frac{R_t}{T} = \frac{C_t \cdot S}{2D^2 K_t / J_a^2} \qquad [1]$$

The effective wake fraction W is given by the relation

$$(1-W) = \frac{V_a}{V} = \frac{J}{J_a}$$

Assuming $J = \dfrac{J_t + J_q}{2}$, we obtain the relation

$$(1-W) = \frac{J_t + J_q}{2J_a} \qquad [2]$$

The effective wake fraction W and the propeller Reynolds number R_e were obtained from the test data of Table 2 in conjunction with the data of Figure 3 as follows: Using each set of K_t, K_q, and J_a values of Table 2, an initial value for $(1-W)$ was assumed and the Reynolds number R_e was calculated from the expression

$$R_e = \frac{b_{0.7}}{\nu} \sqrt{V_a^2 + (0.7\pi nD)^2}$$

$$= \frac{V b_{0.7}}{\nu} \sqrt{(1-W)^2 + \left(\frac{0.7\pi}{J_a}\right)^2} \qquad [3]$$

The plots of Figure 3 were entered on the ordinates K_t and K_q and at the value of R_e the speed coefficients J_t and J_q were obtained by interpolation. A new $(1-W)$ was then obtained from Equation [2]. By such an iterative process final values of $(1-W)$ and R_e were obtained.

Text continued on page 8.

TABLE 1

Offsets and Particulars for Series 58 Form, Model 4198

X in.	Y in.	X in.	Y in.
000.0	0.000	93.6	8.672
3.6	2.569	97.2	8.559
7.2	3.652	100.8	8.431
10.8	4.482	104.4	8.285
14.4	5.171	108.0	8.123
18.0	5.760	111.6	7.945
21.6	6.273	115.2	7.749
25.2	6.721	118.8	7.537
28.8	7.115	122.4	7.304
32.4	7.461	126.0	7.054
36.0	7.762	129.6	6.782
39.6	8.023	133.2	6.489
43.2	8.246	136.8	6.172
46.8	8.437	140.4	5.830
50.4	8.595	144.0	5.465
54.0	8.726	147.6	5.071
57.6	8.829	151.2	4.648
61.2	8.905	154.8	4.194
64.8	8.959	158.4	3.708
68.4	8.989	162.0	3.188
72.0	9.000	165.6	2.630
75.6	8.991	169.2	2.036
79.2	8.962	172.8	1.400
82.8	8.915	176.4	0.722
86.4	8.851	180.0	0.000
90.0	8.780		

Model 4198 Particulars

Serial	40050060-100
Length, ft	15.0000
Diameter, ft	1.5000
Nose radius, ft	0.0750
Tail radius, ft	0.0000
Wetted surface, ft^2	51.622
Volume, ft^3	15.9043
LCB, ft	6.6840

TABLE 2

Basic Coefficients Obtained from Submerged Propulsion Tests

Model 4198 Propeller 3085A

V knots	$10^3 C_t$	K_t	$10\,K_q$	J_a
2	1	0.045	0.137	1.068
	2	0.080	0.168	0.979
	3	0.100	0.188	0.907
	4	0.115	0.202	0.848
	S.P.*3.632	0.110	0.197	0.870
4	1	0.045	0.112	1.059
	2	0.080	0.141	0.973
	3	0.100	0.164	0.902
	4	0.115	0.181	0.841
	S.P. 3.256	0.105	0.169	0.887
6	1	0.045	0.097	1.050
	2	0.080	0.129	0.966
	3	0.100	0.153	0.898
	4	0.115	0.172	0.835
	S.P. 3.125	0.102	0.157	0.889
8	1	0.045	0.089	1.040
	2	0.080	0.124	0.960
	3	0.100	0.149	0.894
	4	0.115	0.169	0.830
	S.P. 2.984	0.100	0.148	0.895
10	1	0.045	0.087	1.032
	2	0.080	0.121	0.954
	3	0.100	0.148	0.889
	4	0.115	0.168	0.830
	S.P. 2.893	0.098	0.145	0.896

