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**PROPELLER PITCH CORRECTION ARISING
FROM LIFTING SURFACE EFFECT**

by

H. W. Lerbs

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Report No. 942

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SUMMARY

Experience has shown that propellers designed from the theory of a moderately loaded propeller are underpitched. An attempt is made in the following discussion to trace the reason for this discrepancy between theory and experience and, further, to develop relations from which the additional pitch may be approximately determined.

A. Introduction

In its present state, the theory of the screw propeller is developed on the assumption that the boundary condition which is introduced by the blades may be neglected. This amounts to replacing the blades by lifting lines instead of by lifting surfaces. The information on the flow obtained from lifting line theory is incomplete since merely the angularity of the flow is established whereas its curvature remains undetermined.

To approximately supplement the theory the boundary condition is introduced afterwards. That is, vortex sheets are introduced for the blades after the angularity has been determined on a basis of lifting line theory. Then, the downwash and the curvature of the flow may be ascertained at each station of the chord length of a blade section from lifting surface theory. However, even this step by step procedure of correcting for the boundary condition is complicated. A solution exists only for the curvature of the flow at the half-way point of the section in the special case that the bound circulation is constant over the chord length. The problem of change of curvature over the chord is left open within this solution, which is due to Ludwig and Ginzel [1, 2, 3].

In spite of these limitations, the existing theory of the curvature of the propeller flow provides valuable information. It follows, for instance, that the curvature at the half-way point arises essentially from self interference. The effect of the other blades, which tend to reduce the flow curvature at the blade under consideration, and also the effect of the free vortex sheets on the curvature

References are listed on Page 15

are small. Further, the curvature depends on the radial distribution of the bound circulation and, for an equal distribution, on blade outline and advance coefficient. From these results, it follows that the nature of the curvature of propeller flow is essentially different from that of two dimensional cascade flow. The application of conclusions from cascade flow to propellers, which is sometimes recommended in literature, is therefore, not justifiable.

Assuming for a moment that the downwash is known at each station of the chord would enable us to correct a thin section such that its properties, particularly the pressure distribution and the curve "lift coefficient versus effective angle of attack", are approximately equal in curved propeller flow and in straight two-dimensional flow. The correction would result in a distortion of the camber line at each station. For practical purposes, the distortion may be approximated by an additional curvature of the camber line corresponding to the flow curvature at the half-way point and by an additional angle of attack corresponding to the change of the curvature over chord. For instance, when the curvature is smaller at the leading edge and greater at the trailing edge than at the half-way point, a positive angle of attack becomes necessary to correct for the change of curvature. Since this change is unknown, only the first correction, viz, that for the camber is applied in designing a propeller. The neglect of the additional angle of attack is considered to be the reason for propellers designed on a theoretical basis to be underpitched.

In the following parts of this note, expressions for the order of magnitude of the additional angle of attack are derived. No attempt has been made to introduce lifting surfaces for the blades. The considerations are based on a simplified lifting surface theory as proposed by Weissinger [4]. Combining the correction for the flow curvature as known from the Ludwig-Ginzel Theory with the correction for the angle of attack a better approximation for the boundary condition may be expected than applying only one of these

corrections. Future effort will be directed towards a rigorous solution of this problem.

B. Simplified lifting surface theory

Weissinger considers a twisted plate of finite span in a flow arising from the velocity of approach and from the bound and free vortex sheets. The problem is to determine the spanwise distribution of the bound circulation. This distribution follows from the boundary condition of the relative flow, viz, that the velocity component perpendicular to the plate be zero. To simplify this problem the bound vorticity is assumed to be concentrated at the one-quarter point of the chord length. Further, the boundary condition is satisfied only at one specified station of the chord length which is chosen at the three-quarter point of the chord. The justification for these simplifications and a comparison between results from the simplified theory and from experiments in the case of plan forms are given in [5].

In the case of propeller design, the problem is reversed since the bound circulation is known (from lifting line theory) and the twist is to be determined such that the bound circulation is generated. Applying Weissinger's method at any radius of the propeller, one obtains the angle of attack of a flat plate, α' , relative to the velocity of approach with which angle the required lift coefficient is produced within the propeller flow. The velocity of approach is that which does not include any induced velocities, i.e., the velocity V^* in Figure 1.

