W. Lounsbery

Ducted Propeller Design

COMPUTER AIDED SHROUDED PROPELLER DESIGN

by

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Abstract

A method of designing shrouded propellers using a computer algorithm was developed which enables the designer to investigate designs quickly and efficiently. An outline of the resultant design procedure is included along with an appropriate discussion of the method. Results of a specific design are compared to an experimental model. The comparison shows satisfactory agreement.

Modifications to Shrouded Propeller Design

In the exit vane design portion of the design method, one of the design requirements must be relaxed. Because of the large number of blades generally required to satisfy the equal torque requirement, only a certain percentage of the torque induced by the propeller blade may be removed.

If the designer specifies that exit vanes are required then the maximum number of vanes must be entered also. This number may coincide with the desired number of vanes. In the exit vane design the chord length at each radial station is compared to the maximum allowable chord length. If the maximum chord is exceeded, the number of exit vanes required to satisfy the torque condition is found by:

$$(B_v)_{req} = \frac{B\ c\ q_r\ C_x}{(C_v)_{max}\ q_{rv}\ C_{xv}}$$

B_v required is then transformed to a integer number and is increased by 1 if the number is not prime to the number of propeller blades. This number must be less than or equal to $(B_v)_{max}$. If B_v is less than or equal to $(B_v)_{max}$ then the design continues. If the maximum number of vanes is exceeded then the torque requirement is changed by requiring the removal of a calculated percentage of the induced torque given by

$$\%\ \text{torque removed} = \frac{(B_v)_{max}\ (C_v)_{max}\ q_{rv}\ C_{xv}}{B\ c\ q_r\ C_x} \times 100$$

(Note: C_{xv} and C_v are values of the coefficients at the radial location which first yielded a chord greater than the maximum allowed.)

Future modifications will include refinement of the present design method and incorporation of off-design performance analysis of the shrouded propeller. More research is planned also for determination of optimum radial thrust distribution. The thrust distribution may be dependent on optimization of noise reduction as well as performance. As stated in the report, this method incorporates a linear radial thrust distribution which was arbitrarily chosen to yield reasonable chord distributions.

List of Symbols

A	Propeller disk area
A_h	Cross-sectional area of the propeller hub
B	Number of propeller blades
B_v	Number of exit vanes
c	Propeller blade chord length
c_s	Shroud chord length
c_v	Exit vane chord length
C_D	Airfoil drag coefficient
C_{D_s}	Shroud drag coefficient referenced to area given by chord length times circumference of shroud
C_L	Airfoil lift coefficient
C_x	Force coefficient acting in a direction normal to propeller axis
C_y	Force coefficient acting forward in direction of propeller axis
C_T	Net thrust coefficient of the propulsive unit $\frac{T}{qA}$
C_{T_p}	Net thrust coefficient of the propeller alone $\frac{Tp}{qA}$
D	Drag force, lbs.
D_s	Shroud drag
e	Swirl factor $\frac{\omega r}{V_A}$
K	Induced velocity factor

K'	Total head rise coefficient
L	Lift force, lbs.
P	Power $\frac{\text{ft-lb}}{\text{sec}}$
q	Freestream dynamic pressure $\frac{\rho V_o^2}{2}$
q_A	Annulus dynamic pressure $\frac{\rho V_A^2}{2}$
q_r	Resultant dynamic pressure $\frac{\rho V_r^2}{2}$
Q	Torque force, ft-lbs.
r	Radial distance from the propeller axis
R	Radius of propeller blade
R_e	Radius of shroud exit
s	Shroud length to radius ratio
T	Net thrust force, lbs
V	Velocity, fps.
V_F	Velocity increment due to the shroud
w	$V_j - V_o$
x	Non-dimensional radial distance $^r/R$
z	Camber ratio
α	Angle of attack
α_{o_L}	angle of attack for zero lift
β	Propeller blade pitch angle

δ	Velocity increment ratio V_F / V_o
δ_i	Velocity increment ratio due to the energy source
δ_o	Velocity increment ratio due to shroud circulation
η	Efficiency
γ	Lift to drag ratio
Ω	Rotation velocity of propeller, radians/sec.
λ_e	External rate of advance $\frac{V_o}{\Omega r}$
λ_i	Internal rate of advance $\frac{V_A}{\Omega r}$
ϕ	Propeller advance angle
ψ	Angle between flow direction at the trailing edge of the exit vane and the propeller axis
θ	Exit vane advance angle
ω	Rotational velocity imparted to the airstream by the propeller

Subscripts

A	annulus
B	propeller blade
j	jet
o	free stream
p	propeller
s	shroud
v	exit vane

INTRODUCTION

There has been a renewed interest in the shrouded propeller recently because this device has several advantages compared to an open propeller in certain flight regimes. The propeller shroud is known to increase thrust and efficiency of restricted diameter propellers at static and low-speed states of operation. The shroud is also known to reduce propeller noise if designed properly (Figure 1). A need exists for a tool that will enable the designer to study various shroud-propeller combinations quickly and efficiently to meet performance design requirements. To meet this need, a program to develop computerized methods for designing shrouded propellers has been initiated at Wichita State University.

ANALYTICAL METHODS USED

The objective of the research is to incorporate methods of various authors into a satisfactory algorithm which will give aerodynamic design information, (number of blades, blade chord, twist, etc.) to meet a set of performance objectives (Figure 4). The method of Kucheman and Weber (Ref. 1) is used to determine the influence of the shroud on the flow velocity at the propeller plane. A modification of G. N. Patterson's method for ducted propeller design is used for the propeller blade and exit vane design.

ANALYSIS

The analysis of the shrouded propeller is an extension of ordinary propeller analysis with the blades surrounded by a circular fairing with airfoil shaped cross sections (Figure 2). However, the flow conditions at the propeller plane of the shrouded propeller differ considerably from that of an open propeller.

As a consequence of the mechanical energy input there is a sudden increase in pressure at the propeller disk; there is no sudden change in kinetic energy for continuity reasons. The pressure increase is subsequently transformed into a kinetic energy increase in the slip-stream. By application of Bernoulli's equation to the flow upstream and downstream of the propeller, the velocity through the propeller disk is obtained.

$$V_A = \tfrac{1}{2}(V_o + V_j) \qquad \text{(Eqn. 1)}$$

Denoting $(V_j - V_o)$ by w, Eqn. 1 becomes

$$\frac{V_A}{V_o} = 1 + \frac{w}{2V_o} \qquad \text{(Eqn. 2)}$$

According to Kucheman and Weber (Ref. 1) there is an additional velocity increment at the propeller plane of a shrouded propeller due to the fairing ring, given by

$$V_F = \delta V_o \qquad \text{(Eqn. 3)}$$

This velocity increment disappears in the slipstream but at the propeller disk

$$\frac{V_A}{V_o} = 1 + \frac{w}{2V_o} + \delta \qquad \text{(Eqn. 4)}$$

Equations (2) and (4) demonstrate the difference in the velocity at the propeller plane of an open and a shrouded propeller. It is evident that for equal diameters the mass flow through a shrouded and an unshrouded propeller is not the same.

From a momentum analysis (Ref. 1) and the definition of the total thrust coefficient, the following relations are derived:

$$C_T = C_{T_p} = 2[1 + \frac{w}{2V_o}] \frac{w}{V_o} \qquad \text{(Plain propeller) (Eqn. 5)}$$

$$C_T = 2[1 + \frac{w}{2V_o} + \delta] \frac{w}{V_o} \qquad \text{(Shrouded Propeller) (Eqn. 6)}$$

The thrust coefficient of the propeller itself is given in either case by Eqn. 5. The velocity increment (w) can be expressed as:

$$\frac{w}{V_o} = \sqrt{1 + C_{T_p}} - 1. \qquad \text{(Eqn. 7)}$$

Thus the difference in the total thrust coefficients is:

$$\Delta C_T = 2\delta\ (\sqrt{1 + C_{T_p}} - 1). \qquad \text{(Eqn. 8)}$$

This additional force must act on the shroud. An increase in annulus velocity ($\delta > o$) yields a thrust force whereas a decrease ($\delta < o$) gives a negative thrust or "induced drag" force acting on the shroud. It is important to note that the analysis has not included viscous fluid effects up to this point.

The jet efficiency of the propeller is given from momentum methods as

$$\eta_j = \frac{2}{1 + \sqrt{1 + C_{T_p}}} \quad \text{(Eqn. 9)}$$

This efficiency depends only on the loading of the propeller itself and not on the total thrust. This implies that by use of a shroud with $\delta > o$, a gain in thrust may be achieved without a loss of efficiency, or the same thrust may be obtained at a higher efficiency.

Since the addition of a fairing around the propeller blades increases the wetted area, the viscous shroud drag must be included in the analysis. To accomplish this, a shroud efficiency is introduced.

$$\eta_s = \frac{T - D_s}{T} = 1 - \frac{\pi c_s D}{A} \frac{C_{D_s}}{C_T} (1 + V_A{}^2/V_o{}^2) \quad \text{(Eqn. 10)}$$

The overall efficiency of the shrouded propeller is

$$\eta = \eta_s \eta_j \quad \text{(Eqn. 11)}$$

Figure 3 (from Ref. 1) shows that the efficiency varies considerably with C_{D_s} and c_s. For any given shroud drag the efficiency is maximum at a specific propeller thrust coefficient. At thrust coefficients less than the one for maximum efficiency, the efficiency decreases rapdily. Thus it is evident that it is impractical to shroud a lightly loaded propeller. It is also evident that the required value of δ must be achieved with a short fairing with a low shroud drag coefficient.

The value of δ must be determined in order to evaluate shroud and propeller thrusts and to determine the flow conditions at the propeller plane. According to Kucheman and Weber (Ref. 1), the additional velocity increment due to the shroud consists of: (a) the velocity increment due to the inherent shroud circulation (δ_o); and (b) the velocity increment due to the presence of an energy source in the annulus of the shroud (δ_i).

Kucheman and Weber evaluate δ_o by the method of singularities, modeling the shroud by a cylindrical distribution of vortex rings. This method leads to complex integrations and functions. However, Helmbold (Ref. 4) has simplified the analysis by limiting the camber ratio and the shroud length to radius ratio. Within the usual range of interest, ($0.5 \leq s \leq 2.0$ and $.05 \leq z \leq 0.1$) according to Helmbold,

$$\delta_o = \left[\frac{R_e}{R}\right]^{\frac{1}{2}} \left[\frac{.458 + 4.431s}{1 + 1.089s}\,z + \frac{2.033 + 4.88s}{1 + 0.893s}\,sz^2\right] - 1$$

The velocity increment due to the energy source can be computed by modeling the propeller by a uniform distribution of sinks on the propeller disk (Ref. 1). From this analysis, it is found that δ_i is proportional to the strength of the sinks representing the propeller and thus is given by

$$\delta_i = K(\sqrt{1 + C_{T_p}} - 1) \qquad \text{(Eqn. 13)}$$

where K is a "constant" of proportionality that is a function of radial position, shroud length/diameter, and propeller position within the shroud annulus. A list of mean values of K can be found in Table 1. Equation (13) demonstrates that δ_i increases as the flight velocity decreases. For this reason two different rates of advance are defined for the shrouded propeller; first the "external" rate of advance is given by

$$\lambda_e = \frac{V_o}{r\Omega} \qquad \text{(Eqn. 14)}$$

second, the internal rate of advance

$$\lambda_i = \frac{V_A}{r\Omega} \qquad \text{(Eqn. 15)}$$

The latter is much more significant because the propeller actually experiences λ_i. With a properly designed shroud, the actual rate of advance λ_i may be maintained more nearly constant than λ_e. This will reduce the necessity of variable-pitch propellers, although experience so far indicates that this potential of shrouded propellers has not been realized (Ref. 2).

