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UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

PROPELLER BLADE INTERFERENCE TEST

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EXPERIMENTAL MODEL BASIN
ERECTED 1898
BUREAU OF
CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

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JANUARY 1934

REPORT NO 375

PROPELLER BLADE INTERFERENCE TEST

U.S. Experimental Model Basin
Navy Yard, Washington, D.C.
January, 1934. Report No. 375

PROPELLER BLADE INTERFERENCE TEST

SUMMARY

The test was made to determine interference correction factors to be used in calculating blade element characteristics for marine propellers. The correction factors are given as a percentage of the lift and drag of an airfoil when tested by itself.

The range of the test takes care of the usual type of marine propellers but does not extend to the long narrow blade type of propeller.

The lift for the blade elements of a wide blade propeller is reduced 40 to 50 per cent while the drag is increased approximately 50 per cent near the hub and decreased by 20 or 25 per cent near the tip (neglecting the effect of aspect ratio on the correction factors).

INTRODUCTION

The idea of analyzing the forces on elementary strips of propeller blades was first published by William Froude in 1878. Drzewiecki also published in 1885 a treatise on blade element theory which is used today and known as the Simple Blade-Element Theory. Several modifications of this theory are given and worked out in detail by Fred E. Weick in Aircraft Propeller design.

THEORY

Figure 1 shows the relations between the blades of a propeller at radius r after expanding from a cylinder to a plane. From this it is obvious at once that a group of airfoils may be set up to represent this condition. By setting the airfoils at different distances apart and with different values of gap and negative stagger, the conditions of any propeller at any radius may be simulated except for blade thickness. To take care of blade thickness two sets with different thicknesses were run.

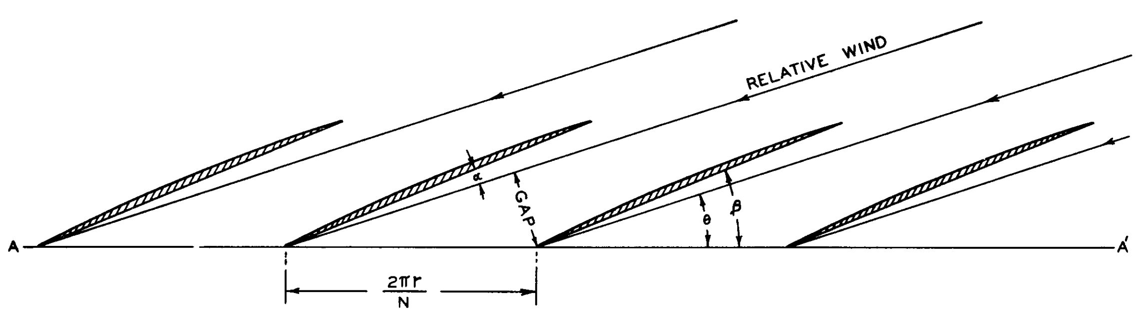


FIG. 1

The distance between corresponding points on the blades of a propeller which compares to the distance between corresponding points of airfoil chords on the frame is $\frac{(2\pi r)}{N}$ which in terms of chord becomes $\frac{(2\pi r)}{Nb}$

where r is the radius under consideration

N is the number of blades

b is the length of chord, or blade width.

The gap is here arbitrarily taken as the component of $\frac{(2\pi r)}{Nb}$ normal to the wind.

Therefore $\frac{\text{Gap}}{\text{Chord}} = \frac{2\pi r}{Nb} \sin\theta$, where θ is the angle of advance of blade element.

$\frac{2\pi r}{Nb}$ would be the reciprocal of the solidity factor if there were no pitch.

It is assumed that in the wind tunnel test the pressure was the same forward and aft of the grid. The velocity of the wind was taken with a pitot tube several feet ahead of the grid set-up. The obstruction of the tunnel cross section was less than 1%.

A multiplane interference test in a wind tunnel cannot be strictly analogous to marine propeller action. The velocities along the span of the airfoil are approximately equal, whereas the velocities along a propeller blade are proportional to the radius.

Then in the wind tunnel there is a decrease in pressure through the grid while in a propeller there is an increase in pressure. Also change in pressure in air is accompanied by a slight change in density while in water the density remains practically constant.

The effect of viscosity on the blade characteristics may be different for water and air especially on the tip vortices.

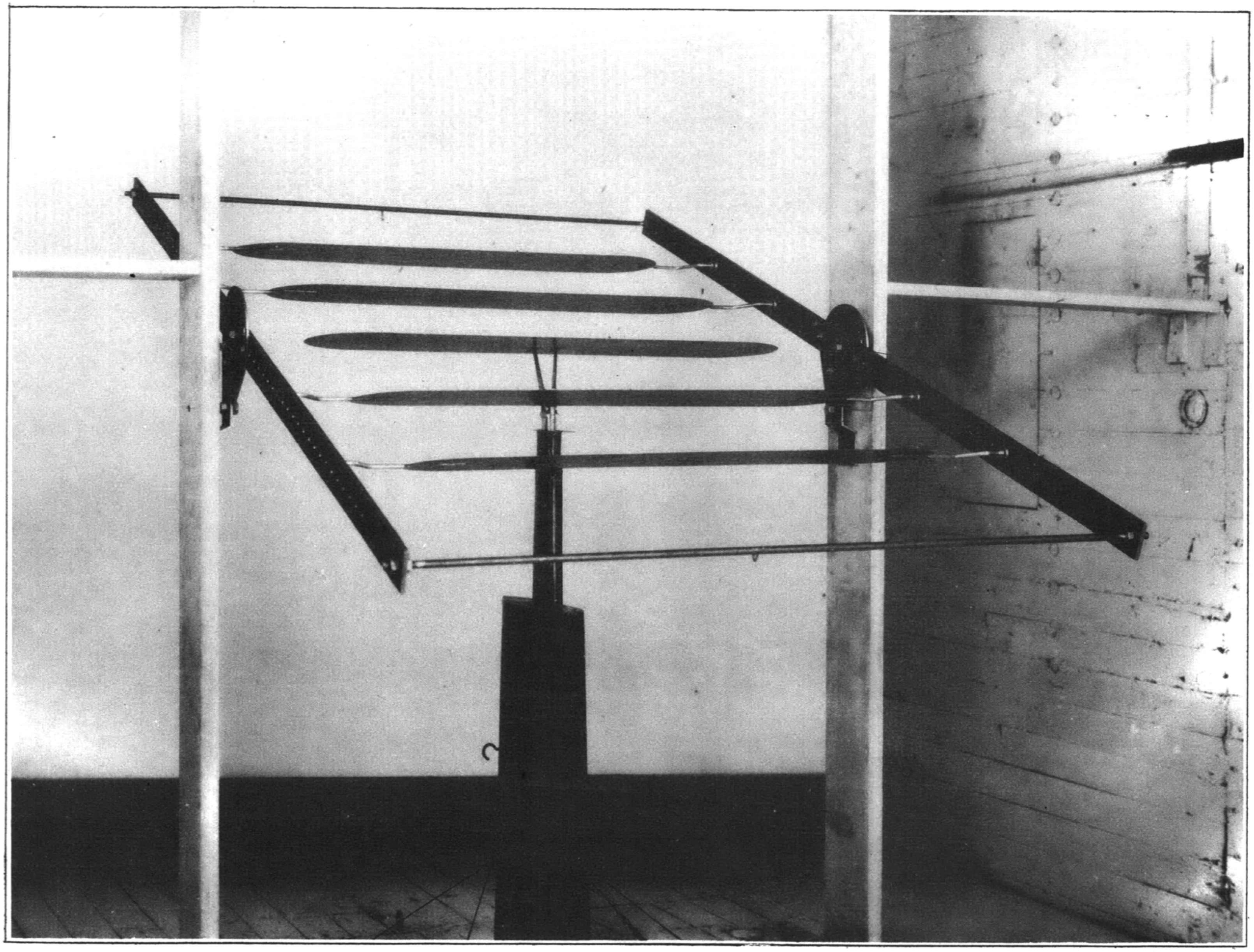
PROCEDURE

Fig. 2 shows the series of airfoils as set up in the wind tunnel.

Fig. 3 gives the details of the airfoils used.

The airfoils were all of uniform plan being 5" by 30" with elliptic ends. The two sets had maximum thicknesses of 1/4" and 1/2" respectively. Each airfoil had an area of 142.25 sq. inches which gives an aspect ratio of 6.33. The test was run with a wind velocity of 40 miles per hour.

The characteristics of one airfoil of each series were determined with the frame in position. The other airfoils were then put on the frame which was so mounted that it rotated about the same axis as the single airfoil on the balance. Throughout the test the chords of the airfoils were parallel and the quarter-chord points were on the center line of the frame.



The airfoils were set at 10°, 20°, 30°, 40°, and 50° to the frame and readings taken for angles of attack of 0, 2°, 4°, 6°, 8°, and 10° with distances between chords as measured along the frame of 3, 4, 5, 7, 9, and 11 inches for the thick airfoils and distances of 5, 7, 9, 11, and 13 inches for the thin airfoils.

Table I presents the lift and drag characteristics of the airfoils used when tested with the frame in position.

Table II is a summary of the data (faired) for the thin series of airfoils and Table III summarizes the data (not faired) for the thick airfoils.

RESULTS

Figs. 4 and 5 give contours of constant lift correction factors plotted against angle of attack and gap/chord ratio. Figs. 6 and 7 give the same thing for drag though it is plotted in a different manner. To use these charts multiply the characteristic of the airfoil to be used by the factor obtained from the chart. It will be necessary to interpolate for thickness and spacings.

