AN EXPERIMENTAL INVESTIGATION
OF PARTIALLY SHROUDED PROPELLERS

by

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Thesis Supervisors:
Prof. Justin E. Kerwin
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ABSTRACT

Results are reported for a series of experiments in which forces associated with a propeller fitted with a partial shroud are measured. The shroud is partial in the sense that it subtends only 180° of the propeller circumference rather than the full circumference, as is commonly the case. S. J. Gordon in 1966 proposed that such a shroud could be used as a rudder if mounted so that it can be moved from one side to another on the propeller circumference. A difference in velocity between the water moving on each side of the shroud produces a radial force which can be directed to either side by moving the shroud.

The quantities measured were the radial and axial force on the shroud, termed "lift" and "drag", and the thrust and torque on the propeller. Measurements were made in a propeller tunnel using a series of four different half shrouds with a single propeller. Variations were made in the geometric properties of the shrouds and in the orientation of the shrouds to the incoming flow with the object of determining the effect of these properties on the behavior of the propeller-shroud combination. Graphs of shroud and propeller performance characteristics are presented and methods of interpreting and comparing them are suggested.

It is found that rather large radial forces can be obtained with partial shrouds while getting very little accompanying drag. Under many operating conditions a thrust will be developed from the shroud. The forces on the shroud were found to be very sensitive to the angle of attack of the shroud and to a lesser extent on the camber of the shroud crossection. The shroud has a marked effect on the propeller characteristics and the results indicate that a higher pitch propeller than would be chosen otherwise might be desirable when using a partial shroud.

The partial shroud as a steering system seems to offer particularly good characteristics for applications where good maneuverability at low speeds is desired such as in tugs or salvage vessels. With more research and design development it might prove superior in a more general range of applications.

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CONTENTS

INTRODUCTION

In 1966 S. J. Gordon (1) proposed that an incomplete propeller shroud could be used to good advantage as a steering device for a ship. The shroud would be constructed in much the same way as a Kort Nozzle except that it would not extend completely around the propeller circumference. If the shroud were of the accelerating type, the fluid on the inner surface would be moving faster than fluid on the outer surface, and a pressure difference would exist between the inner and outer surfaces by Bernoulli's Principle. With a complete shroud this pressure difference is balanced radially by symmetry, but if the shroud is incomplete a radial force vector passing through the center of the open sector will be the resultant of this pressure difference. If the incomplete shroud is mounted so that it can be rotated around the circumference of the propeller this force can be directed to any desired angle. Directing it to left or right will produce a steering force, and to proceed directly ahead the force can be positioned either straight up or down. Directing it upward will produce a virtual decrease in ship weight and pointing the force downward will tend to hold the stern underwater. A decelerating shroud, which produces a higher pressure on the inner surface can be expected to produce a similar effect but with the radial force in the opposite direction and with somewhat more drag.

Gordon (1) developed a method for calculating the forces which might be expected to result from a system made up of a propeller and a shroud of arbitrary included angle. Calculations based on this

method indicated that the partial shroud would have some very desirable characteristics as a steering device. Among these were:

(1) Much less drag than a conventional rudder. In fact, additional thrust would be obtained from the device under some operating conditions.

(2) Appreciable steering force with little or no way on.

(3) Greater steering force than would be obtained with a conventional rudder of equal surface area.

Possible problems forseen were:

(1) Shroud induced propeller cavitation and vibration.

(2) Propeller induced shroud vibration.

The results of a preliminary experimental investigation (2) indicated that the anticipated forces could be realized in practice.

It was the intent of this investigation to determine experimentally the forces obtained from a propeller-partial shroud system and to investigate the effect of varying certain geometric properties of the shroud. It is felt that the results obtained establish the feasibility of a partial shroud steering system, from a hydrodynamic standpoint, and provide information of use in designing a practical steering shroud for use on a ship or boat.

PROCEDURE

Quantities of particular interest in determining the performance of a propeller-partial shroud system are the radial force produced by the shroud, the axial force on the shroud, the propeller thrust, and the propeller torque. The most accurate and convenient way of measuring these forces seemed to be through the use of a propeller tunnel, and the tunnel at M.I.T. was used in this investigation.

A partial shroud subtending 180° of arc, a "half shroud", was selected for these experiments as being the easiest to mount for instrumentation and intuitively probably the most suitable. Shrouds subtending either a larger or smaller arc would provide less radial force or "lift" and, after shroud mounting problems are considered, would probably cause more drag. All shrouds were based on an NACA 66-010 section profile on an a = .6 mean line with various changes of angle of attack and lift coefficient which will be described below. Data for designing shroud sections was taken from tables in Reference (3).

The propeller used had the following characteristics:

3 Blades

6.34" Diameter

$^{Pitch}/_{Diameter} = .6$

Expanded Area Ratio = .4

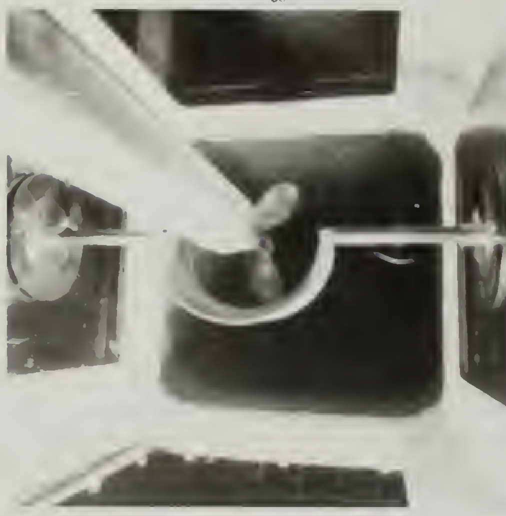
This propeller would be similar to those used on tugs, tow boats, and other low speed, high load applications. It was felt that the substan-

tial low speed steering force and the expected low speed thrust augmentation would make this steering device particularly attractive in such applications. There seems to be no reason, however, why use of the device should be restricted to low speed ships. As will be seen, this device can be used to advantage on higher speed, low thrust coefficient applications also.

The test section of the M.I.T. propeller tunnel is about four feet long and has a square crossection with 20 inch sides. Each of the four sides contains a large removable plexiglas window. Two windows have been fitted to mount a hydrofoil dynamometer as shown in figures (1) and (2). This dynamometer measures lift and drag and was easily adapted to support the shrouds. The propeller drive system in the tunnel is arranged so that the propeller can be easily moved back and forth in the test section even while the propeller is running. The shroud was mounted on struts between the two sections of the hydrofoil dynamometer and then the propeller was positioned in the shroud. The propeller could then be driven through its normal drive system with thrust and torque measured by the installed propeller dynamometer system and lift and drag on the shroud measured independently by the hydrofoil dynamometer. The velocity of flow past the propeller and shroud could be varied by changing the tunnel impeller speed.

The test procedure was to bring the propeller speed up to a value which would provide adequate force levels for measurement and then vary the propeller loading conditions by changing the speed of flow with the impeller. As only two strain gage indicators were available, one series

A



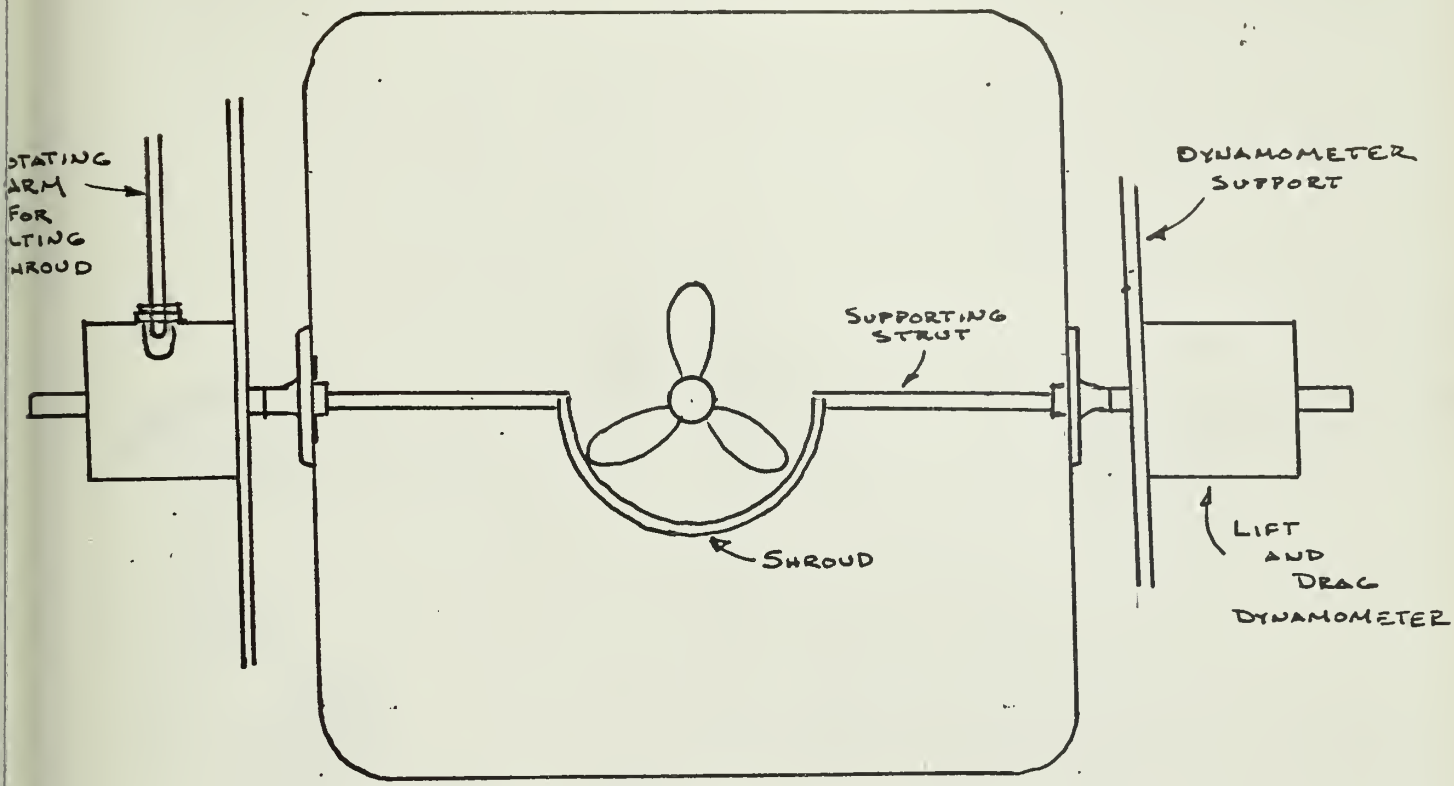
B

C

D

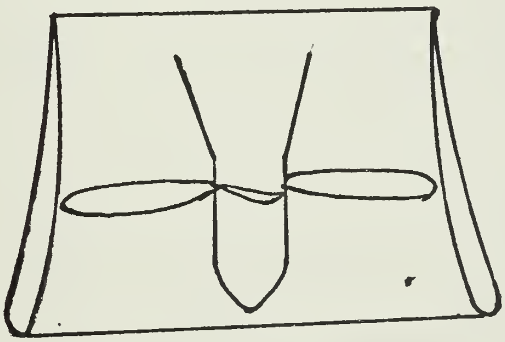
PROPELLER TUNNEL TEST SECTION
WITH APPARATUS IN PLACE

FIG 1



PROPELLER TUNNEL CROSSECTION

A

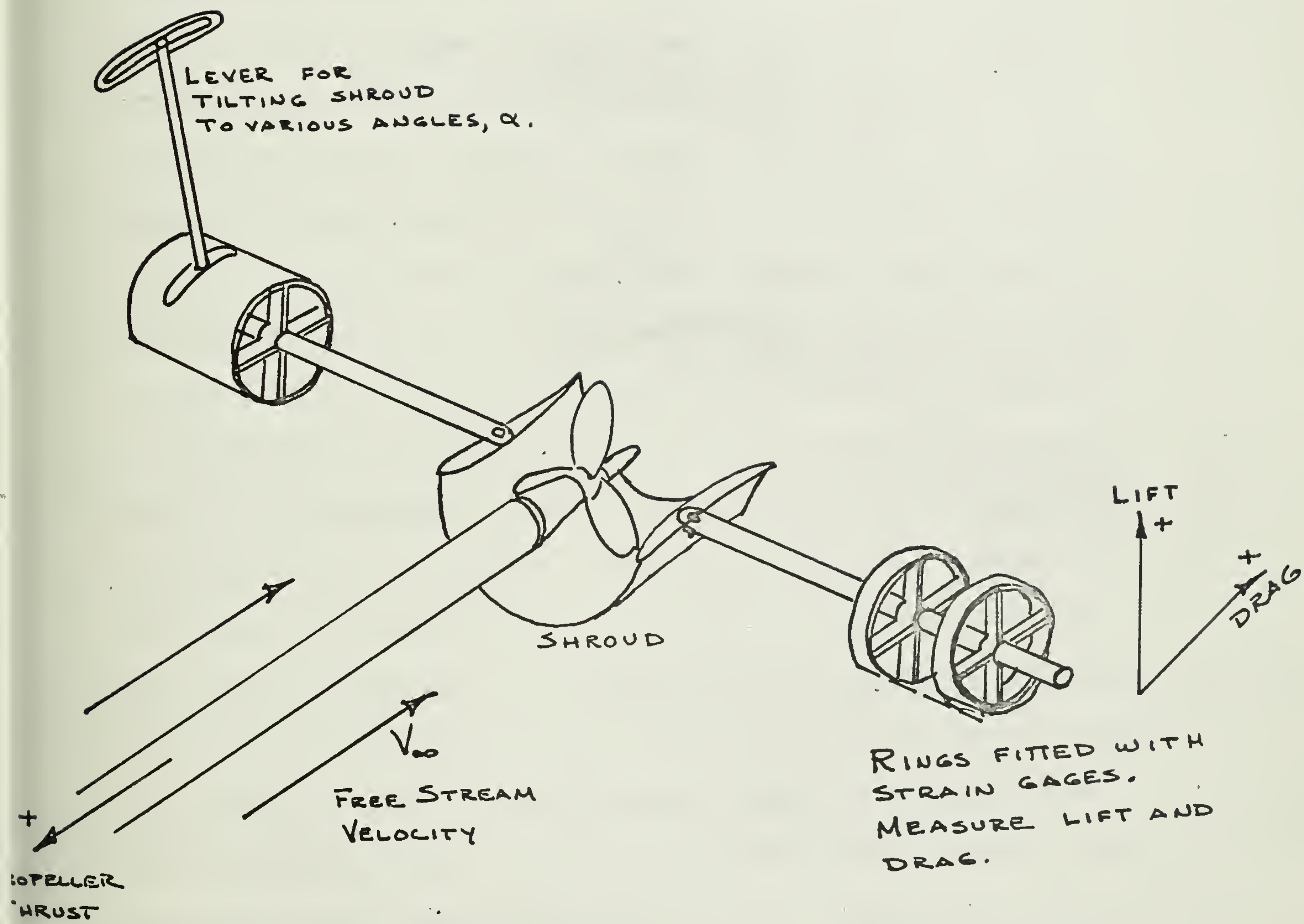


TOP VIEW OF

PROPELLER IN SHROUD

B

FIG 2



SHROUD SUPPORT,
AND
LIFT AND DRAG MEASURING
APPARATUS

FIG. 2C

of runs at a given propeller speed and various flow velocities would be made to measure shroud lift and drag, and then a similar series made for measuring thrust and torque. The lift and drag of the supporting struts was measured by making a series of runs with no shroud in place. These values were then subtracted from other data to obtain the pure shroud lift and drag.

The hydrofoil dynamometer was constructed so that the shroud could be rotated about an axis perpendicular to the propeller axis without changing the orientation of the lift and drag sensors. This permitted a rapid qualitative investigation of the effect of changing the angle of attack of the shroud lifting surface. Each shroud was constructed with some given angle between the lengthwise shroud axis and the nose-tail line of the lifting section which was a set property of the individual shroud. By rotating the shroud about its crosswise axis in the dynamometer mounting, however, an effective change in this orientation could be obtained. This change varies from a maximum at the center of the half shroud arc to zero at the edges, but as most of the effective measured lift is generated near the center of the shroud arc this method can be expected to give an excellent qualitative indication of the effect of varying the angle between the lifting surface and the propeller axis. With a promising angle thus determined a shroud can be built with that angle designed into it. Such a shroud can be expected to give much better performance. In this paper when the half shroud is tilted in such a way that the slope of the section nose-tail line is negative with respect to the propeller axis the angle is called negative. If the shroud section is tilted the other way, tending to

produce a positive angle of attack with the incoming flow, then the angle is considered positive. This is illustrated in figure (3).

It was also possible to move the propeller back and forth along the length of the shroud using the movable propeller shaft. This permitted checking the effect of the lengthwise placement of the propeller on performance. The shroud was designed to allow a small clearance between the blade tips and the inner surface at the point of smallest shroud diameter. When the propeller is moved away from this point the clearance is increased, so performance at the new position may be somewhat less than if the desired small clearance could be maintained. An increase in performance even with greater clearance would strongly suggest that the new lengthwise position was more advantageous, however.

Experimental observations were made in two segments. In the first segment two shrouds were investigated. Both shrouds were based on the same section profile, NACA 66-010, but had different mean lines. One had a high lift $a = .6$ $C_L = 1.0$ mean line and the other a lower lift $a = .6$ $C_L = 0.2$ mean line. After considering the results of this first series two additonal shrouds were designed and built and investigated in segment two.

A review of some of the literature on Kort Nozzles indicated that many of these shrouds had been built with an angle of between 10 and 15 degrees of contraction between the leading and trailing edges. Theoretical considerations seemed to suggest that a much smaller angle would be better however, and the first two shrouds were built with a convergence angle of 3.5°. The first series of tests indicated that even greater change in this direction was desirable and the second