If the freestream velocity and total thrust required are specified along with propeller diameter and geometry of the shroud, the velocity conditions at the propeller disk and a required propeller thrust coefficient can be calculated by the method just outlined (see Figure 5).

Propeller Design

The actual propeller design method used is a modification of the method of Patterson (Ref. 6). The method used is quite similar to open propeller design (Figure 6). Two conditions, however, make rather important changes in the blade design of shrouded propellers. Because of the shroud there is no immediate contraction of the slipstream behind the propeller. Secondly, the shroud acts as an end plate for the propeller blade provided the tip clearance is small. This not only minimizes the necessity of accounting for vortex downwash but also acts to increase blade loading toward the tips. These conditions produce a considerable difference between shrouded and unshrouded propeller blade planform.

It has already been stated that no increase of axial velocity can occur through the propeller disk, however, the propeller does impart twist to the airstream and consequently increases its absolute velocity. The "swirl factor" e is given by

$$e = \frac{\omega r}{V_A} \qquad \text{(Eqn. 16)}$$

where ω is the rotational velocity induced by the propeller. Half of the rotation imparted to the flow is thought of as being induced in front of the propeller disk and the remainder is induced in the slipstream. The value of e must be determined to completely describe the velocity which the blade section of the propeller experiences (Figure 7).

According to Pope (Ref. 7)

$$e = \frac{K'\lambda_i}{2\eta} \qquad \text{(Eqn. 17)}$$

where K' is the total head rise coefficient given by

$$K' = \frac{\eta \quad P}{q_A \; V_A \; (A - A_h)} \qquad \text{(Eqn. 18)}$$

Combining Equations (17) and (18)

$$e = \lambda_i \frac{P}{2 \; q_A \; V_A \; (A - A_h)} \qquad \text{(Eqn. 19)}$$

where $$P = \frac{TV_o}{\eta} \qquad \text{(Eqn. 20)}$$

From the propeller flow diagram (Figure 7), it can be shown that the advance angle ϕ is given by

$$\phi = \tan^{-1} \left[\frac{V_A}{\Omega r - \frac{1}{2} e V_A} \right] \qquad \text{(Eqn. 21)}$$

which differs considerably from the advance angle of an unshrouded propeller.

If a propeller rpm is specified then the resultant flow conditions are completely described for each blade element.

The force coefficient of the propeller blade element acting in the axial (thrust) direction is:

$$C_y = C_L \cos\phi - C_D \sin\phi. \qquad \text{(Eqn. 22)}$$

The force coefficient acting in the plane of rotation (torque component) is:

$$C_x = C_L \sin\phi + C_D \cos\phi. \qquad \text{(Eqn. 23)}$$

The elemental thrust and torque are given by

$$dT_p = Bc\ Cy\ q_r\ R\ dx \qquad \text{(Eqn. 24)}$$

and $$dQ = Bc\ C_x\ q_r\ R^2\ x\ dx \qquad \text{(Eqn. 25)}$$

where $$x = r/R \qquad \text{(Eqn. 26)}$$

The blade element efficiency is defined as

$$\eta_{BE} = \frac{V_o\ dT_p}{\Omega dQ}, \qquad \text{(Eqn. 27)}$$

which reduces to

$$\eta_{BE} = \lambda_e \frac{(1 - \frac{\tan\phi}{\gamma})}{(\tan\phi + 1/\gamma)} \qquad \text{(Eqn. 28)}$$

where γ is the airfoil lift to drag ratio. From Eqn. 28 it is seen that for a given radial position for maximum ~~the~~ elemental blade efficiency of each blade element, the airfoil section chosen for the propeller blade must operate at the angle of attack, and consequently the C_L, for maximum γ. The mean blade element efficiency is determined by

$$\eta_B = \frac{1}{1-x_o} \int_o^1 \eta_{BE}\ dx \qquad \text{(Eqn. 29)}$$

Using this value and η_s the total efficiency is determined by

$$\eta = \eta_B \, \eta_s \, C_T / C_{T_p} \qquad \text{(Eqn. 30)}$$

which yields a more exact unit efficiency than the efficiency given by Eqn. 11. The ratio of total thrust to propeller thrust coefficient must be included in Eqn. 30 because the propeller blade efficiency is defined as a function of propeller thrust alone.

Using Eqn. 24 and solving for c gives the required chord distribution

$$c = \frac{1}{B \; R \; C_y \; q_r} \; \frac{dT_p}{dx} \qquad \text{(Eqn. 31)}$$

It is found that the radial thrust distribution is required to determine the chord distribution. One approach is to specify a constant radial thrust distribution. However, this requires extremely large blade chords at the root of the propeller blade. To alleviate this problem the thrust variation is allowed to increase linearly with the radius. By specifying the maximum root chord allowed the required radial thrust variation can be determined. The required chord distribution may then be computed from Eqn. 31. The angle of pitch (β), required at each radial position is simply

$$\beta = \phi + \alpha \qquad \text{(Eqn. 32)}$$

The complete propeller geometry (i.e. chord, pitch, etc.) is now known along with the shroud-propeller unit efficiency and thrust. Using the improved computation of efficiency a new power requirement can be computed from Eqn. 20 and the propeller design method is iterated until convergence of power required is achieved.

EXIT VANE DESIGN

As stated previously the propeller induces swirl or twist in the airstream. It has also been shown that for high efficiencies the thrust coefficient should be high, which implies high power requirements. If the power input is high, large amounts of twist are imparted to the flow and some means of transforming the rotational energy to a pressure rise must be used. The supporting struts required for the shroud may be designed to serve also as flow straightners. The general procedure for designing the exit vane is shown in Figure 8.

Two requirements are specified for the exit vane design (Ref. 2):

1. The thrust produced by the exit vanes must be greater than zero.
2. The torque induced by each radial blade element of the exit vane must equal the torque induced by the propeller at that radial station.

Examining the exit vane flow diagram (Figure 9), it should be noticed that the magnitude and direction of the flow at each radial station is determined by the propeller design. The angle between the flow direction and the shroud axis is

$$\theta = \tan^{-1} (1/2\ e) \qquad \text{(Eqn. 33)}$$

It is desirable that the flow at the trailing edge of the exit vane be parallel to the shroud axis. For large angles of θ this condition requires unrealistic amounts of camber. Thin airfoil theory indicates that for a two-dimensional airfoil the air flow direction at the trailing edge is parallel to the camber line and the slope of the camber line is equal to the angle of zero lift. By this theory the angle between the flow direction and the axial direction is minimized by minimizing the angle ψ (Figure 9). Choosing the airfoil on this basis, the section characteristics are known.

Transferring the section force coefficients to the shroud-propeller axes yields

$$C_{y_V} = C_L \sin \theta - C_D \cos \theta \qquad \text{(Eqn. 34)}$$

$$C_{x_V} = C_L \cos \theta + C_D \sin \theta \qquad \text{(Eqn. 35)}$$

which reduce to

$$C_{y_V} = C_L \cos \theta \ (\tan \theta - 1/\gamma_V) \qquad \text{(Eqn. 36)}$$

$$C_{x_V} = C_L \cos \theta \ (1 + \frac{\tan \theta}{\gamma_V}) \qquad \text{(Eqn. 37)}$$

To maximize the thrust produced at each radial station, γ_V must be maximized. Therefore the airfoil section, angle of attack, C_L and γ_V are known.

From the torque design requirement

$$r \, q_{r_V} \, B_V \, c_V \, C_{xV} = r \, q_r \, B \, c \, C_x \qquad \text{(Eqn. 38)}$$

and solving for the vane chord required

$$c_V = \frac{B \, c \, qr \, C_x}{B_V \, q_{rV} \, C_{xV}} \qquad \text{(Eqn. 39)}$$

where

$$\frac{qr}{q_{rV}} = \frac{\cos^2 \theta}{\sin^2 \phi} \qquad \text{(Eqn. 40)}$$

which is specified by the propeller design.

The elemental vane thrust is given by

$$dT_V = R \, B_V \, c_V \, q_{rV} \, C_{yV} \, dx \qquad \text{(Eqn. 41)}$$

then the total vane thrust is

$$T_V = R \, B_V \int_0^1 c_V \, q_{rV} \, C_{yV} \, dx \qquad \text{(Eqn. 42)}$$

which is integrated numerically by the computing routine. If $T_V < 0$ then the first design condition is not satisfied, and an airfoil section with a higher maximum γ_V must be chosen. If c_V required exceeds the allowable vane chord then the number of exit vanes must be increased or the section must operate at a higher C_L. If the second alternative is chosen, however, the condition of $T_V > 0$ becomes more difficult to satisfy.

Since, the design criteria requires a specific thrust from the propulsive unit, the thrust produced by the shroud, propeller, and exit vanes must equal the thrust required, or

$$T = T_S + T_P + T_V \qquad \text{(Eqn. 43)}$$

If the thrusts match, the design of the unit is complete. If the right side of Eqn. 43 is greater than T then the thrust required of the propeller itself should be reduced until

$$T_P + T_V = T - T_S \qquad \text{(Eqn. 44)}$$

This method requires redesign of the propeller blades in order to keep maximum efficiency.

DESIGN PROGRAM

A computerized algorithm was programmed on Wichita State University's IBM 360/44 computer to design shrouded propellers by the method outlined. Figures 4, 6, and 8 illustrate the basic logic associated with this computerized method. For those interested in the details of the program a Fortran Listing can be found in Appendix A. The input data required and the method of input are described in Appendix B. The program does not require a great deal of storage and is operable on an IBM 1130 with 16K core configuration.

COMPUTATIONAL RESULTS

Typical results of the computer routine are shown in Figures 10 and 11. Figure 10 is a comparison of chord distribution and blade pitch angle for an experimental shrouded propeller model and shrouded propeller designed by the method outlined. The design conditions were:

Velocity = 60 mph.
Thrust = 10.0 lbs.
Diameter = 1.16 feet
Altitude = 7000 feet
Advance Ratio = .82

EFFICIENCY

Calculated	Measured
.68 (present paper)	.62 (Hoehne, Ref. 3)

The experimental shrouded propeller tested by Hoehne was not designed by the specific method outlined herein. The radial thrust variation of the Hoehne propeller was non-linear and for this reason the theoretical results are not expected to coincide precisely with experimental data. In view of this difference, the comparison is deemed to be satisfactory. The blade pitch angles calculated are extremely close to the actual pitch angles, as shown in Figure 11. This is due to the fact that the pitch angles are not directly dependent on the radial thrust loading. The blade chords of the two propellers are shown to be quite similar. Estimation of actual efficiency is slightly non-conservative.

No comparison of exit vanes designed by Hoehne was attempted. The design method used for the exit vanes differed considerably from the design method used in typical experimental work.

CONCLUDING REMARKS

The discrepancy between actual and measured efficiencies may be due to tip clearance effects which produce changes in the airfoil characteristics. The effect of radial thrust variation should be studied and the variation chosen which produces maximum performances.