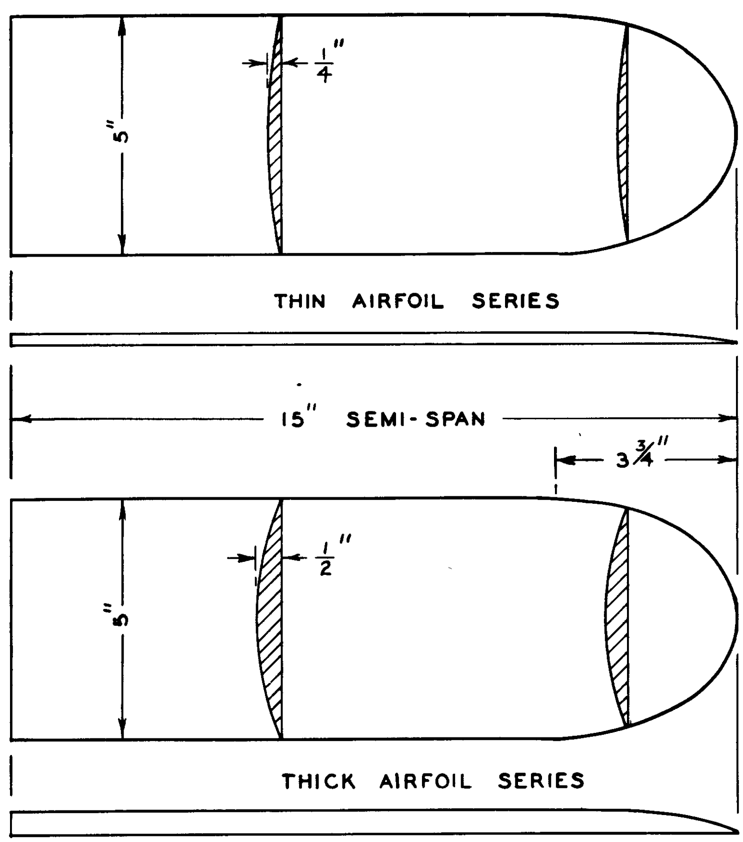


FIG. 3

TABLE I

SINGLE AIRFOIL TEST - FRAME ONLY
FAIRED VALUES OF LIFT AND DRAG

AIRFOIL SERIES	Angle of Attack (degrees)	Net Measured Forces (Pounds)	
		Lift = L_o	Drag = D_o
Thin - 1/4"	-4	-0.79	+0.151
	-2	-0.07	0.083
	0	+0.65	0.060
	+2	1.39	0.071
	4	2.10	0.117
	6	2.75	0.204
	8	3.37	0.340
	+10	+3.93	+0.542
Thick - 1/2"	-4	+0.61	+0.159
	-2	1.28	0.115
	0	1.91	0.104
	+2	2.48	0.121
	4	2.96	0.156
	6	3.39	0.214
	8	3.80	0.284
	+10	+4.19	+0.368

TABLE II

FAIRED VALUES OF LIFT AND DRAG FOR THIN AIRFOILS (POUNDS)

$\frac{2\pi r}{Nb}$		1.0		1.4		1.8		2.2		2.6	
Frame to Chord	Angle of Attack (degrees)	5" Spacing		7" Spacing		9" Spacing		11" Spacing		13" Spacing	
		L	D	L	D	L	D	L	D	L	D
10°	0	0.01	0.056	0.13	0.076	0.21	0.077	0.26	0.081	0.28	0.076
	2	0.25	0.073	0.40	0.086	0.50	0.081	0.58	0.086	0.66	0.084
	4	0.48	0.093	0.66	0.113	0.79	0.105	0.88	0.117	1.00	0.111
	6	0.71	0.126	0.93	0.154	1.08	0.150	1.20	0.165	1.32	0.160
	8	0.95	0.169	1.21	0.202	1.38	0.212	1.51	0.230	1.63	0.227
	10	1.19	0.219	1.48	0.258	1.68	0.282	1.82	0.298	1.90	0.308
20°	0	0.01	0.076	0.22	0.084	0.31	0.084	0.32	0.077	0.32	0.075
	2	0.30	0.079	0.60	0.090	0.72	0.089	0.81	0.084	0.86	0.082
	4	0.59	0.096	0.96	0.120	1.13	0.116	1.25	0.120	1.33	0.120
	6	0.90	0.138	1.34	0.172	1.54	0.176	1.66	0.182	1.81	0.190
	8	1.20	0.196	1.72	0.238	1.91	0.253	2.06	0.263	2.21	0.275
	10	1.50	0.271	2.07	0.317	2.24	0.340	2.44	0.364	2.53	0.378
30°	0	0.03	0.082	0.23	0.082	0.33	0.079	0.35	0.077	0.37	0.074
	2	0.41	0.083	0.68	0.091	0.81	0.084	0.88	0.084	0.92	0.081
	4	0.78	0.099	1.12	0.121	1.29	0.117	1.45	0.123	1.47	0.122
	6	1.16	0.141	1.56	0.174	1.76	0.183	1.91	0.192	1.98	0.195
	8	1.55	0.205	1.97	0.248	2.20	0.270	2.35	0.283	2.47	0.295
	10	1.93	0.289	2.36	0.342	2.63	0.365	3.77	0.400	2.88	0.412

TABLE II (CONT'D)

FAIRED VALUES OF LIFT AND DRAG FOR THIN AIRFOILS (POUNDS)

$\frac{2\pi r}{Nb}$		1.0		1.4		1.8		2.2		2.6	
Frame to Chord	Angle of Attack (degrees)	5" Spacing		7" Spacing		9" Spacing		11" Spacing		13" Spacing	
		L	D	L	D	L	D	L	D	L	D
40°	0	0.10	0.082	0.24	0.081	0.36	0.074	0.40	0.077	0.40	0.071
	2	0.51	0.084	0.72	0.086	0.90	0.078	0.97	0.085	1.01	0.081
	4	0.92	0.104	1.20	0.119	1.44	0.116	1.54	0.125	1.59	0.122
	6	1.31	0.149	1.68	0.175	1.95	0.181	2.05	0.198	2.14	0.193
	8	1.70	0.215	2.12	0.253	2.41	0.275	2.53	0.293	2.64	0.305
	10	2.06	0.296	2.53	0.350	2.79	0.376	2.99	0.424	3.08	0.430
50°	0	0.14	0.084	0.29	0.076	0.35	0.074	0.41	0.078	0.42	0.068
	2	0.55	0.082	0.81	0.082	0.93	0.077	1.01	0.086	1.04	0.077
	4	0.96	0.104	1.30	0.109	1.50	0.112	1.59	0.127	1.63	0.119
	6	1.38	0.151	1.79	0.166	2.00	0.177	2.12	0.203	2.20	0.188
	8	1.79	0.217	2.22	0.252	2.46	0.270	2.65	0.297	2.73	0.300
	10	2.17	0.302	2.65	0.354	2.92	0.378	3.14	0.438	3.20	0.435

TABLE III

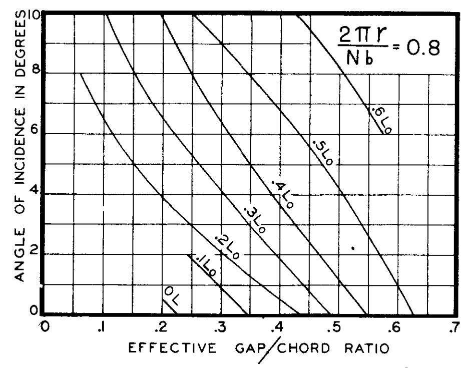
UNFAIRED VALUES OF LIFT AND DRAG FOR THICK AIRFOILS (POUNDS)

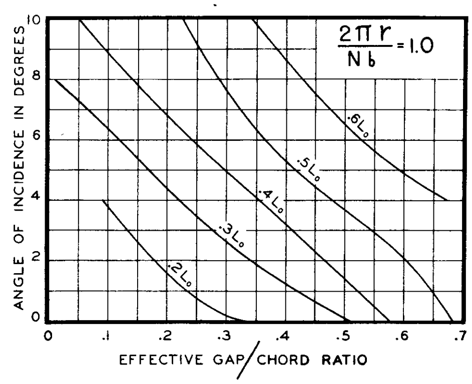
	$\frac{2\pi r}{Nb}$	0.6		0.8		1.0		1.4		1.8		2.2	
Frame to Chord	Angle of Attack (degrees)	3" Spacing		4" Spacing		5" Spacing		7" Spacing		9" Spacing		11" Spacing	
		L	D	L	D	L	D	L	D	L	D	L	D
10°	0			-0.07	0.168	0.27	0.139	0.65	0.162	0.88	0.169	1.03	0.162
	2			+0.20	0.159	0.46	0.147	0.89	0.185	1.14	0.199	1.36	0.189
	4			0.41	0.171	0.62	0.166	1.13	0.212	1.38	0.229	1.57	0.239
	6			0.52	0.187	0.85	0.208	1.41	0.276	1.66	0.287	1.89	0.290
	8			0.66	0.213	1.26	0.265	1.83	0.345	2.08	0.370	2.31	0.365
	10			1.05	0.263	1.59	0.308	2.12	0.392	2.34	0.427	2.53	0.432
20°	0	-0.24	0.282	0.07	0.196	0.38	0.171	0.81	0.169	1.06	0.164	1.22	0.156
	2	-0.35	0.220	0.38	0.184	0.69	0.177	1.16	0.194	1.43	0.183	1.62	0.191
	4	-0.31	0.167	0.65	0.202	1.02	0.215	1.54	0.236	1.82	0.241	2.04	0.237
	6	+0.15	0.167	0.89	0.227	1.33	0.260	1.85	0.292	2.22	0.310	2.46	0.315
	8	0.67	0.208	1.11	0.282	1.61	0.330	2.16	0.363	2.61	0.390	2.81	0.402
	10	0.78	0.231	1.38	0.347	1.93	0.407	2.53	0.458	2.91	0.485	3.09	0.470
30°	0	0.33	0.232	0.28	0.202	0.64	0.174	0.97	0.166	1.19	0.159	1.33	0.149
	2	0.60	0.227	0.69	0.199	1.01	0.192	1.37	0.187	1.62	0.187	1.78	0.176
	4	0.82	0.226	1.04	0.218	1.38	0.217	1.80	0.219	2.05	0.231	2.29	0.232
	6	1.07	0.238	1.38	0.260	1.75	0.267	2.17	0.278	2.52	0.305	2.75	0.308
	8	1.25	0.272	1.74	0.313	2.06	0.336	2.65	0.370	2.98	0.385	3.10	0.368
	10	1.43	0.313	2.07	0.378	2.55	0.424	3.05	0.458	3.19	0.455	3.29	0.440

TABLE III (CONT'D)

UNFAIRED VALUES OF LIFT AND DRAG FOR THICK AIRFOILS (POUNDS)