*Model self-propulsion condition

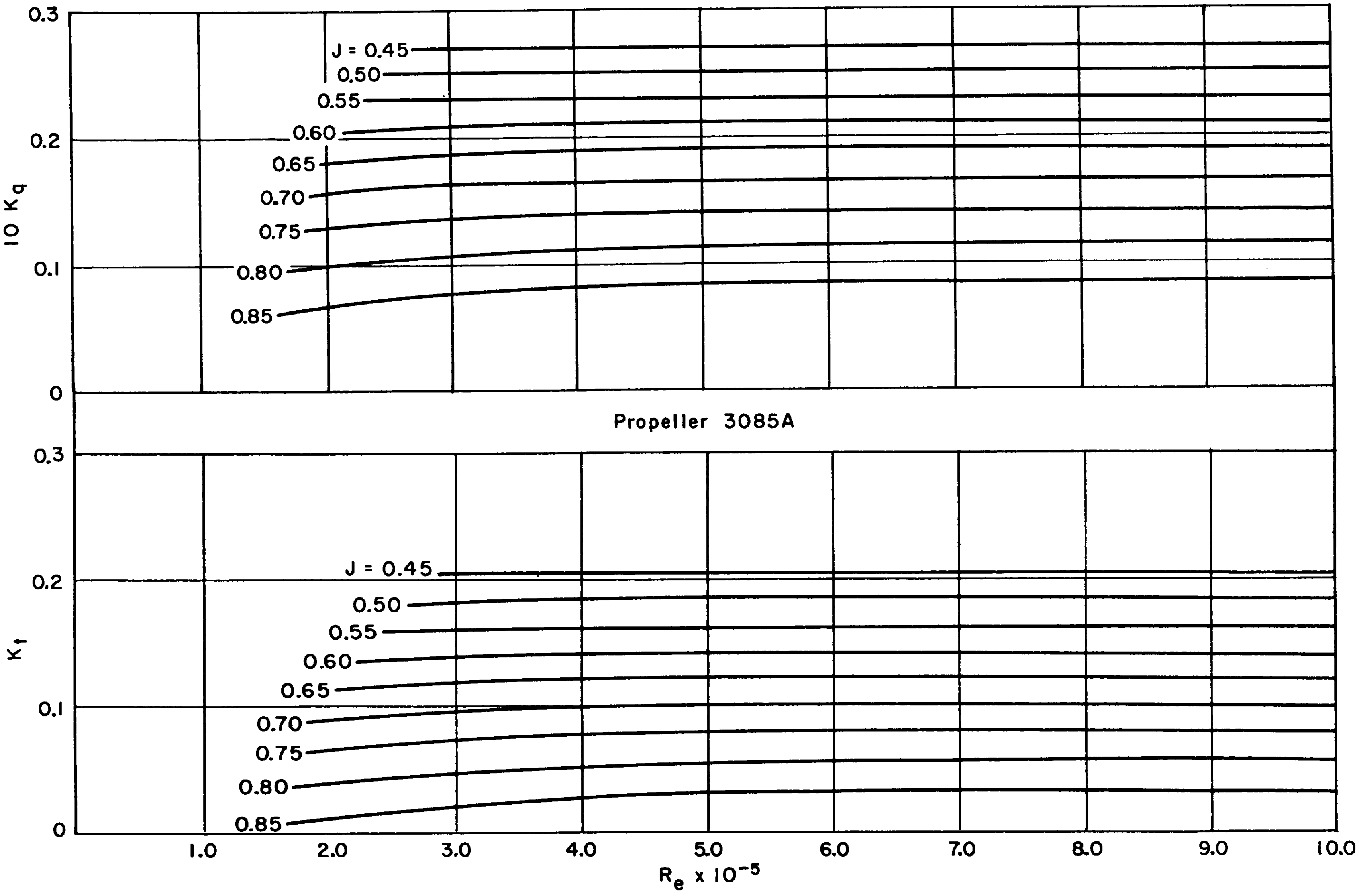

Figure 3 – Effect of Reynolds Number on Open-Water Performance of Propeller 3085A