Let (w_n) be the sum of the velocity components perpendicular to V^* which are induced at $(0.75c)$ from the bound and free vortices. Then, the boundary condition is satisfied at $(0.75c)$ if the plate is given the following angle of attack:

$$(1) \quad \alpha' = (w_n/V^*) = (w_n/V^*)_b + (w_n/V^*)_f$$

Assuming that the gradient of the lift-angle curve of the section at the radius under consideration equals that of a flat

plate, α' is identical with the angle of attack of the line of zero lift of the section. Therefore, the angle of attack of the chord line of the section relative to V^* equals $(\alpha' - \alpha_0)$, see Figure 2. For a pitch correction, we are interested in the angle of attack of the chord line relative to the resultant relative velocity V . This angle equals

$$(2) \quad \Delta\alpha = \alpha' - (\alpha_0 + \alpha_i)$$

In this relation, α_0 and α_i are known quantities. In order to ascertain α' , the components perpendicular to V^* of the velocities are determined which are induced at $(0.75c)$ both from the free vortex sheets and from the bound vortices of the propeller.

(a) Velocity components induced from the free vortex sheets.

Since the bound vortex is assumed to be situated at the one-quarter point, $c/4$, a discontinuity of the tangential component occurs at this point. The tangential component is zero in front of this point and equals w_t behind. The axial component varies continuously over the chord length. This variation is appreciable and can not be neglected in these considerations. The radial component does not enter since the flow in the tangential plane is considered.

Let $(w_a)_{0.25}$ be the axial component of the induced velocity at $(0.25c)$, which is known from lifting line theory, and $(w_a)_{0.75}$ that at $(0.75c)$. Then,

$$h = (w_a)_{0.75} / (w_a)_{0.25}$$

which numerically is between 1 and 2. Assuming optimum flow, i.e., that the resultant of the axial and tangential induced velocity components is perpendicular to V at station $(0.25c)$, see Figure 1., it develops that the part of α' which arises from the free vortex sheets is approximately represented by

$$(5) \quad (w_n/V^*) f \alpha_i \frac{2}{1 + \cos^2 \beta_i \left(\frac{2}{h} - 1\right)}$$