A logical improvement will be to incorporate off-design performance analysis and open-propeller design capability into the computer routine. These additions will greatly enhance the value of the present program.

References

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Figures and Tables:

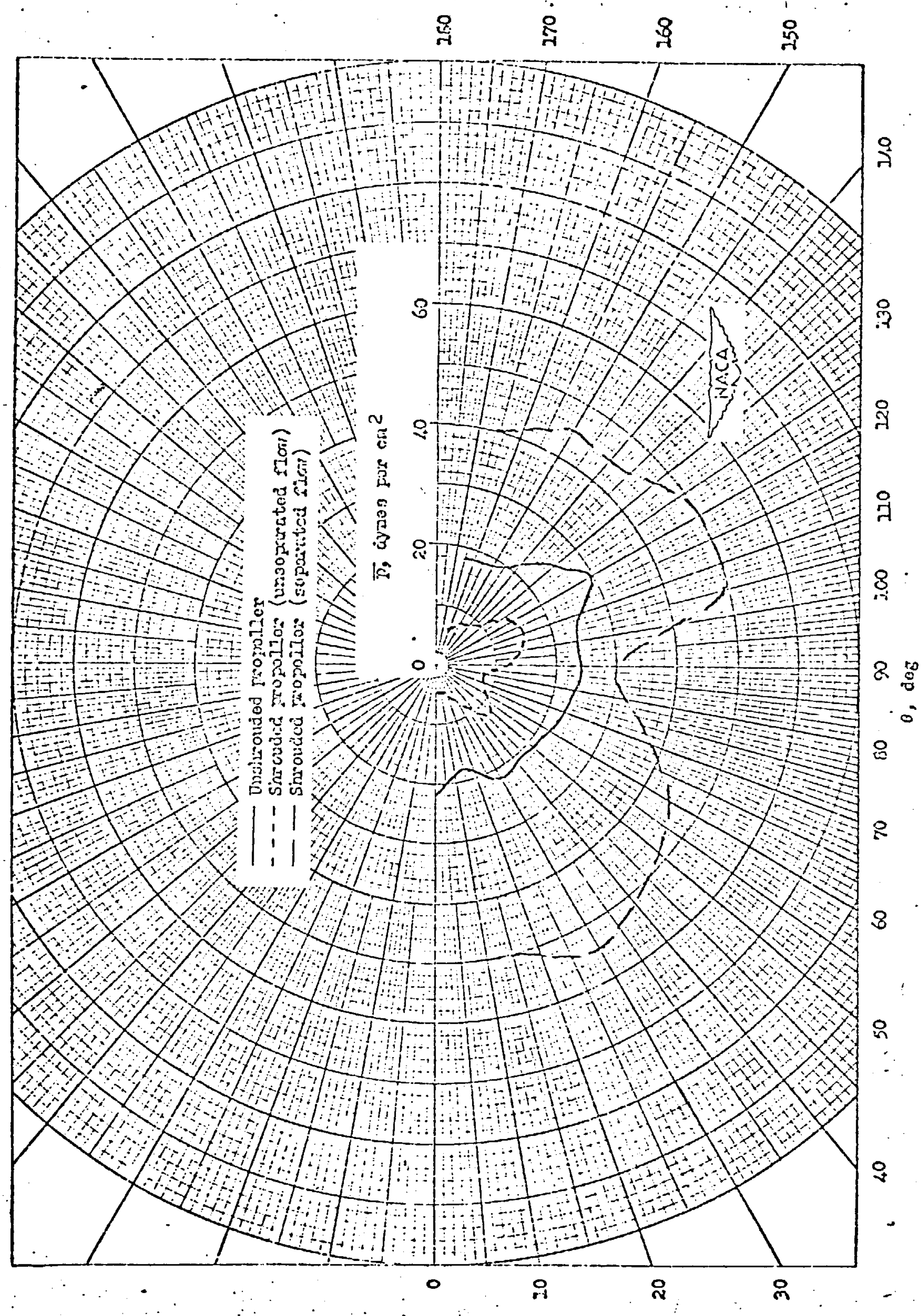

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Figure 1. Shroud effect on propeller noise generation.