	$\frac{2\pi r}{Nb}$	0.6		0.8		1.0		1.4		1.8		2.2	
Frame to Chord	Angle of Attack (degrees)	3" Spacing		4" Spacing		5" Spacing		7" Spacing		9" Spacing		11" Spacing	
		L	D	L	D	L	D	L	D	L	D	L	D
40°	0	0.75	0.217	0.68	0.189	0.86	0.170	1.09	0.157	1.27	0.157	1.41	0.149
	2	1.00	0.216	1.09	0.191	1.30	0.178	1.50	0.181	1.72	0.174	1.89	0.177
	4	1.13	0.204	1.38	0.207	1.65	0.207	1.94	0.214	2.23	0.221	2.41	0.224
	6	1.30	0.227	1.68	0.235	2.02	0.261	2.41	0.283	2.72	0.290	2.90	0.288
	8	1.50	0.245	1.97	0.287	2.43	0.324	2.88	0.352	3.04	0.353	3.13	0.342
	10	1.83	0.303	2.48	0.372	2.81	0.398	3.06	0.415	3.22	0.411	3.39	0.418
50°	0			0.93	0.161	1.06	0.164	1.23	0.154	1.42	0.146	1.45	0.140
	2			1.25	0.174	1.44	0.176	1.65	0.174	1.90	0.174	1.96	0.164
	4			1.58	0.197	1.80	0.206	2.14	0.214	2.39	0.217	2.50	0.219
	6			1.95	0.237	2.25	0.263	2.59	0.273	2.85	0.270	2.92	0.273
	8			2.34	0.300	2.60	0.327	2.90	0.330	3.08	0.330	3.16	0.325
	10			2.64	0.357	2.79	0.367	3.07	0.382	3.31	0.388	3.47	0.403





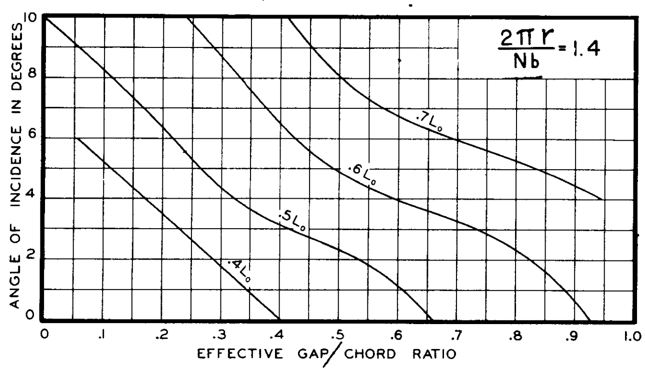
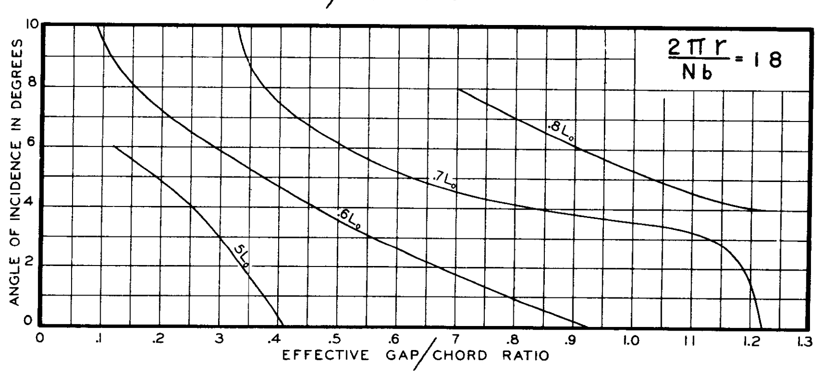


FIGURE 4

BLADE INTERFERENCE TEST

5"x 30"x ½" AIRFOILS

LIFT CORRECTION FACTORS



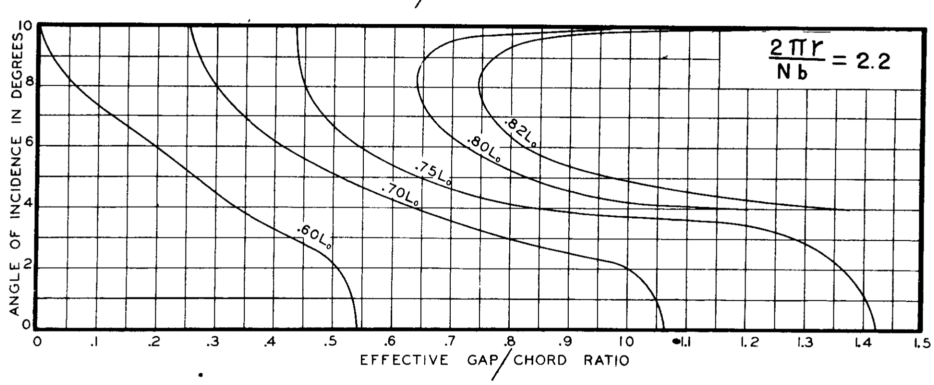
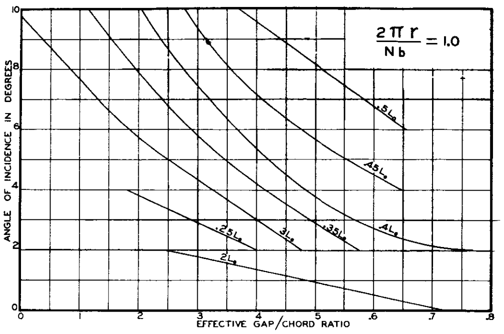


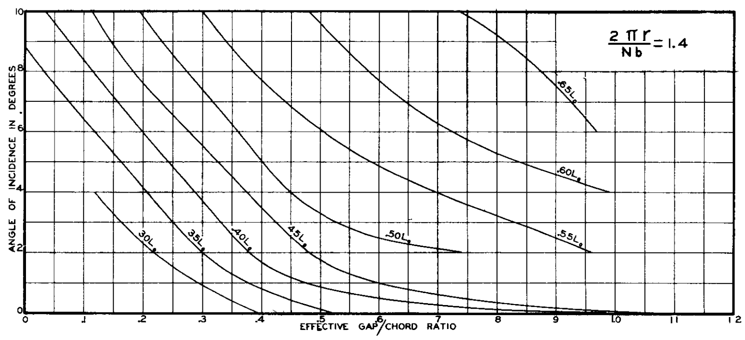
FIGURE 5

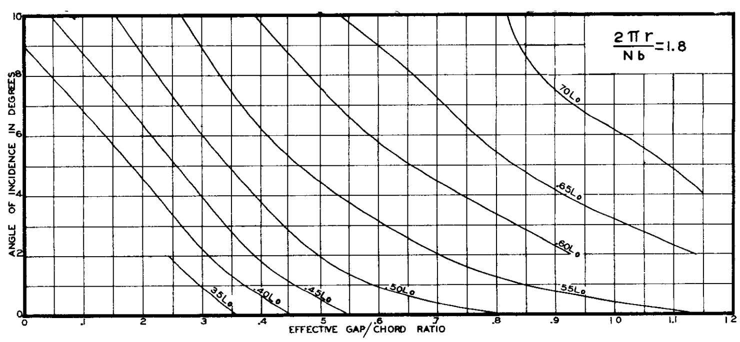
BLADE INTERFERENCE TEST

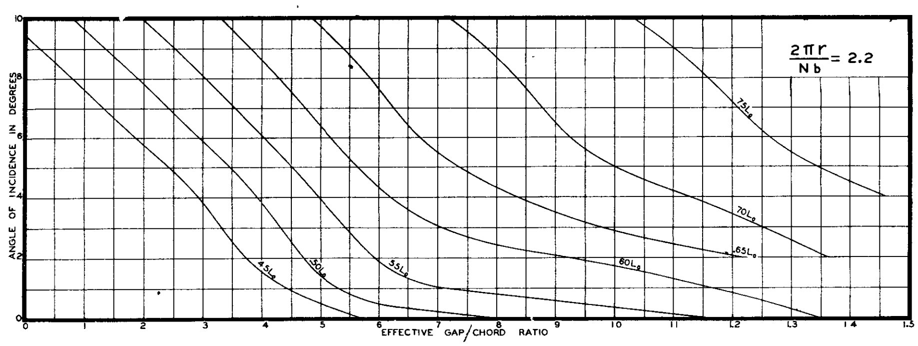
5"x30"x¼" AIRFOILS

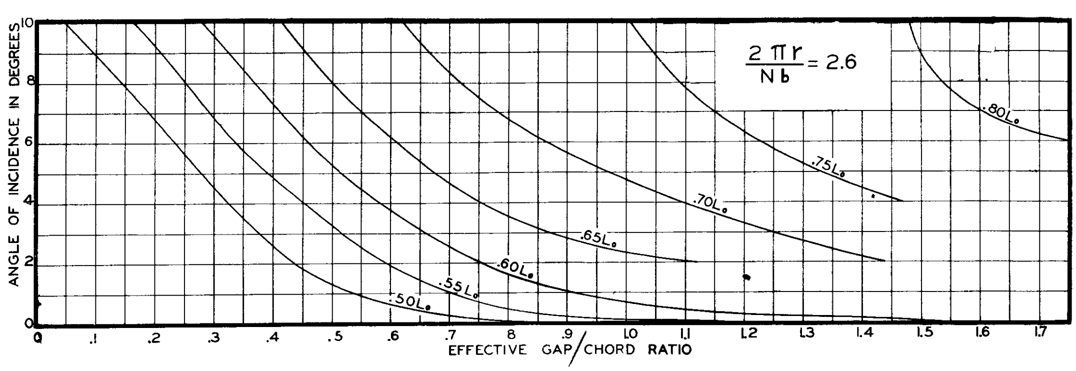
LIFT CORRECTION FACTORS











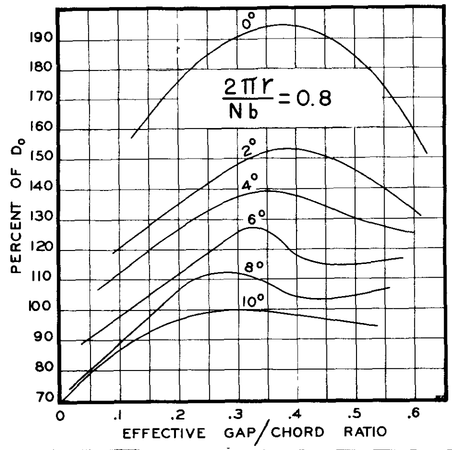
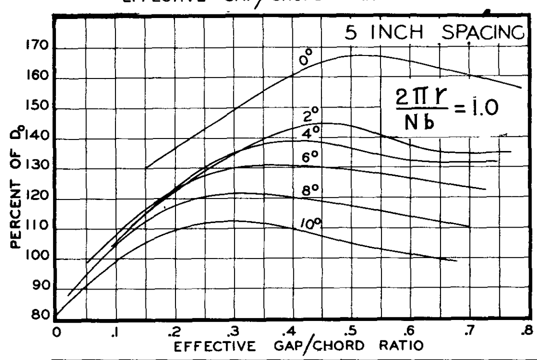