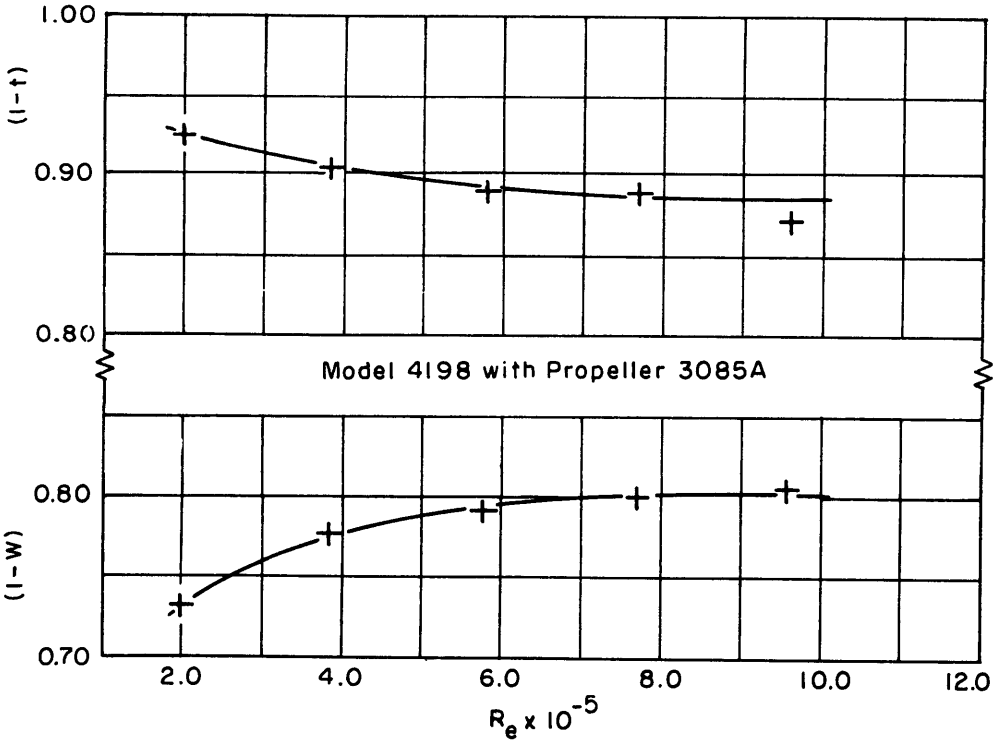

Figure 4 – Variation of Thrust Deduction and Wake Factors with Propeller Reynolds Number at Propulsion Condition

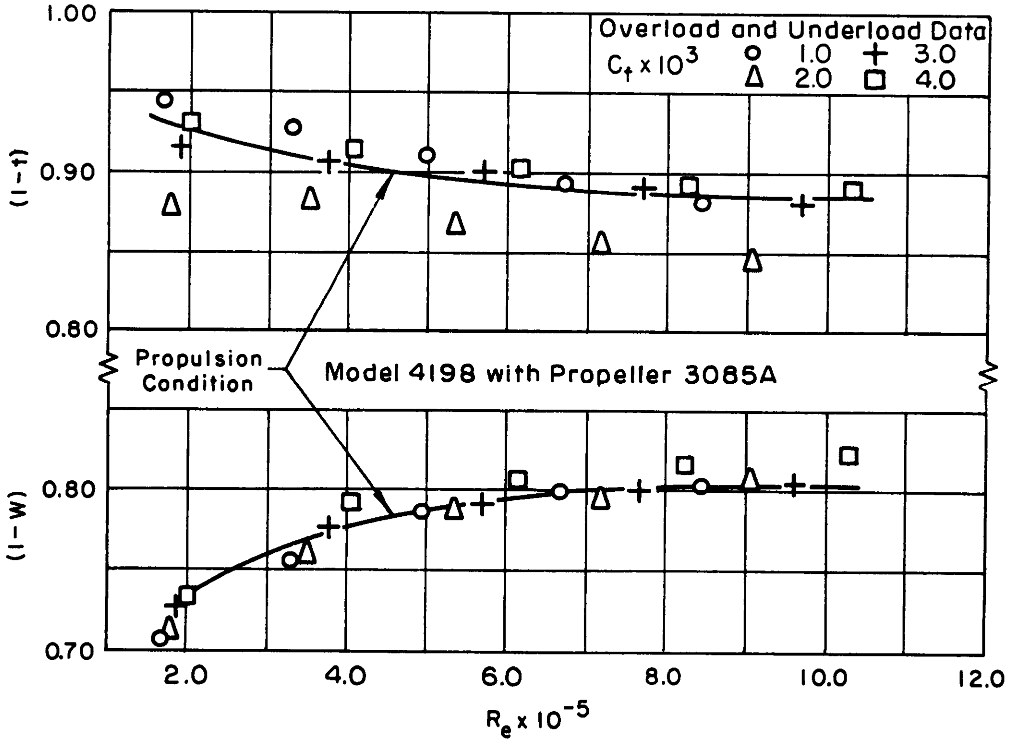

Figure 5 – Variation of Thrust Deduction and Wake Factors with Propeller Reynolds Number at Overload and Underload Conditions

The significant features of the data contained in Figures 3 and 4 will now be discussed. First, the open-water K_t and K_q curves versus Reynolds number show scale effect within the range of test data. It can be seen from Figure 3 that both the K_t and K_q curves drop in the lower range of Reynolds numbers; the effect is greater with increasing values of J. The Model Basin has previously indicated a critical Reynolds number of approximately 5×10^5 to be used as a guide in fixing a lower limit on open-water propeller tests. The present additional data confirm the adequacy of this criterion.