SHROUDED PROPELLER

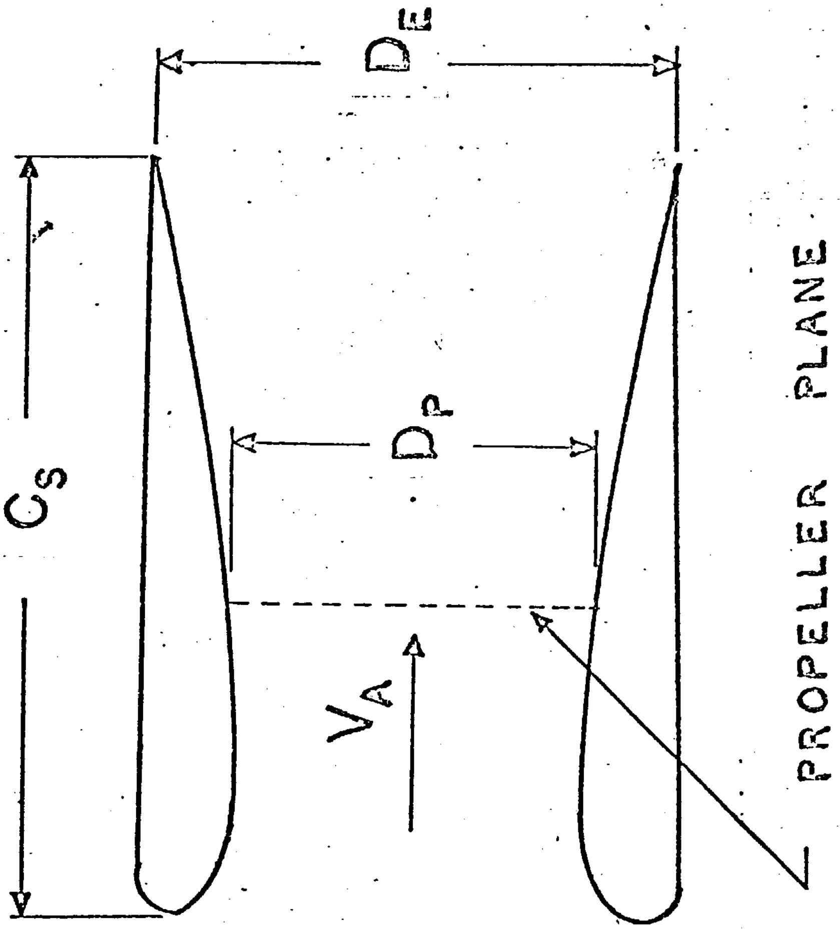


Figure 2. Shroud characteristics

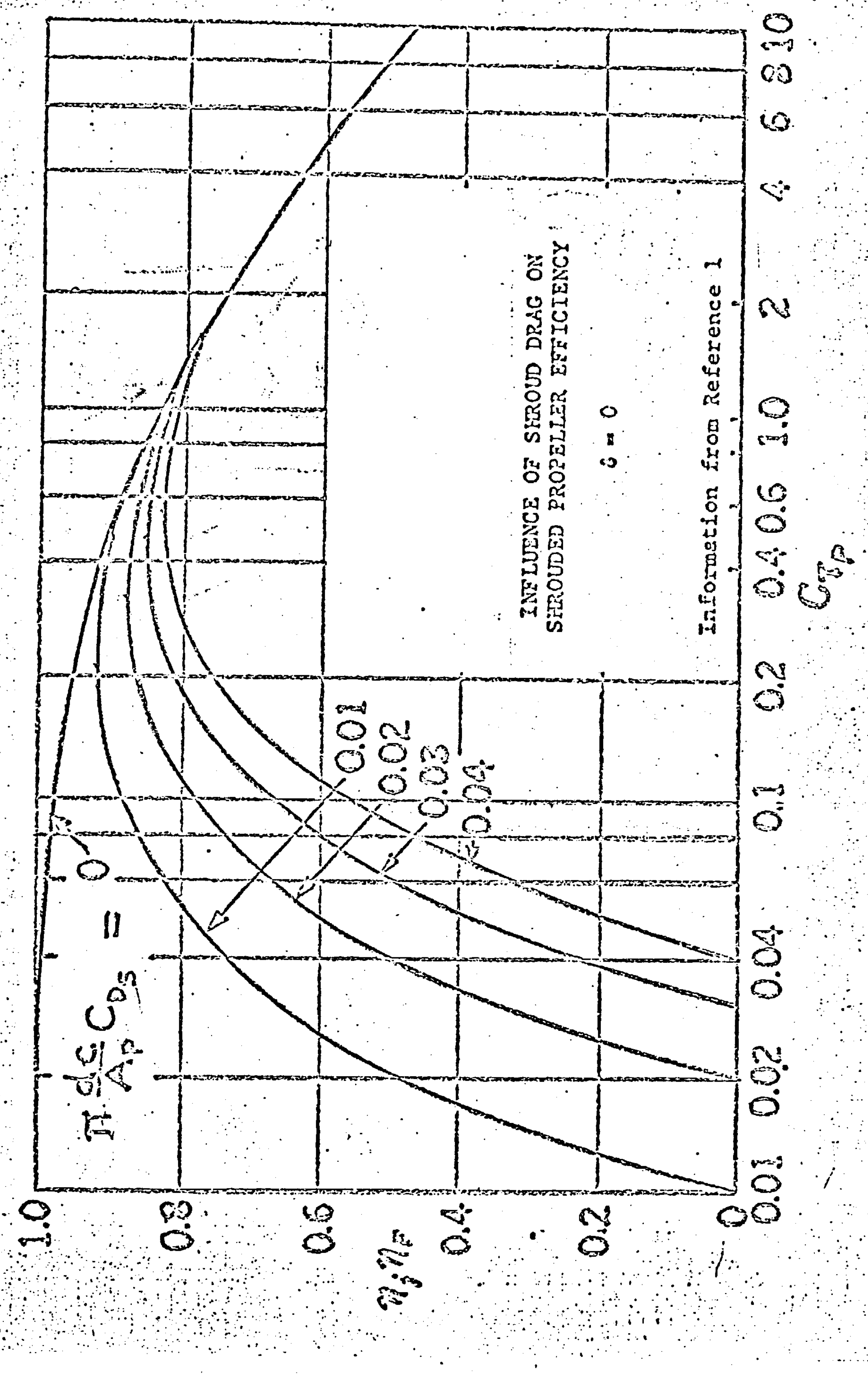


Figure 3. Effect of shroud drag on total efficiency

Shrouded Propeller Design

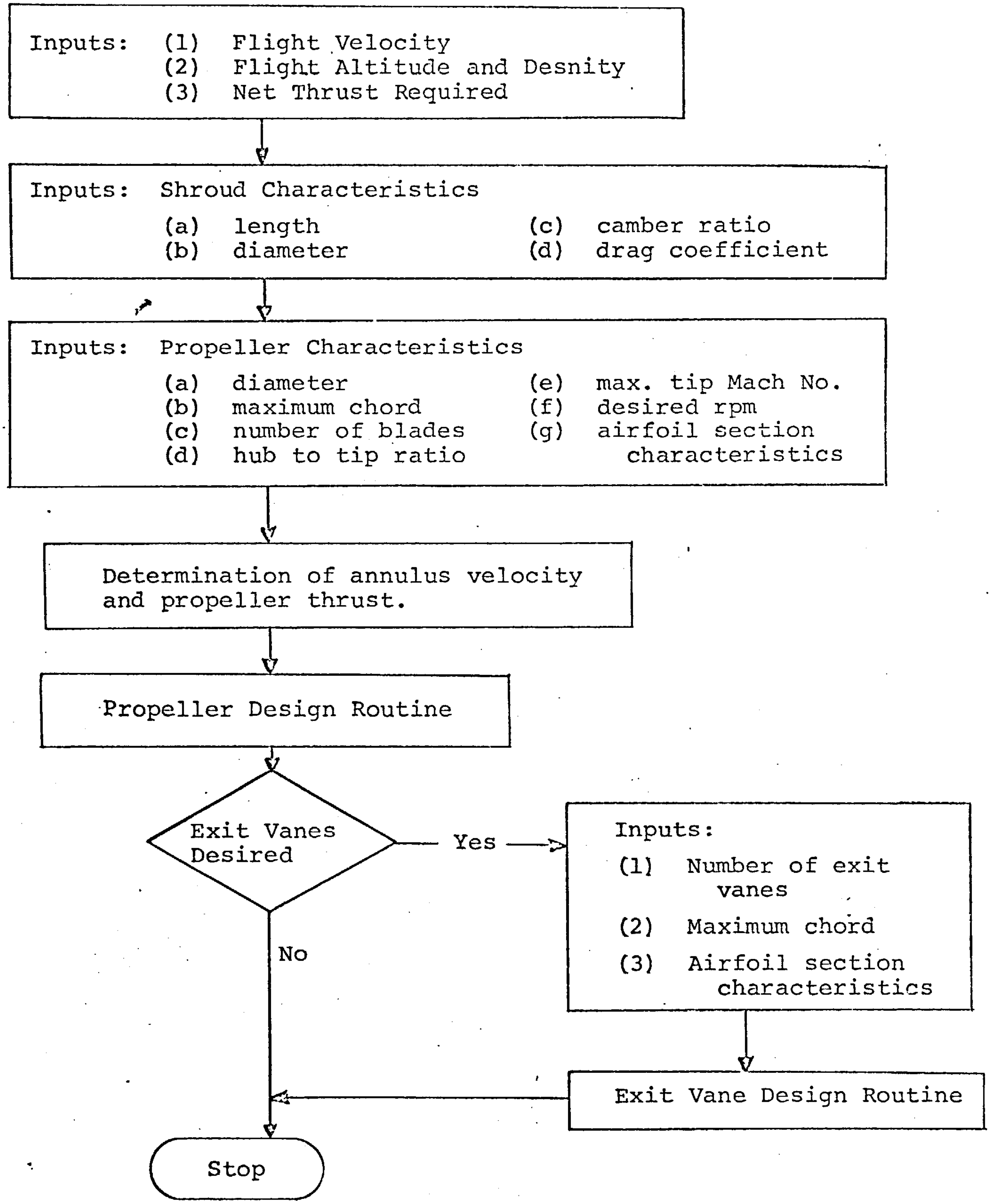


Figure 4. Shrouded propeller design procedure

Determination of Annulus Velocity and Propeller Thrust