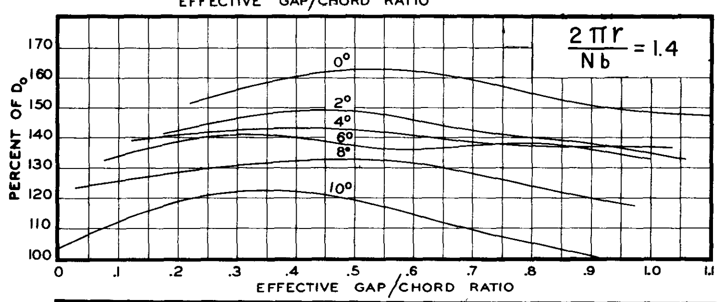
FIGURE 6

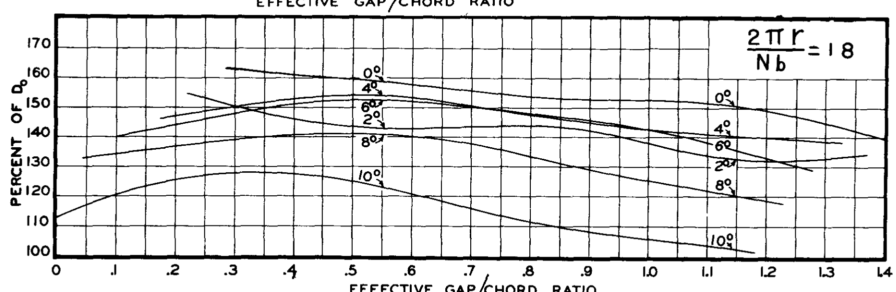
BLADE INTERFERENCE TEST

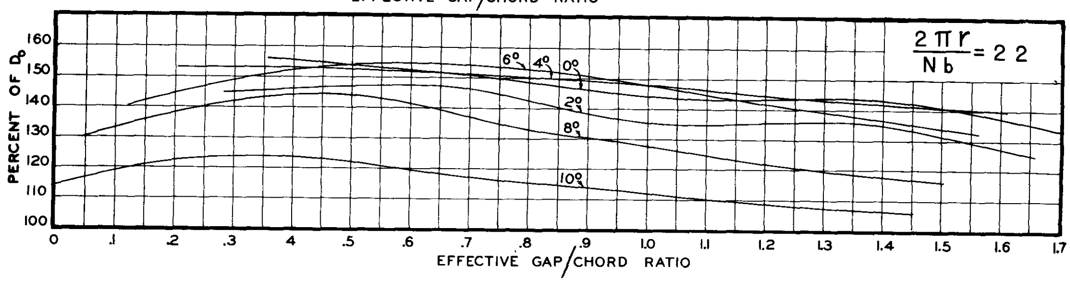
5" x 30" x ½" AIRFOILS

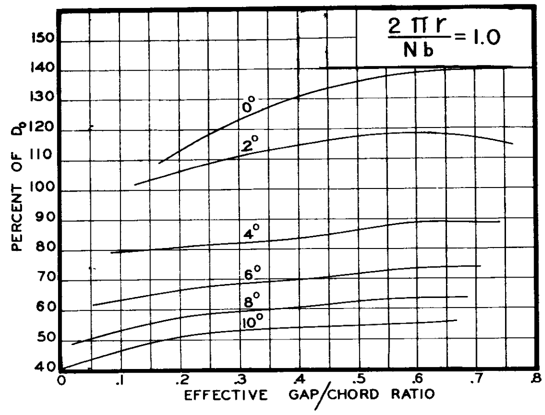
DRAG CORRECTION DATA

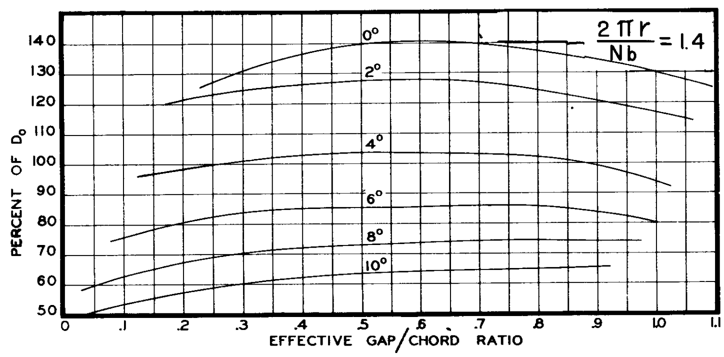


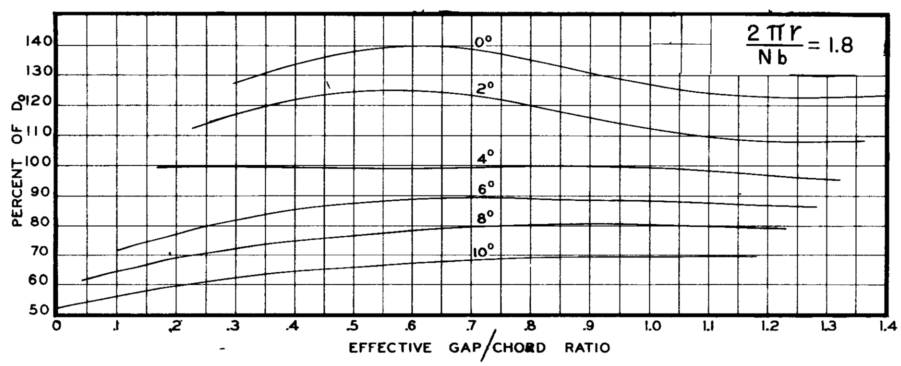


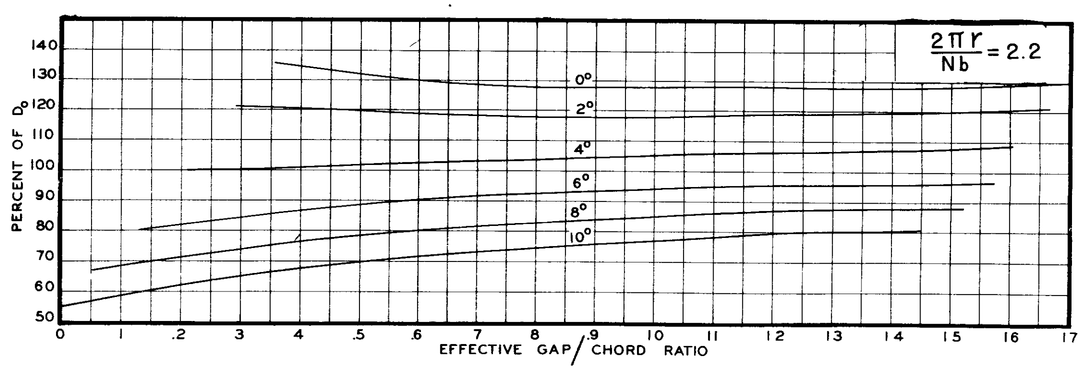












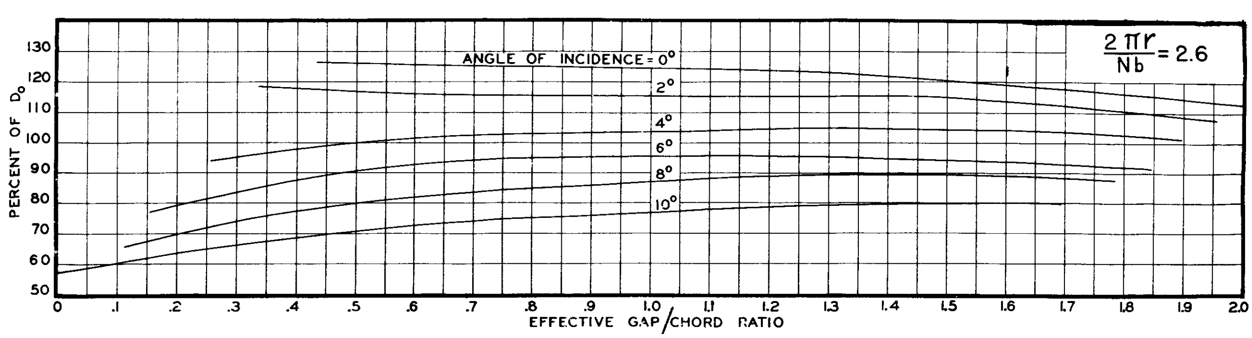


FIGURE 7

BLADE INTERFERENCE TEST

5" x 30" x 4" AIRFOILS

DRAG CORRECTION DATA

APPENDIX

ANALYSIS OF MARINE PROPELLER WITH MULTIPLANE INTERFERENCE CORRECTION FACTORS

Symbols Used.

r	– radius as a fraction of total radius
b	– blade width, in terms of unit radius
t	– blade thickness in terms of unit radius
N	– number of blades
P	– pitch
D	– diameter
β	– helix angle
θ	– angle of advance
α	– angle of attack
α_a	– angle of attack, absolute
G	– gap
C_L	– lift coefficient
A.R.	– aspect ratio
ℓ	– lift interference correction factor
C_L'	– lift coefficient corrected for interference
i	– induced drag factor
C_{Di}	– induced drag coefficient
C_D	– drag coefficient
d	– drag interference correction factor
C_D'	– drag coefficient corrected for interference
λ_1	– lift and drag coefficients resolved parallel to shaft
λ_2	– lift and drag coefficients resolved perpendicular to shaft
ρ	– density of water (1.94 slugs per cu. ft. for fresh water)
s	– slip ratio
dr	– length of blade element
dC_T	– portion of C_T contributed by blade element
dC_Q	– portion of C_Q contributed by blade element
h	– radius of hub
C_T	– thrust coefficient for propeller
C_Q	– torque coefficient for propeller
e	– efficiency
M.W.R.	– mean width ratio (Taylor)
B.T.F.	– blade thickness fraction

Summary

The propeller is analyzed by:

(1) Determining the lift and drag characteristics of blade elements at several radii.

(a) The lift characteristic is obtained from the formula

$$C_L = \frac{0.096\alpha_a}{1 + \frac{1.75}{A.R.}} \qquad \text{(Higgins)}$$

where the absolute angle of attack $\alpha_a = \alpha + \frac{180}{\pi}\frac{t}{b}$ for circular back airfoils. A.R. is aspect ratio which is given by the length of the blade divided by the mean width.

t is blade thickness

b is blade width

α is taken as the angle corresponding to the slip angle.

(b) The drag characteristic is found by adding the profile drag to the induced drag. An approximate value of .009 is used for the profile drag coefficient. The induced drag is determined by the formula

$$C_{D_i} = C_L^2 \cdot \frac{c}{4} \cdot \frac{s}{s^2-y^2} \qquad \text{(Glauert)}$$

where c is the mean chord, s is length of blade and y is the distance of the blade element from the hub.