Referring to Figure 4 (propulsion condition) it is seen that considerable scale effect is also present in the factors $(1-t)$ and $(1-W)$ within the same range of Reynolds numbers as covered by the open-water tests. The most salient feature of the curves of $(1-t)$ and $(1-W)$ shown in Figure 4 is that both curves approach zero slope at the high end of the Reynolds scale. Based on these results it appears that R_e critical is about the same for the submerged propulsion test and the open-water test. In the present case, it appears desirable that propulsion tests should be conducted on a well-streamlined (nonseparating flow)* body of revolution at a critical Reynolds number at least equal to the recommended open-water value of 5×10^5 . A generally accepted opinion with respect to surface-ship model propulsion tests is that the critical value of the Reynolds number for a propeller behind a model is somewhat less than that of a propeller in open water. This opinion is based on the assumption that turbulent flow exists in the vicinity of the propeller. As mentioned earlier, a turbulence stimulating device (sand strip) was placed on the model near the bow for each test. Although the propeller when placed behind the model is undoubtedly working in a region of at least partial turbulent flow, the extent of the turbulence in the boundary layer at the stern might be critical for the lower test speeds. The flow about the innermost propeller blade elements could be either laminar or transitional in the region $R_e < 5 \times 10^5$. An effective Reynolds number cannot be evaluated from the propulsion data. In any event the character of the wake is a function of both hull and propeller Reynolds number and the combined effects are shown in Figure 4.

Referring to Figure 5 (overload and underload conditions) it is seen that the scatter exhibited by the data points is appreciable. The $(1-t)$ and $(1-W)$ data points for $C_t \times 10^3 = 3.0$ agree quite well, of course, with the propulsion condition because the C_t values for the model propulsion condition are close to this value. It is of interest to note that $(1-t)$ appears to have a minimum value in the neighborhood of $C_t \times 10^3 = 2.0$. It should be pointed out that the order of magnitude of the underload and overload is from about 0.3 times the propulsion load to 1.3 times the propulsion load, respectively.

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*Visual observations and motion pictures of the flow as indicated by means of dye and tufts of yarn have been made.

CONCLUSIONS

In agreement with previous Model Basin criteria, a critical Reynolds number of approximately 5×10^5 is indicated and recommended for use in conducting open-water propeller tests. In view of the experimental thrust deduction and wake factors obtained in this study, it appears reasonable to conclude that model propulsion tests on submerged streamlined bodies-of-revolution should not be conducted at Reynolds numbers which are lower than the critical value recommended for open-water propeller tests.

ACKNOWLEDGMENT

The author is grateful to the members of the Model Basin staff who participated in the conduct of the test program. Particularly the cooperation of Mr. W.H. Norley, formerly of the Research and Propellers Branch, in providing the open-water data is greatly appreciated.