SHROUD AT POSITIVE ANGLE α, SOLID LINES
SHROUD AT NEGATIVE ANGLE α, DASHED LINES

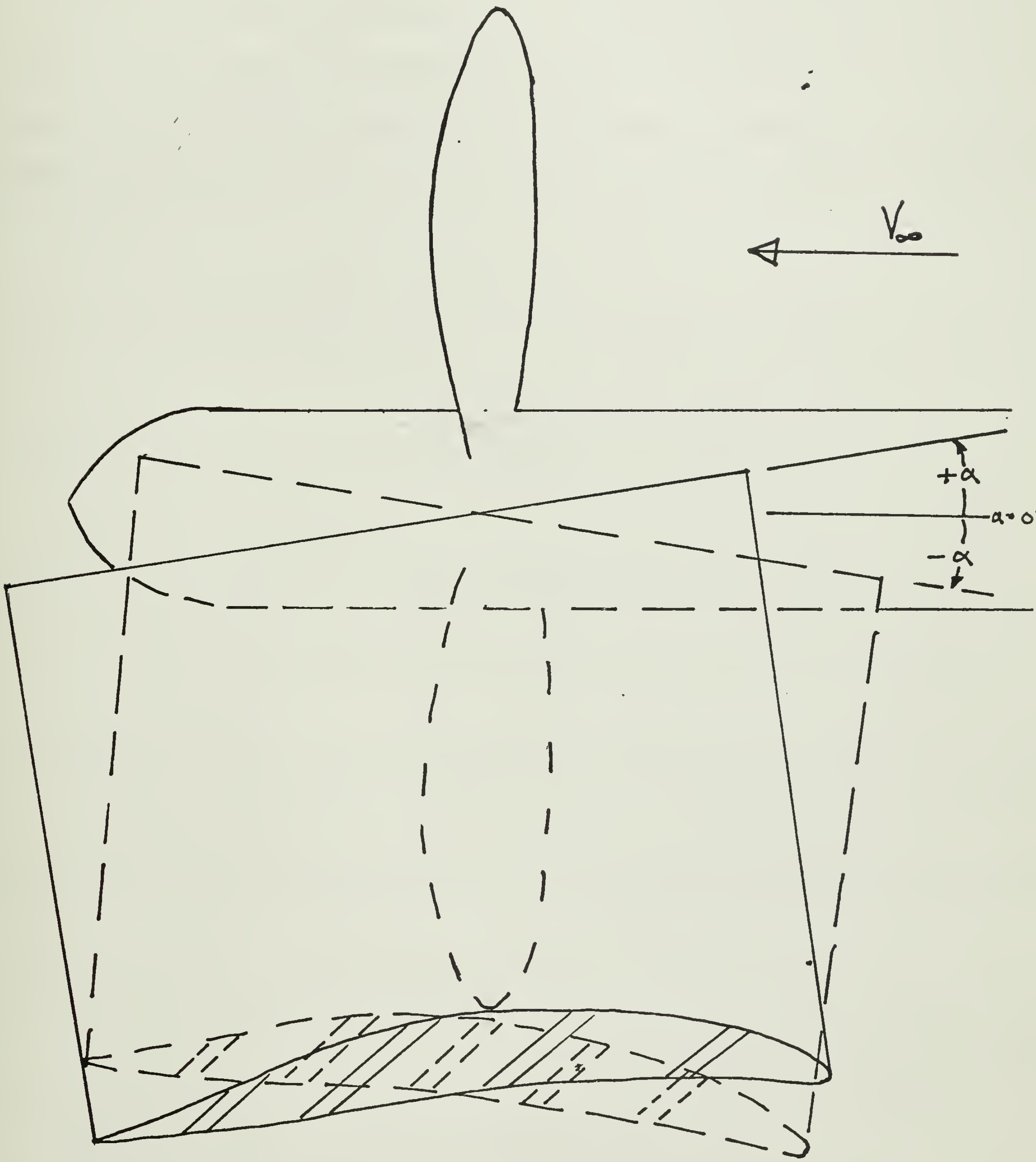
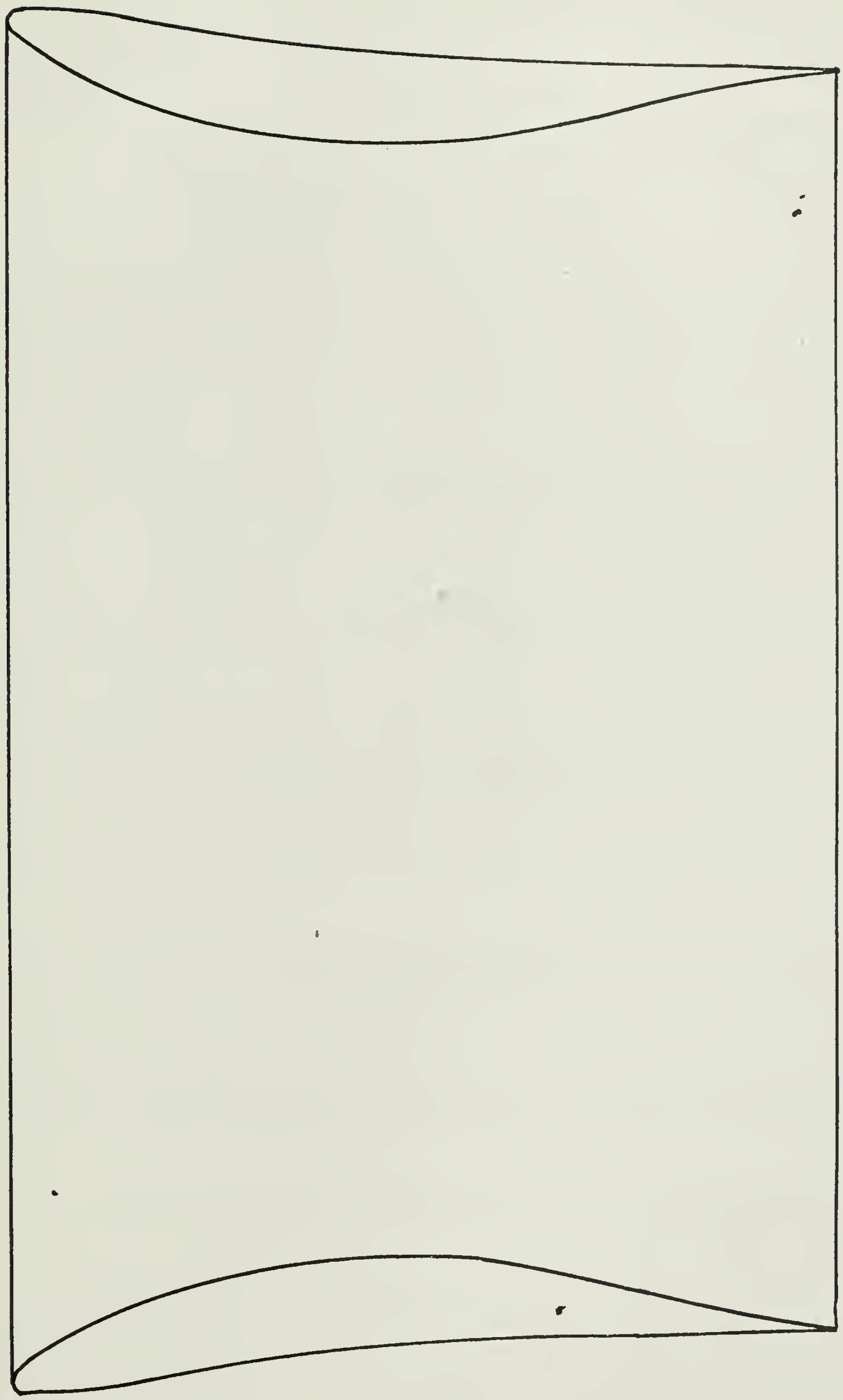


FIG. 3

series shrouds were built with a divergence between leading and trailing edges. One of these shrouds had a nominal lift coefficient of 1.0 and the other 2.0. The $C_L = 1.0$ shroud was given a divergence of 1° and the $C_L = 2.0$ a divergence of 6°. In addition the $C_L = 2.0$ shroud was made so that the propeller was placed farther back along the chord of the shroud. Diagrams of these shrouds are given in figures (4) thru (7).

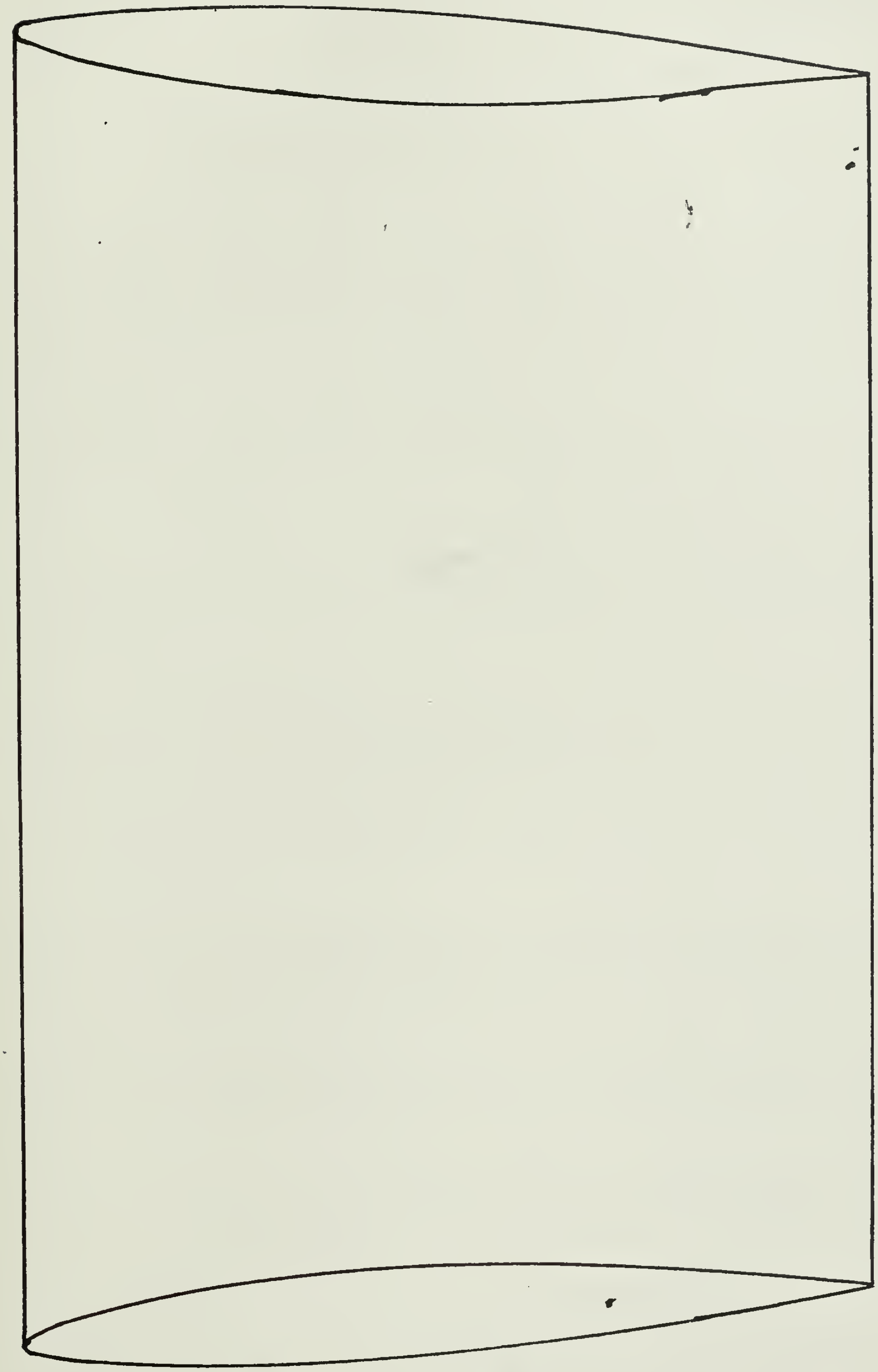
Series I



$C_L = 1.0 \qquad \alpha = -3.5°$

Fig. 4

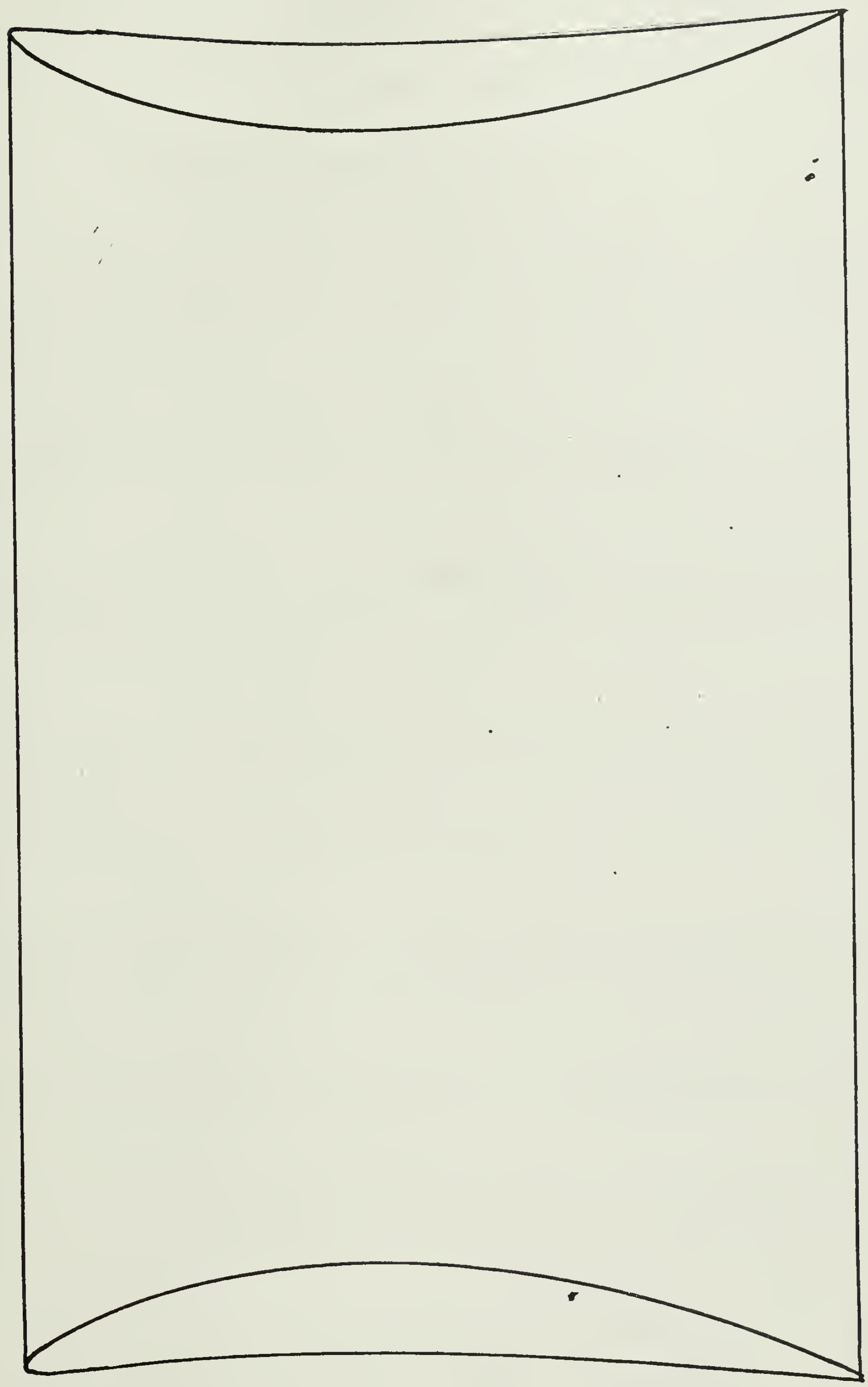
SERIES I



$C_L = .2 \qquad \alpha = -3.5°$

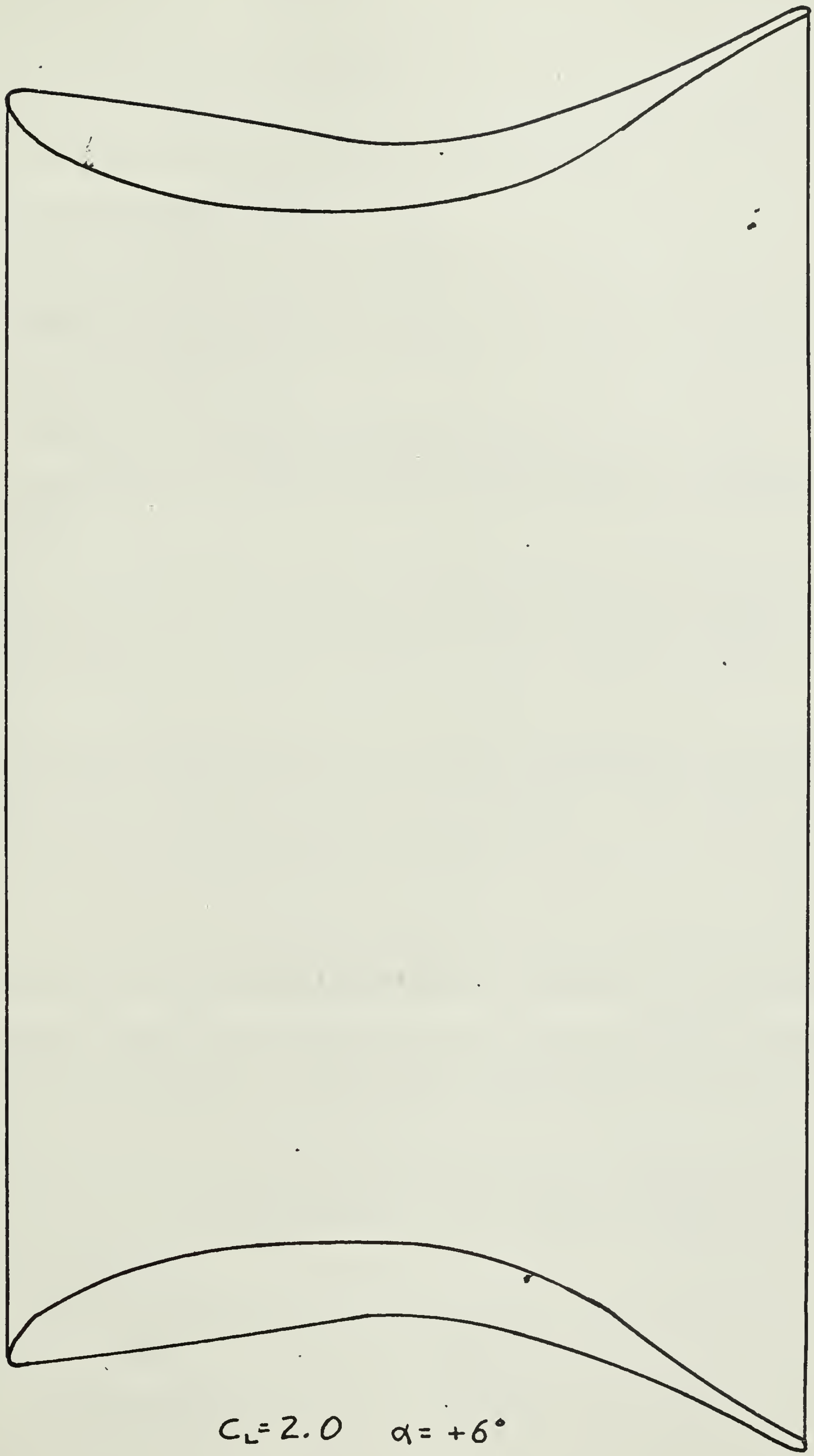
FIG. 5

SERIES II.



$C_L = 1.0 \quad \alpha = +1°$

FIG. 6



$C_L = 2.0 \quad \alpha = +6°$

FIG. 7

RESULTS

Test Series I

Figure (8) shows shroud lift and drag plotted versus free stream velocity for a shroud having the following characteristics:

Minimum inside diameter 6.4"

Chord Length 4.8"

NACA 66-010 section on a = .6,

C_L = 1.0 mean line

Designed convergence angle of nose-tail line = -3.5°

Lift and drag are plotted for various values of tilt angle, α . Propeller speed was 1200 RPM.

Figure (9) gives the same information for another shroud having the same characteristics as above except that C_L = 0.2. Propeller speed was also 1200 RPM.

In figure (10) the shroud lift at $\alpha = +3.5^{\circ}$ with the C_L = 1.0 shroud is plotted with thrust, propeller torque, and efficiency. The thrust, torque, and efficiency are those existing with the shroud in place and at the above angle.

Figures (11), (12), and (13) show the effect on shroud lift and drag of moving the propeller forward and backward along the chord length of the shroud. The C_L = 0.2 shroud was used at $\alpha = -7^{\circ}, 0^{\circ}, +7^{\circ}$ as shown.

Figures (14) thru (20) are propeller characteristic curves of the propeller with the C_L = 1.0 shroud attached at the values of angle α indicated. The quantities plotted are:

Thrust coefficient - $K_T = \dfrac{T}{\rho\ n^2\ D^4}$

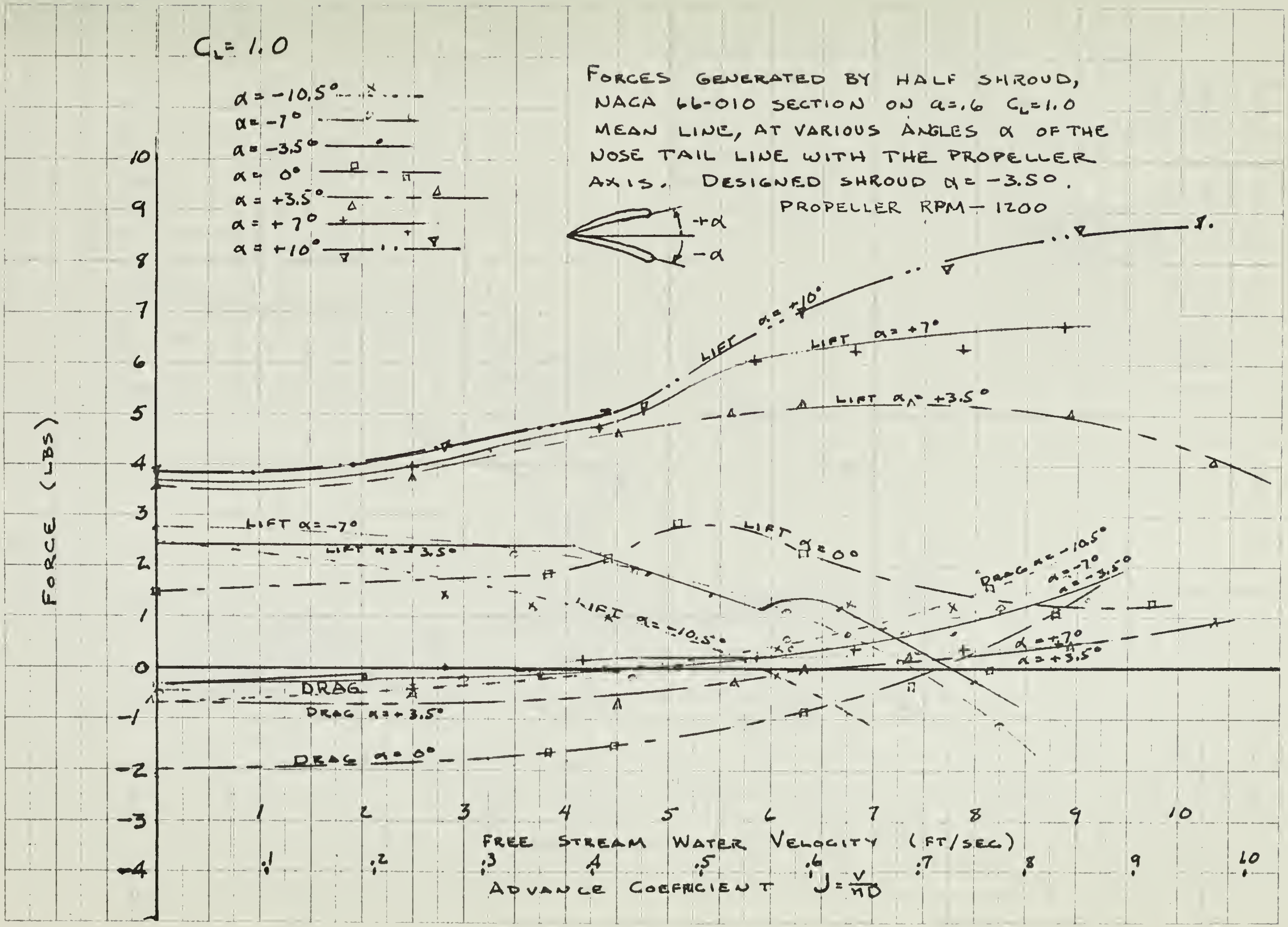
Torque coefficient - $K_Q = \dfrac{Q}{\rho\ n^2\ D^5}$