(2) Correcting for blade interference.

The lift and drag characteristics determined as in (1) are then corrected for interference by factors obtained from Figs. 4, 5, 6, and 7. A double interpolation is necessary for intermediate values of $\frac{2\pi r}{Nb}$ and t. This is best done graphically.

(3) Resolving the characteristics parallel and normal to the propeller axis.

This is done by the formulas

$$\lambda_1 = C_L' \cos\theta - C_D' \sin\theta$$

$$\lambda_2 = C_L' \sin\theta + C_D' \cos\theta$$

where C_L' and C_D' are the lift and drag characteristics after correcting for blade interference; λ_1 and λ_2 refer to thrust and torque forces respectively.

(4) Determining the thrust and torque characteristic of each blade element multiplying by the number of blades and integrating.

The characteristics of a blade element are determined from the formulas

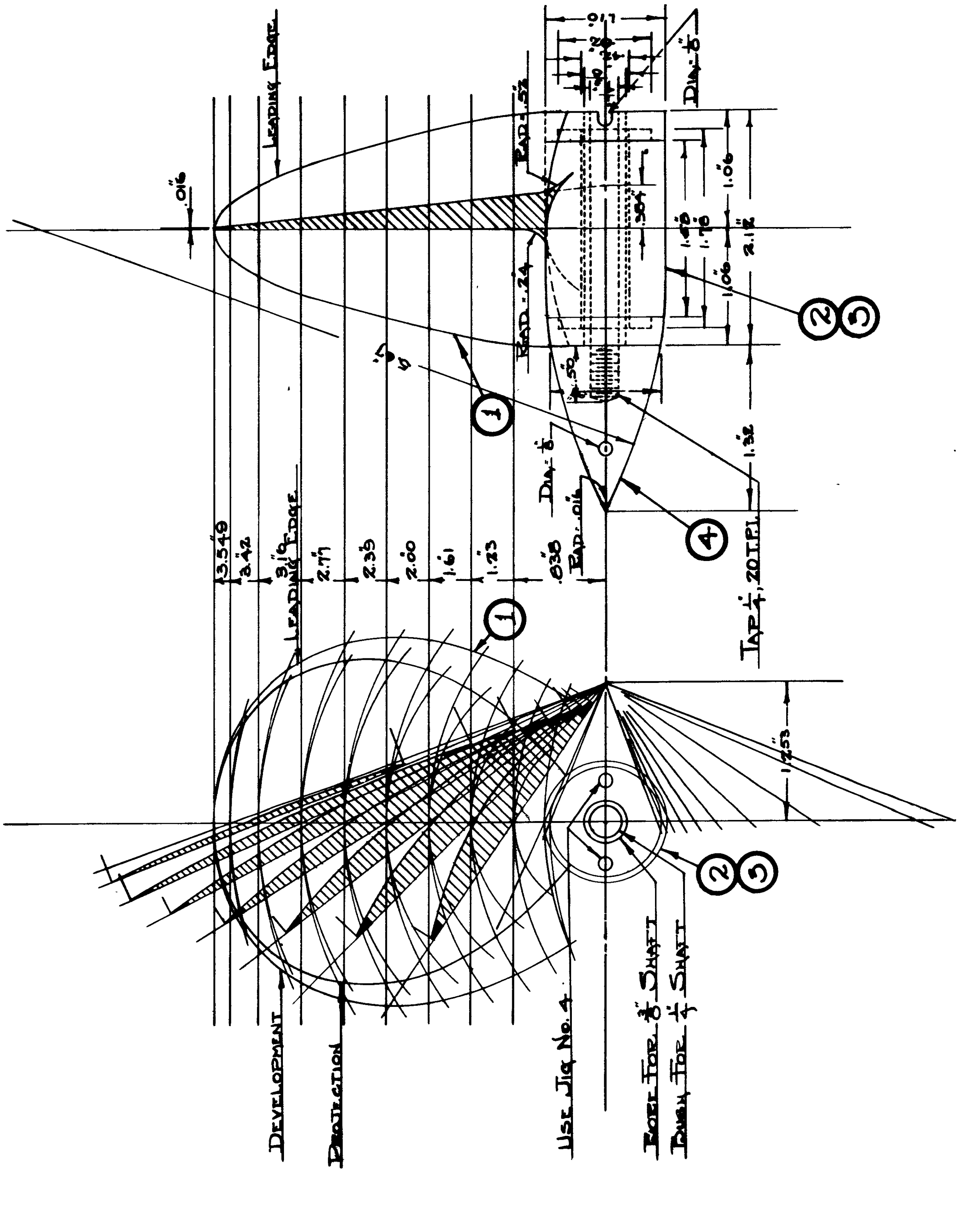

Leading Edge
Development
Projection
Use Jig No. 4
Bore For 3/16" Shaft
Bush For 1/4 Shaft
Tap 1/4, 20 T.P.I.
Rad. .24
Rad. .52
Rad. .016
Dia. 1/8
13.549
3.42
3.16
2.77
2.35
2.00
1.61
1.23
.838
1.32
1.253
.016

FIGURE 8

$$\frac{d\ C_T}{d\ r} = \frac{1}{8}\lambda_1 \rho\, b\ (1-s)^2 \csc^2\theta \quad \text{(for one blade)}$$

$$\frac{d\ C_Q}{d\ r} = \frac{2}{16\ P/D}\, b\ r\ (1-s)^2 \csc^2\theta$$

where ρ is the density of the water, b is blade width and r is the radius both in terms of unit radius, s is the slip ratio and θ is the angle of advance.

The propeller used in this analysis is of the type used on destroyers. It is represented by propeller models numbers 1214-15 and tested at the U.S. Experimental Model Basin on a model of the U.S.S. HAMILTON. These propellers have been the object of considerable research and it was thought advisable to attempt the application of the interference correction factors to these propellers. A reproduction of the drawing for these model propellers is given in Fig. 8. These models have the following dimensions: Diameter = 7.097", Pitch = 7.87", Mean width ratio = 0.41, Total projected area = 21.75 sq. in., Ratio of projected area to disc area = 0.55, Blade thickness fraction = .0592, Linear ratio ship to model = 15.5.

Fig. 9 is a velocity diagram of the action of a blade element with reference to water at some distance from the ship.

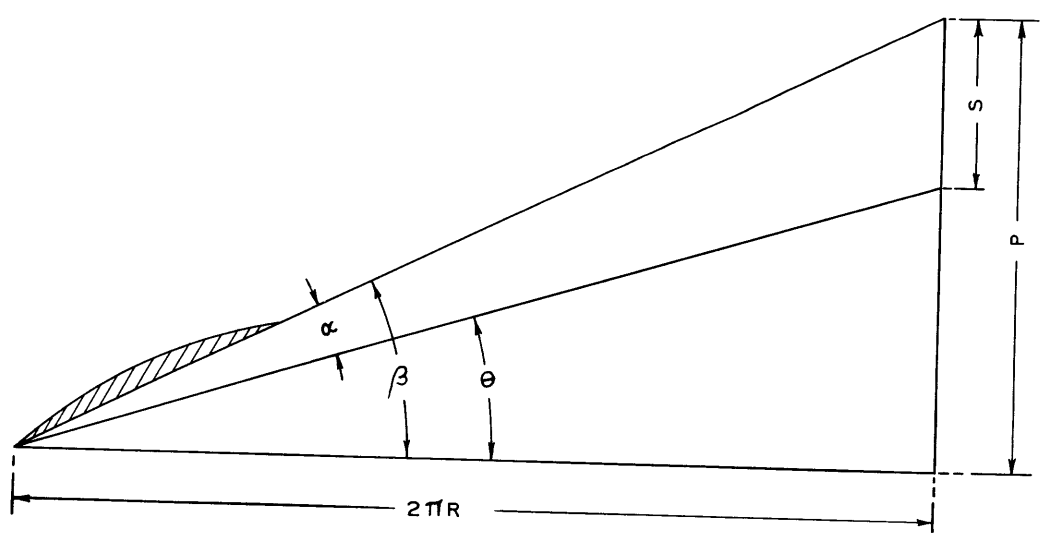


FIG. 9

This analysis is based on airfoil theory with empirical blade interference correction factors. These factors are taken from the contours of figs. 4, 5, 6 and 7 and plotted as in figs. 10 and 11. The spots indicate the values as read from the contours showing that the correction curves for drag are not very reliable. These curves should be drawn for thickness ratios, angles of attack and gap-chord ratios near the values of the portion of the propeller for which they are to be used.