The difficulty in applying this relation lies in making a

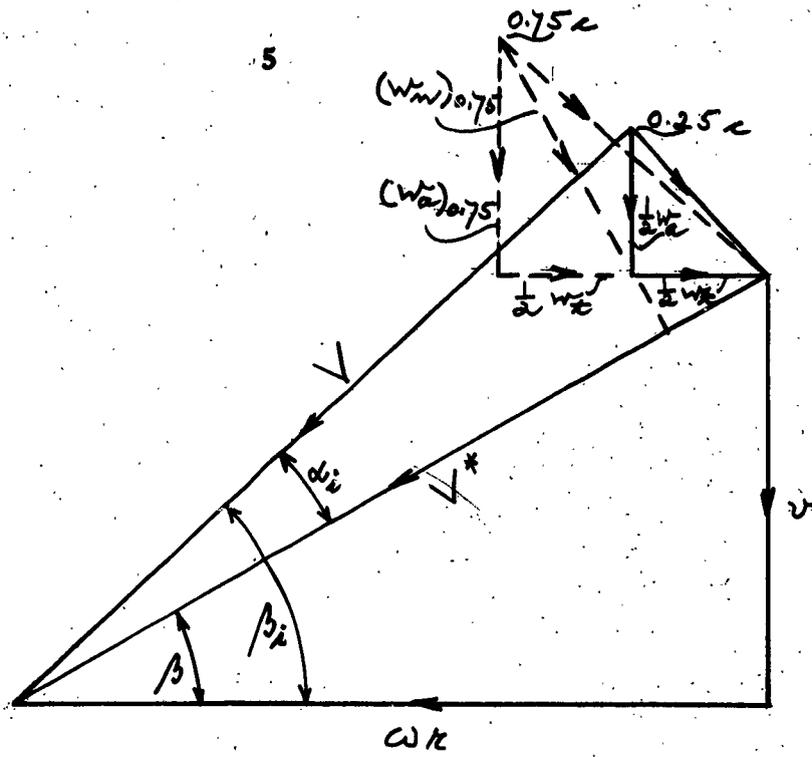


Figure 1. Effect of the free vortex sheets at station 0.75c

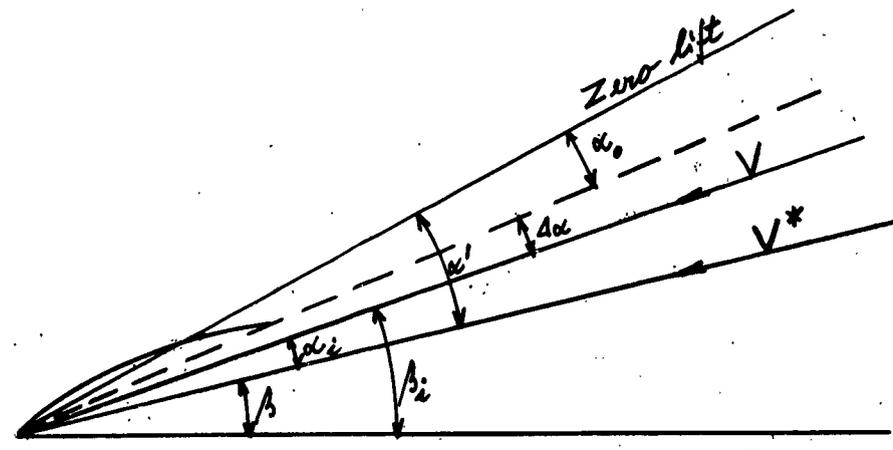


Figure 2. Definition of angles

sufficiently accurate determination of h . The integration over the helical vortex sheets to ascertain $(w_a)_{0.75}$ is performed in the Appendix, the numerical evaluation of the integrals, however, requires an appreciable amount of time. To obtain a simple approximation a propeller with infinitely many blades is considered. In this case, the free vortex system may be resolved, at any radius, into a semi-infinite row of ring vortices, which are perpendicular to the axis, and into straight vortices of semi-infinite length, which are parallel to the axis. The axial velocity component is generated only by the ring vortices. To determine its increase over the chord length, an integration over the velocity fields of the ring vortices is necessary. This integration is easier than for helical vortex sheets but is still laborious. However, for the inflow, it is known, that the field of a semi-infinite row of ring vortices is identical with that of an axis-symmetrical distribution of sinks over the disc. Further, the velocity potential of a sink-disc is in complete analogy with the gravitational potential of a solid disc the latter being known from text books.

The scheme of a sink-disc enables us to approximately determine the dependence of the axial component of the induced velocity on position for the flow in front of the disc. To obtain information on the flow behind, the tentative assumption is made that the rate of increase of the axial component is symmetrical about the disc. This assumption complies with the general character of the axial component, viz., continuous increase from zero far in front to a value in the ultimate wake which is twice the value at the disc.

On a basis of this assumption, it develops from the velocity potential of a sink disc that

$$h = 2 - \left[\frac{V}{(w_a)_{0.25}} \sin\theta + \frac{u}{(w_a)_{0.25}} \cos\theta \right]$$

where

$$(6) \quad \tan\theta = \frac{x}{\sin\beta_1} \frac{D}{c}$$

and where

$$q > R \begin{cases} \frac{v}{(w_a)_{0..25}} = \frac{1}{8} \left(\frac{R^4}{q}\right) P_2' - \frac{1}{16} \left(\frac{R^6}{q}\right) P_4' + \frac{5}{128} \left(\frac{R^8}{q}\right) P_6' \dots \\ \frac{u}{(w_a)_{0..25}} = \frac{1}{2} \left(\frac{R^2}{q}\right) - \frac{3}{8} \left(\frac{R^4}{q}\right) P_2 + \frac{5}{16} \left(\frac{R^6}{q}\right) P_4 \dots \end{cases}$$

$$q < R \begin{cases} \frac{v}{(w_a)_{0..25}} = P_1' - \frac{1}{2} \left(\frac{q}{R}\right) P_2' + \frac{1}{8} \left(\frac{q^3}{R}\right) P_4' \dots \\ \frac{u}{(w_a)_{0..25}} = P_1 - \left(\frac{q}{R}\right) P_2 + \frac{1}{2} \left(\frac{q^3}{R}\right) P_4 \dots \end{cases}$$

Within these expressions, q represents the distance from the origin to the point of reference and θ the angle between q and the axis (spherical coordinates). The functions P_n , which depend on $\cos \theta$, are the Legendre polynomials and the prime means the derivative relative to θ .