Efficiency - $\eta = \frac{T V_a}{Q \omega} = \frac{K_T J}{2 \pi K_Q}$

Advance coefficient - $J = \frac{V_a}{n D}$

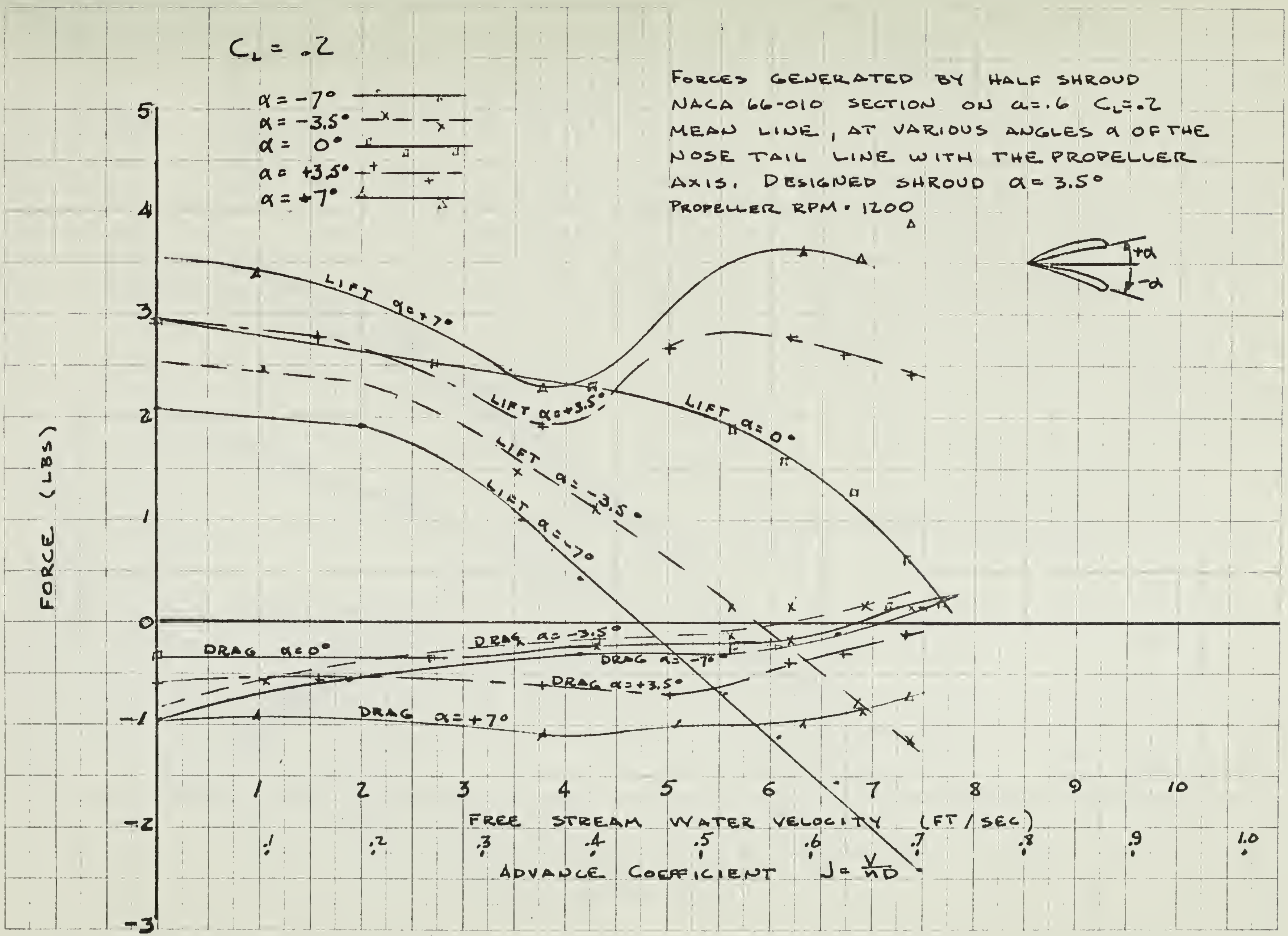
These diagrams are for the propeller only. The thrust of the shroud was not added in determining K_T.

Figure (21) is the propeller characteristic curves with no shroud attached.



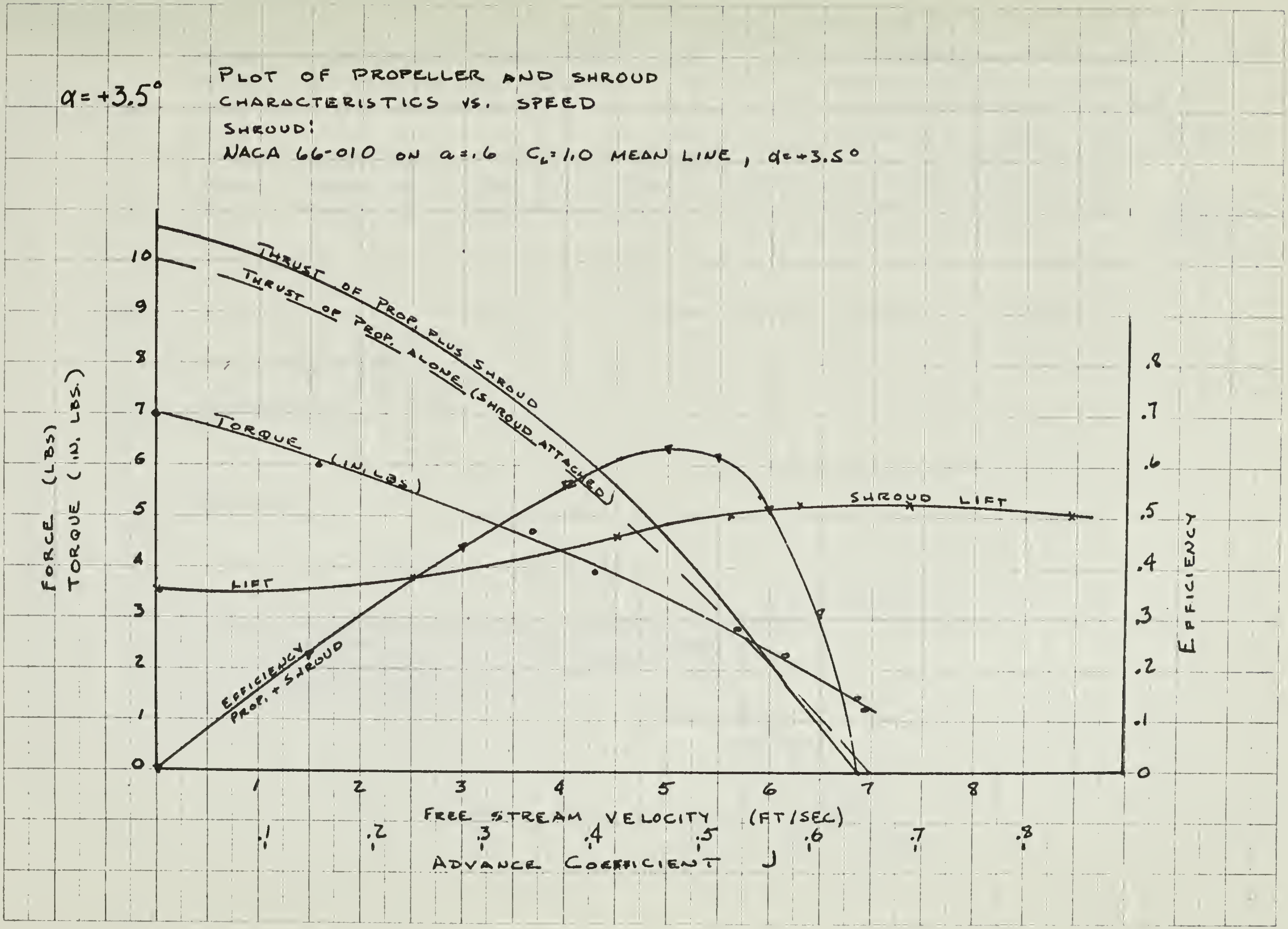
$C_L = 1.0$
α = −10.5°
α = −7°
α = −3.5°
α = 0°
α = +3.5°
α = +7°
α = +10°
FORCES GENERATED BY HALF SHROUD, NACA 66-010 SECTION ON a=.6 C_L=1.0 MEAN LINE, AT VARIOUS ANGLES α OF THE NOSE TAIL LINE WITH THE PROPELLER AXIS. DESIGNED SHROUD α = −3.5°.
PROPELLER RPM − 1200
+α
−α
LIFT α = +10°
LIFT α = +7°
LIFT α = +3.5°
LIFT α = −7°
LIFT α = −3.5°
LIFT α = 0°
LIFT α = −10.5°
DRAG α = −10.5°
α = −7°
α = −3.5°
α = +7°
α = +3.5°
DRAG
DRAG α = +3.5°
DRAG α = 0°
FORCE (LBS)
FREE STREAM WATER VELOCITY (FT/SEC)
ADVANCE COEFFICIENT $J = \frac{V}{nD}$

FIG. 8



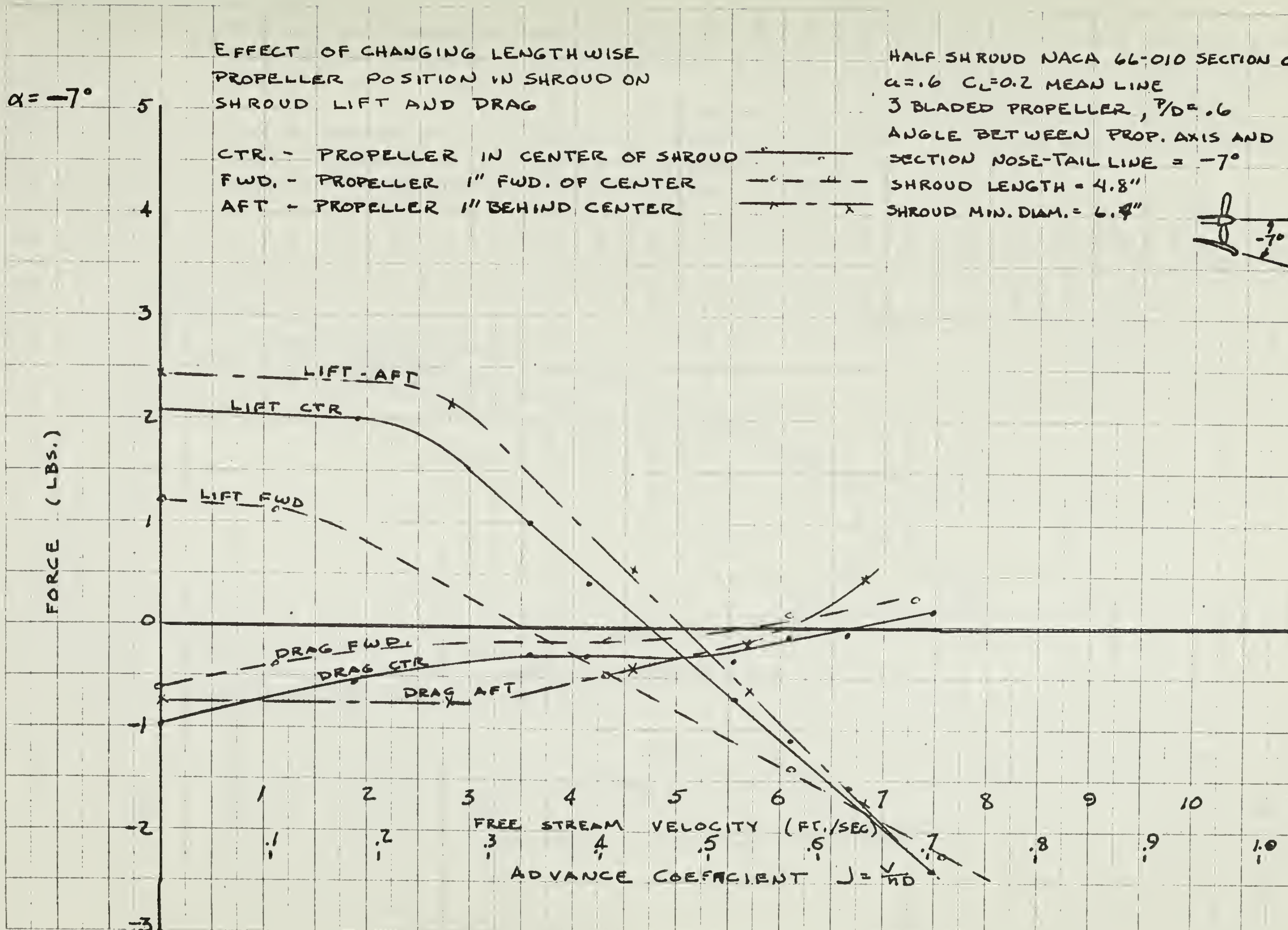
C_L = .2
α = -7°
α = -3.5°
α = 0°
α = +3.5°
α = +7°
FORCES GENERATED BY HALF SHROUD NACA 66-010 SECTION ON a=.6 C_L=.2 MEAN LINE, AT VARIOUS ANGLES α OF THE NOSE TAIL LINE WITH THE PROPELLER AXIS. DESIGNED SHROUD α = 3.5°
PROPELLER RPM = 1200
+α
-α
LIFT α=+7°
LIFT α=+3.5°
LIFT α= 0°
LIFT α= -3.5°
LIFT α= -7°
DRAG α=0°
DRAG α= -3.5°
DRAG α= -7°
DRAG α=+3.5°
DRAG α=+7°
FORCE (LBS)
5
4
3
2
1
0
-1
-2
-3
1 2 3 4 5 6 7 8 9 10
FREE STREAM WATER VELOCITY (FT/SEC)
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
ADVANCE COEFFICIENT J = V/nD

FIG. 9



α = +3.5°
PLOT OF PROPELLER AND SHROUD
CHARACTERISTICS VS. SPEED
SHROUD:
NACA 66-010 ON a=.6 C_L=1.0 MEAN LINE, α=+3.5°
THRUST OF PROP. PLUS SHROUD
THRUST OF PROP. ALONE (SHROUD ATTACHED)
TORQUE (IN. LBS.)
LIFT
SHROUD LIFT
EFFICIENCY PROP. + SHROUD
FORCE (LBS)
TORQUE (IN. LBS.)
EFFICIENCY
FREE STREAM VELOCITY (FT/SEC)
ADVANCE COEFFICIENT J

FIG. 10



α = −7°
EFFECT OF CHANGING LENGTHWISE PROPELLER POSITION IN SHROUD ON SHROUD LIFT AND DRAG
CTR. - PROPELLER IN CENTER OF SHROUD
FWD. - PROPELLER 1" FWD. OF CENTER
AFT - PROPELLER 1" BEHIND CENTER
HALF SHROUD NACA 66-010 SECTION ON
a=.6 CL=0.2 MEAN LINE
3 BLADED PROPELLER, P/D=.6
ANGLE BETWEEN PROP. AXIS AND
SECTION NOSE-TAIL LINE = −7°
SHROUD LENGTH = 4.8"
SHROUD MIN. DIAM. = 6.4"
−7°
LIFT - AFT
LIFT CTR
LIFT FWD
DRAG FWD.
DRAG CTR
DRAG AFT
FORCE (LBS.)
5
4
3
2
1
0
−1
−2
−3
1
2
3
4
5
6
7
8
9
10
FREE STREAM VELOCITY (FT./SEC)
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
ADVANCE COEFFICIENT J = V/nD

FIG. 11

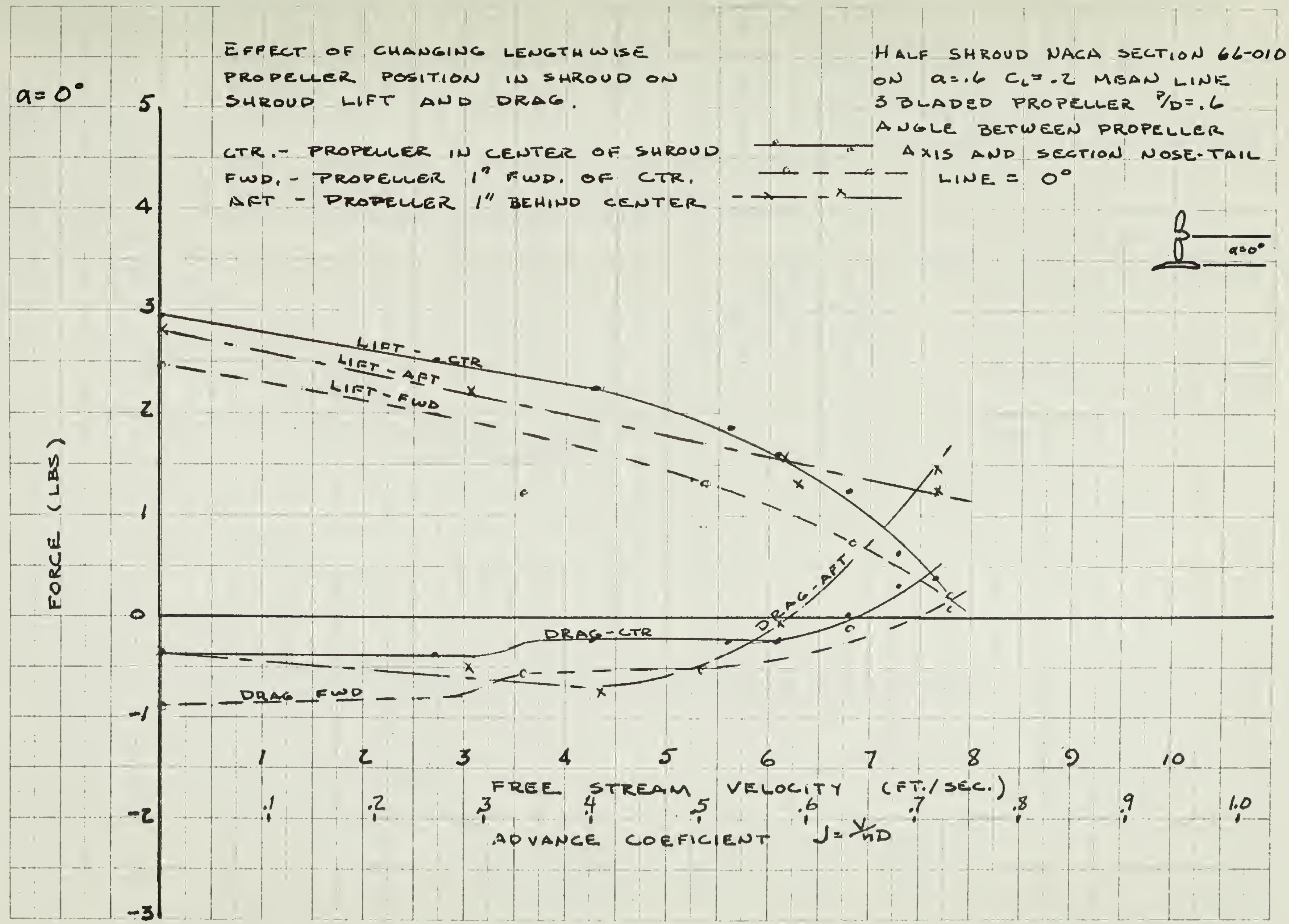

a= 0°
Effect of changing lengthwise propeller position in shroud on shroud lift and drag.
CTR. - Propeller in center of shroud
FWD. - Propeller 1" FWD. of CTR.
AFT - Propeller 1" behind center
Half shroud NACA section 66-010 on a=.6 C_L=.2 mean line
3 bladed propeller P/D=.6
Angle between propeller axis and section nose-tail line = 0°
LIFT - CTR
LIFT - AFT
LIFT - FWD
DRAG - CTR
DRAG - AFT
DRAG FWD
FORCE (LBS)
FREE STREAM VELOCITY (FT./SEC.)
ADVANCE COEFICIENT J= V/nD