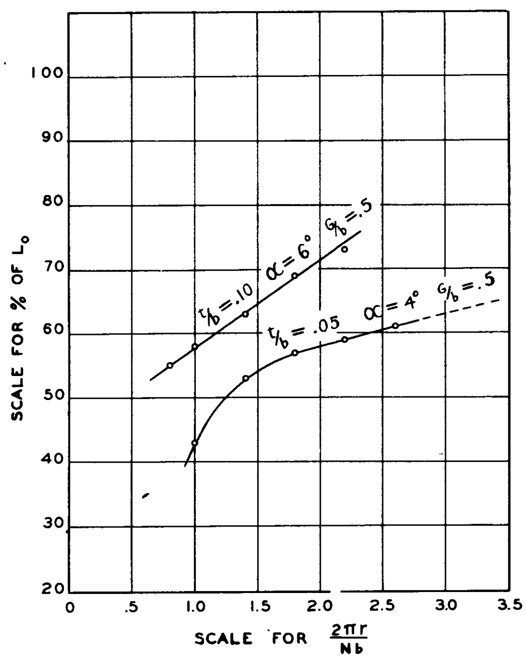


FIGURE 10

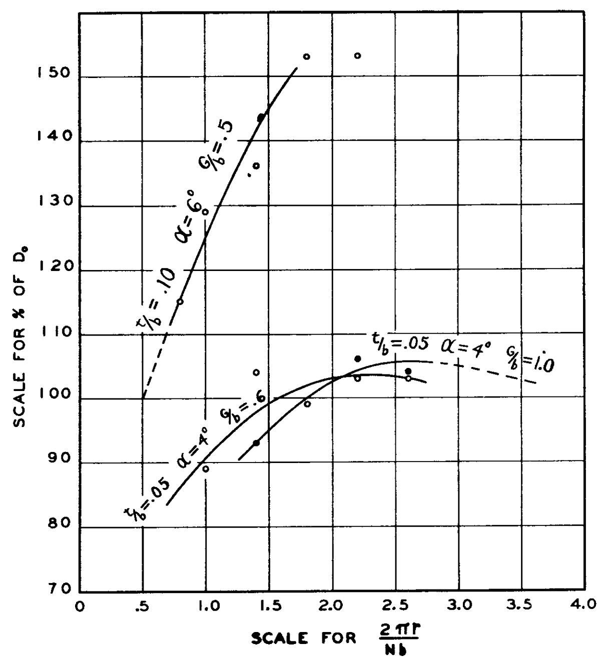


FIGURE 11

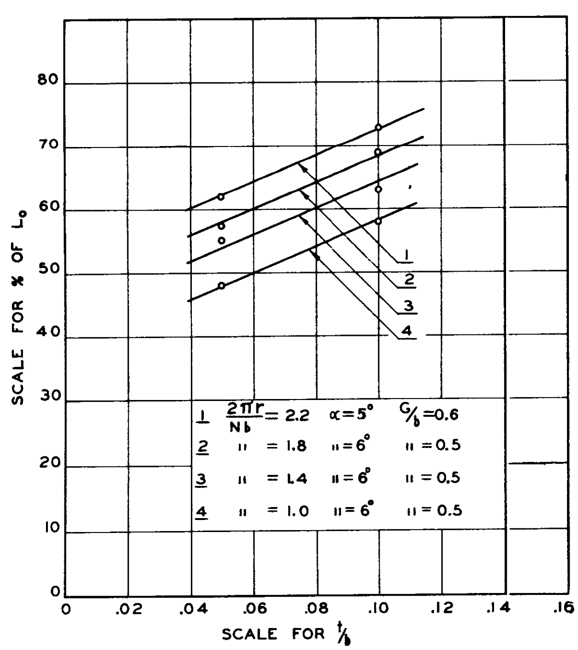


FIGURE 12

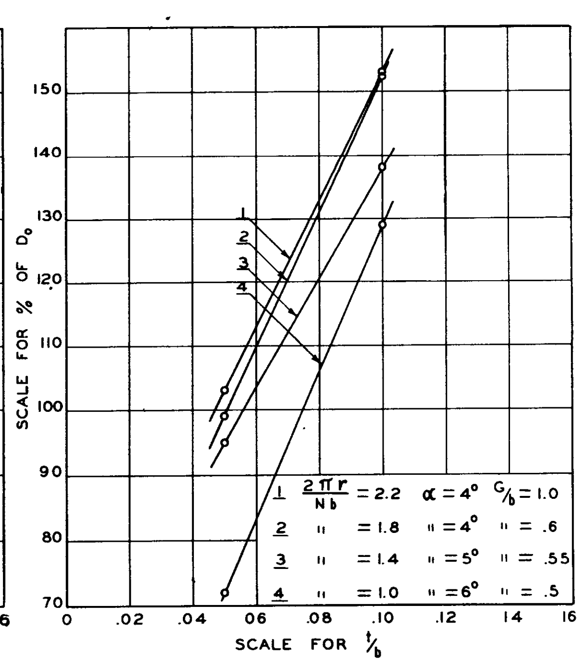


FIGURE 13

Figs. 12 and 13 show the effect of thickness as nearly as can be determined from only two thicknesses. The interference factor for a blade section is taken from the chart in Figs. 4, 5, 6 and 7 having the nearest value of $\frac{2\pi r}{Nb}$ and $\frac{t}{b}$ and is then interpolated or extrapolated by using Figs. 10, 11, 12 and 13.

Fig. 14 shows the variation of the lift correction factor (l) and the corrected lift coefficient (C_L') with radius for the propeller used in this analyses. No correction has been made on the lift for tip vortex.

The drag is more difficult and uncertain to deal with. It is assumed for this analysis that the hub acts as a limiting wall so that there is no hub vortex. The effect of the tip vortex is then calculated by a formula given by Glauert.

$$C_{D_i} = C_L^2 \cdot \frac{c}{4} \cdot \frac{s}{s^2-y^2}$$

where c is the mean chord, s the semi span and y the distance from mid-span to section under consideration. For this analysis c = D x M.W.R., s = R – h and y = r – h. The value $\frac{c}{4} \cdot \frac{s}{s^2-y^2} = i$ is given in col. 15, Table IV, V and VI. The value of i at the tip goes to infinity but since this is impossible because of viscosity the value of a fair curve of C_{D_i} at r = 1 is taken. Fig. 15 gives values of C_{D_i}, d and C_D'. $C_D' = d(C_{D_i} + .009)$. The value .009 is an approximation of the profile drag. Some values of profile drag determined at the Navy Yard wind tunnel indicate that the profile drag for circular arc sections changes but very little with thickness. For this reason the figure .009 is used for all sections.