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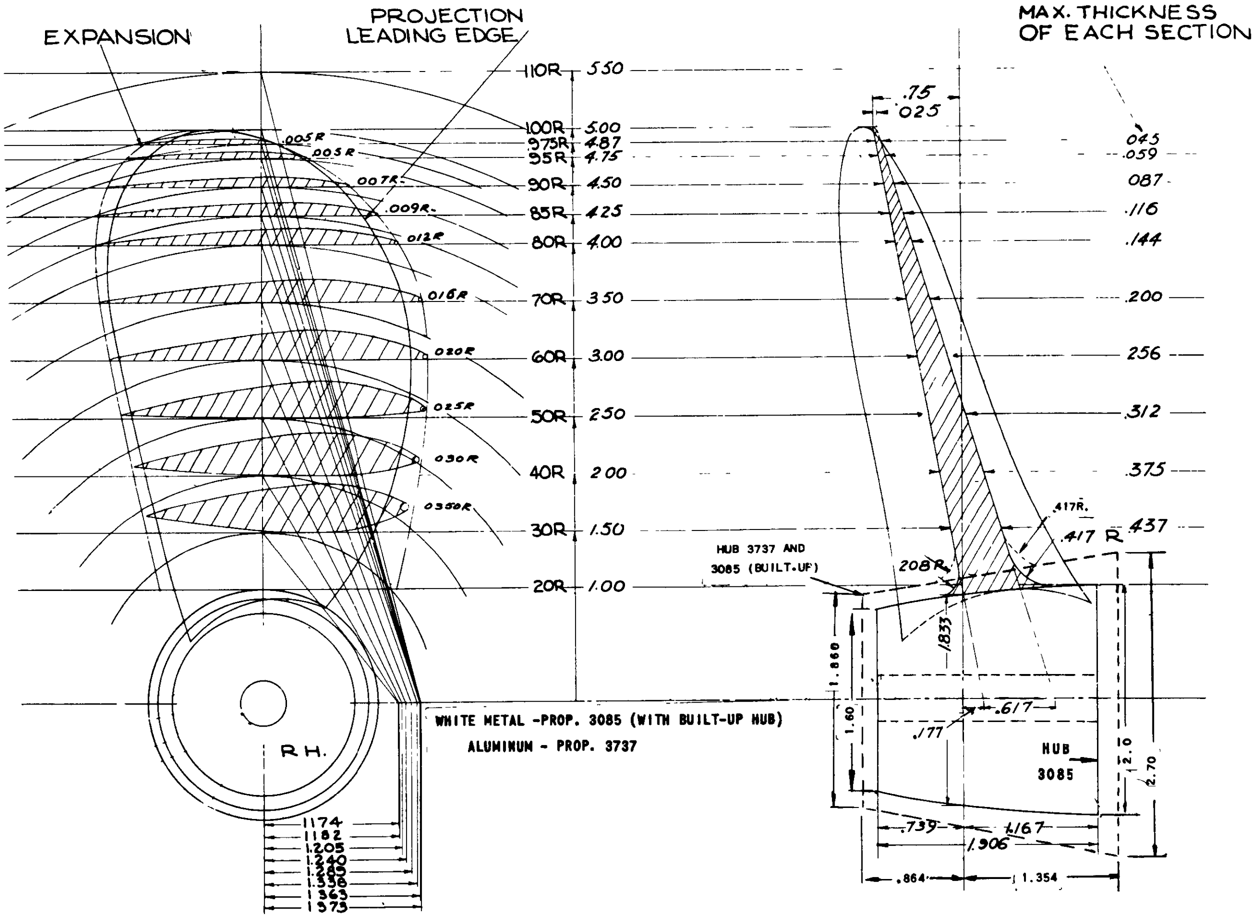
APPENDIX A

PROPELLER 3085 A
DRAWING AND CHARACTERISTIC CURVES

Number of Blades	4
Exp. Area Ratio	0.551
MWR	0.276
BTF	0.062
P/D (at 0.7 R)	0.810
Diameter	10.000 in.
Pitch (at 0.7 R)	8.099 in.
Rotation	R.H.
Tested for	DTMB



Propellers 3085A and 3737

REYNOLDS NUMBER, $R_e = b_{0.7}\frac{\sqrt{V_a^2+(0.7\pi nD)^2}}{\nu}$

THRUST COEFFICIENT, $K_t = \frac{T}{\rho n^2 D^4}$

TORQUE COEFFICIENT $K_q = \frac{Q}{\rho n^2 D^5}$

SPEED COEFFICIENT, $J = \frac{V_a}{nD}$

EFFICIENCY, $e = \frac{TV_a}{2\pi Qn} = \frac{K_t}{K_q} \times \frac{J}{2\pi}$

T = THRUST
Q = TORQUE
n = REVOLUTIONS PER UNIT TIME
V_a = SPEED OF ADVANCE
$b_{0.7}$ = SECTION LENGTH AT 0.7 RADIUS
D = DIAMETER
P = PITCH
ν = KINEMATIC VISCOSITY
ρ = DENSITY OF WATER

NUMBER OF BLADES.........	4
EXP. AREA RATIO..........	0.551
MWR......................	0.276
BTF......................	0.062
P/D (AT 0.7R)............	0.810
DIAMETER.................	10.000 Ins.
PITCH (AT 0.7R)..........	8.099 Ins.
ROTATION.................	R.H.