For $x = 0.7$, the function h is represented on Figure 3 on a basis of θ . The underlying calculations do not take into account the dependence of $(w_a)_{0..25}$ on radius, therefore, they are sufficiently accurate only at one certain radius. Including the dependence into the considerations causes considerable additional numerical work which does not seem justifiable for these approximations.

(b) Velocity components induced from the bound vortex lines.

The bound vortex lines are assumed to be straight lines which are situated in a plane, i.e., effects from rake and skew back of the blades are neglected. Further, the sections are assumed situated on straight lines instead of on circular arcs.

According to simplified lifting surface theory, the induced velocities are calculated at $(0.75c)$, the position of the bound vortices being at $(0.25c)$. For such configuration the integral by Biot-Savart yields the results that (see Figure 4)

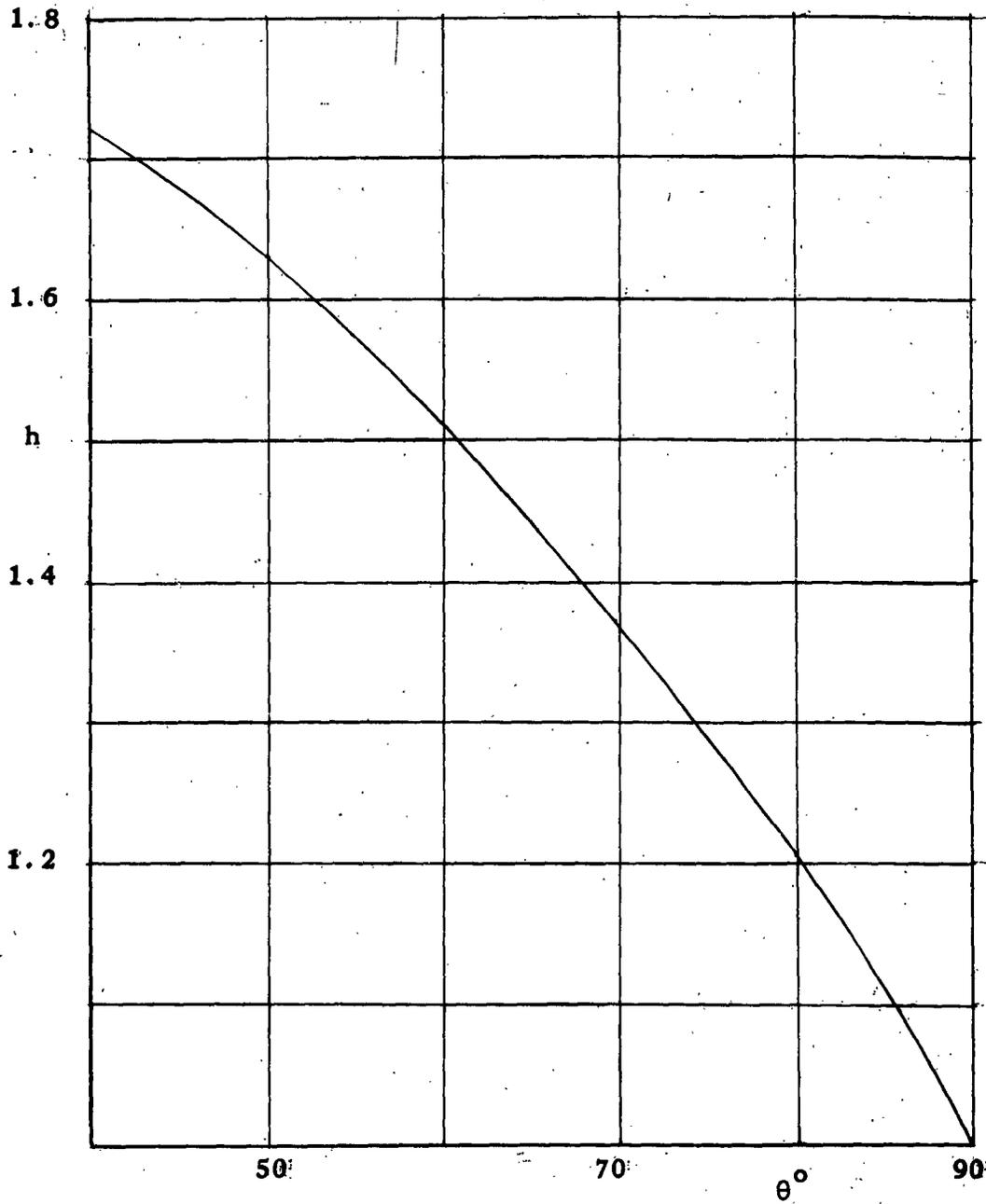


Figure 3. The function h for x=0.7

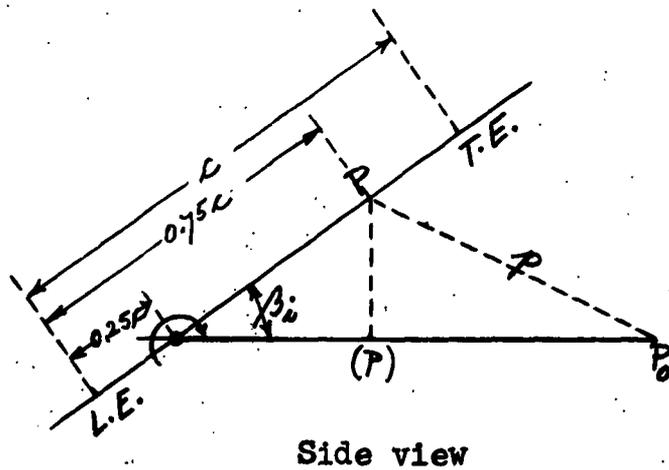
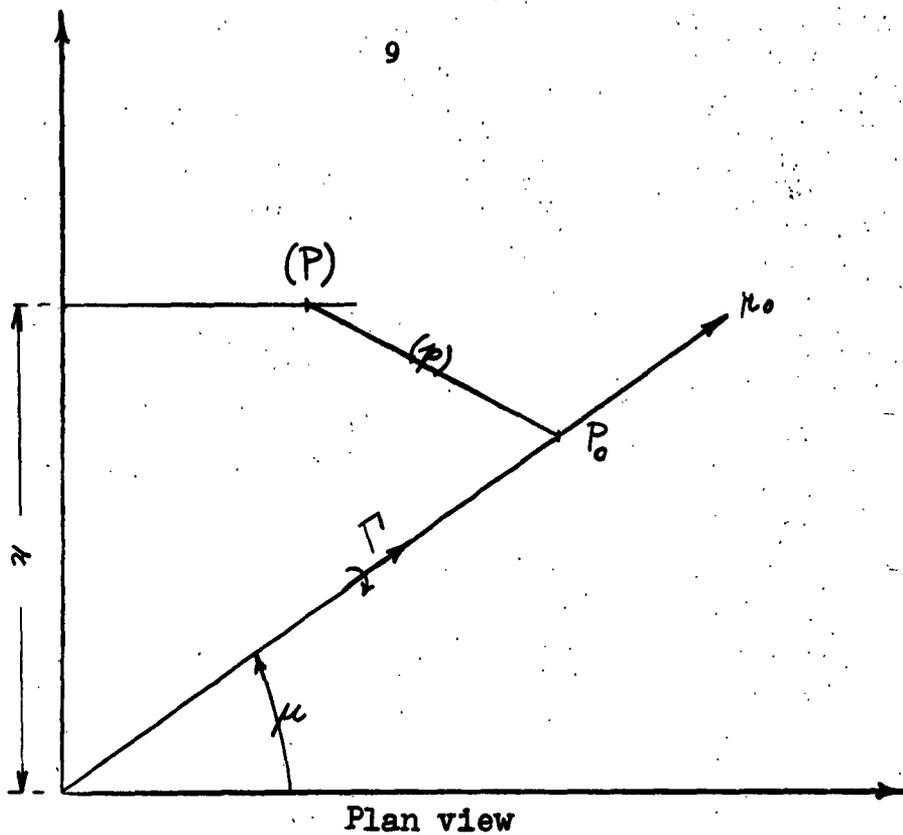