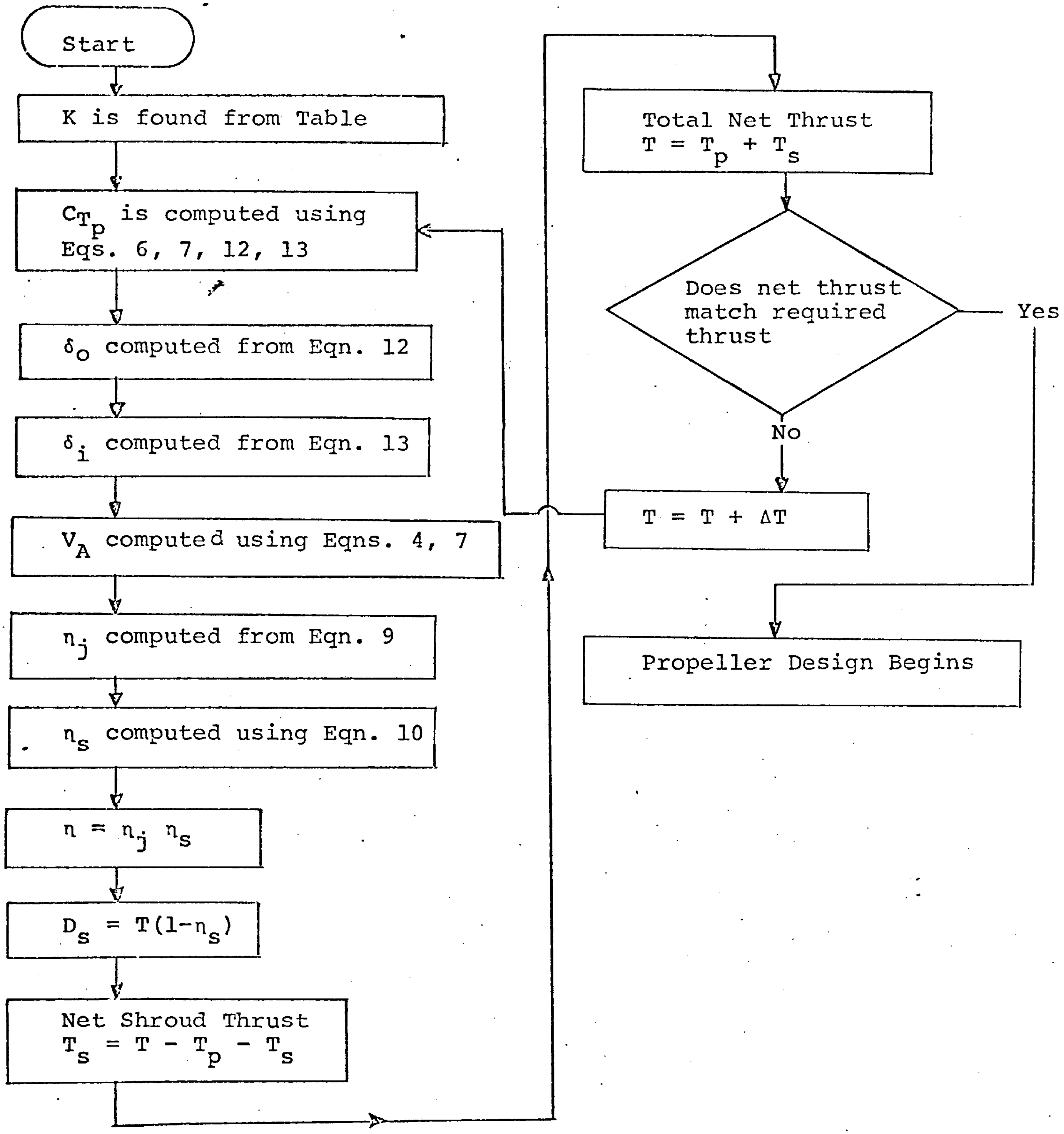


Figure 5. Procedure for determining the annulus velocity and propeller thrust

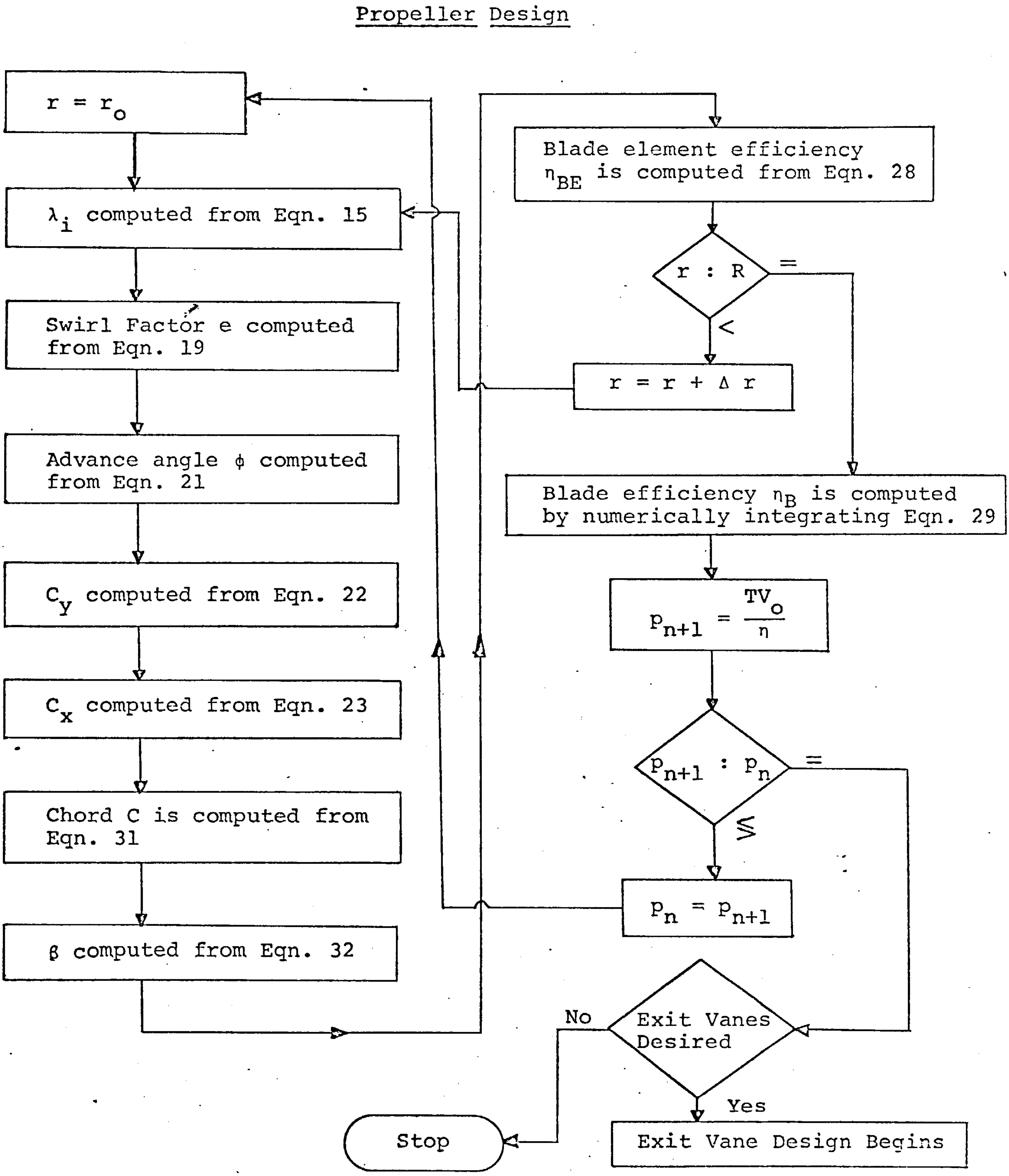


Figure 6. Propeller design procedure

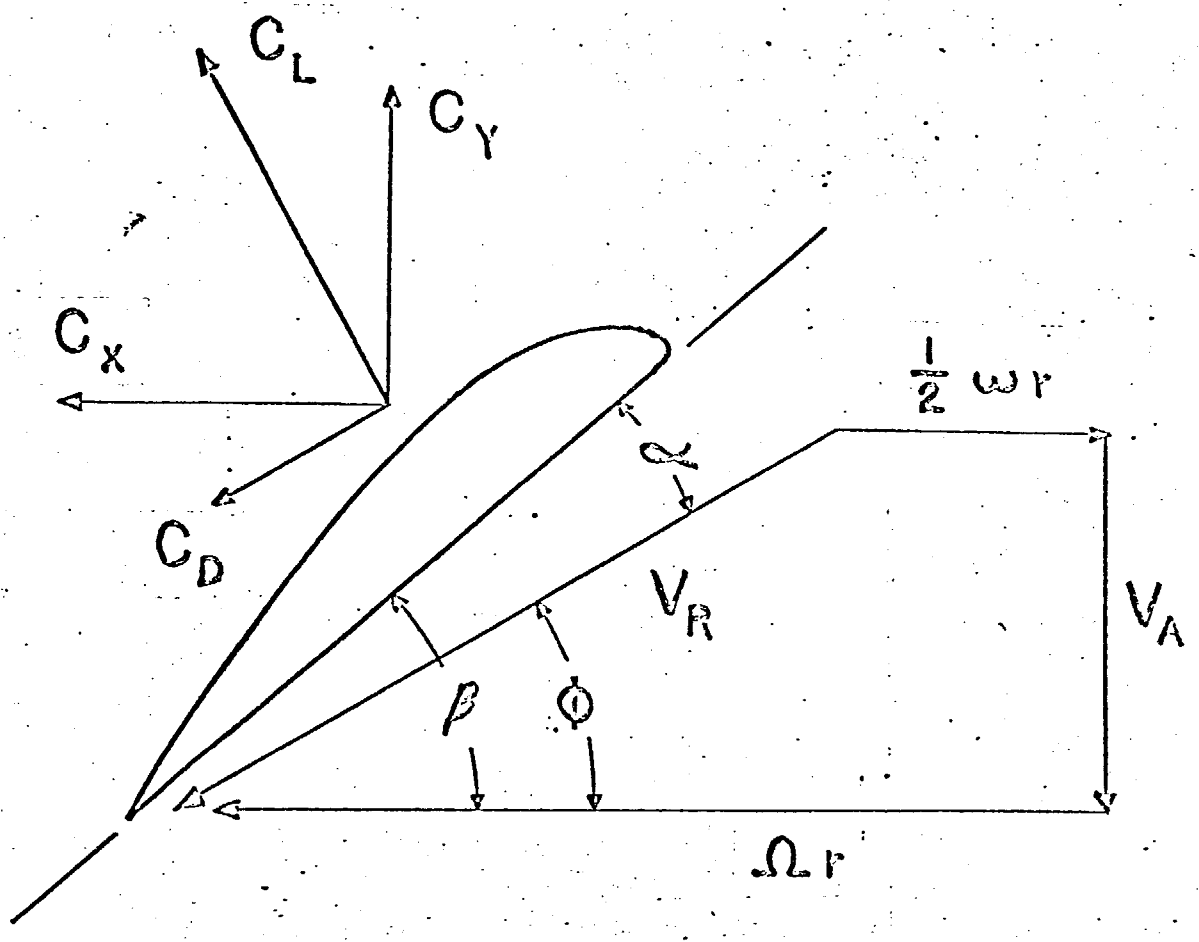


Figure 7. Flow diagram for Propeller Blade Element

Exit Vane Design

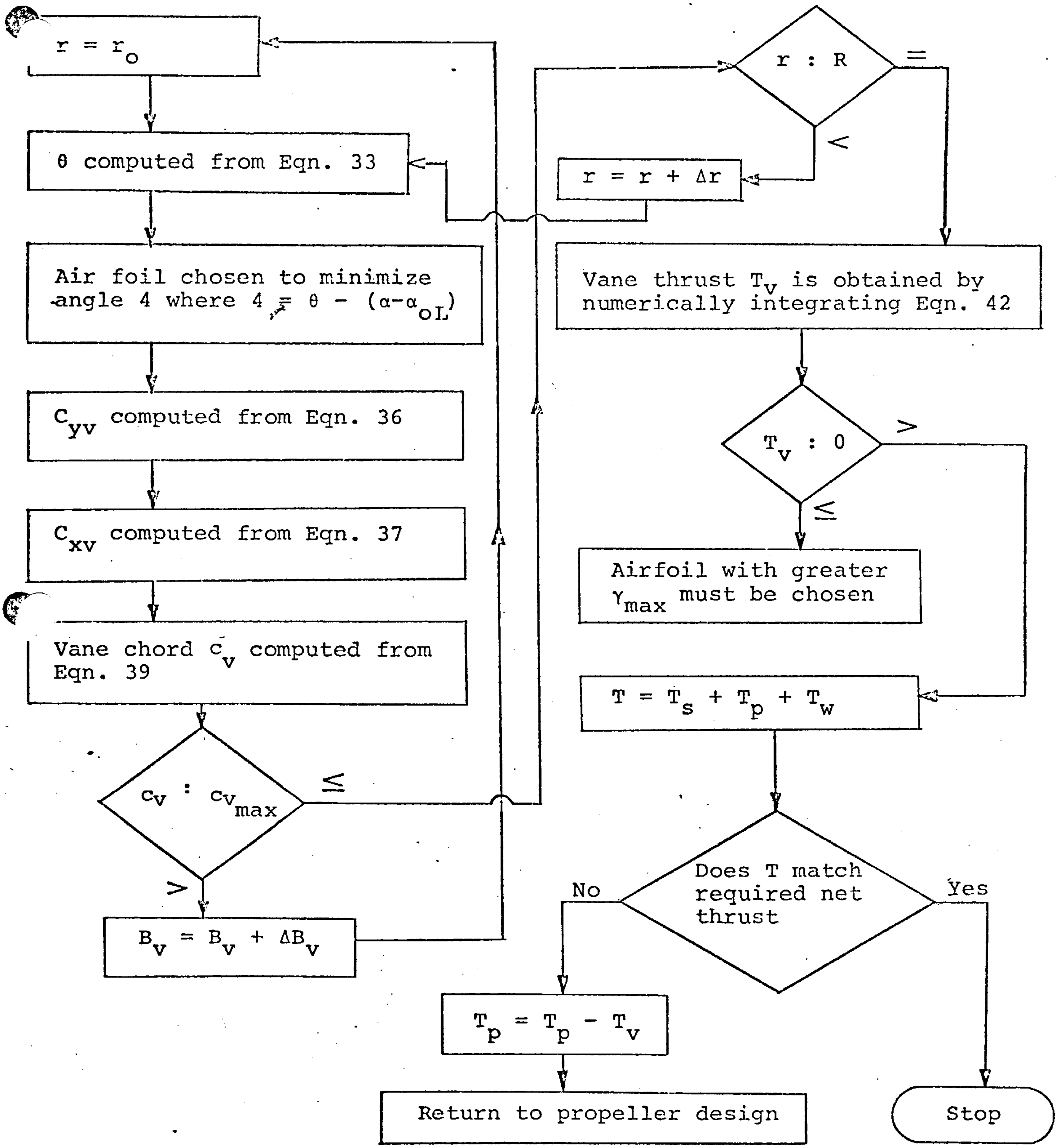
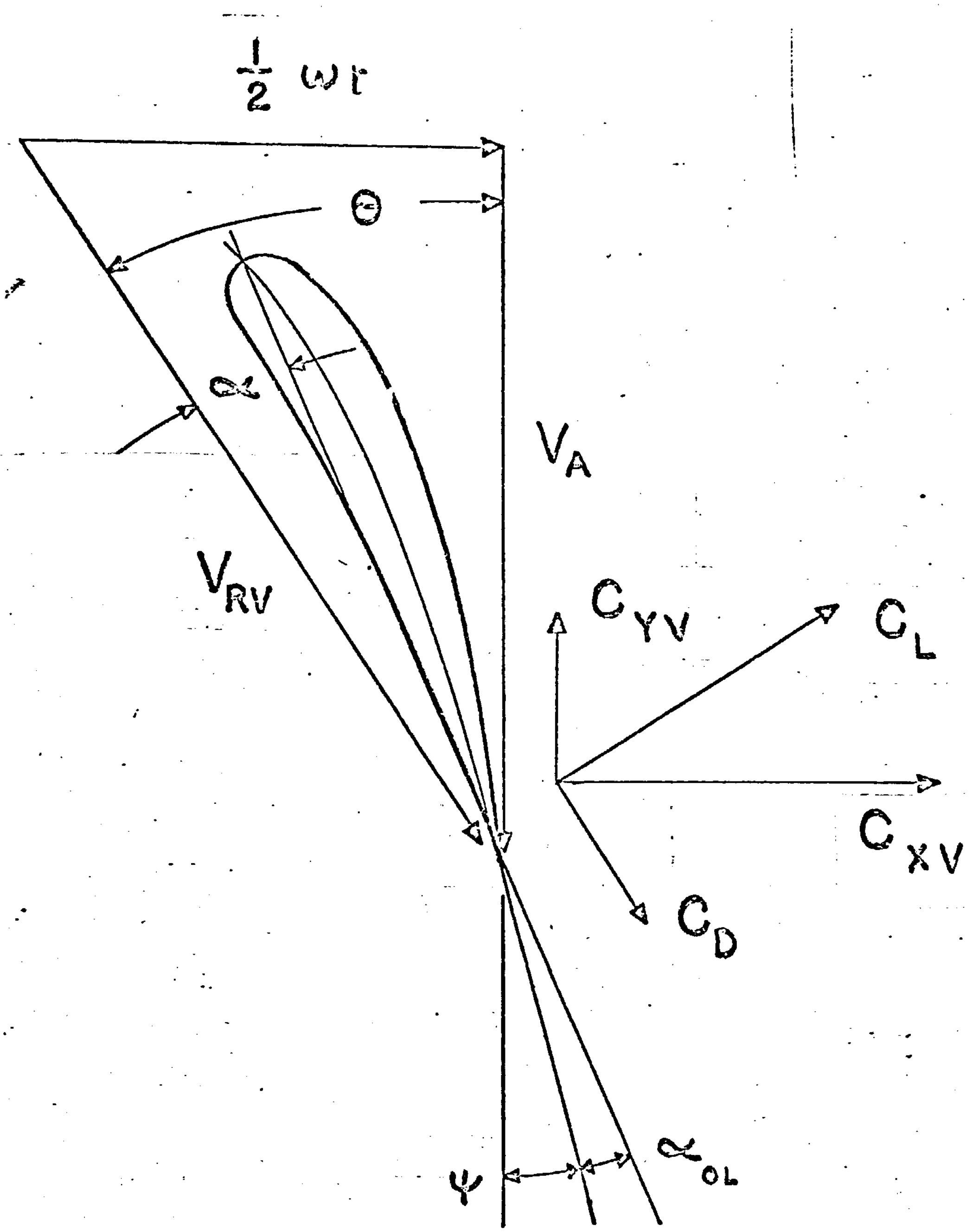