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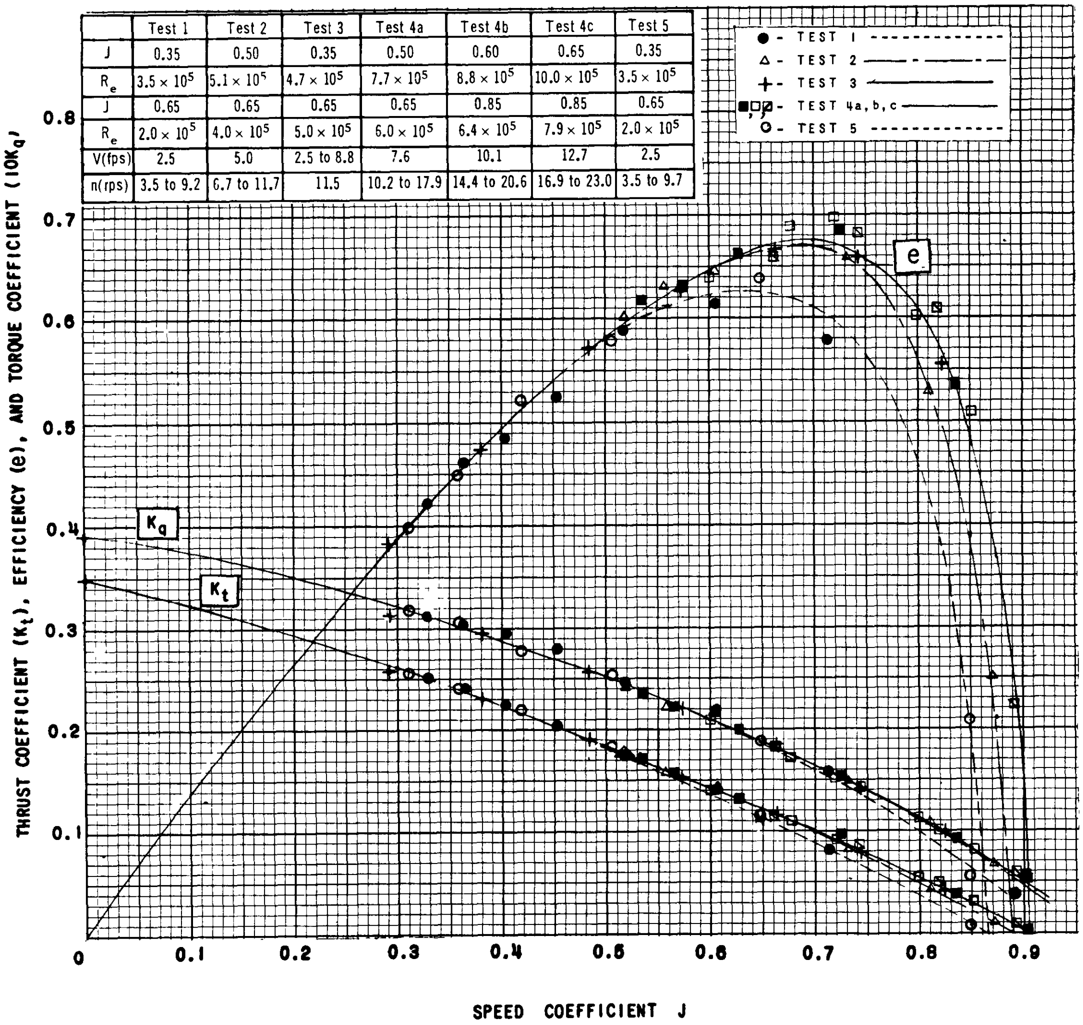

	Test 1	Test 2	Test 3	Test 4a	Test 4b	Test 4c	Test 5
J	0.35	0.50	0.35	0.50	0.60	0.65	0.35
R_e	3.5×10^5	5.1×10^5	4.7×10^5	7.7×10^5	8.8×10^5	10.0×10^5	3.5×10^5
J	0.65	0.65	0.65	0.65	0.85	0.85	0.65
R_e	2.0×10^5	4.0×10^5	5.0×10^5	6.0×10^5	6.4×10^5	7.9×10^5	2.0×10^5
V(fps)	2.5	5.0	2.5 to 8.8	7.6	10.1	12.7	2.5
n(rps)	3.5 to 9.2	6.7 to 11.7	11.5	10.2 to 17.9	14.4 to 20.6	16.9 to 23.0	3.5 to 9.7

Characteristic Curves of Propeller 3085 A for Various Reynolds Numbers

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2. Propellers (Marine)--Performance--Reynolds number effects
3. Reynolds number effects
4. Ship models--Model TMB 4198

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