Figure 4. Effect of bound vortex lines at station $P = 0.75c$

$$\left(\frac{w}{V^*}\right)_b = \frac{\sin \beta_i}{2} \left[\sin(\rho, x_0) \frac{\rho}{R} \right] \int_{x_h}^1 \frac{G(x_0) dx_0}{(\rho/R)^3}$$

where

$$\left(\frac{\rho}{R}\right)^2 = (x_0 \cos \mu - \frac{c}{D} \cos \beta_i)^2 + (x_0 (\sin \mu - x^2) + (\frac{c}{D} \sin \beta_i))^2$$

Within these and the following expressions, the pitch angle of a section is approximated by β_i

The component of w which is perpendicular to V^* is obtained from the following relations:

$$\left(\frac{w_n}{V^*}\right)_b = \left(\frac{w}{V^*}\right)_b (\cos \lambda \sin \beta_i - \cos \nu \cos \beta_i)$$

$$\cos \lambda = \frac{\frac{c}{D} \sin \beta_i \sin \mu}{\sin(\rho, x_0) \frac{\rho}{R}}$$

$$\cos \nu = \frac{x \cos \mu - \frac{c}{D} \cos \beta_i \sin \mu}{\sin(\rho, x_0) \frac{\rho}{R}}$$

Introducing the expression for $(w/V^*)_b$, one obtains

$$(7) \quad \left(\frac{w_n}{V^*}\right)_b = \frac{\sin \beta_i}{2} \sum_{\mu} \left[\left(\frac{c}{D} \sin \mu - x \cos \beta_i \cos \mu \right) \int_{x_h}^1 \frac{G(x_0) dx_0}{(\rho/R)^3} \right]$$

In these relations, the position of a bound vortex line is fixed by the angle μ (Figure 4). The formula gives the induced velocity at the three-quarter point P at any radius x of a blade which is in the position $\mu = 90^\circ$, from any other bound vortex line in position μ . That is, for $\mu = 90^\circ$ the self interference of the blade follows. The mutual inductions are obtained when introducing the proper values of μ for the rest of the blades. For instance, for a 3-bladed propeller, the angles are $\mu = 210^\circ$

and $\mu = 330^\circ$, respectively. The total induction at P is, then, the sum of the individual inductions in which summation the right signs follow from the formula.

(c) Additional Pitch

The formulas (5) to (7) permit an approximate determination of the quantity α' , equation (1), when β_i and α_i are known from lifting line theory. The integral which occurs in (7) is calculated by numerical integration for each of the blades. It follows then from (1), (2) and (5) that:

$$(8) \quad \Delta\alpha \doteq \left(\frac{w_n}{V^*} \right) \frac{1 - \cos^2 \beta_i \left(\frac{2}{h} - 1 \right) - \alpha_0}{b \left(1 + \cos^2 \beta_i \left(\frac{2}{h} - 1 \right) \right)}$$

The angle α_0 depends essentially on the camber line of the section.

For the $a=1$ camber line

$$\alpha_0 = 0.12c_L \text{ (radians)}$$

and for a circular arc camber line

$$\alpha_0 = 0.13c_L \text{ (radians)}$$

Both of these numerical values are taken from [6].

With the expression (8) for $\Delta\alpha$ the additional pitch becomes

$$(9) \quad \frac{\Delta(P/D)}{P/D} = \frac{\tan(\beta_i + \Delta\alpha) - 1}{\tan \beta_i} - 1 \\ \doteq \Delta\alpha \left(\tan \beta_i + \frac{1}{\tan \beta_i} \right),$$

$\Delta\alpha$ being introduced in radians.

C. Numerical results

From reasons mentioned before the accuracy of this approximate theory is not sufficient to determine the dependence of the additional pitch on radius. The following numerical calculations are performed at the radius $x=0.7$. For this radius, an average of the additional pitch $\Delta(P/D)$ is obtained which is in satisfactory agreement with test results.

Two different propellers are considered of which the design conditions, the type of circulation distribution, the type of camber line and the expanded blade area ratio are listed in the

following table.