Figure 8. Exit vane design procedure

EXIT VANE DESIGN



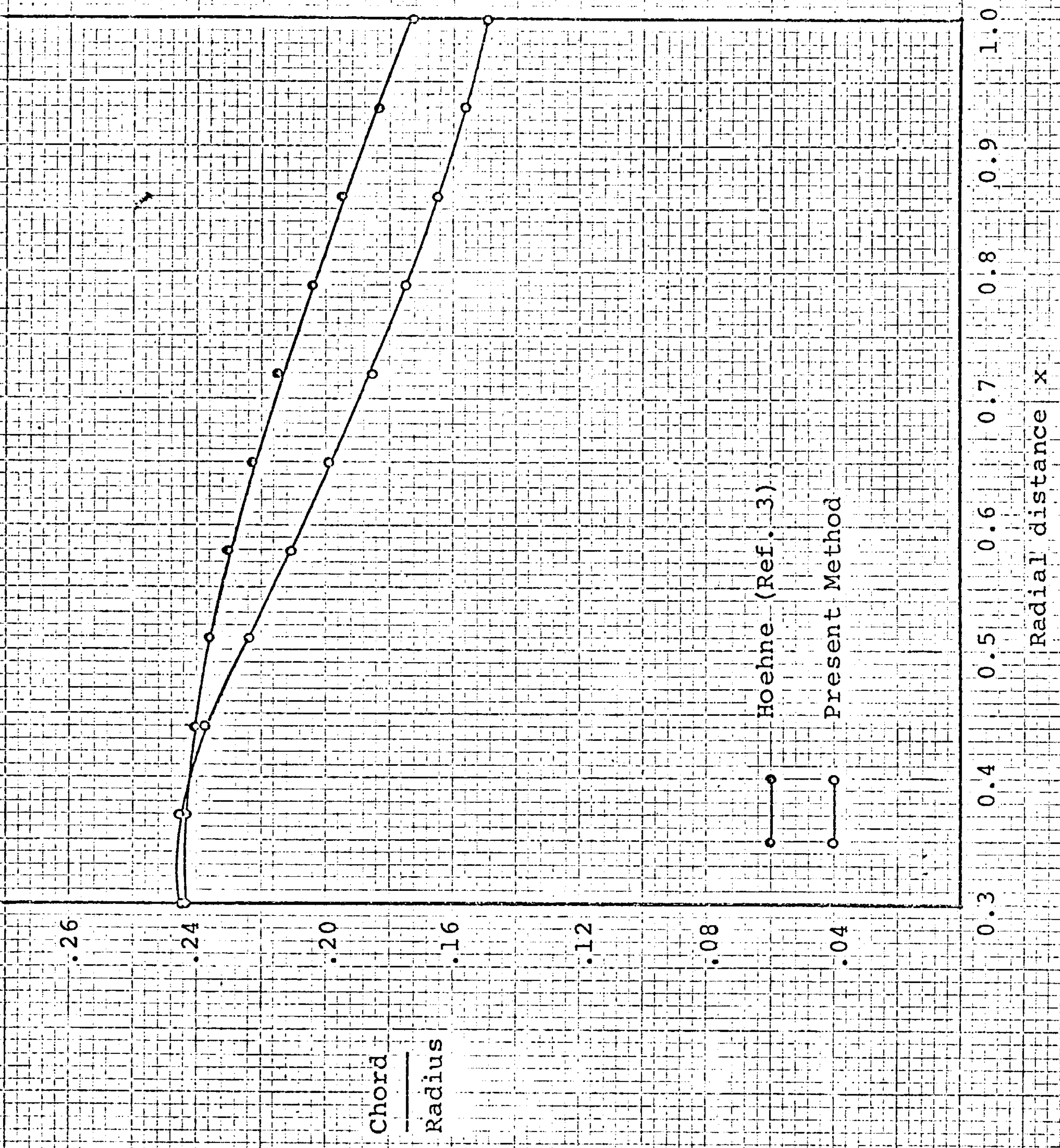


Figure 10. Comparison of Blade Chord Length

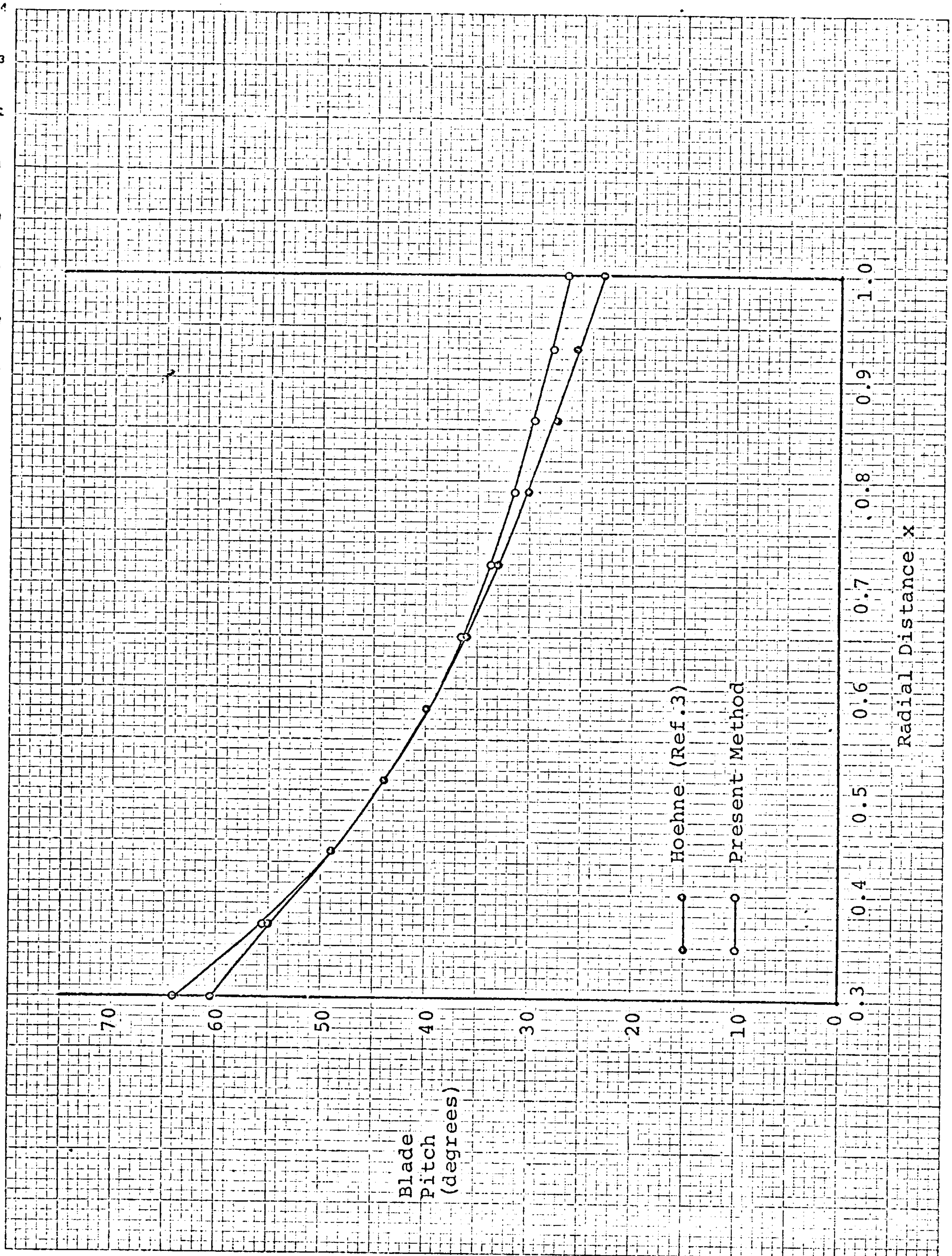


Figure 11. Comparison of propeller blade pitch angles

$\frac{\text{Length}}{\text{Diameter}}$	K (mean value)	
	Propeller at Exit or Entry	Propeller at Central position
0	0	0
.25	.24	.33
.50	.25	.39
.75	.25	.43
1.0	.25	.46

Information from Ref. 1

Table 1. Induced Velocity Factor

Appendix A:

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C       SHROUDED PROPPELLER DESIGN PROGRAM
C       PROGRAMMED BY TOM SHEEHY
C
        COMMON INDEX,INDP,NV,NVM
        REAL LOC,LOD,K,LAM(50)
        DIMENSION P(50),ETABE(50),CHORD(50),X(50),BETA(50),EFF(50),
       1F(50),PHI(50),ELAM(50),TL(50),DODX(50),CXP(50),TYPE(20)
C
C       STATEMENT FUNCTIONS
        GAMB(Y)=2.0*VA/(DP*AV*Y)
        EX(Y)=GAMB(Y)*POWR/(RO*VA**3.0*(AP-AH))
        ELAMB(Y)=GAMB(Y)*VO/VA
        TANG(Y)=GAMB(Y)/(1.0-.5*EX(Y)*GAMB(Y))
        ETA(Y)=ELAMB(Y)*(1.0-1.0/LOD*TANG(Y))/(TANG(Y)+1.0/LOD)
C
        IND=1
        INDM=1
        INDEX=1
        INDP=1
        IN=5
        IO=6
        READ(IN,2)IP,EPS
        READ(IN,5)RO,VO,T,VS,A
        READ(IN,4)B,XO,DP
        READ(IN,6)RPM,TMACH
        READ(IN,4)LOD,CL,ALPHA
        READ(IN,5)SL,CR,CDS,LOC,DE
        READ(IN,6)CMAX,BMAX
        READ(IN,499)TYPE
                                 NVM
        READ(IN,500)IV,CV,NV,~~NAF~~,NAF
      2 FORMAT(I10,F10.5)
      4 FORMAT(3F10.5)
      5 FORMAT(5F15.5)
      6 FORMAT(2F10.3)
    499 FORMAT(20A4)                3
    500 FORMAT(I5,F10.4,2I5)
C
        IF(VO-EPS)7,7,8
      7 MOC=2
        GO TO 9
      8 MOC=1
      9 CONTINUE
        BV=NV
        TV=0.0
        T2=T
        D2=0.0
        VO=VO*5280.0/3600.0
        ALPHA=ALPHA/57.3
        PI=3.1416
     17 AP=PI*DP*DP/4.0
        R=DP/2.0
        AE=PI*DE*DE/4.0
        AH=PI*XO*XO*DP*DP/4.0
        I=1
```