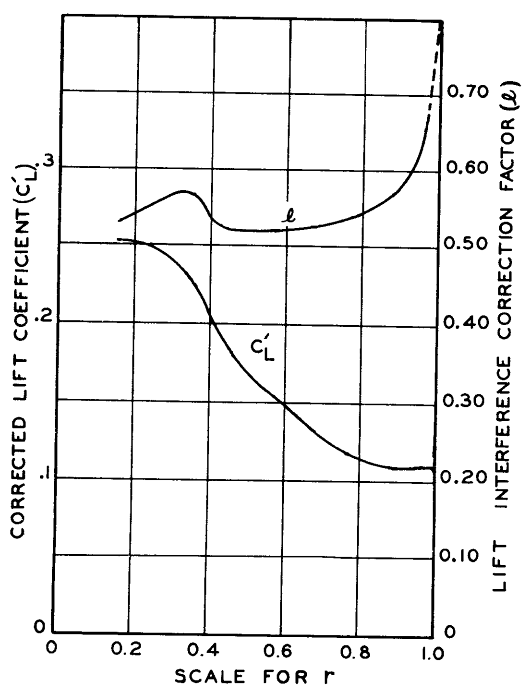


FIG. 14

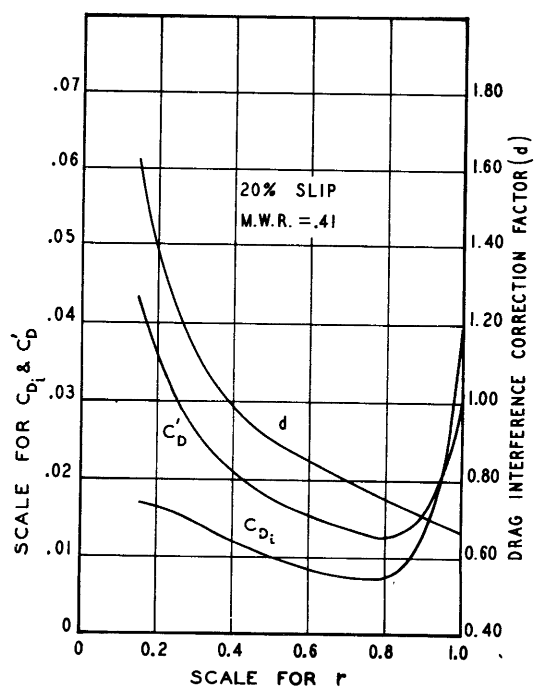


FIG. 15

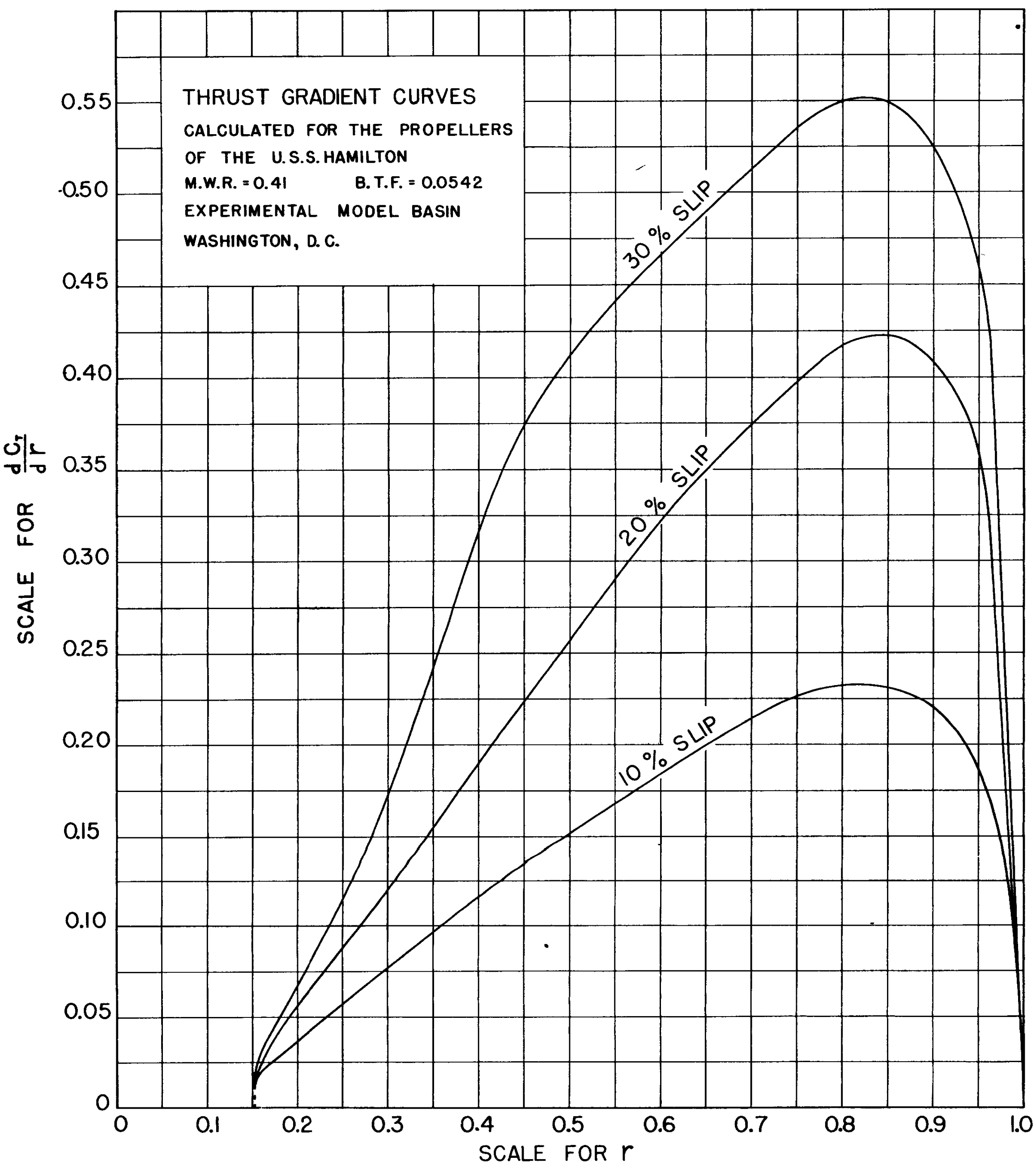
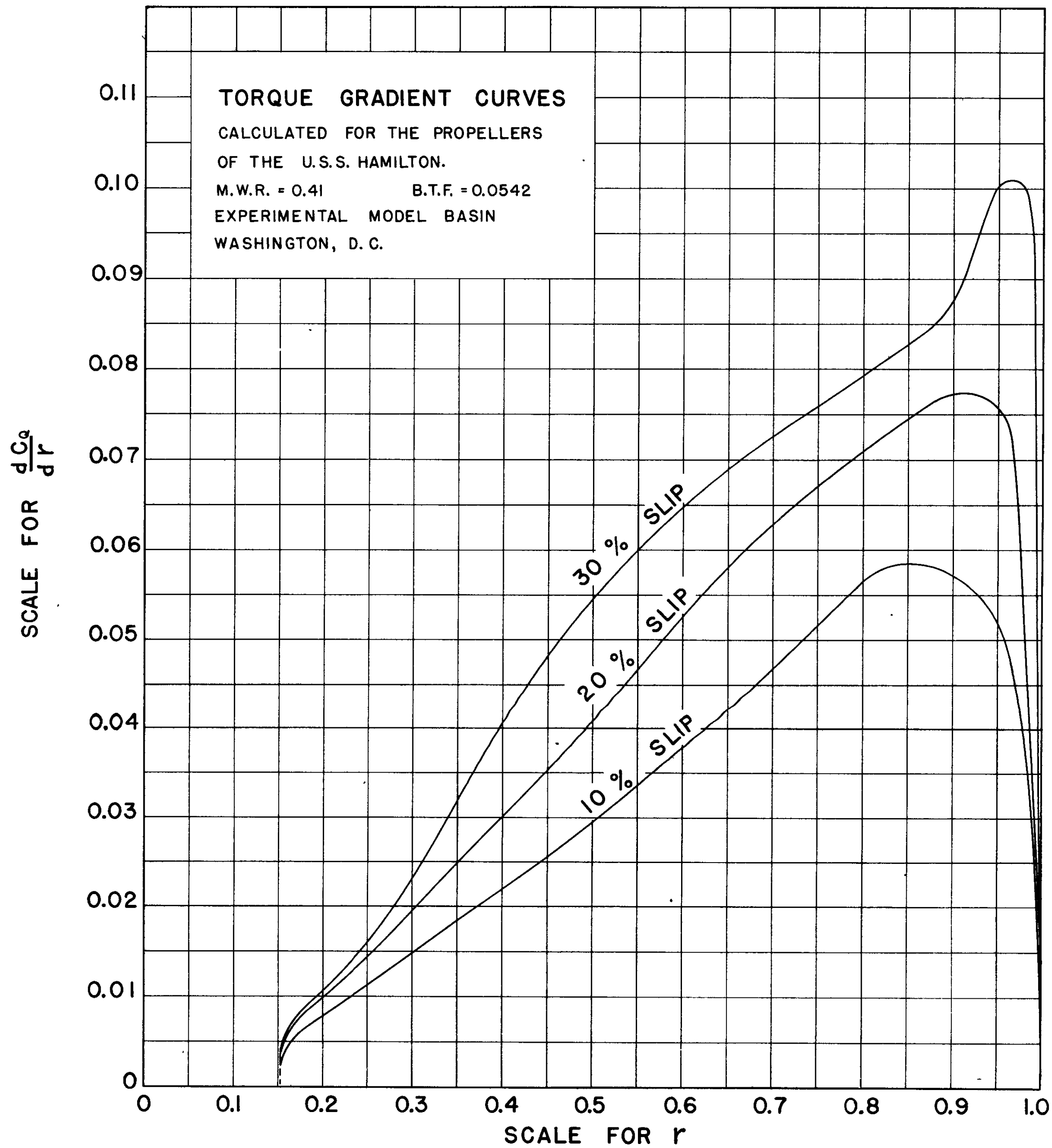

THRUST GRADIENT CURVES
CALCULATED FOR THE PROPELLERS
OF THE U.S.S. HAMILTON
M.W.R. = 0.41 B.T.F. = 0.0542
EXPERIMENTAL MODEL BASIN
WASHINGTON, D. C.
30 % SLIP
20 % SLIP
10 % SLIP
SCALE FOR $\frac{dC_T}{dr}$
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
SCALE FOR r

FIGURE 16



TORQUE GRADIENT CURVES
CALCULATED FOR THE PROPELLERS
OF THE U.S.S. HAMILTON.
M.W.R. = 0.41
B.T.F. = 0.0542
EXPERIMENTAL MODEL BASIN
WASHINGTON, D. C.
30 % SLIP
20 % SLIP
10 % SLIP
SCALE FOR $\frac{dC_Q}{dr}$
SCALE FOR r
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIGURE 17

Fig. 16 gives the thrust-gradient curves for 10, 20 and 30% slip. Integration of these curves gives for 10% slip, C_T = 0.130; 20% slip, C_T = 0.224 and 30% slip, C_T = 0.316.

Fig. 17 shows the torque-gradient curves. The curve for 30% slip shows a decided hump at the 0.95 radius. Since 30% slip is in the cavitating range this region of the curve is not reliable. Integration of these gives C_Q = 0.0289, 0.0388 and 0.0480 at 10, 20 and 30% slip respectively.

Fig. 18 gives a comparison of the characteristics of these propellers as obtained in the Experimental Model Basin and the calculated values. It is to be noted that the calculated values of C_T compare fairly well with the experimental values but indicate a steeper curve. The calculated values of C_Q are all low while the efficiency curve is shoved to the right.

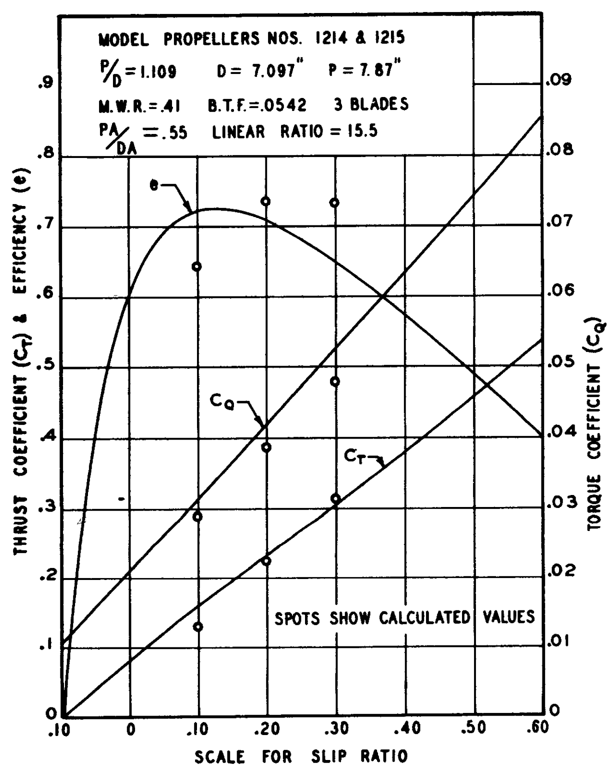


FIG. 18

Fig. 19 gives curves showing the effect on interference of changing the slip or changing the number of blades. The dotted portions indicate the regions of extrapolation.

Tables IV, V and VI give the calculations for the curves in Figs. 16 and 17.

Col. 26 gives fairly high values of efficiency at the hub section but this is obtained by neglecting the effect of friction or boundary layer along the hub, and the changes in the lift curve slope due to changes in blade thickness fraction.

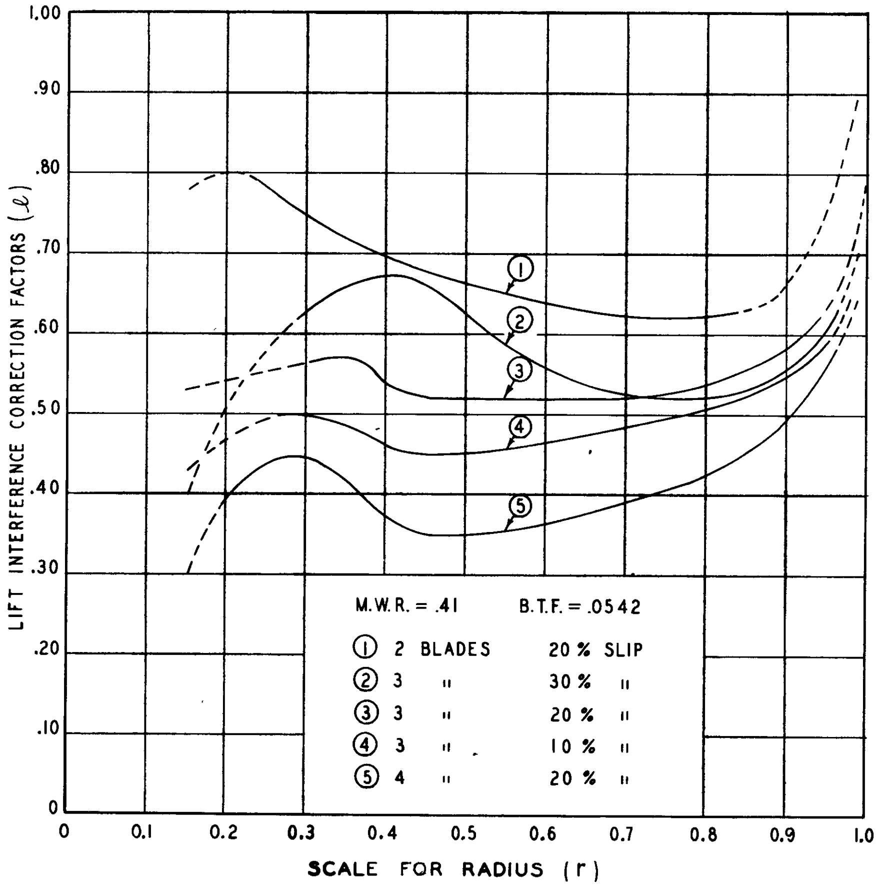


Fig. 19

Explanation of Columns in **Tables IV, V** and VI

ol. 1 r - radius divided by tip radius

2 b - blade width divided by tip radius

3 t - blade thickness divided by tip radius

4 t/b - section thickness fraction

5 $\frac{2\pi r}{Nb}$ - circumference of circle of radius r divided by number of blades and blade width gives the distance in terms of chord between corresponding points of two adjacent blades.