No.	Design Conditions				Circulation Distribution	Camber Line
	λ	c_T	z	EAR		
1	.301	.465	6	.91	Non-optimum	a=0.8
2	.268	.500	4	.82	Non-optimum	a=1

In the design of these propellers, allowance has been made for the curvature of the flow at the half-way point of a section as known from [1] to [3]. With this allowance, test results showed a lack of pitch which is given in the last line of the following table. The additional pitch has been determined as follows:

EQUATION		NO. 1	NO. 2
β_i	} Lifting line theory	27.0	24.6
α_i (radian)		.0647	.0639
c_L		.1180	.108
θ	(6)	77.5	74.2
h	Fig. 3	1.249	1.308
$(w_n/V^*)_b$	(7)	.0082	.0072
α_o (radian)	(6)	.0160	.0126
$\Delta\alpha$ (radian)	(8)	.0152	.0196
$\frac{\Delta(P/D)}{P/D}$ o/o	(9)	3.8	5.2
$\frac{\Delta(P/D)}{P/D}$ o/o	Test	3.2	4.9

D. Conclusions

Comparison of the last two lines shows that the average of the additional pitch as determined by simplified lifting surface theory is slightly greater than follows from test data in order to meet the design conditions. Since these differences may be explained by the approximations introduced, the result enables us to conclude that the lack of pitch of lifting line theory arises from the boundary condition at the blades which is not satisfied within this theory. The allowance for the curvature of the flow at the half-way point of a section is insufficient

to approximately satisfy the condition. In addition, an angle of attack must be introduced to obtain a sufficient approximation. With these two corrections for the boundary condition, lifting line theory provides a reliable basis for the design of a propeller. However, a rigorous lifting surface theory is desirable to accurately determine the necessary distortion of the camber line both at each station of the chord and at each radius of the propeller.

APPENDIX

Rigorous expression for $(w_a)_{0.75}$

The axial component of the induced velocity $(w_a)_{0.75}$ follows, at any radius, from the integral by Biot-Savart when integrating over a symmetrical system of z helical vortex sheets, see [7]. These sheets originate at $(0.25c)$ and go to infinity. The axial component of the velocity induced by these sheets is determined at the point $(0.75c)$ of a section at radius $x=r/R$ which point is situated on one of the vortex sheets. It develops, then, that the ratio $h=(w_a)_{0.75}/(w_a)_{0.25}$ is represented by the following expression:

$$h = 1 + \frac{I}{(w_a/v)_{0.25}}$$

$(w_a/v)_{0.25}$ being known from lifting line theory and I being

defined by

$$I = 2\pi \int_{x_h}^1 \frac{1}{x_0} \frac{dG}{dx_0} \sum_{m=1}^z \int_0^b \frac{\left[\frac{x}{x_0} \cos(\varphi_m + \zeta) - 1 \right] d\zeta}{\left[1 + \left(\frac{x}{x_0} \right)^2 - 2 \left(\frac{x}{x_0} \right) \cos(\varphi_m + \zeta) + (\zeta \tan \beta_{i0})^2 \right]^{\frac{3}{2}}} dx_0$$

$$\varphi_m = (m-1) \frac{2\pi}{z}, \quad m=1, 2, \dots, z$$

$$b = \frac{c}{d} \frac{\cos \beta_i}{x}$$

By the sum of the inner integrals, the effect of a system of z symmetrical vortex lines of radius x_0 at the three-quarter point of the section at radius x is represented. By the outer integral, the integration over all the vortex lines is performed and the effect of the vortex sheets at the three-quarter point is obtained.

A numerical evaluation of the inner integral is made somewhat difficult if $m=1$ and $\zeta=0$. For this combination of variables, the integrand has a singularity when $x=x_0$ which necessitates to introduce an "induction factor" as discussed in [7].

List of Main Symbols

T	thrust
$D=2R$	propeller diameter
P	pitch
z	number of blades
c	chord length of any section
$x=r/R$	non-dimensional radial co-ordinate
x_h	non-dimensional radius of the hub
v	speed of advance
w_a	axial component of induced velocity
w_t	tangential component of induced velocity
n	revolutions per second
$\lambda=v/\pi n D$	advance coefficient
$C_T = \frac{T}{\frac{\rho R^2 \pi v^2}{2}}$	thrust loading coefficient
c_L	lift coefficient of any section
Γ	circulation
$G=\Gamma/\pi D v$	non-dimensional circulation
α	angle of attack
α_0	angle between chord line and zero lift line of any section

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2. Propellers (Marine) - Design - Theory
3. Propeller blades (Marine) - Boundary layer - Theory
4. Surfaces - Lift.
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