```
      T1=T
      CT1=2.0*T/(RO*VO*VO*AP)
      DEL=2.0
C
C     ************************************************************************
   18 CT=2.0*T/(RO*VO*VO*AP)
      SIG=2.0*SL/DE
      DELO1=(.459+4.431*SIG)*CR/(1.0+1.089*SIG)
      DELO2=(2.033+4.88*SIG)*SIG*CR*CR/(1.0+.893*SIG)
      REORP=(DE/DP)*(DE/DP)
C
C     THE VELOCITY FRACTION INDUCED BY THE SHROUD CIRCULATION
C     IS REPRESENTED BY DELO
      DELO=(REORP)*(1.0+DELO1+DELO2)-1.0
      IF(LOC/SL-.40)20,20,22
   20 K=.25
      GO TO 26
   22 IF(LOC/SL-.6)24,20,20
   24 K=SQRT(.0312*(SL/DP-.24))+.30
   26 CONTINUE
      FCTP1=(2.0*DELO-4.0*K)
      FCTP2=4.0*(1.0+2.0*K)*(CT+1.0-2.0*K+2.0*DELO)
      FCTP3=2.0*(1.0+2.0*K)
 9000 FORMAT(F50.5)
      FCTP=-FCTP1/FCTP3+SQRT(ABS(FCTP1**2+FCTP2))/FCTP3
C
C     THE VELOCITY FRACTION INDUCED BY THE PRESCENCE OF THE
C     PROPELLER AND HUB WITHIN THE SHROUD IS REPRESENTED BY DELI
      DELI=K*(FCTP-1.0)
C
C     THE ANNULUS VELOCITY IS GIVEN BY VA
   28 VA= VO*(1.0+.5*(FCTP-1.0)+DELI+DELO)
C     CALCULATE SHROUD EFFICIENCY
      ETAS=1.0-4.0*SL/DP*CDS/CT*(1+VA*VA/(VO*VO))/2.0
      DS=.25*RO*DP*PI*SL*CDS*(VA*VA+VO*VO)
C     CALCULATE JET EFFICIENCY
      ETAJ=2.0/(1.0+FCTP)
C     TOTAL EFFICIENCY
      ETAP=ETAS*ETAJ
      P(I)=T*VO/ETAP
      POWR=P(I)
      CTP=FCTP*FCTP-1.0
      TP=.5*RO*VO*VO*CTP*PI*R*R
C
C     NET SHROUD THRUST
      TS=T-TP-DS
      CTS=2.0*TS/(RO*VO*VO*AP)
      TNT=TP+TS
      IF(ABS(TNT-T1)-EPS)29,29,27
   27 IF(TNT-T1)50,29,55
   50 TR=T+DS/DEL
      T2=T
      D2=DS
      GO TO 60
```

```
      55 T=T2
         DS=D2
         DEL=DEL*5.0
         TR=T+DS/DEL
      60 T=TR
         CT=2.0*T/(RO*VO*VO*AP)
         GO TO 26
      29 CONTINUE
         T=T1
         CT=CT1
         CTPU=CTP
         TPU=TP
      25 CONTINUE
C        ****************************************************************
C        PROGRAM NOW ENTERS PROPELLER DESIGN PROCEDURE
C
         AV=2.0*PI*RPM/60.0
         DX=(1.0-XO)/IP
CD
C   ********************************************************************
      32 AREA=0.0
         J=1
         X(J)=XO
         TXCT=TP/(1.0-XO)
         PHI(J)=ATAN(TANG(X(J)))
         TXMC=.5*RO*VA*VA*R*B/LOD*CL*CMAX/SIN(PHI(J))*(LOD/(TANG(X(J)))-1.)
C
C        ****************************************************************
         IF(1.0-.5*EX(X(J))*GAMB(X(J)))33,33,35
      33 DPMIN=2.0/AV*VA/X(J)/SQRT(1.98*GAMB(X(J))/EX(X(J)))
         WRITE(IO,9000)DPMIN
C
      34 FORMAT(/10X,'DIAMETER HAS BEEN INCREASED TO ALLOW DESIGN TO CONTIN
        1UE     NEW DIAMETER IS  ',F10.4/)
C
         IND=2
         DP=DPMIN
         GO TO 17
C        ****************************************************************
C
      35 CONTINUE
         LAM(J)=GAMB(X(J))
         E(J)=EX(X(J))
         PHI(J)=ATAN(TANG(X(J)))
         BETA(J)=PHI(J)+ALPHA
         DTDX=2.0*(TXCT-TXMC)/(1.0-XO)*(X(J)-XO)+TXMC
         TL(J)=DTDX
         CHN=2.0*DTDX*SIN(PHI(J))
         CHD=RO*VA*VA*R*B/LOD*CL*(LOD/(TANG(X(J)))-1.0)
         CHORD(J)=CHN/CHD
CA
         QR=.5*RO*(VA/SIN(PHI(J)))**2.0
         CX=CL*(SIN(PHI(J))+COS(PHI(J))/LOD)
         CXP(J)=CX
```

```
      DQDX(J)=B*CX*Q2*CHORD(J)*R*R*X(J)
  100 ELAM(J)=ELAMB(X(J))
      ETABE(J)=ETA(X(J))
      IF(IP-(J-1))103,103,102
  102 J=J+1
      X(J)=X(J-1)+DX
      GO TO 35
C3
  103 CONTINUE
      VR=VA/SIN(PHI(J))
      TMN=VR/VS
C     *******************************************************************
      IF(TMACH-TMN)40,45,45
   40 INDM=2
C
   42 FORMAT(/10X,'TIP MACH NUMBER EXCEEDS MAXIMUM ALLOWED   RPM HAS BEE
     1N SET TO ',F10.2/)
C
      RPM=60.0*SQRT((TMACH*VS)**2.0-VA*VA)/(PI*DP)
      GO TO 25
   45 CONTINUE
C  **********************************************************************
C
C     BLADE EFFICIENCY IS CALCULATED BY A WEIGHTED AVERAGE OF
C     BLADE ELEMENT EFFICIENCIES
C
C     QSF CALCULATES INTEGRAL OF BLADE ELEMENT EFFICIENCIES
C     BY SIMPSON'S RULE (SCIENTIFIC SUBROUTINE PACKAGE - IBM)
C
      CALL QSF(DX,ETABE,EFF,J)
      ETAS=EFF(J)/(1.0-XO)
C  **********************************************************************
C
      ETAP=ETAB*ETAS*CT/CTP
      P(I+1)=T*VO/ETAP
  109 IF(ABS(P(I+1)/P(I)-1.0)-EPS)115,115,110
  110 I=I+1
      POWP=P(I)
      GO TO 32
C     AVERAGE BLADE CHORD IS DETERMINED TO COMPUTE SOLIDITY(SIGB)
  115 CORD=0.0
C
C     *******************************************************************
      GO TO (116,117),IV
C
C     SUBROUTINE VANE DESIGNS EXIT VANES IF DESIGNER HAS REQUESTED VANES
C
  116 CALLVANE(J,B,BV,CV,E,PHI,CXP,CHORD,X,NAF,DX,R,VA,TV,RO)
      IF(TV)502,502,504
  502 INDP=3
      GO TO 117
  504 TP1=TPU-TV
      IF(ABS(TP1-TP)-EPS)520,510,510
  510 TP=TP1
```

```
      CTP=2.0*TP/(RO*VO*VO*AP)
      INDEX=2
      GO TO 25
  520 TP=TP1
      CTP=2.0*TP/(RO*VO*VO*AP)
      INDP=2
C
C     *****************************************************************
C
  117 CONTINUE
      CTV=2.0*TV/(RO*VO*VO*AP)
      DO 118 IJ=1,J
      CORD=CORD+CHORD(IJ)
  118 CONTINUE
      ACORD=CORD/J
      SIGB=B*ACORD*2.0/(PI*DP)
      HP=P(I+1)/550.0
      AVI=VA*60.0/(RPM*DP)
      AVE=VO*AVI/VA
C  **********************************************************************
C
C     DESIGN HAS BEEN COMPLETED   RESULTS ARE NOW READY
C     FOR PRINTOUT
C
      VO=VO*3600.0/5280.0
      VA=VA*3600.0/5280.0
      ALPHA=ALPHA*57.3
      WRITE(IO,200)
  200 FORMAT(1H1,35X,'SHROUDED PROPELLER DESIGN'/36X,25(1H*)//36X,
     1'PROGRAMMED BY T.W. SHEEHY'/)
      WRITE(IO,205)VO,VA,A
  205 FORMAT(10X,'FLIGHT CONDITIONS:'/20X,'FLIGHT VELOCITY     =',F10.2,
     1' MPH'/20X,'ANNULUS VELOCITY    =',F10.2,' MPH'/20X,'ALTITUDE
     2     =',F10.0,' FT'/)
      WRITE(IO,210)SL,DE,CDS,CR
  210 FORMAT(10X,'SHROUD CHARACTERISTICS:'/20X,'LENGTH                =',
     1F10.2,' FT',7X,'EXIT DIAMETER      =',F10.2,' FT'/20X,'DRAG COEFFIC
     2IENT    =',F10.4,10X,'CAMBER RATIO        =',F10.4/)
      WRITE(IO,215)DP,XO,RPM,LOC,B,SIGB,TMN
  215 FORMAT(10X,'PROPELLER CHARACTERISTICS:'/20X,'DIAMETER               ='
     1,F10.2,' FT',7X,'HUB/TIP RATIO      =',F10.2/20X,'RPM
     2  =',F10.2,10X,'LOCATION IN SHROUD=',F10.3,' FT'/20X,'NO. OF BLADE
     3S        =',F10.0,10X,'SOLIDITY FACTOR    =',F10.3/20X,'TIP MACH NO.
     4        =',F10.3/)   <------------ change
      GO TO (217,216),IND
  216 WRITE(IO,34)DP
  217 GO TO (219,218),INDM
  218 WRITE(IO,42)RPM
  219 WRITE(IO,499)TYPE
      WRITE(IO,220)LOD,CL,ALPHA
  220 FORMAT(/25X,'(L/D)MAX =',F8.2,6X,'CL =',F6.3,5X,'ALPHA =',F6.2/)
      WRITE(IO,226)AVI,AVE
  226 FORMAT(16X,'INTERNAL ADVANCE RATIO =',F10.3,5X,'EXTERNAL ADVANCE R
     1ATIO =',F10.3//)
```

```
      DO 320 N=1,J
      BETA(N)=BETA(N)*57.3
  320 PHI(N)=PHI(N)*57.3
      MN=(J-1)/10
CE
C     *******************************************************************
  223 WRITE(IO,225)
  225 FORMAT(15X,'X(R)',5X,'LAM(E)',4X,'LAM(I)',5X,'SWIRL',
     16X,'BETA',7X,'PHI',5X,'CHORD',7X,'ETA',7X,'DTP/DX'/)
      DO 232 N=1,J,MN
      X(N)=X(N)+.00001
      WRITE(IO,230)X(N),ELAM(N),LAM(N),E(N),BETA(N),PHI(N),
     1CHORD(N),ETABE(N),TL(N)
  230 FORMAT(10X,8F10.4,F13.4)
  232 CONTINUE
  233 CONTINUE
      WRITE(IO,235)HP,T,TS,TP,ETAP,ETAS,ETAB,CT,CTP
  235 FORMAT(//10X,'PROPELLER PERFORMANCE:'//20X,'POWER REQUIRED       ='
     1,F10.2,' HP'//20X,'TOTAL THRUST         =',F10.2,' LBS',6X,'SHROUD
     2THRUST       =',F10.2,' LBS'/61X,'PROPELLER THRUST   =',F10.2,' LBS
     3'//20X,'TOTAL EFFICIENCY     =',F10.4,10X,'SHROUD EFFICIENCY  =',
     4F10.4/61X,'PROP EFFICIENCY     =',F10.4//20X,'TOTAL THRUST COEFF. =
     5',F10.4,10X,'PROP THRUST COEFF. =',F10.4)
      WRITE(IO,237)CTS,CTV
  237 FORMAT(60X,'SHROUD THRUST COEFF.=', F10.4/61X,'VANE THRUST COEFF.
     1=',F10.4/)
C   ********************************************************************
      GO TO (236,240),IV
  236 CALLVANE(J,B,BV,CV,E,PHI,CXP,CHORD,X,NAF,DX,R,VA,TV,RO)
  240 CONTINUE
      CALL EXIT
      END
```