Fig. 12

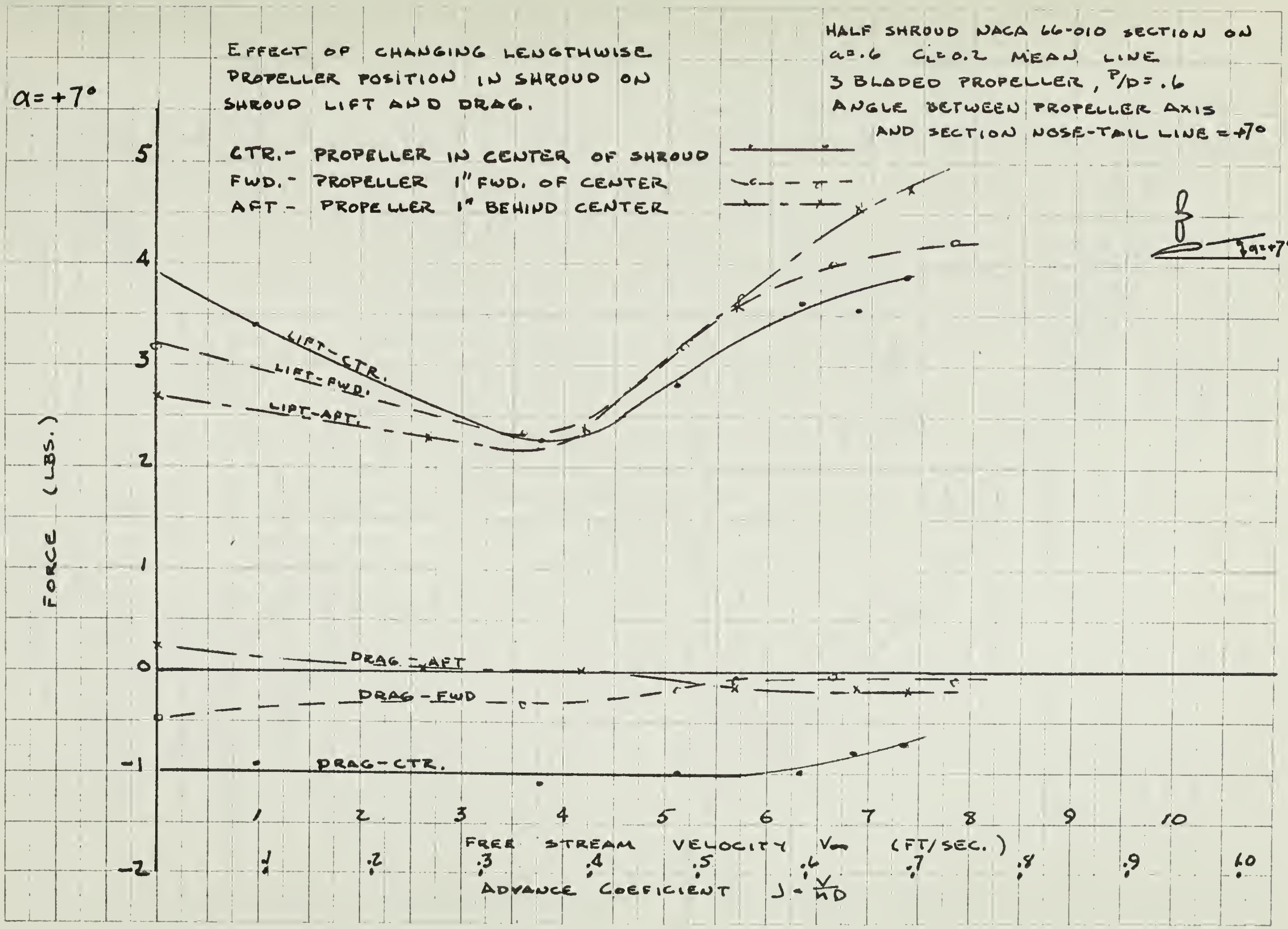

$\alpha = +7°$
Effect of changing lengthwise propeller position in shroud on shroud lift and drag.
CTR. - Propeller in center of shroud
FWD. - Propeller 1" fwd. of center
AFT - Propeller 1" behind center
Half shroud NACA 66-010 section on a=.6 C_L=0.2 mean line
3 bladed propeller, P/D = .6
Angle between propeller axis and section nose-tail line = +7°
$\alpha = +7°$
LIFT-CTR.
LIFT-FWD.
LIFT-AFT.
DRAG-AFT
DRAG-FWD
DRAG-CTR.
FORCE (LBS.)
5
4
3
2
1
0
-1
-2
1
2
3
4
5
6
7
8
9
10
FREE STREAM VELOCITY V_∞ (FT/SEC.)
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
ADVANCE COEFFICIENT $J = \frac{V}{nD}$

Fig. 13

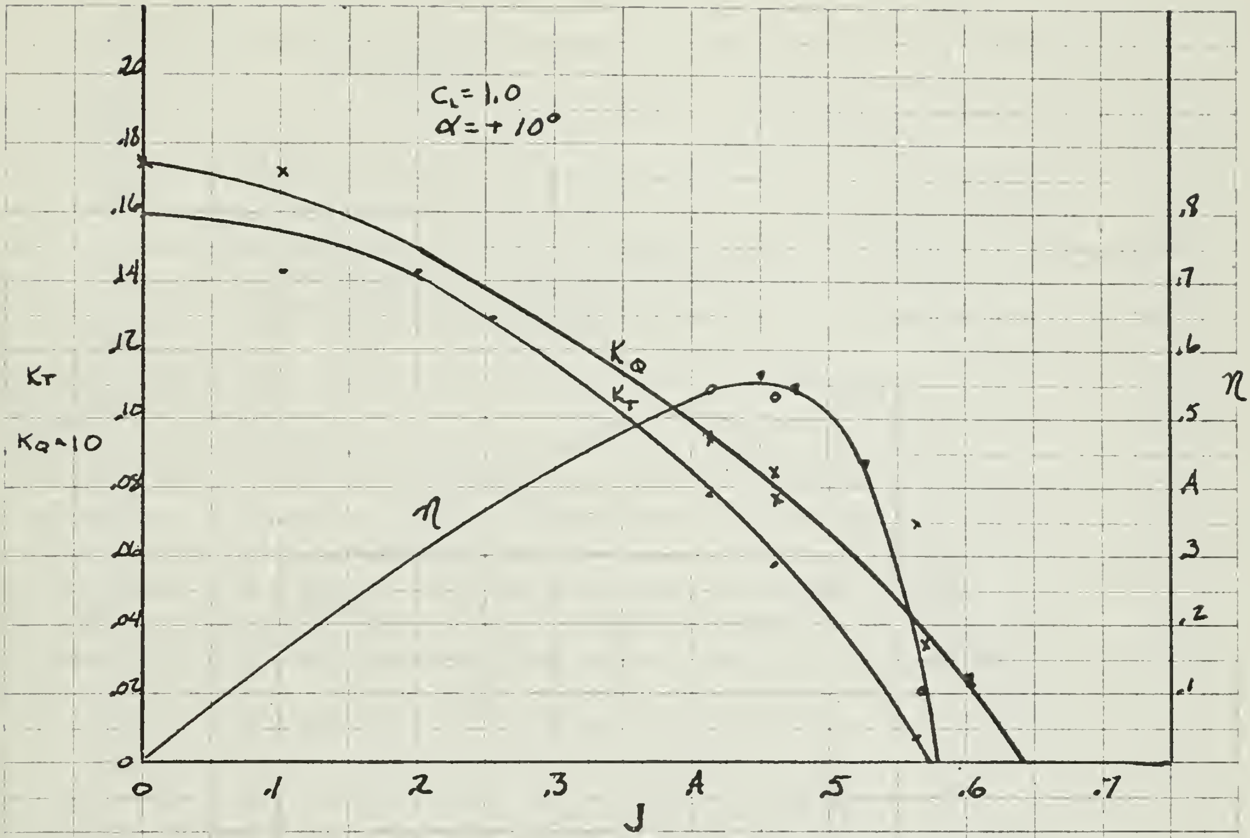

$C_L = 1.0$
$\alpha = +10°$
K_T
$K_Q \times 10$
K_Q
K_T
η
J

FIG. 14

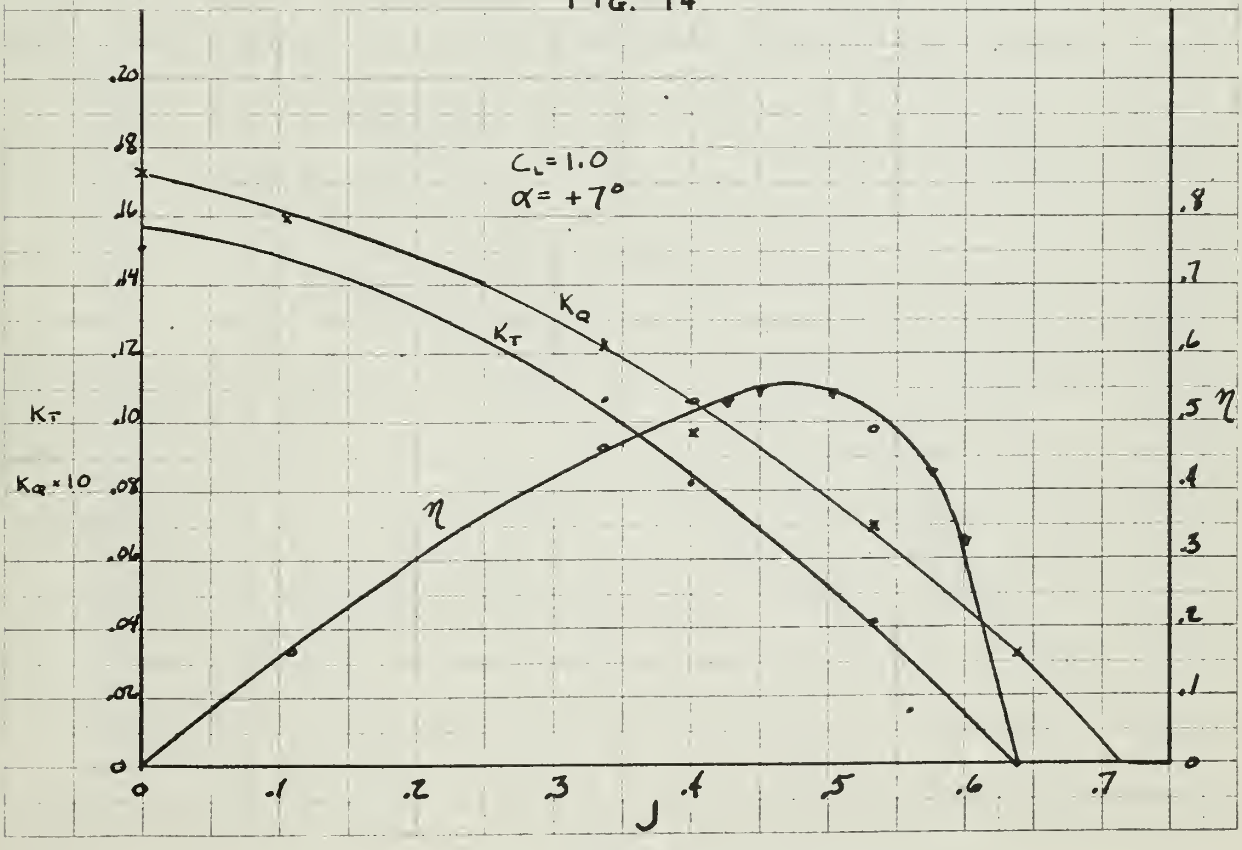
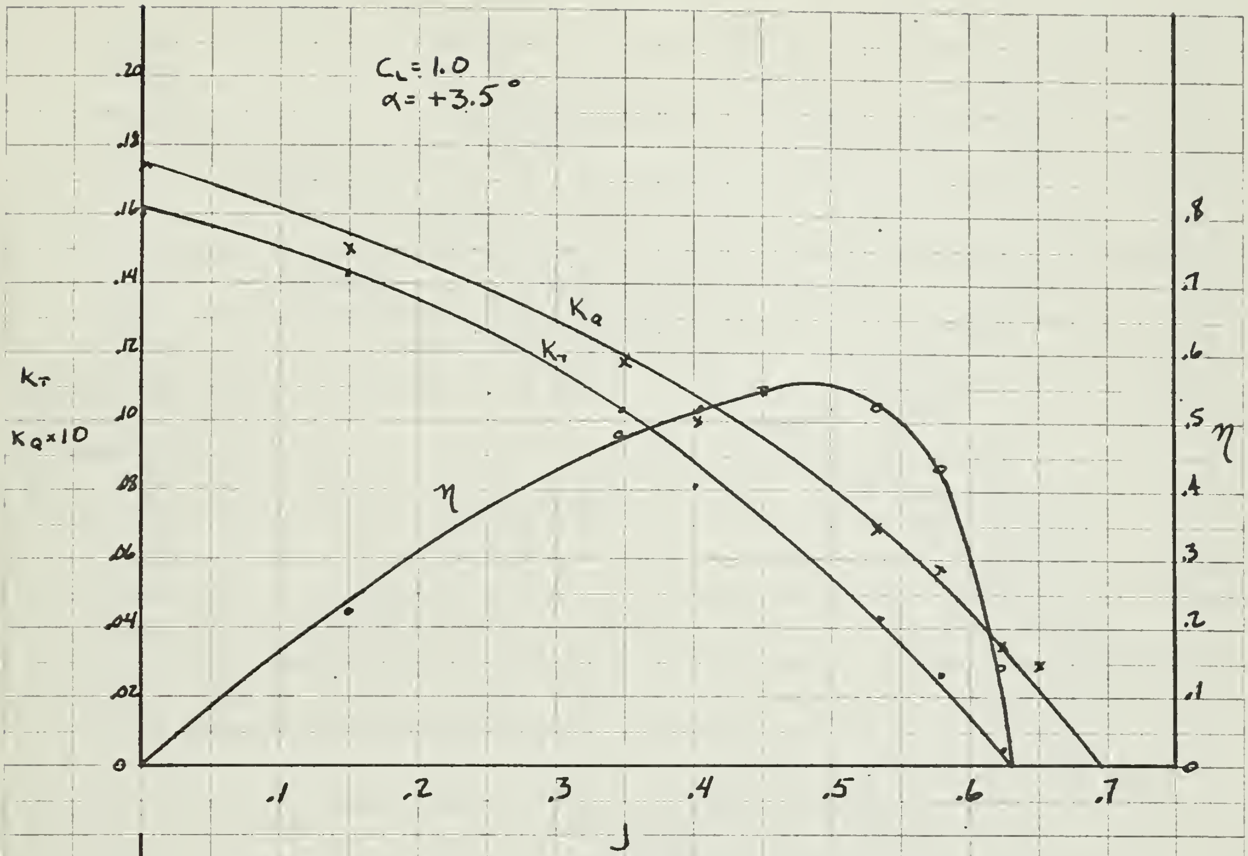
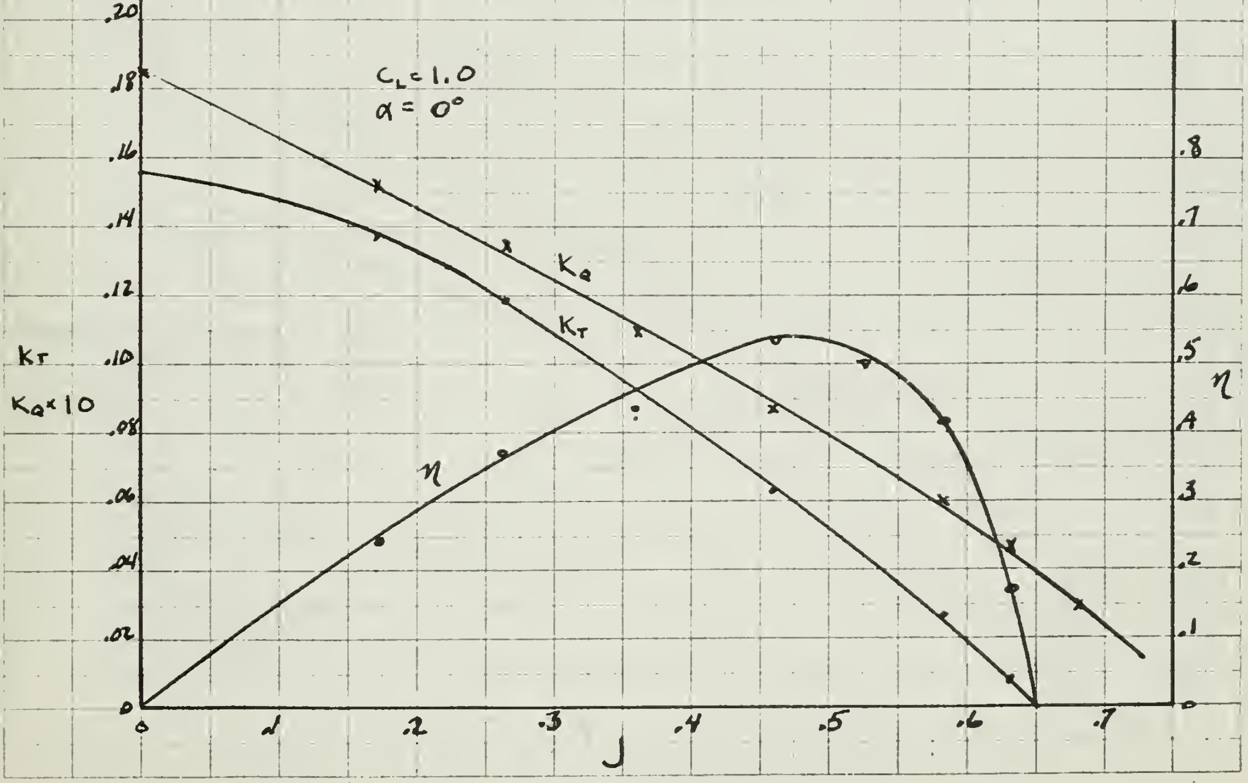

$C_L = 1.0$
$\alpha = +7°$
K_T
$K_Q \times 10$
K_Q
K_T
η
J

FIG. 15



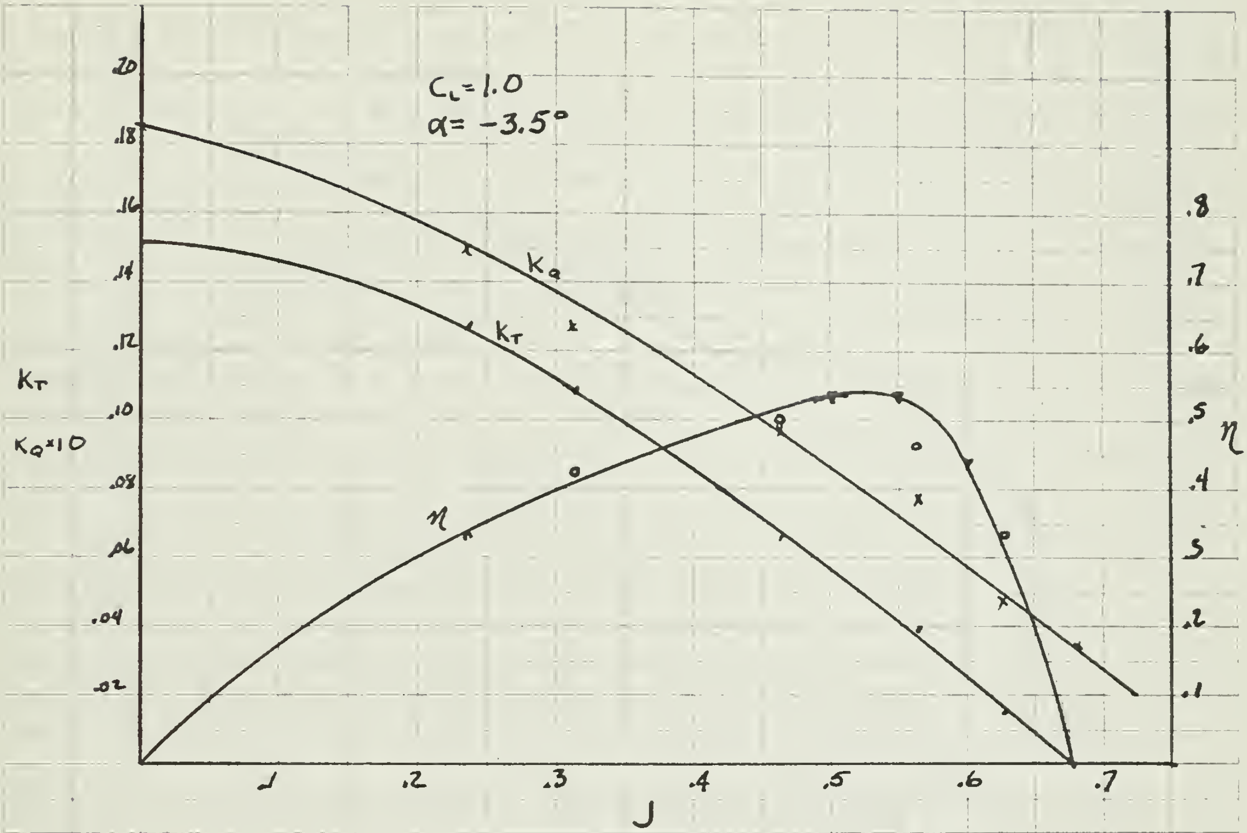
$C_L = 1.0$
$\alpha = +3.5°$
K_Q
K_T
η
K_T
$K_Q \times 10$
η
J