6 β - helix angle or nominal pitch angle

7 θ - angle of advance

8 α - angle of attack $= \beta - \theta$

9 $\frac{180}{\pi}\frac{t}{b}$ - angle of attack (negative) for zero lift

10 α_a - absolute angle of attack $= \alpha + \frac{180}{\pi}\frac{t}{b}$

11 G/b - gap/chord $= \frac{2\pi r}{Nb} \sin \theta$

12 C_L - absolute lift coefficient from formula $C_L = \dfrac{.096\,\alpha_a}{1 + \frac{1.75}{A.R.}}$

where A.R. = $\frac{\text{length of blade}}{\text{dia. x mean width ratio}}$

Col. 13 ℓ – interference correction factors for lift from Blade Interference Test

14 C_L' – absolute lift coefficient corrected for interference

15 i – $\frac{c}{4} \times \frac{s}{s^2-y^2}$ where c is mean chord, s is length of blade and y is distance from hub to section. (Glauert)

16 C_{D_i} – Induced drag coefficient absolute = i C_L^2

17 C_D – drag coefficient = C_{D_i} + .009. .009 is a mean value of the profile drag of several circular arc sections.

18 d – interference correction factor for drag.

19 C_D' – drag coefficient corrected for interference.

20 λ_1 – lift and drag coefficients resolved parallel to shaft.

$$\lambda_1 = C_L' \cos\theta - C_D' \sin\theta$$

21 K_1 – $3/8\rho b\,(1-s)^2 \csc^2\theta$

22 $\frac{d\,C_T}{d\,r}$ – $\lambda_1 K_1$

23 λ_2 – lift and drag coefficients resolved in direction of torque.

$$\lambda_2 = C_L' \sin\theta + C_D' \cos\theta$$

24 K_2 – $\frac{3\rho\, br\,(1-s)^2 \csc^2\theta}{16\ P/D}$

25 $\frac{d\,C_Q}{d\,r}$ – $\lambda_2\ K_2$

26 e – $\frac{d\,C_T}{dr} \Big/ \frac{d\,C_Q}{d\,r} \times \frac{1-s}{2\pi}$

TABLE IV

ANALYSIS OF PROPELLERS OF U.S.S. HAMILTON FROM AIRFOIL THEORY WITH MULTIPLANE INTERFERENCE CORRECTION FACTORS AT 10% SLIP

1	2	3	4	5	6	7	8	9	10	11	12	13
r	b	t	t/b	$\frac{2\pi r}{Nb}$	β	θ	α	$\frac{180}{\pi}\frac{t}{b}$	α_a	G/b	C_L	ℓ
.1522	.631	.0921	.146	0.50	66° 41'	64° 24'	2.28°	8.36	10.64	.45	.380	.43
.2361	.727	.0837	.115	0.68	56° 13'	53° 23'	2.83	6.59	9.42	.55	.336	.49
.3466	.823	.0721	.088	0.88	45° 31'	42° 30'	3.01	5.02	8.03	.59	.287	.49
.4537	.919	.0612	.067	1.03	37° 53'	35° 04'	2.82	3.81	6.63	.59	.237	.45
.5636	.975	.0499	.051	1.21	32° 04'	29° 24'	2.66	2.93	5.59	.60	.200	.46
.6735	.998	.0383	.038	1.41	27° 40'	25° 15'	2.42	2.20	4.62	.60	.165	.48
.7806	.958	.0270	.028	1.71	24° 20'	22° 08'	2.20	1.62	3.82	.64	.136	.50
.8905	.809	.0158	.020	2.30	21° 38'	19° 38'	2.00	1.18	3.18	.77	.114	.54
.9638	.544	.0082	.015	3.71	20° 07'	18° 14'	1.88	0.86	2.74	1.16	.098	.61

14	15	16	17	18	19	20	21	22	23	24	25	26
C_L'	i	C_{Di}	C_D	d	C_D'	λ_1	K_1	$\frac{d\,C_T}{d\,r}$	λ_2	K_2	$\frac{d\,C_Q}{d\,r}$	e
.163	.077	.011	.020	1.69	.034	.039	.458	.018	.162	.031	.0051	50.1
.165	.078	.009	.018	1.44	.026	.077	.650	.050	.147	.071	.0104	68.8
.141	.082	.007	.016	1.22	.020	.091	1.063	.097	.110	.166	.0183	75.9
.107	.088	.005	.014	1.18	.016	.079	1.666	.132	.075	.336	.0252	74.9
.092	.101	.004	.013	1.17	.015	.073	2.387	.174	.058	.606	.0352	71.0
.079	.124	.003	.012	1.17	.014	.065	3.185	.207	.047	.983	.0441	67.3
.068	.145	.003	.012	1.15	.014	.058	3.985	.231	.039	1.402	.0547	60.6
.062	.318	.004	.013	1.03	.014	.053	4.225	.224	.034	1.698	.0575	55.6
.060	.918	.009	.018	.92	.016	.052	3.270	.170	.034	1.420	.0483	50.5

TABLE V

ANALYSIS OF PROPELLERS OF U.S.S. HAMILTON FROM AIRFOIL THEORY WITH MULTIPLANE INTERFERENCE CORRECTION FACTORS AT 20% SLIP

1	2	3	4	5	6	7	8	9	10	11	12	13
r	b	t	t/b	$\frac{2\pi r}{Nb}$	β	θ	α	$\frac{180}{\pi}\frac{t}{b}$	α_a	G/b	C_L	ℓ
.1522	.631	.0921	.146	0.50	66° 41'	61° 41'	5.00°	8.36°	13.36°	.44	.477	.53
.2361	.727	.0837	.115	0.68	56° 14'	50° 06'	6.13	6.59	12.72	.52	.454	.55
.3466	.823	.0721	.088	0.88	45° 31'	39° 11'	6.33	5.02	11.35	.56	.405	.57
.4537	.919	.0612	.067	1.03	37° 53'	31° 55'	5.95	3.81	9.76	.55	.349	.52
.5636	.975	.0499	.051	1.21	32° 03'	26° 38'	5.42	2.93	8.35	.54	.298	.52
.6735	.998	.0383	.038	1.41	27° 40'	22° 45'	4.91	2.20	7.11	.55	.254	.52
.7806	.958	.0270	.028	1.71	24° 20'	19° 54'	4.43	1.62	6.05	.58	.216	.54
.8905	.809	.0158	.020	2.30	21° 38'	17° 30'	4.13	1.18	5.31	.69	.190	.57
.9638	.544	.0082	.015	3.71	20° 07'	16° 20'	3.78	0.86	4.64	1.05	.165	.66

14	15	16	17	18	19	20	21	22	23	24	25	26
C_L'	i	C_{Di}	C_D	d	C_D'	λ_1	K_1	$\frac{d\,C_T}{d\,r}$	λ_2	K_2	$\frac{d\,C_Q}{d\,r}$	e
.253	.077	.017	.026	1.63	.043	.082	0.379	.031	.243	.028	.0068	58.1
.250	.078	.016	.025	1.26	.032	.136	0.576	.078	.212	.062	.0130	76.6
.231	.082	.013	.022	1.05	.023	.164	0.960	.158	.164	.150	.0246	81.4
.181	.088	.011	.020	.94	.019	.144	1.532	.220	.112	.313	.0351	80.0
.155	.101	.009	.018	.87	.016	.132	2.260	.299	.084	.575	.0483	78.7
.132	.124	.008	.017	.81	.014	.116	3.110	.361	.064	.944	.0604	76.1
.117	.145	.007	.016	.76	.012	.106	3.865	.410	.051	1.361	.0694	75.3
.108	.318	.011	.020	.71	.015	.099	3.770	.413	.046	1.674	.0770	68.4
.109	.918	.025	.034	.68	.023	.099	3.199	.317	.053	1.390	.0737	43.0

TABLE VI

ANALYSIS OF PROPELLERS OF U.S.S. HAMILTON FROM AIRFOIL THEORY WITH MULTIPLANE INTERFERENCE CORRECTION FACTORS AT 30% SLIP

1	2	3	4	5	6	7	8	9	10	11	12	13
r	b	t	t/b	$\frac{2\pi r}{Nb}$	β	θ	α	$\frac{180}{\pi}\frac{t}{b}$	α_a	G/b	C_L	ℓ
.1522	.631	.0921	.146	0.50	66° 41'	58° 23'	8.30°	8.36°	16.66°	.43	.595	.40
.2361	.727	.0837	.115	0.68	56° 14'	46° 18'	9.93	6.59	16.52	.49	.590	.56
.3466	.823	.0721	.088	0.88	45° 30'	35° 29'	10.03	5.02	15.05	.51	.538	.66
.4537	.919	.0612	.067	1.03	37° 53'	28° 34'	9.32	3.81	13.13	.50	.469	.66
.5636	.975	.0499	.051	1.21	32° 03'	23° 40'	8.38	2.93	11.31	.49	.404	.58
.6735	.998	.0383	.038	1.41	27° 40'	20° 09'	7.52	2.20	9.72	.49	.347	.53
.7806	.958	.0270	.028	1.71	24° 20'	17° 34'	6.77	1.62	8.39	.52	.300	.52
.8905	.809	.0158	.020	2.30	21° 38'	15° 30'	6.13	1.18	7.21	.62	.257	.55
.9638	.544	.0082	.015	3.71	20° 07'	14° 23'	5.73	0.86	6.59	.92	.235	.63

14	15	16	17	18	19	20	21	22	23	24	25	26
C_L'	i	C_{D_i}	C_D	d	C_D'	λ_1	K_1	$\frac{d\,C_T}{d\,r}$	λ_2	K_2	$\frac{d\,C_Q}{d\,r}$	e
.238	.077	.027	.036	1.32	.048	.084	0.310	.026	.228	.021	.0048	60.6
.330	.078	.027	.036	1.08	.039	.200	0.496	.099	.266	.053	.0141	78.4
.355	.082	.024	.033	.89	.027	.274	0.870	.239	.228	.136	.0311	85.5
.310	.088	.019	.028	.76	.021	.262	1.434	.376	.166	.294	.0487	86.0
.234	.101	.017	.026	.67	.017	.207	2.160	.447	.110	.549	.0604	82.5
.184	.124	.015	.024	.65	.016	.168	3.000	.501	.078	.910	.0710	78.6
.156	.145	.013	.022	.58	.013	.145	3.750	.544	.059	1.321	.0780	77.7
.141	.318	.021	.030	.53	.016	.132	4.041	.533	.053	1.622	.0860	69.1
.148	.918	.051	.060	.63	.038	.134	3.141	.421	.074	1.364	.1009	46.5

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