```
      SUBROUTINE VANE(J,B,BV,CV,E,PHI,CXP,CHORD,X,NAF,DX,R,VA,TV,RO)
      COMMON INDEX,INDP, NV, NVM
      REAL LODV(50)
      INTEGER AFS(50)
      DIMENSION E(50),PHI(50),CXP(50),CHORD(50),X(50)
      DIMENSION ANGV(50),VELR(50),CXV(50),CLV(50),
     1AOL(50),ANGA(50),VC(50),BETAV(50),L(50),FX(50),CTV(50),Y(50)
      PI=3.1416
      INDVC=1
      IO=6
      IN=5
      D=57.3   ——  TR = 1.00   ←—— note
C
      GO TO (1,50,200),INDP
    1 GO TO (2,7),INDEX
    2 DO 6 I=1,NAF
      READ(IN,4)AFS(I),AOL(I),ANGA(I),CLV(I),LODV(I)
    4 FORMAT(I5,4F10.4)
      AOL(I)=AOL(I)/D
      ANGA(I)=ANGA(I)/D
    6 CONTINUE
    7 CONTINUE   ———— cord = 0.0
      DO 40 I=1,J
      ANGV(I)=ATAN(E(I)/2.0)
      VELR(I)=COS(ANGV(I))/SIN(PHI(I))
      NDEX=0
      XDIF=1000.0
      DO 20 N=1,NAF
      DIF=ANGV(I)-(ANGA(N)-AOL(N))
      IF(ABS(DIF)-XDIF)10,10,20
   10 XDIF=ABS(DIF)
      NDEX=NDEX+1
   20 CONTINUE
      L(I)=NDEX
      N=NDEX
      CXV(I)=CLV(N)*(COS(ANGV(I))+SIN(ANGV(I))/LODV(N))
      VC(I)=B/BV*VELR(I)*VELR(I)*CXP(I)/CXV(I)*CHORD(I) * TR   ←———— note
      CTV(I)=CLV(N)*(SIN(ANGV(I))-COS(ANGV(I))/LODV(N))
      QV=RO/2.0*(VA/COS(ANGV(I)))**2
      FX(I)=R*BV*CTV(I)*VC(I)*QV
      BETAV(I)=ANGV(I)-ANGA(N)                         CORD = CORD + VC(I)
      CDIF=VC(I)-CV
      IF(CDIF)40,40,26
   26 INDVC=2
C
   28 FORMAT(/10X,'MAXIMUM VANE CHORD HAS BEEN EXCEEDED   NUMBER OF EXIT
     1 VANES HAS BEEN INCREASED TO    ',F5.0/)
C
      BV=BV+2.0
      GO TO 7                  ACORD = CORD/J
   40 CONTINUE  ←——            SIGV = BV * 2.0 * ACORD/(PI * [illegible])
C     ******************************************************************
C
C     SUBROUTINE QSF USES SIMPSON'S RULE TO INTEGRATE FOR NET THRUST
```

```
C       OBTAINED FROM THE EXIT VANES
C
        CALL QSF(DX,FX,Y,J)
        TV=Y(J)
        RETURN
   50   CONTINUE
C       ****************************************************************
C
C       EXIT VANE DESIGN COMPLETE
C       RESULTS ARE NOW READY FOR PRINTOUT
C
        WRITE(IO,100)
  100   FORMAT(1H1,10X,'EXIT VANE CHARACTERISTICS'/10X,26(1H*)/)
        WRITE(IO,110)CV,BV
  110   FORMAT(10X,'MAXIMUM CHORD ALLOWED =',F10.4,5X,'NUMBER OF EXIT VANE
       1S =',F5.0/)
        GO TO (230,220),INDVC
  220   WRITE(IO,28)BV
  230   WRITE(IO,112)
  112   FORMAT(26X,'VANE        VANE',15X,'AIRFOIL'/17X,'X(R)',5X,'CHORD',
       15X,'PITCH',5X,'THETA',4X,'SECTION',6X,'L/D',7X,'AOL',5X,'ALPHA',
       24X,'DTV/DX'/)
        DO 120 I=1,J
        AOLD=AOL(L(I))*D
        ANGAD=ANGA(L(I))*D
        ANGVD=ANGV(I)*D
        BETAD=BETAV(I)*D
        WRITE(IO,114)X(I),VC(I),BETAD,ANGVD,AFS(L(I)),LODV(L(I)),
       1AOLD,ANGAD,FX(I)
  114   FORMAT(11X,4F10.3,I10,4F10.3)
  120   CONTINUE
        WRITE(IO,122)TV
  122   FORMAT(/10X,'NET EXIT VANE THRUST =',F10.2,' LBS'/)
        WRITE(IO,130)
  130   FORMAT(//10X,'AIRFOIL SECTION DESIGNATIONS'/)
        DO 140 I=1,NAF
        READ(IN,135)
  135   FORMAT('                                                              ')
        WRITE(IO,135)
  140   CONTINUE
        RETURN
  200   WRITE(IO,210)
  210   FORMAT(/10X,'EXIT VANE DESIGN HAS BEEN TERMINATED DUE TO INABILITY
       1 TO SATISFY THRUST>0 REQUIREMENT'/)
        RETURN
        END
```

230 WRITE(IO,240)
WRITE(IO,340) PTR

[illegible] #

Appendix B:

Computer Input Data

Data cards are used to input data to the shrouded propeller program. The cards and the data required are listed below:

Card 1.

Columns	1 - 10	Integer designating the number of blade stations for which results are desired. Must be greater than ten - right justified.
	11 - 20	Real variable designating the desired zero accuracy.

Card 2.

Columns	1 - 15	Density in slugs/ft^3.
	16 - 30	Freestream velocity in mph.
	31 - 45	Net Thrust required in lbs.
	46 - 60	Velocity of sound in fps.
	61 - 75	Altitude in feet.

Card 3.

Columns	1 - 10	Number of propeller blades desired.
	11 - 20	Hub to tip ratio.
	21 - 30	Diameter of the propeller in feet.

Card 4.

Columns	1 - 10	Desired propeller rpm.
	11 - 20	Maximum allowable tip Mach number.

Card 5.

Columns	1 - 10	Propeller blade maximum lift to drag ratio.
	11 - 20	Lift coefficient for max. L/D
	21 - 30	Angle of attack for max. L/D in degrees.

Card 6.

Columns	1 - 15	Shroud length in feet.
	16 - 30	Shroud airfoil camber ratio.
	31 - 45	Drag coefficient of the shroud.
	46 - 60	Distance of propeller plane from leading edge of shroud in feet.
	61 - 75	Exit diameter of the shroud in feet.

Card 7.

Columns	1 - 10	Maximum propeller root chord allowed in feet.
	11 - 20	Maximum number of propeller blades allowed.

Card 8.

Columns	21 - 80	Any alphabetic or numeric characters that designate the airfoil used for the propeller blade.

Card 9.

Column	5	Enter 2 if exit vanes are not desired - leave rest of card blank. Enter 1 if exit vanes are desired.
Columns	6 - 15	Enter maximum allowable chord length of vanes required in feet.
	16 - 20	Enter number of exit vanes desired. (Integer - right justified)

21 - [illegible] [illegible]
[illegible] - right justified

	21 - 25 25 - 30	Enter number of airfoil sections from which exit vanes are chosen. Designated "NAF". (Integer - right justified)

Cards 10 to "NAF".

Columns	1 - 5	Airfoil integer designation for program. (Right justified)
	6 - 15	Angle of zero lift in degrees; if negative must be entered as such.
	16 - 25	Angle of attack for maximum lift/drag in degrees.
	26 - 35	Lift coefficient for max. L/D.
	36 - 45	Maximum lift to drag ratio of airfoil.

Cards (NAF + 1) to 2(NAF).

Columns	5 - 10	Airfoil designation number for program. (Integer - right justified)
	15 - 55	Any alphabetic or numeric characters used for standard airfoil designation.

Cards 10 through 2(NAF) are not required if exit vanes are not desired. If exit vanes are desired the number of cards supplied must equal twice the number "NAF" entered in columns 21-25 of card 9. Unless otherwise specified all values are entered as floating point numbers.

Appendix C:

```
                              SHROUDED PROPELLER DESIGN,
                              *************************
                                          .
                              PROGRAMMED BY T.W. SHEEHY

FLIGHT CONDITIONS:
          FLIGHT VELOCITY     =     60.00 MPH
          ANNULUS VELOCITY    =     83.70 MPH
          ALTITUDE            =     7000. FT

SHROUD CHARACTERISTICS:
          LENGTH              =      0.53 FT       EXIT DIAMETER      =      1.16 FT
          DRAG COEFFICIENT    =    0.0150          CAMBER RATIO       =    0.0085

PROPELLER CHARACTERISTICS:
          DIAMETER            =      1.16 FT       HUB/TIP RATIO      =     0.30
          RPM                 =   5550.00          LOCATION IN SHROUD=     0.260 FT
          NO. OF BLADES       =        4.          SOLIDITY FACTOR    =     0.254
          TIP MACH NO.        =     0.327

          PROPELLER BLADE SECTION  RAF-6  E

               (L/D)MAX =    66.00      CL = 0.900      ALPHA =  6.00

     INTERNAL ADVANCE RATIO =      1.144     EXTERNAL ADVANCE RATIO =     0.820

    X(R)      LAM(E)     LAM(I)      SWIRL       BETA        PHI       CHORD       ETA        DTP/DX

   0.3000     0.8702     1.2140     0.4063     64.1799     58.1799     0.1420     0.5220      3.4390
   0.3700     0.7056     0.9843     0.3294     55.5974     49.5974     0.1427     0.5824      5.3266
   0.4400     0.5933     0.8277     0.2770     49.0753     43.0753     0.1375     0.6157      7.2143
   0.5100     0.5119     0.7141     0.2390     43.9823     37.9823     0.1302     0.6354      9.1019
   0.5800     0.4501     0.6279     0.2101     39.9139     33.9139     0.1225     0.6491     10.9896
   0.6500     0.4016     0.5603     0.1875     36.6003     30.6003     0.1151     0.6563     12.8773
   0.7200     0.3626     0.5058     0.1693     33.8558     27.8558     0.1081     0.6617     14.7649
   0.7900     0.3304     0.4610     0.1543     31.5494     25.5494     0.1017     0.6652     16.6526
   0.8600     0.3036     0.4235     0.1417     29.5866     23.5866     0.0959     0.6675     18.5402
   0.9300     0.2807     0.3916     0.1311     27.8974     21.8974     0.0906     0.6690     20.4279
   1.0000     0.2611     0.3642     0.1219     26.4295     20.4295     0.0858     0.6697     22.3156

PROPELLER PERFORMANCE:

          POWER REQUIRED      =      2.34 HP

          TOTAL THRUST        =     10.00 LBS      SHROUD THRUST      =      0.98 LBS
                                                   PROPELLER THRUST   =      9.01 LBS

          TOTAL EFFICIENCY    =    0.6837          SHROUD EFFICIENCY  =    0.9624
                                                   PROP EFFICIENCY    =    0.6404

          TOTAL THRUST COEFF. =    1.1314          PROP THRUST COEFF. =    1.0198
                                                  SHROUD THRUST COEFF.=    0.1112
                                                   VANE THRUST COEFF. =    0.0
```