FIG. 16



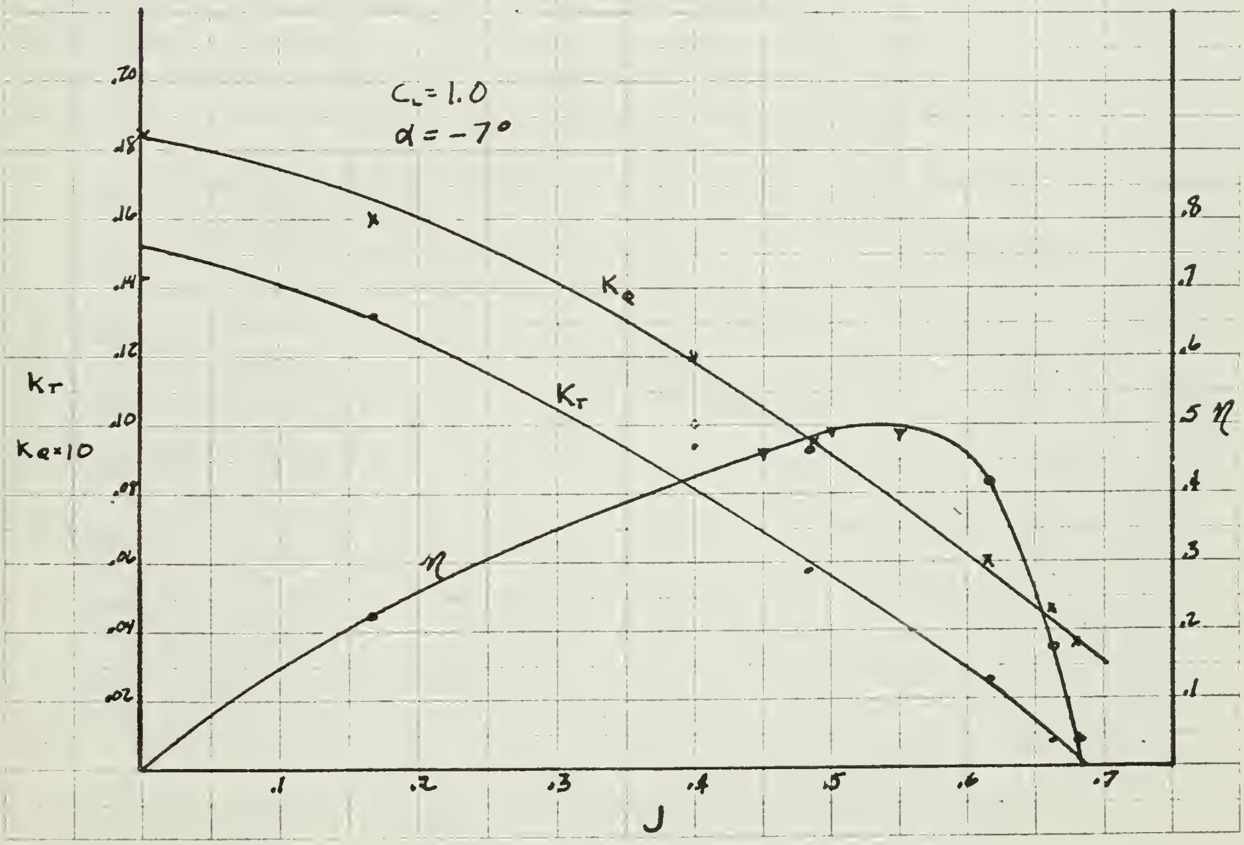
$C_L = 1.0$
$\alpha = 0°$
K_Q
K_T
η
K_T
$K_Q \times 10$
η
J

FIG. 17



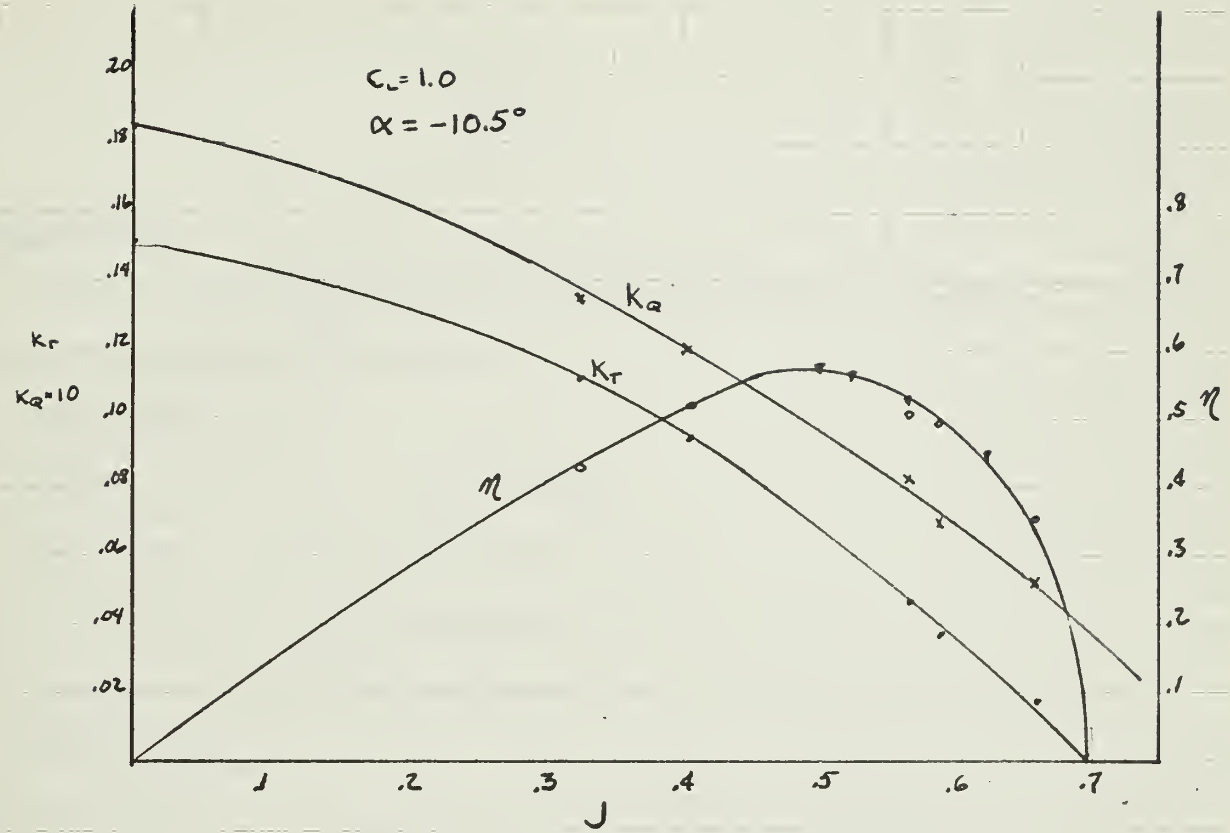
$C_L = 1.0$
$\alpha = -3.5°$
K_Q
K_T
η
K_T
$K_Q \times 10$
J

FIG. 18



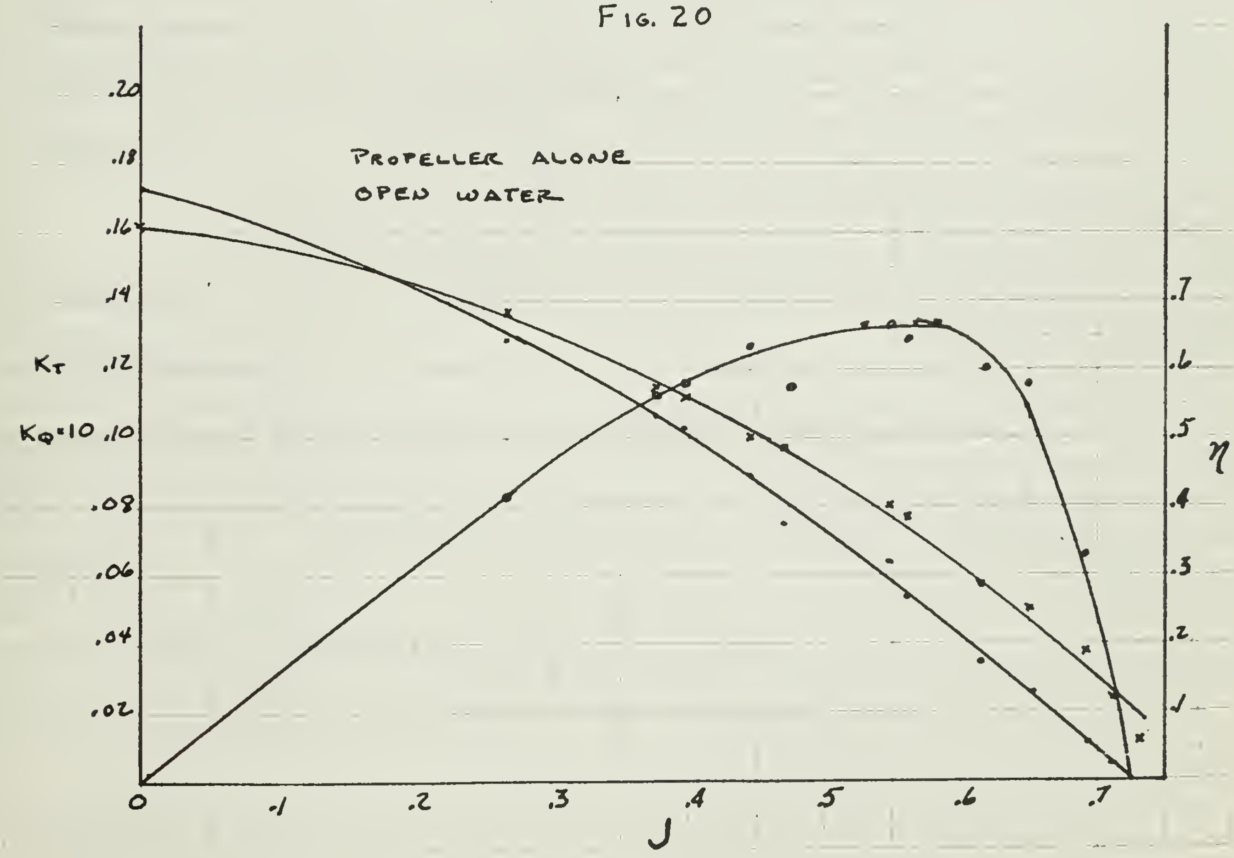
$C_L = 1.0$
$\alpha = -7°$
K_Q
K_T
η
K_T
$K_Q \times 10$
J

FIG. 19



$C_L = 1.0$
$\alpha = -10.5°$
K_Q
K_T
η
K_T
$K_Q \cdot 10$
J

FIG. 20



PROPELLER ALONE
OPEN WATER
K_T
$K_Q \cdot 10$
η
J

FIG. 21

RESULTS

Test Series II

Figures (22) and (23) show lift and drag generated by shrouds having the following characteristics:

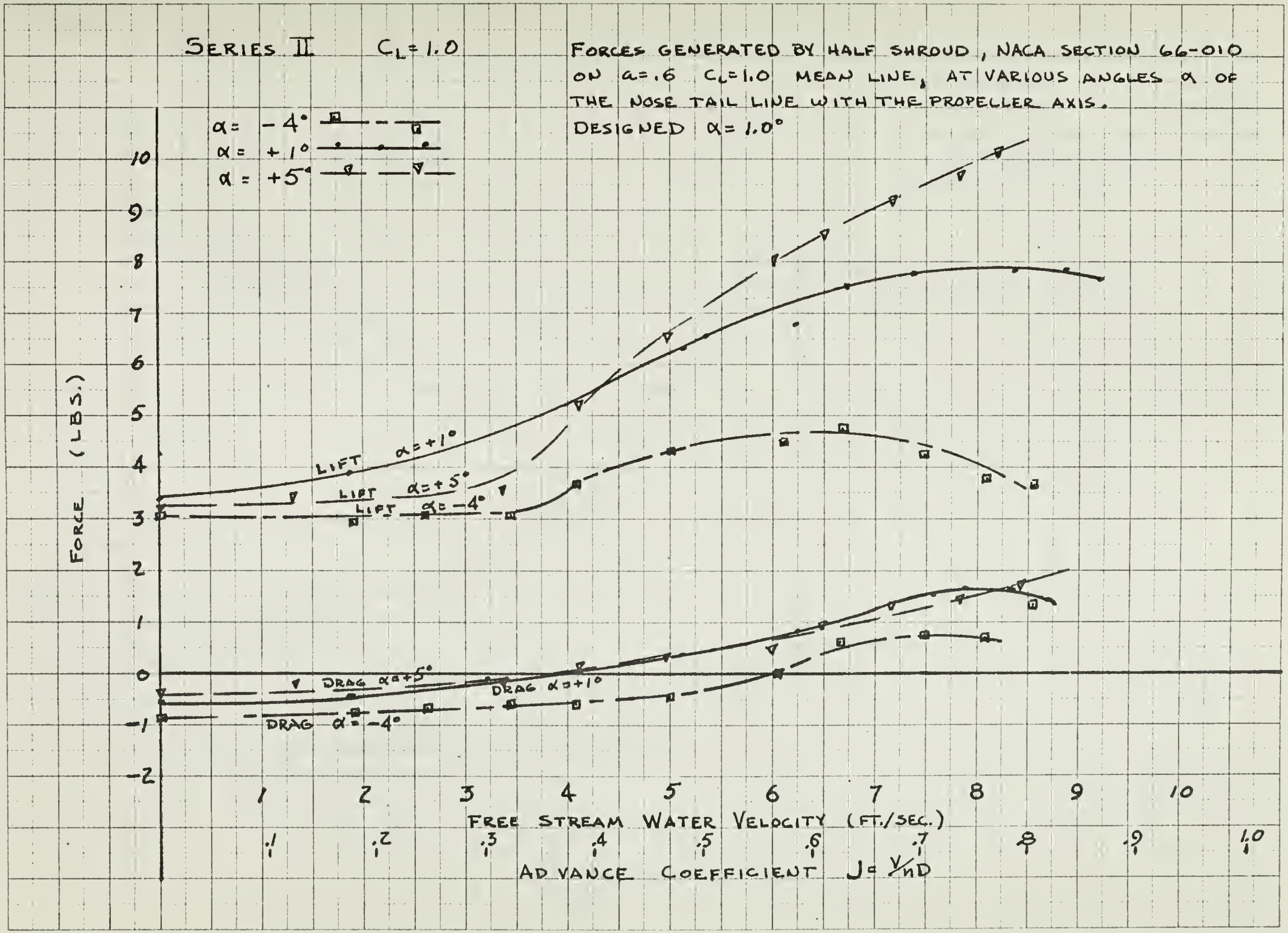
Figure (22)

Section	NACA 66-010
Mean line	$C_L = 1.0$
	$a = .6$
Designed α	$+ 1^{o}$
Chord/Diameter	.8

Figure (23)

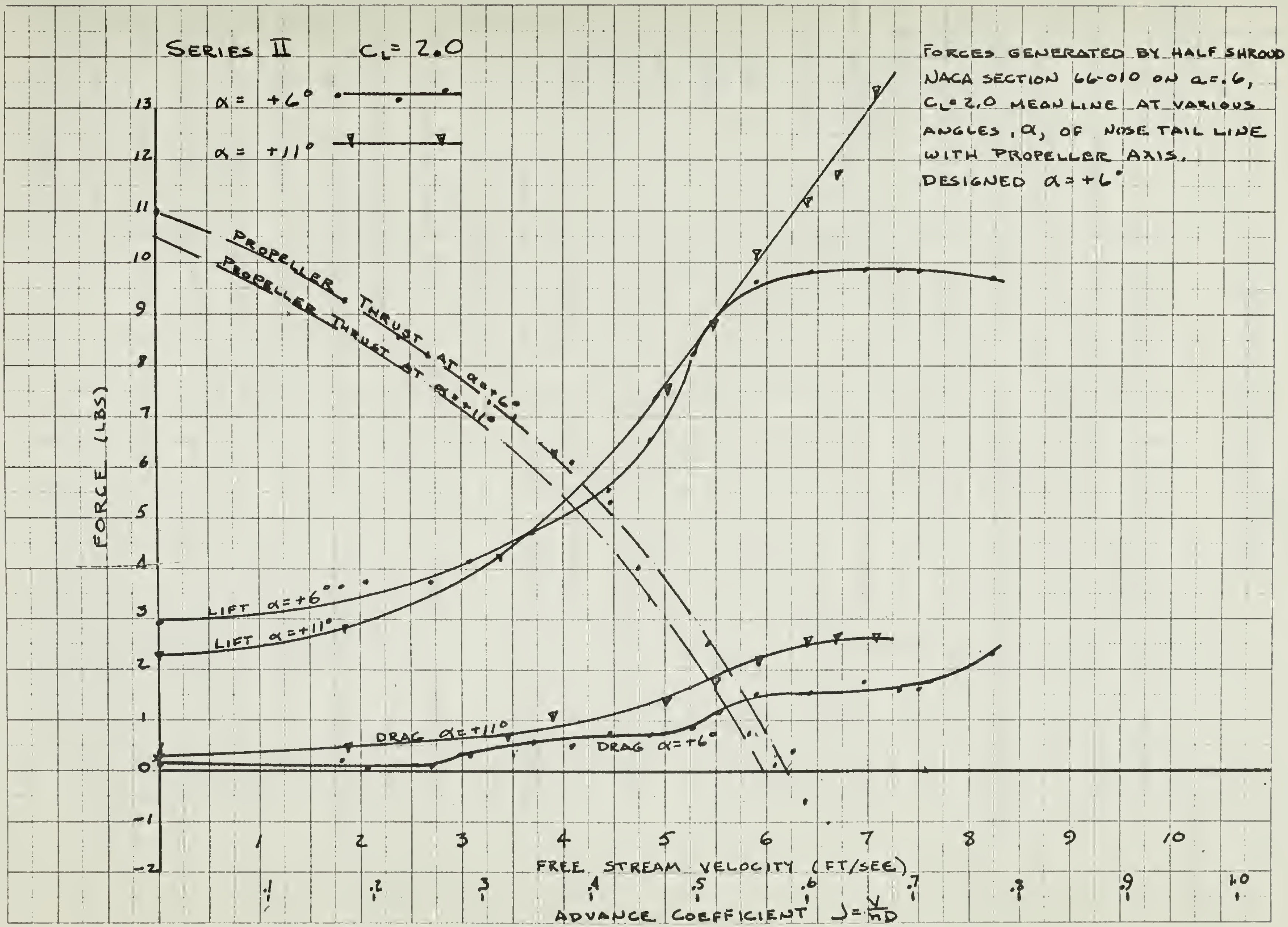
Section	NACA 66-010
Mean line	$C_L = 2.0$
	$a = .6$
Designed α	$+ 6^{o}$
Chord/Diameter	.8

The propeller used was the same as in the previous series and the other values of angle α plotted were obtained by tilting the shroud as before.



SERIES II $C_L = 1.0$
FORCES GENERATED BY HALF SHROUD, NACA SECTION 66-010 ON $a=.6$ $C_L=1.0$ MEAN LINE, AT VARIOUS ANGLES α OF THE NOSE TAIL LINE WITH THE PROPELLER AXIS.
DESIGNED $\alpha = 1.0°$
$\alpha = -4°$
$\alpha = +1°$
$\alpha = +5°$
LIFT $\alpha=+1°$
LIFT $\alpha=+5°$
LIFT $\alpha=-4°$
DRAG $\alpha=+5°$
DRAG $\alpha=+1°$
DRAG $\alpha=-4°$
FORCE (LBS.)
FREE STREAM WATER VELOCITY (FT./SEC.)
ADVANCE COEFFICIENT $J = V/nD$

FIG. 22



SERIES II $C_L = 2.0$
$\alpha = +6°$
$\alpha = +11°$
FORCES GENERATED BY HALF SHROUD
NACA SECTION 66-010 ON $a = .6$,
$C_L = 2.0$ MEAN LINE AT VARIOUS
ANGLES, α, OF NOSE TAIL LINE
WITH PROPELLER AXIS.
DESIGNED $\alpha = +6°$
PROPELLER THRUST AT $\alpha = +6°$
PROPELLER THRUST AT $\alpha = +11°$
LIFT $\alpha = +6°$
LIFT $\alpha = +11°$
DRAG $\alpha = +11°$
DRAG $\alpha = +6°$
FORCE (LBS)
FREE STREAM VELOCITY (FT/SEC)
ADVANCE COEFFICIENT $J = \frac{V}{nD}$

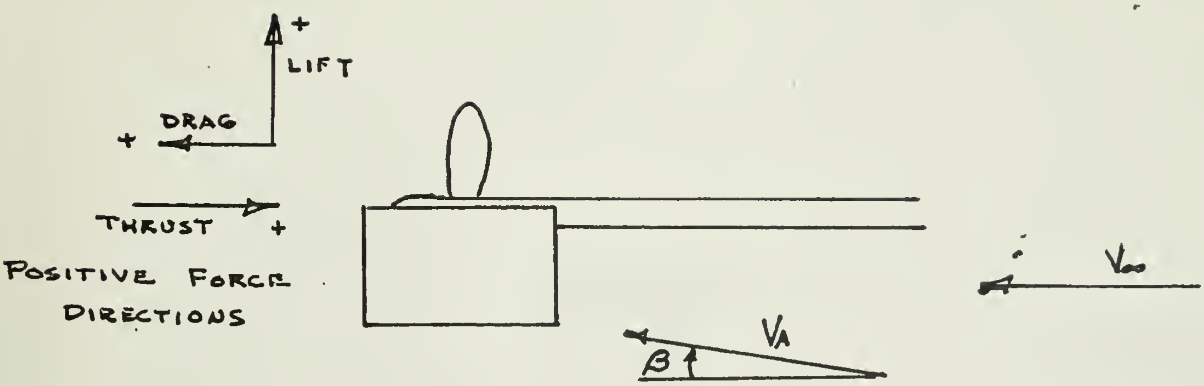
Fig. 23

DISCUSSION OF RESULTS SERIES I

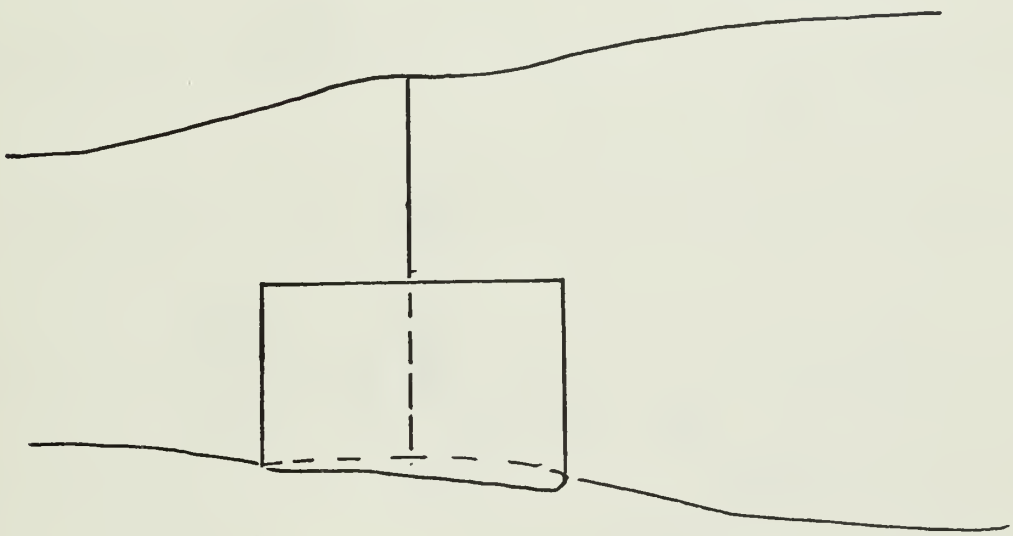
Test Series I

The lift and drag developed by a lifting surface will, of course, be a strong function of the fluid velocity field in which it is placed as well as the geometrical properties of the surface itself. A partial shroud placed adjacent to a propeller is in a rather complicated velocity field and the forces generated must be interpreted with regard given to the features of this field. For a shroud one of the most important variations in the velocity field seems to be the change in the radial component, q_r, in proportion to the axial component, $V_\infty + q_x$, of the fluid velocity, V_A, in the vicinity of the propeller and shroud. At low speeds, giving high thrust coefficients, the radial component will be relatively large giving a large inflow angle, β. As speed is increased, giving smaller thrust coefficients, the relative magnitude of q_r decreases, so angle β decreases with the flow direction approaching the axial as a limit. The velocity components are illustrated in Figure (24).

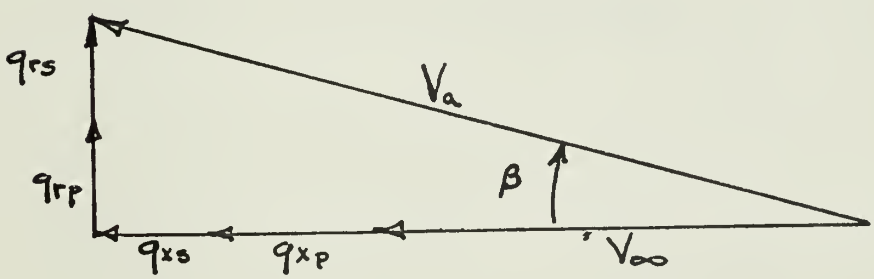
If the incident flow on the shroud comes in at some angle, β , to the horizontal (assuming the propeller axis to be horizontal) we know that the lift produced by the shroud, or any lifting surface, will be perpendicular to that direction. As illustrated in Figure (25) this will result in a forward thrust. If the lift produced by the shroud is large with respect to its drag this will produce a larger ahead thrust as well as a large steering force. Tilting the shroud back and forth can change the relative magnitude of lift and drag but will not change the direction of these forces. The direction is



FLOW IN VICINITY OF PROPELLER

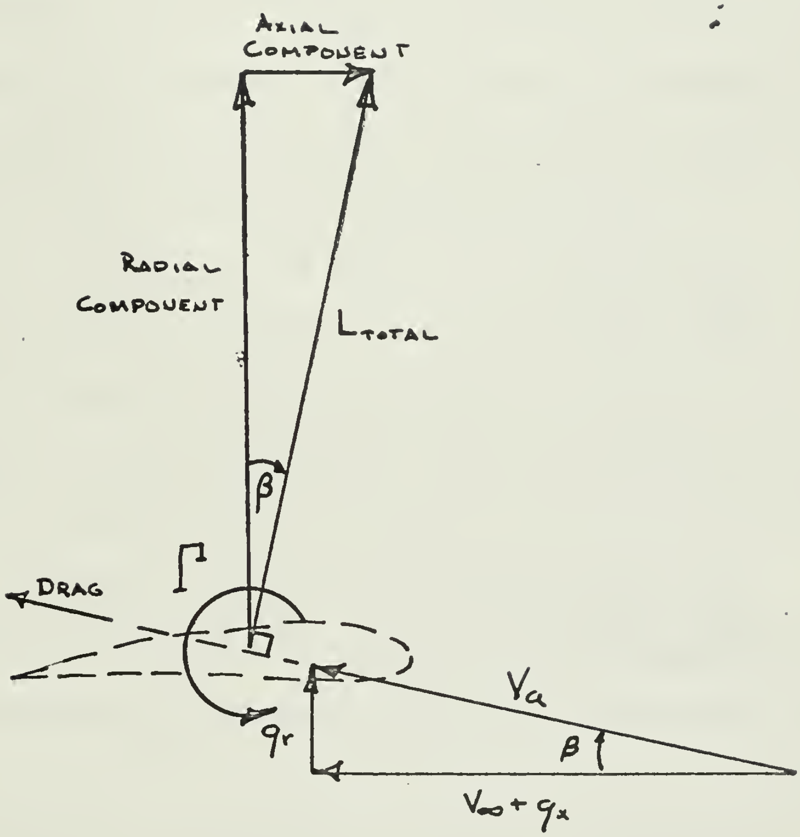


CONTROL VOLUME



VELOCITY COMPONENTS

FIG. 24



Force and Velocity
Components
on a Lifting Surface

Fig. 25

determined by the direction of the incident fluid velocity which is principally determined by the propeller. The object, therefore, is the old problem of designing and orienting the lifting surface in such a way as to obtain high lift with low drag.

Gordon in Reference (1) has suggested a method for computing the direction and speed of the incident velocity field. For a shroud of $C_L = 1.0$, $\alpha = +3.5^{\circ}$, whose characteristics are plotted in Figure (10) with the propeller at 1200 RPM , we can compute that angle β is 29.5 degrees at $V_{\infty} = 5.0$ ft/sec. Details of the computation are given in Appendix A, and β is plotted versus speed in Figure (26). In addition, three dimensional effects will result in variations in the effective angle of attack of a partial shroud. Significant change in the direction of incoming flow with respect to the shroud can therefore be expected for different operating conditions in practical applications. The shroud should be designed to provide adequate steering force over all operating conditions and minimum drag at cruising speeds. Mounting the shroud in such a way that the angle of attack at cruising speed is the ideal angle of attack might be a way of accomplishing this.

Examining Figures (8) and (9), where lift is plotted versus speed for various orientation angles α, we can see that lift remains positive with increasing speed for positive values of α and decreases, finally going negative for negative values of α . Much of this behavior can be explained by considering the changes in relative flow direction with increasing velocity. At low values of flow speed the inflow angle is quite sharp and the section is definitely at a positive angle of attack.

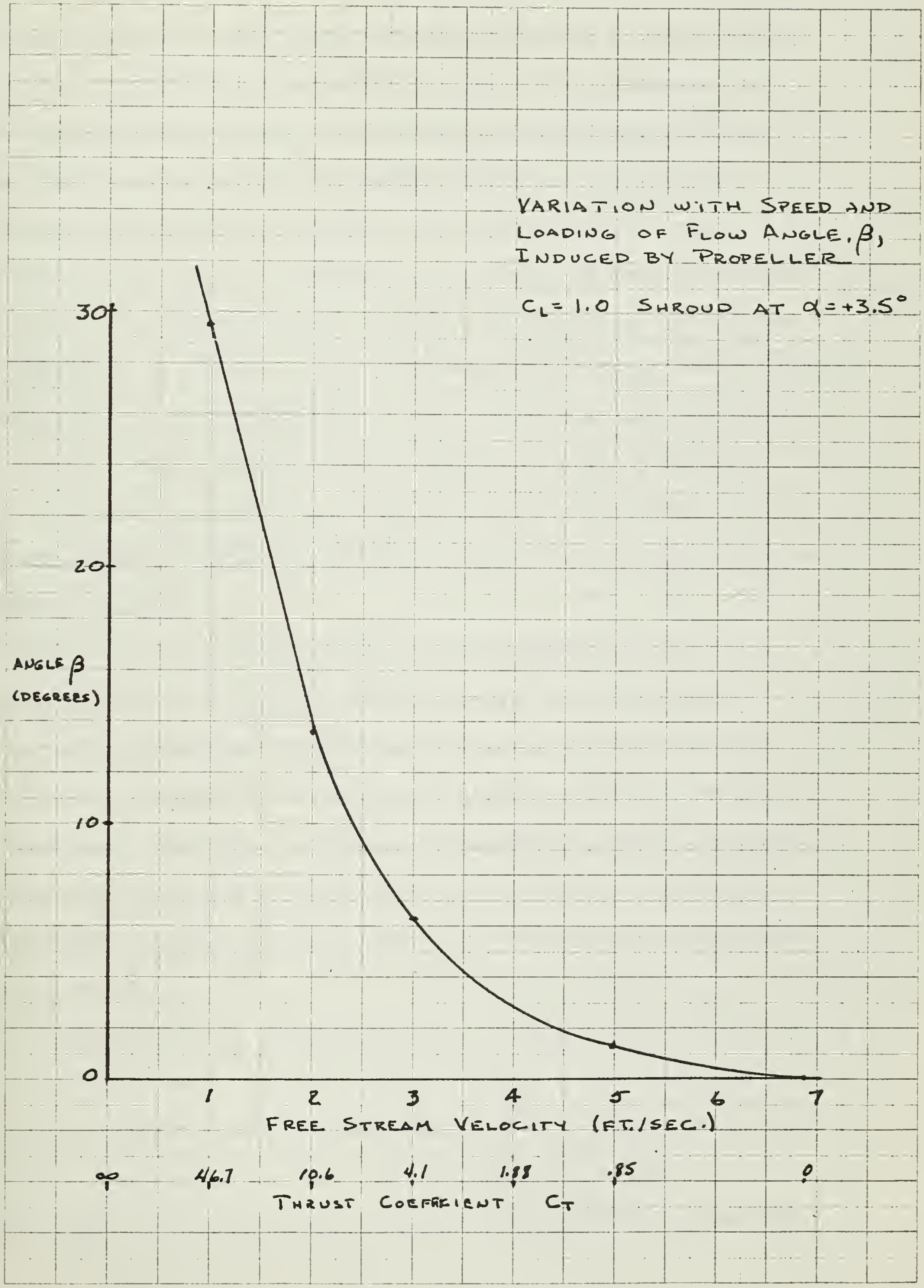

VARIATION WITH SPEED AND LOADING OF FLOW ANGLE, β, INDUCED BY PROPELLER
$C_L = 1.0$ SHROUD AT $\alpha = +3.5°$
30
20
10
0
ANGLE β (DEGREES)
1
2
3
4
5
6
7
FREE STREAM VELOCITY (FT./SEC.)
∞
46.7
10.6
4.1
1.88
.85
0
THRUST COEFFICIENT C_T

FIG. 26

As speed increases the angle β is reduced resulting in a smaller angle of attack. For the shrouds mounted with a negative γ, the effective angle of attack goes negative as the incoming velocity vector flattens out at higher speeds and the lift rapidly transfers to the opposite direction. For a positive γ, however, the angle of attack remains such that positive lift is retained at all speeds. As speed is increased from $V_\infty = 0$, two conflicting effects will be in operation. The increasing speed tends to increase lift and the decreasing angle of attack operates to decrease lift. This interaction seems to produce a fairly constant lift until the angle of attack change becomes more gradual and the velocity effect predominates, giving a more rapid change either up or down, depending on whether the effective angle of attack at this point is positive or negative.

In interpreting the results for this first series it should be borne in mind that the designed γ for the shrouds was - 3.5 degrees. The values shown are those obtained by tilting the mounting back and forth and are literally correct only at the center section of the shroud. The total lift, therefore, is actually the summation of that from segments at angles varying from the listed angle at the center to - 3.5 degrees at the edges, all weighted by the cosine of their circumferential angle from the center.

In comparing the $C_L = 1.0$ section with the $C_L = 0.2$ section we see that at low speeds, where the angle of attack is very high, the lift developed is at about the same level for both shrouds. As speed is increased, however, the effect of camber becomes more evident. As camber always acts in the positive direction the high lift section does

not reverse its lift as rapidly for negative α values as the $C_L = 0.2$ section. For positive α , the lift reaches a higher value with the high camber section, as would be expected.

An additional effect on lift produced by the propeller will come into play at a speed between 6 and 7 ft/sec when the propeller exceeds full slip and thrust goes negative. When this happens the propeller tends to block the flow on the inside of the shroud, reducing circulation and therefore lift.

On the $C_L = 0.2$ diagram the lift curves for $\alpha = 0^{\circ}$, $+ 3.5^{\circ}$, and $+ 7^{\circ}$ are particularly interesting. At $\alpha = + 3.5^{\circ}$ and $+ 7^{\circ}$ the lift seems to be governed by decreasing angle of attack until about 3.75 ft/sec when it begins to rise. At this speed the rapid change in angle of attack with speed would have slowed and any stall have been eliminated. The lift then grows with increasing velocity until about $V_{\infty} = 6$ ft/sec where propeller drag effects begin to be felt. At $\alpha = 0^{\circ}$ all of the shroud except the center section is actually at a slight negative angle. At higher speeds much of the shroud is therefore at a negative angle of attack and this coupled with low camber and propeller drag drives the resultant lift to zero.

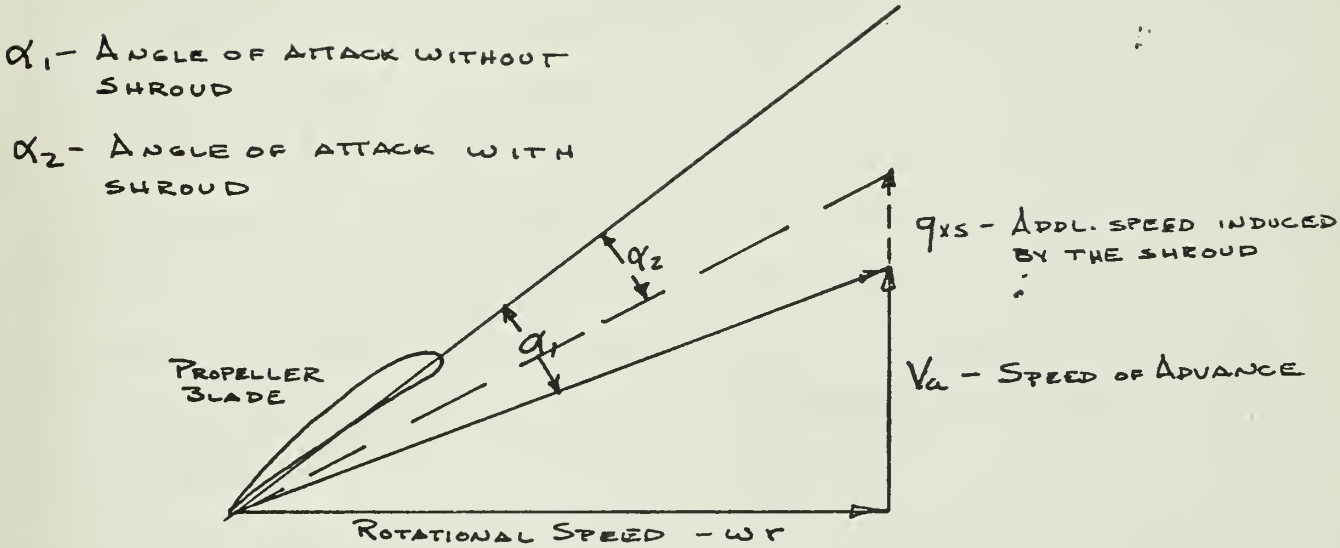
In Figure (10) the lift developed by the $C_L = 1.0$ shroud at $\alpha = + 3.5$ degrees is plotted with thrust, torque, and efficiency. This shows the level of lift in comparison to thrust at various operating conditions, and it is interesting to note that the lift, or steering force, at the most efficient condition is about the same as the total thrust.

The effect of changing the chordwise position of the propeller in

the shroud was investigated and the results are shown in Figures (11), (12), and (13). The shroud was designed for the propeller to be in the center of the shroud and there was minimum clearance between the propeller tips and the shroud in that position. When the propeller was moved either forward or back this clearance increased. Some of the effects noted therefore, could be from this difference in tip clearance. In Figure (11) with $\alpha = -7^{o}$ the best performance seems to be obtained by moving the propeller aft. This is possibly due to better supression of separation and more regular flow over the shroud with the pressure discontinuity caused by the propeller moved further back. With a negative angle α the tip clearance in the forward position was very great and we see that performance was low in that case. For a positive angle, $\alpha = +7^{o}$, performance was poorest at low speeds with the propeller aft. This was possibly due to partial blockage of the flow into the propeller by the shroud with the flow coming in from a steep angle. As speed is increased, and the inflow angle is reduced, the performance gets much better. At $\alpha = 0^{o}$ the differences in performance between the three positions are probably due to tip clearance effects.

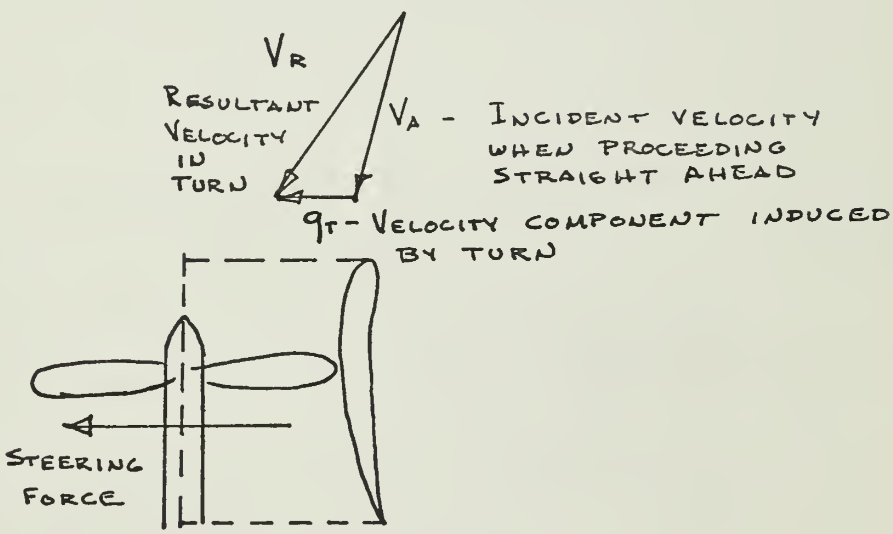
Certainly one of the most important aspects of shroud performance is the drag created by the device. As can be seen from the diagrams, under most operating conditions the shroud produces an ahead thrust rather than a drag. A drag is produced at high speeds but generally only beyond the point where propeller thrust has gone to zero and therefore out of the practical operating range. This is fortuitous, of course, but we must consider the complete propeller-shroud system before arriving at any conclusions as to the benefit actually realized from this thrust.

The shroud accelerates the water flowing past the propeller blades which results in a smaller angle of attack at the blades and therefore less lift from the blade meaning less thrust from the propeller. This effect is illustrated in Figure (27). This unloading may result in less torque being required to drive the propeller, however. With the shroud in place the propulsive system should be considered to be the propeller plus the shroud, and the efficiency is the propeller thrust plus the shroud thrust times ship speed divided by propeller torque times rotational speed. This efficiency should be compared with the conventional propeller efficiency in determining the true effect of the shroud on ship speed. For a steering shroud the drag of a conventional rudder should be subtracted from open propeller thrust to make a fair comparison. If the propulsive efficiency of the propeller plus shroud exceeds that of an unshrouded propeller (with rudder drag added in) then the shroud is clearly superior. The tremendous increase in drag created when a conventional rudder is put over will not be experienced with a steering shroud. It can be expected that the drag on the shroud will be much the same when turning as when proceeding straight ahead and this should produce superior maneuverability, especially when coupled with the ability of the shroud to produce large steering forces with little or no way on the ship. The effect on the shroud velocity field which would be caused by relative motion of a turning ship could not be duplicated in the propeller tunnel, but from examination of a vector diagram it can be anticipated that the effect would be to increase the effective angle of attack somewhat. This should not be any great problem. As seen in the diagrams, an increased angle of



EFFECT OF SHROUD ON PROPELLER ANGLE OF ATTACK

FIG. 27



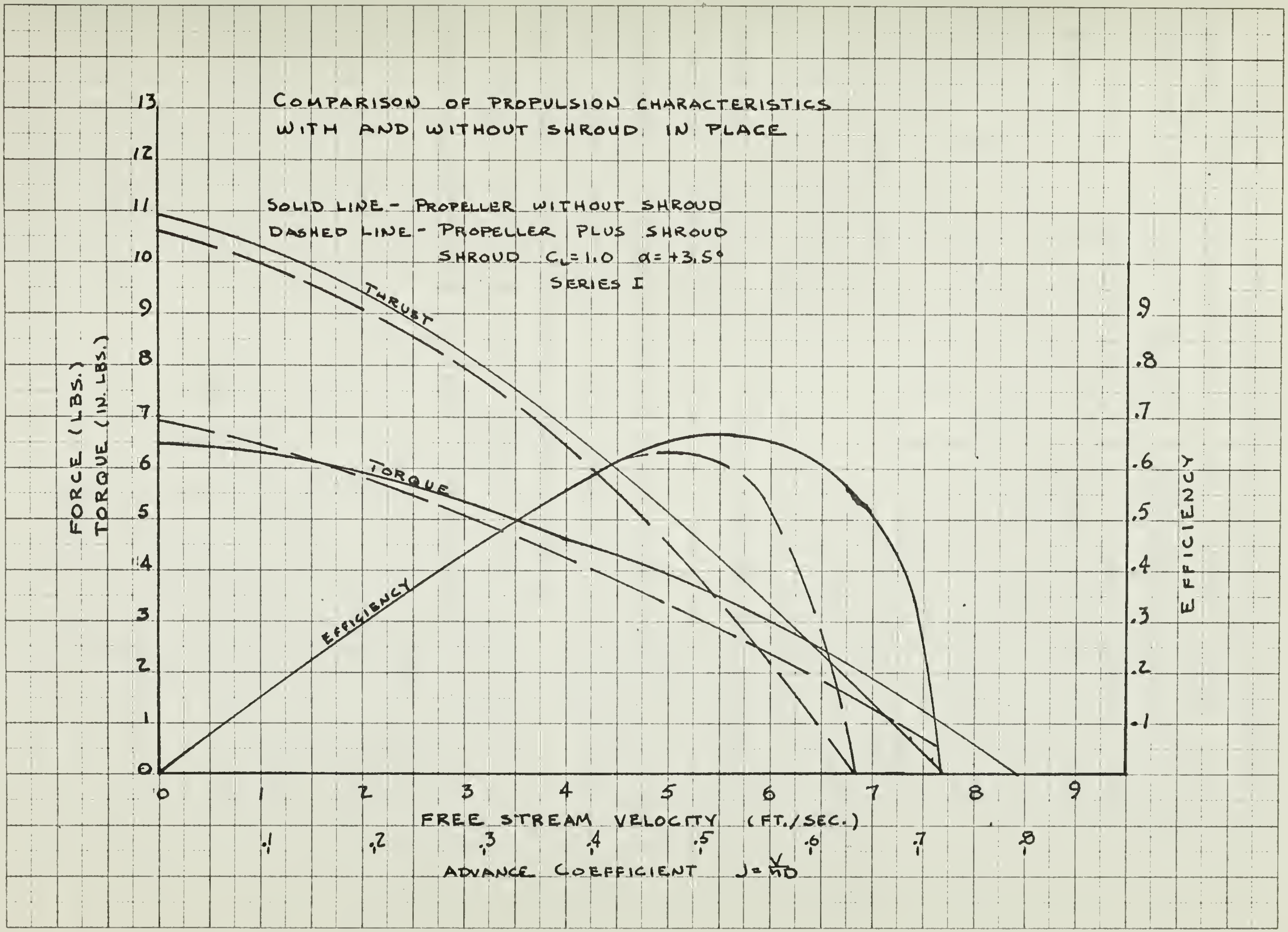
EFFECT OF SHIP MOTION IN A TURN ON THE VELOCITY FIELD

FIG. 28

attack causes increased lift and sometimes a small increase in drag over the range of angles investigated.

In Figures (14) thru (20) the propeller characteristics with the $C_L = 1.0$ (designed $\alpha = -3.5^{\circ}$) shroud in place are plotted. In these plots only propeller thrust was considered; shroud thrust or drag was not added in. The most notable change seems to be the range of speeds over which positive thrust occurs. Thrust goes to zero at lower speeds as α is increased.

Comparing Figures (14) thru (20) with Figure (21), for the propeller without shroud, we see that the maximum efficiency attained is degraded about 10% with the shroud attached. For a more realistic comparison, the shroud thrust should be added in the shrouded propeller characteristic and the rudder drag subtracted from the unshrouded characteristic. When this is done for the $C_L = 1.0$, $\alpha = +3.5^{\circ}$ case, Figure (29), the maximum efficiency with shroud is about 4% less than for the open propeller and occurs at a lower speed. It seems likely that because of the accelerated flow inside the shroud the use of a higher pitch propeller would be advantageous for shroud applications. If for some operating speed, say 5.5 ft/sec. in Figure (29), we find an unshrouded propeller is most efficient at P/D = .6; we might find that better efficiency could be obtained at this speed using a shrouded propeller with a higher pitch. As only one propeller was available for this series of experiments this possibility could not be investigated here. An adequate investigation of propulsion characteristics will require testing of the shroud with a series of propellers with systematically varied Pitch/Diameter ratio.



COMPARISON OF PROPULSION CHARACTERISTICS
WITH AND WITHOUT SHROUD IN PLACE
SOLID LINE - PROPELLER WITHOUT SHROUD
DASHED LINE - PROPELLER PLUS SHROUD
SHROUD $C_L = 1.0$ $\alpha = +3.5°$
SERIES I
THRUST
TORQUE
EFFICIENCY
FORCE (LBS.)
TORQUE (IN. LBS.)
EFFICIENCY
FREE STREAM VELOCITY (FT./SEC.)
ADVANCE COEFFICIENT $J = \frac{V}{nD}$
0
1
2
3
4
5
6
7
8
9
10
11
12
13
.1
.2
.3
.4
.5
.6
.7
.8
.9

Fig. 29

In Figure (30) forces during a turn are plotted for comparison between a typical rudder and the $C_L = 1.0$, $\alpha = + 3.5^{\circ}$ shroud. The rudder forces are computed from data in Reference (7) for a high aspect ratio rudder at a deflection angle just on the point of stall. Sample calculations are given in Appendix A. Rudder lift and drag increases sharply with speed, but shroud forces are less sensitive to velocity changes. When the rudder drag is subtracted from the open propeller thrust the net thrust is less than that from the shrouded system and therefore higher speed in the turn can be realized with the shroud. In Figure (30) better maneuverability will be obtained with the shroud up to 3.5 ft/sec as steering lift and net thrust are both greater up to that point. Beyond 3.5 ft/sec. the two systems can be compared by reducing the rudder deflection to the point where the lift is the same as the shroud and comparing the net thrust at that deflection with the thrust of the shroud system. Characteristics for other shrouds and other rudders can be plotted and compared similarly.

The results of these studies indicate that a shroud steering system will provide superior maneuverability in comparison with a rudder, at lower speeds. Superior maneuverability at higher speeds seems possible with a shroud but will require more careful design and further study of the effect of design variations. A reduction in propulsive efficiency at higher speeds with the shroud was observed, but this might be offset by simply choosing a higher pitch propeller.

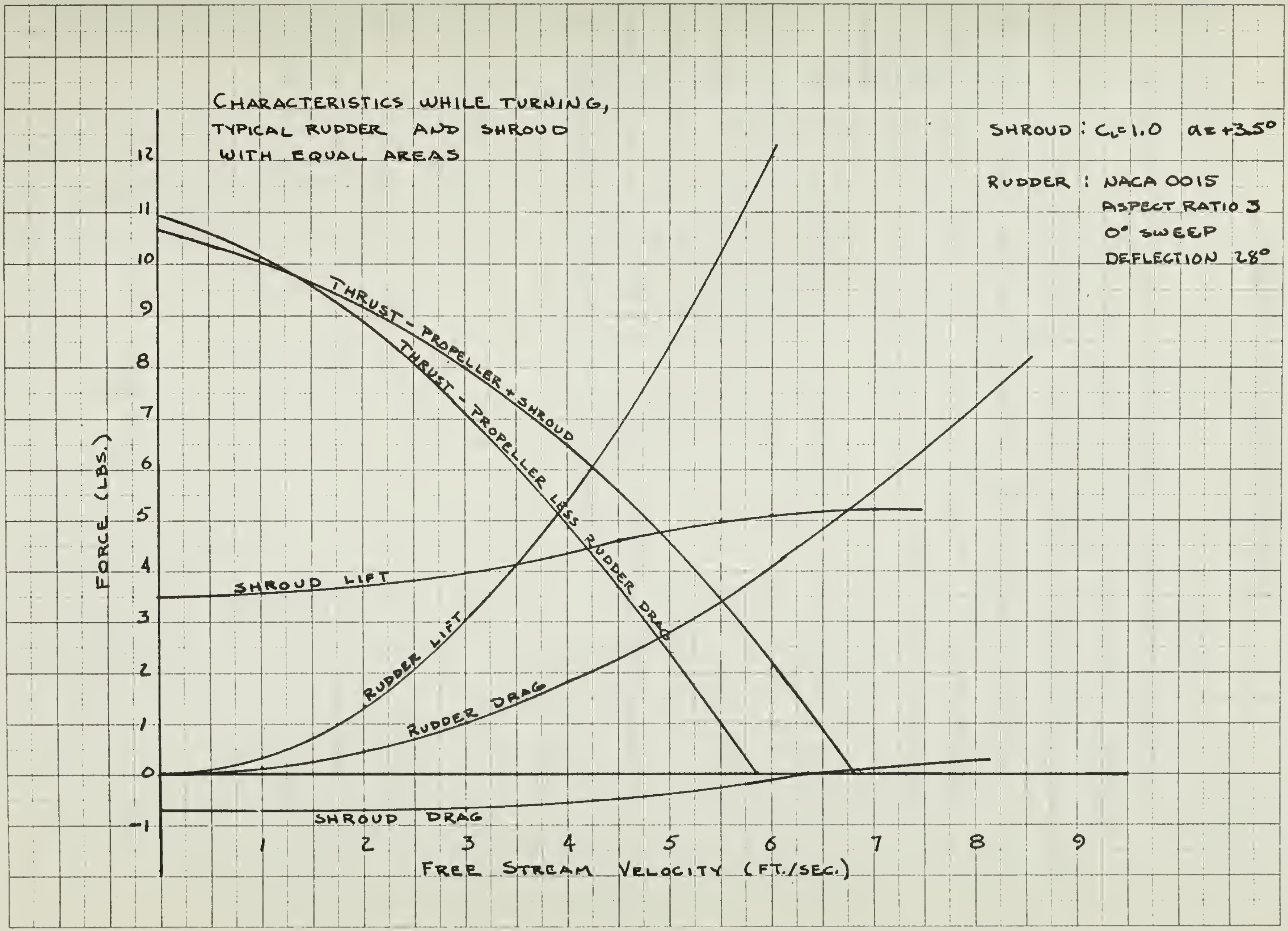

CHARACTERISTICS WHILE TURNING,
TYPICAL RUDDER AND SHROUD
WITH EQUAL AREAS
SHROUD : C_L=1.0 α=+3.5°
RUDDER : NACA 0015
ASPECT RATIO 3
0° SWEEP
DEFLECTION 28°
THRUST - PROPELLER + SHROUD
THRUST - PROPELLER LESS RUDDER DRAG
SHROUD LIFT
RUDDER LIFT
RUDDER DRAG
SHROUD DRAG
FORCE (LBS.)
FREE STREAM VELOCITY (FT./SEC.)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
1
2
3
4
5
6
7
8
9

FIG. 30

DISCUSSION OF RESULTS SERIES II

Test Series II

The shrouds used in the second series of tests were designed to have a positive angle, α, all around in the hope that additional ahead thrust could be obtained from a greater forward component of lift at the expense of little additional drag. Unfortunately this did not prove to be the case. Greater lift was obtained from these shrouds, but the drag was also somewhat greater than that obtained with earlier shrouds.

The $C_L = 1.0$ shroud was the same section as used in the previous series except that its design α was $+ 1^{\circ}$ rather than -3.5°. The $C_L = 2.0$ section had a very large camber and was made so that the propeller fit with minimum clearance at about the 3/4 chord point. Very high lifts were obtained with this section at higher speeds but were apparently not great enough to offset the increased drag.

CONCLUSIONS

A half shroud can be used as practical steering device from a hydrodynamic standpoint. The results indicate that a shroud steering device will be superior to a rudder in applications where good maneuverability at low speeds is desired such as in tugs and salvage vessels. It has not been demonstrated that the shroud would be superior at higher speeds, but with further study and development this might prove to be the case.

To provide positive lift over the entire range of propeller operation the shroud must be designed so that at least the section near the center has a positive angle of attack with respect to the incoming flow. The best Lift/Drag characteristics were obtained with the shroud at a positive angle of attack near the center and a slight negative angle of attack at the edges.

RECOMMENDATIONS

The preceding can be considered as no more than an initial investigation of the subject of partial shrouds as steering devices. Many questions are still to be answered. Among these are:

The effect of changing the pitch of the propeller.

The effect of changing the shape of the shroud edges.

The effect of changing the included circumferential angle of the shroud.

The effect of changing the basic section and mean line type.

Further investigation of the effect of changing the nose tail line angle, α , at various circumferential positions on the shroud.

Closer investigation of the details of flow in the vicinity of the shroud.

Development of practical methods of mounting a rotatable shroud on a ship or boat.

Underway tests of the maneuverability of a ship or boat fitted with a shroud steering system.

With further investigation of the above topics greatly improved ship maneuverability using smaller control surfaces and smaller control machinery might become possible.

SYMBOLS

A - Area

A_n - Coefficient in Fourier expansion.

a - Fraction of chord length over which designed pressure difference is constant.

C_L - Lift coefficient, $C_L = \frac{L}{1/2\ \rho\ V_\infty^2\ A}$

C_T - Thrust coefficient $C_T = \frac{T}{1/2\ \rho\ V_\infty^2 A}$

D - Diameter of propeller

$\vec{F}$ - Force vector

J - Advance coefficient, $J = \frac{V}{nD}$

K_Q - Torque coefficient, $K_Q = \frac{Q}{\rho\ n^2\ D^5}$

K_T - Thrust coefficient, $K_T = \frac{T}{\rho\ n^2\ D^4}$

ℓ - Chord length

n - Rotations per second

Q - Torque

q_r - Induced speed in the radial direction

q_{r_p} - Radial speed induced by the propeller

q_{r_s} - Radial speed induced by the shroud

q_x - Induced speed in the axial direction

q_{x_p} - Axial speed induced by the propeller

q_{x_s} - Axial speed induced by the shroud

r - Propeller radius

T_p - Propeller thrust

T_s - Shroud thrust

T - Thrust $(T_P + T_s)$

V_a - Speed of advance through the fluid seen by the propeller

V_r - Radial speed

V_x - Axial speed

V_∞ - Free stream velocity

α - Angle between lifting section nose-tail line and longitudinal shroud axis.

β - Angle between the propeller axis and the direction of the fluid velocity vector.

Γ - Circulation

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ACKNOWLEDGEMENTS

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APPENDIX

APPENDIX A

I. Calculation of Flow Speed and Direction at Shroud Entrance

Using the method outlined in Ref. (2) calculate the velocity vector at the shroud entrance for the $C_L = 1.0$ shroud of test series I tilted at $\alpha = +3.5^{\circ}$.

As defined in Ref. (3)

$$\tau = \frac{T - T_s}{T}$$

and for a partial shroud

$$\tau' = 1 - \frac{180^{\circ}}{\theta} \frac{T_s}{T}$$

For a half shroud $\theta = 90^{\circ}$ so

$$\tau' = 1 - \frac{2T_s}{T}$$

and for the shroud in question at $V_{\infty} = 1$ ft/sec.

$$\frac{T_s}{T} = .0594 \quad \text{so} \quad \tau' = .881$$

The thrust coefficient

$$C_T = \frac{T}{1/2\ \rho\ V^2\ \pi\ r^2} = 46.7$$

It was shown in Ref. (3) that

$$\frac{q_{x_s}}{V} = \frac{1 - \tau}{2\tau} \left[1 + (1 + \tau\ C_T\ )^{1/2} \right]$$

and for a partial shroud we may say

$$\frac{q_{x_s}}{V} = \frac{1 - \tau'}{2\ \tau'} \left[1 + (1 + \tau'\ C_T\ )^{1/2} \right]$$

For the case in question $\frac{q_{x_s}}{V} \doteq .506.$

$$V_x = V_\infty + q_{x_s} = 1.506 \text{ ft/sec at the propeller plane.}$$

The propeller thrust coefficient

$$C_{T_P} = \frac{\tau' T}{1/2\, \rho\, V_x^2\, \pi r^2} = 18.16$$

Induced axial and radial velocities from the propeller may be computed from tabulated data in Ref. (6). (Some of these tables are reproduced in Ref. (2)). From these data at the shroud leading edge ($\frac{x}{R} = -.78$, $r/_R = 1.24$):

$$\frac{\vec{U}}{U\,C_T} = .0384 \qquad \frac{\vec{V}}{U\,C_T} = .0425$$

Then

$$q_{x_p} = \left(\frac{\vec{U}}{UC_T}\right) V_x\, C_{T_P} = .0384 \times 1.506 \times 18.16 = 1.05 \text{ ft/sec}$$

$$q_{r_p} = \left(\frac{V}{UC_T}\right) V_x\, C_{T_P} = .0425 \times 1.506 \times 18.16 = 1.16 \text{ ft/sec}$$

Velocity components at the shroud leading edge are:

Axial - $V_x = V_\infty + q_{x_p} = 2.05$ ft/sec

Radial - $V_r = q_{r_p} = 1.16$ ft/sec

Resultant - $V_a = 2.35$ ft/sec

Flow angle $\beta = \tan^{-1} \frac{1.16}{2.05} = 29.5^\circ$

Similarly at $V_\infty = 5$ ft/sec we can compute:

$\tau' = .826$

$C_T = .85$

$\frac{q_{x_s}}{V} = .242 \qquad q_{x_s} = 1.21$ ft/sec

$V_x = V_\infty + q_{x_s} = 6.21$ ft/sec at the propeller plane.

$$C_{T_P} = \frac{.826 \times 4.6}{.2162 \times 38.5} = .4565$$

At the leading edge

$$q_{x_p} = .0384 \times 6.21 \times .4565 = .109 \text{ ft/sec}$$

$$q_{r_p} = .0425 \times 6.21 \times .4565 = .1205 \text{ ft/sec}$$

$$V_x = 5.0 + .109 = 5.109 \text{ ft/sec}$$

$$V_y = .1205 \text{ ft/sec}$$

$$V_A = 5.11 \text{ ft/sec}$$

$$\beta = \tan^{-1} \frac{.1205}{5.109} = 1.35^\circ$$

II. Calculation of Lift on a Typical Shroud Section Using Gordon's Method as Described in Reference (2)

Consider the shroud used in test series I with $C_L = 1.0$, $\alpha = -3.5^\circ$, $V_\infty = 2.5$ ft/sec, and propeller speed of 1200 RPM

$$\tau' = 1 - \frac{180^\circ}{90^\circ} \times \frac{T_s}{T} = 1 - 2 \times \frac{.4}{8.8} = .909$$

$$C_T = \frac{T}{1/2\ \rho\ V^2\ \pi\ r^2} = \frac{8.8}{.2162 \times 6.25} = 6.52$$

$$\frac{q_{x_s}}{V} = \frac{1 - \tau'}{2\tau'} \left[1 + (1 + \tau'\ C_T)^{1/2} \right] = .182$$

$$q\ x\ s = .454$$

$$V_x = 2.5 + .454 = 2.954$$

$$C_{T_P} = \frac{\tau'\ T}{1/2\ \rho\ V_x^2\ \pi\ r^2} = \frac{.909 \times 8.8}{.2162 \times 7.83} = 4.72$$

Using the tables from Hough and Ordway as reproduced in Reference (2):

At the propeller location, 1/2 chord point,

$$x/_R = 0 \text{ and } r/_R = 1.0$$

$$\left(\frac{U}{U\ C_T} \right) = .250 \qquad \left(\frac{\vec{V}}{U\ C_T} \right) = \text{Indeterminate}$$

$$q_{x_p} = \frac{U}{UC_T} V_x C_{T_p} = .250 \times 2.954 \times 4.72 = 3.50 \text{ ft/sec}$$

At the 1/4 chord point where the concentrated vortex representing the lifting surface is assumedto be located, $\frac{x}{R} = -.375$, $\frac{r}{R} = 1.03$

$$\frac{U}{U\ C_T} = .080$$

$$q_{x_p} = .111 \text{ ft/sec}$$

At the 3/4 chord point which establishes the boundary conditions in the Weissinger methods, $\frac{x}{R} = .376$, $r/_R = \frac{3.47}{3.20} = 1.083$

$$\frac{\vec{U}}{UC_T} = -.017 \qquad \frac{\vec{V}}{VC_T} = -.089$$

$$q_{x_p} = -.236 \text{ ft/sec}$$

$$q_{r_p} = -.124 \text{ ft/sec}$$

The slope of the section mean line at the 3/4 chord point is -.1827. The nose tail line is at -3.5° with the horizontal. Using the Weissinger boundary condition that the velocity vector be parallel to the mean line at the 3/4 chord point we may write:

$$\frac{q_{rs} + q_{rp}}{V\infty + q_{x_s} + q_{x_p}} = \tan\ (\arctan .1827 - 3.5^{\circ}) = .121$$

$$q_{rs} = .121\ (2.718) - .124 = .204 \text{ ft/sec}$$

Simultaneous equations determining the four coefficients in the Fourier cosine series representation of circulation distribution are:

$$.580\,A_o + 1.72\,A_1 + 2.235\,A_2 + 4.035\,A_3 = .204$$

$$.545\,A_o + .980\,A_1 + .495\,A_2 - 1.043\,A_3 = .204$$

$$.496\,A_o + .575\,A_1 + .382\,A_2 - .355\,A_3 = .204$$

$$1.0\,A_o + 0\,A_1 - 1.0\,A_2 + 0\,A_3 = 0$$

Solving simultaneously:

$$A_o = A_2 = 1.003$$

$$A_1 = -1.420$$

$$A_3 = -.0515$$

The cosine series representation of $\Gamma(\theta)$ therefore is:

$$\Gamma(\theta) = 1.003 - 1.420 \cos\theta + 1.003 \cos 2\theta - .0515 \cos 3\theta$$

By the Kutta - Joukowski Law:

$$\vec{F}_r(\theta) = -\rho\, V_{x_p}\, \Gamma(\theta)$$

and lift, $L = r_{\frac{1}{4}} \int_{-\frac{\pi}{2}}^{\pi/2} \vec{F}_r(\theta) \cos\theta\, d\theta = -\rho\, V_{x_p}\, r_{\frac{1}{4}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \Gamma(\theta) \cos\theta\, d\theta$

at the 1/4 chord point

$$V_{x_p} = V_\infty + q_{x_p\,1/4} = 2.5 + .111 = 2.611$$

$$L = -(1.94)(2.611)(.296)(3.150) = -4.72 \text{ lbs.}$$

(Negative sign means force directed radially inward, the positive direction for experimental data)

The measured lift under these conditions was 2.4 lbs.

III Computation of Drag From a Typical Conventional Rudder Having the Same Area as the Shroud Tested

Planform area of shroud = Planform area of rudder = A = .366 sq. ft.

Consider an all-movable rudder having the following characteristics:

Section	NACA 0015
Aspect Ratio	3
Taper Ratio	.45
Sweep Angle	0
Tip Shape	Square

From Reference (7) the drag coefficient, C_D , for this shape is .009 for an angle of attack, α, of 0°. The drag therefore is:

V_a = 1.0 ft/sec $D = .009 \times \frac{1.94}{2} \times 1 \times .366 = .0032$ lbs

V_a = 5.0 ft/sec   D = .08 lbs.

So the drag is small at 0° deflection.

Computing for lift and drag with rudder deflection, assume $\alpha/\delta = 5/7$ where

α = angle of attack

δ = rudder deflection

From figure 62 Reference (7):

δ	α	$\delta - \alpha$	C_L	L	C_D	D	V_a
21°	15°	6°	.79	7.0	.087	.772	5
28°	20°	9.2°	.98	8.69	.164	1.454	5
21°	15°	6°	.79	1.12	.087	.124	2
28°	20°	9.2	.98	1.39	.164	.232	2

T_o = Side thrust = $L \cos(\delta - \alpha) - D \sin(\delta - \alpha)$

D_o = Drag = $L \sin(\delta - \alpha) + D \cos(\delta - \alpha)$

APPENDIX B

TABULATION OF DATA

$\alpha = -3.5^{\circ}$ $C_L = 1.0$ $a = .6$ $\ell/D = .8$ NACA 66_2 010

PROP RPM	LBS LIFT	LBS DRAG	WATER VELOCITY Voo, fps
1200	2.45		0
	2.40		.8
	2.32		2.49
	2.40		4.08
	1.82		4.80
	1.43		5.40
	1.15		5.90
	1.36		6.02
	1.14		6.67
	.77		7.10
	.32		7.45
	-.25	1.94	8.03
		1.34	7.35
		.01	6.95
		-.14	2.03
		-.14	3.75
		0.0	5.08
		.40	6.23
		.64	6.76
		.68	7.78
		1.05	8.50
		1.31	9.10
1400	2.60	1.41	9.61
	3.84	2.41	7.75
	3.88	1.40	6.36
	3.27	.23	5.06
	2.60	-.45	3.40
	2.50	-1.63	1.32
Move Propeller 3/4" Back From Smallest Diam. Section			
1200	3.07	0	0
	2.64	0	2.92
	2.69	.04	4.43
	1.67	.80	6.22
	.84	1.04	6.91
	-.55	1.58	7.86
	-2.25	2.10	9.05
	2.25		4.74
	2.16		2.14
Return Prop. To Smallest Diam. Chg. α to -7°			
1200	2.72	-.45	0
	2.25	-.21	3.5
	1.90	-.17	4.66
	1.10	.58	6.16
	.11	.61	7.27
	-2.02	1.14	8.25
Chg. Shroud to $\alpha = -10.5^{\circ}$			
	2.47	-.61	0
	1.45	0	2.82

PROP RPM	LBS LIFT	LBS DRAG	WATER VELOCITY (FPS)
	1.20	.37	3.66
	1.02	0	4.36
	-.11	.39	6.06
	-.94	1.26	6.76
	-1.23	1.19	7.76
1200	-1.16	2.12	8.74
	-3.26	3.23	9.60
		-.98	0
Chg α To - 13.5°			
1200	1.86	0	0
	1.48	0	1.99
	-.24	.6	4.41
	-1.20	.59	5.62
	-1.89	.90	6.22
	-2.37	1.62	6.77
	-3.14	2.03	7.80
	-6.11	4.35	9.67
	+.97	-1.27	2.92
Chg α to 0°			
1200	1.49	-2.07	0
	1.80	-1.61	3.81
	2.13	-1.52	4.41
	2.86	-2.20	5.06
	2.21	-.86	6.30
	2.08	-.36	7.36
	1.59	-.03	8.21
	1.04	1.13	8.76
	1.26	1.30	9.70
Chg. α To + 3.5°			
1200	3.56	-.61	0
	3.77	-.55	2.51
	4.62	-.71	4.51
	5.02	-.29	5.63
	5.21	0	6.31
	5.25	+.27	7.36
	5.02	+.46	8.94
	4.09	+.90	10.35
Chg α To + 7°			
1200	3.68	-.37	0
	3.94	-.38	2.48
	4.67	+.11	4.32
	6.07	+.12	5.83
	6.25	+.72	6.82
	6.29	+.70	7.88

PROP RPM	LBS LIFT	LBS DRAG	WATER VELOCITY (FPS)
	6.75	1.00	8.82
	9.24	5.00	10.01
CHG.	α to + 10°		
1200	3.78	-.123	0
	4.32	-.26	2.82
	5.01	+.30	4.76
	7.00	.74	6.29
	7.72	.98	7.89
	8.63	1.66	9.02
	8.83	7.36	10.2

PROP. RPM	LBS THRUST	IN. LBS. TORQUE	F.P.S. V	J	K_T	K_Q	EFFICIENCY M
$C_L = 1.0$		$\alpha = +10°$					
1200	10.1	7.4	0	0	.1590	.0175	0
	9.0	6.0	2.14	.201	.1432	.0150	.307
	4.9	3.8	4.39	.412	.0780	.00950	.541
	3.5	3.1	4.88	.458	.0580	.00775	.532
	.5	2.8	6.03	.566	.00796	.00700	.103
	-.5	.9	6.71	.630	-.00796	.00225	-.392
	2.6	3.4	4.87	.456	.0414	.00850	.356
	.9	1.4	6.19	.570	.01435	.00350	.380
	.4	1.0	6.41	.601	.00637	.00250	.245
	9.0	6.9	1.07	.1002	.1432	.01725	.134
$\alpha = +7°$							
1200	9.5	6.9	0	0	.151	.0173	0
	9.8	6.4	1.13	.106	.156	.0160	.165
	6.7	4.9	3.58	.336	.107	.0123	.466
	5.1	3.9	4.26	.400	.0812	.00975	.531
	2.6	2.8	5.69	.534	.0414	.00700	.495
	0.0	1.3	6.81	.639	0	.00326	0
	1.0	2.2	6.01	.564	.0159	.00800	.179
	9.5	7.4	0	0	.151	.0185	0
$\alpha = +3.5°$							
1200	10.0	7.0	0	0	.160	.0175	0
	9.0	6.0	1.59	.149	.143	.0150	.226
	6.5	4.7	3.69	.346	.103	.01175	.483
	5.1	3.9	4.28	.401	.0812	.0098	.530
	2.7	2.8	5.69	.533	.043	.0070	.521
	1.7	2.3	6.16	.579	.027	.00575	.433

PROP. RPM	LBS THRUST	IN. LBS. TORQUE	F.P.S. V	J	K_T	K_Q	EFFICIENCY M
	.3	1.4	6.85	.643	.0048	.00350	.141
	-.5	1.2	6.93	.650	-.008	.0030	-.276
	9.5	7.4	0	0	.149	.0185	0
$\alpha = 0^o$							
1200	9.8	7.4	0	0	.156	.0185	0
	8.7	6.1	1.82	.171	.1386	.0153	.247
	7.5	5.4	2.81	.264	.1192	.0135	.372
	5.3	4.4	4.17	.358	.0844	.0110	.437
	4.0	3.5	4.90	.460	.0637	.00875	.534
	1.7	2.4	6.20	.582	.0271	.0060	.419
	.5	1.9	6.74	.632	.0080	.00475	.175
	-.5	1.2	7.25	.680	-.0080	.0030	-.289
	9.2	7.4	0	0	.1465	.0185	0
$\alpha = 3.5^o$							
1200	9.5	7.4	0	0	.151	.0185	0
	8.0	5.8	2.52	.236	.1273	.0145	.33
	6.8	5.1	3.33	.3125	.1082	.01275	.423
	4.1	3.9	4.94	.4635	.0653	.00975	.495
	2.5	3.1	6.01	.564	.0398	.00775	.462
	1.0	2.4	6.69	.627	.01592	.00475	.335
	0.0	1.4	7.24	.680	0	.00350	0
$\alpha = -7.0^o$							
1200	9.0	7.4	0	0	.1432	.0185	0
	8.3	6.4	1.78	.167	.132	.0160	.221
	5.9	4.8	4.26	.400	.094	.0120	.500
	3.6	3.8	5.16	.485	.0573	.0095	.467
	1.6	2.4	6.58	.617	.0255	.0060	.420
	.5	1.9	7.05	.662	.00796	.00975	.177
	.2	1.5	7.24	.680	.00319	.00375	.0922
$\alpha = 10.5^o$							
1200	9.5	7.4	0	0	.1513	.0185	0
	7.0	5.4	3.46	.325	.1113	.0135	.430
	5.9	4.8	4.32	.405	.0940	.0120	.508
	2.9	3.3	6.03	.566	.0462	.00825	.506
	2.3	2.8	6.26	.588	.0366	.00700	.492
	1.1	2.1	7.01	.659	.0175	.00525	.351
	-.2	1.3	7.72	.725	-.00319	.00325	-.114
	9.3	7.7	0	0	.148	.193	0

Change shroud to one with a nominal lift coefficient of .2. This shroud also has a crossection of Std. NACA 66-010 based on an a = .6 mean line and has $\ell/_D = .8$

PROP RPM	LBS LIFT	LBS DRAG	F.P.S. Vos
$C_L = .2$		$\alpha = -7^{\circ}$	
1200	2.09	-.975	0
	2.00	-.554	1.91
	1.00	-.274	3.58
	.43	-.30	4.15
	-.70	-.34	5.55
	-1.10	-.10	6.08
	-1.55	-.10	6.66
	-2.41	+.15	7.47
$C_L = .2$		$\alpha = -3.5^{\circ}$	
1200	2.46	-.61	1.05
	1.48	-.39	3.53
	1.14	-.49	4.28
	0.14	-.10	5.61
	-.17	+.15	6.20
	-.87	+.15	6.93
	-1.14	+.13	7.37
$C_L = .2$		$\alpha = 0^{\circ}$	
1200	2.94	-.37	0
	2.53	-.36	2.73
	2.26	-.23	4.29
	1.86	-.24	5.61
	1.24	+.01	6.78
	.61	+.31	7.28
	.39	+.41	7.65
	1.59	-.25	6.08
Shroud	$C_L = .2$	$\alpha = +3.5^{\circ}$	
1200	2.94	-.61	0
	2.79	-.60	1.59
	1.90	-.61	3.77
	2.66	-.72	5.01
	2.78	-.40	6.18
	2.61	-.32	6.72
	2.42	-.12	7.35
	$C_L = .2$	$\alpha = +7^{\circ}$	
1200	3.40	-.925	.98
	2.27	-1.10	3.77
	2.84	-.99	5.10

PROP RPM	LBS LIFT	LBS DRAG	V.P.S. Vos
	$C_L = .2$		$\alpha = +7^o$
	3.62	-.98	6.31
	3.55	-.78	6.86
	3.89	-.72	7.35
$C_L = .2$ $\alpha = +7^o$	Move Propeller 1" Fwd. in Shroud		
1200	3.19	-.488	0
	2.33	-.310	3.60
	3.21	-.160	5.19
	3.69	-.050	5.70
	4.00	-.05	6.64
	4.23	-.10	7.84
$C_L = .2$ $\alpha = +7^o$	Move Prop. 1" aft of ctr. in shroud		
1200	2.70	+.24	0
	2.30	+.03	2.67
	3.69	-.29	5.70
	4.54	-.28	6.88
	4.75	-.36	7.32
	2.38	+.02	4.21
$C_L = .2$ α ' 0^o	Prop. 1" aft of ctr.		
1200	2.82	-.366	0
	2.22	-.47	3.06
	2.24	-.74	4.36
	1.57	-.03	6.15
	1.30	+.73	6.29
	1.25	+1.48	7.66
$C_L = .2$ $\alpha = 0^o$	Prop. 1" fwd. of ctr.		
1200	2.46	-.854	0
	1.22	-.55	3.59
	1.31	-.50	5.35
	.74	-.10	6.80
	.23	+.08	7.80
$C_L = .2$ $\alpha = -7^o$	Prop. 1" fwd of ctr.		
1200	1.23	-.61	0
	1.13	-.38	1.124
	-.47	-.14	4.34
	-1.36	+.11	6.10
	2.22	+.27	7.32

PROP RPM	LBS LIFT	LBS DRAG	F.P.S. Vos
C_L = .2	α = -7°	PROP 1" Aft of ctr.	
1200	2.46	-.731	0
	2.15	-.73	2.81
	.55	-.39	4.59
	-.62	-.17	5.70
	-1.72	+.47	6.83

RUN	PROP. RPM	THRUST (LBS.)	TORQUE (IN LBS.)	WATER VELOCITY F.P.S.	J	K_T	K_Q	EFFICIENCY
	Propeller without shroud							
341	1200	10.9	6.5	0	0	.173	.01625	0
342		8.1	5.5	2.85	.267	.129	.01375	.415
343		6.7	4.6	4.0	.375	.1065	.01150	.557
344		6.45	4.5	4.23	.397	.103	.01125	.580
345		5.6	4.0	4.74	.445	.089	.01000	.634
346		4.7	3.9	5.0	.469	.075	.00975	.576
347		3.8	3.2	5.83	.547	.064	.00800	.662
348		3.4	3.0	5.96	.560	.054	.00750	.646
349		2.2	2.3	6.56	.616	.035	.00575	.600
350		1.75	2.0	6.94	.615	.026	.00500	.580
351		.7	1.5	7.39	.693	.011	.00375	.330
352		.3	1.0	7.59	.712	.0048	.00250	.287
353		-.9	.5	8.17	.766	-.0143	.00125	0
358		9.7	6.0	1.87	.175	.154	.01500	.289
359		7.5	5.0	3.38	.317	.119	.01250	.507
360		6.5	4.5	4.17	.392	.103	.01127	.576
361		4.4	3.5	5.50	.516	.070	.00874	.661
362		3.2	2.8	6.10	.572	.051	.00700	.667
363		1.5	1.9	7.06	.672	.024	.00475	.533
364		1.3	1.6	7.21	.677	.0206	.00400	.560
365		.7	1.1	7.50	.705	.011	.00275	.455

Put on shroud $C_L = 1.0$, Designed $\sigma = 1.0$, Actual $\sigma = 1.0$

RUN	PROP. RPM	THRUST (LBS.)	TORQUE (IN LBS.)	WATER VELOCITY F.P.S.	J	K_T	K_Q	EFFICIENCY
391	1200	9.5	6.5	0				0
392		8.1	5.6	2.11				.298
393		6.9	4.9	3.26				.440
394		5.2	3.9	4.04				.515
395		3.75	3.1	4.70				.544
396		1.6	2.25	5.52				.375
397		1.25	1.8	5.84				.387
398		.2	1.0	6.35				.122
399		-.2	.7	6.51				
400		-1.6	0	7.01				

Lift Drag Velocity

$C_L = 1.0 \quad \sigma = +1^{\circ}$

RUN	PROP. RPM	THRUST (LBS.)	TORQUE (IN LBS.)	WATER VELOCITY F.P.S.
411	1200	3.40	-.49	0
412		3.88	-.47	1.87
413		3.76	-.05	3.21
415		6.30	+.38	5.12
416		6.54	+.60	5.70
417		6.79	+.93	6.23
418		7.51	+.73	6.74
420		7.75	1.64	7.88
421		7.75	1.34	8.36
422		7.63	1.21	8.70
423		4.24	-.61	0

RUN	PROP. RPM	LIFT	DRAG	VELOCITY F.P.S.	
	$C_L = 1.0$	Chg. α to $+5^o$			
424	1200	3.15	-.36	0	
425		3.39	-.20	1.33	
426		3.51	-.12	3.38	
427		5.09	+.15	4.13	
428		6.54	.31	4.98	
429		8.00	.25	6.01	
430		8.48	.95	6.50	
431		9.09	1.30	7.17	
432		9.70	1.44	7.85	
433		10.10	1.74	8.46	
	$C_L = 1.0$	Chg. α to -4^o			
434	1200	3.03	-.85	0	
435		2.91	-.79	1.91	
436		3.03	-.65	2.61	
437		3.03	-.58	3.44	
438		3.64	-.57	4.08	
439		4.24	-.42	5.00	
440		4.48	0	6.11	
441		4.72	.65	6.67	
442		4.24	.78	7.48	
443		3.88	.70	8.09	
444		3.64	1.33	8.55	
Chg. Shroud to $C_L = 2.0$, Designed $\alpha = +6^o$ shroud, place at $\alpha = +6^o$					
		THRUST (LBS.)	TORQUE (IN. LBS)	VELOCITY (F.P.S.)	EFFICIENCY
445	1200	11.0	7.3	0	0
446		9.3	6.1	1.87	.272
447		8.55	5.6	2.39	.353
448		7.3	4.9	3.28	.467
449		6.1	3.9	4.08	.610
450		4.0	3.1	4.74	.585
451		.7	1.1	5.83	.355
452		.1	.7	6.09	.083
453		-.6	.1	6.39	
454		1.0	-.3	6.61	
455		10.8	7.4	0	0
456		8.2	5.2	2.67	.403
457		7.0	4.4	3.52	.535
458		5.3	3.4	4.46	.695
459		2.5	1.9	5.41	.682
460		.4	.55	6.26	.436
	Chg α to $+11^o$ with $C_L = 2.0$ shroud				
461	1200	10.5	7.1	0	0
462		9.0	6.1	1.82	.257

RUN	PROP RPM	THRUST (LBS.)	TORQUE (IN.LBS.)	VELOCITY (F.P.S.)	EFFICIENCY
463		7.3	5.1	2.92	.400
464		6.5	4.6	3.44	.465
465		5.1	3.6	4.17	.565
466		3.4	2.8	4.84	.562
467		1.1	1.8	5.70	.333
468		.7	1.4	5.90	.282
469		.3	1.1	6.09	.166
470		-1.0	.2	6.50	
471		-1.2	0	6.57	

$C_L = 2.0$ $\quad \alpha = +11^{\circ}$

RUN	PROP RPM	LIFT (LBS)	DRAG (LBS)	VELOCITY (F.P.S.)
474	1200	2.30	+.71	0
475		2.91	.42	1.86
476		4.24	.65	3.38
477		4.49	.38	3.51
478		6.28	1.04	4.41
479		7.51	1.39	5.01
480		8.85	1.76	5.49
481		10.19	2.13	5.90
482		11.15	2.55	6.42
483		11.75	2.57	6.71
484		13.30	2.66	7.06
485		2.30	.24	0

$C_L = 2.0$ Chg. α to $+ 6^{\circ}$ (Designed α)

RUN	PROP RPM	LIFT (LBS)	DRAG (LBS)	VELOCITY (F.P.S.)
486	1200	2.91	+.12	0
487		3.76	.20	1.82
488		3.88	.05	2.07
489		4.85	.59	3.67
490		5.57	.78	4.46
491		6.55	.70	4.85
492		8.24	.85	5.26
493		9.57	1.51	5.90
494		9.81	1.56	6.43
495		9.93	1.73	6.97
496		9.93	1.57	7.30
497		9.93	1.61	7.50
498		9.70	2.30	8.24
499		2.91	.24	0
500		3.88	.07	2.70
501		4.12	.35	3.09
502		4.72	.50	4.15