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USER'S MANUAL FOR A FORTRAN IV COMPUTER PROGRAM FOR CALCULATING--ETC(U)
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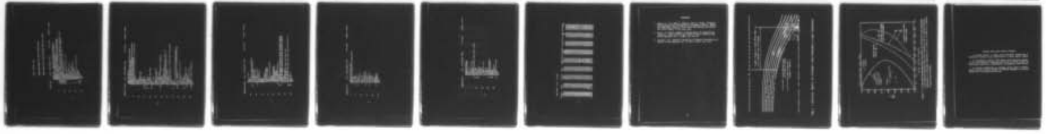

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Bethesda, Md. 20084

USER'S MANUAL FOR A FORTRAN IV COMPUTER PROGRAM FOR CALCULATING PROPELLER/STERN BOUNDARY-LAYER INTERACTION ON AXISYMMETRIC BODIES

by

T.T. Huang

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

SHIP PERFORMANCE DEPARTMENT
DEPARTMENTAL REPORT

December 1976

SPD-737-02

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BOUNDARY LAYER INTERACTION ON AXISYMMETRIC BODIES

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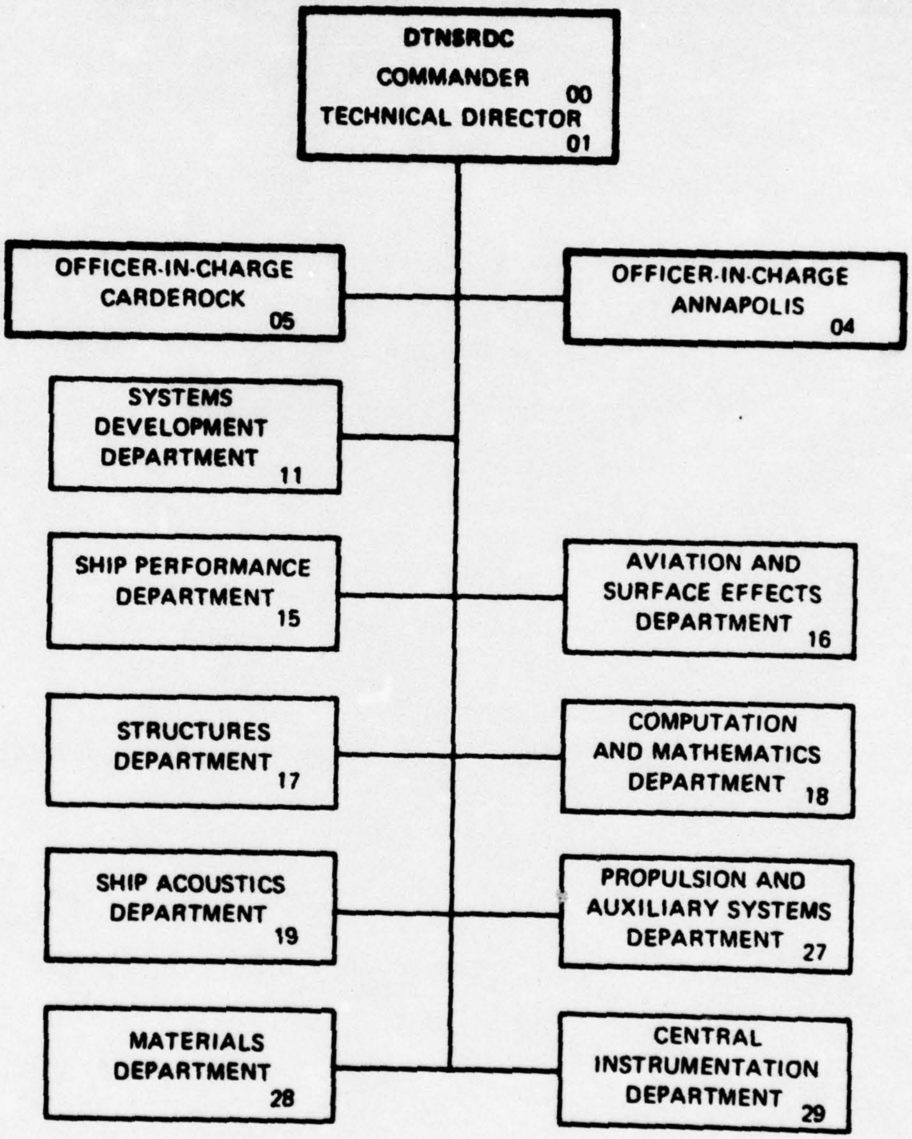

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

(14) 1. REPORT NUMBER: SPD-737-02 ✓

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

(6) 4. TITLE (*and Subtitle*): USER'S MANUAL FOR A FORTRAN IV COMPUTER PROGRAM FOR CALCULATING PROPELLER/STERN BOUNDARY-LAYER INTERACTION ON AXISYMMETRIC BODIES.

(9) 5. TYPE OF REPORT & PERIOD COVERED: FINAL rept.,

6. PERFORMING ORG. REPORT NUMBER

(10) 7. AUTHOR(s): T. T./Huang

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
David W. Taylor Naval Ship R&D Center ✓
Bethesda, Maryland 20084

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
625543N
W.U. 1520-004 & 1500-200

11. CONTROLLING OFFICE NAME AND ADDRESS:
Naval Material Command & Naval Sea Systems Command
Washington, DC

(11) 12. REPORT DATE: Dec[redacted] 1976

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)

(12) 19p.

15. SECURITY CLASS. (*of this report*): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Propeller
Wake
Interaction
Boundary Layer

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

A computer program which calculates the inviscid approximation of propeller/stern boundary-layer interaction is given. The description includes a summary of the inviscid theory and the assumptions used, an outline of the numerical procedure and computation method, a numerical example, FORTRAN listing, and input and output instructions. This program is designed to compute the effective velocity profile from the measured nominal velocity profile for propeller design.

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S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

389694

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ABSTRACT

A computer program which calculates the inviscid approximation of propeller/stern boundary-layer interaction is given. The description includes a summary of the inviscid theory and the assumptions used, an outline of the numerical procedure and computation method, a numerical example, FORTRAN listing, and input and output instructions. This program is designed to compute the effective velocity profile from the measured nominal velocity profile for propeller design.

ADMINISTRATIVE INFORMATION

This work was sponsored by the Naval Material Command/Naval Sea Systems Command under the Direct Laboratory Funding Program for Hydrodynamics of Very High-Speed Submarines, Element Number 62543N. The work was performed under internal Work Units 1520-004 and 1500-200.

INTRODUCTION

A propeller axisymmetric-stern boundary-layer computer program is documented on the basis of the theory derived in Reference 1. The parameters relevant to this computer program are briefly discussed below.

Many ship propellers have a radius which is about the same order of magnitude as the boundary-layer thickness at the propeller location. The nominal wake distribution is defined as the velocity distribution at the propeller plane in the absence of a propeller. For the model, the

---

1 Huang, T.T., H.T. Wang, N. Santelli, and N.C. Groves, "Propeller/Stern/Boundary-Layer Interaction on Axisymmetric Bodies: Theory and Experiment," David W. Taylor Naval Ship Research and Development Center Report 76-0113 (Dec 1976).

nominal velocity distribution is usually measured by a standard wake rake at the propeller disc in the absence of a propeller. The nominal wake distribution for the full-scale ship is usually computed by adding a scale-effect correction to the measured model's nominal wake distribution.

An operating propeller produces an upstream suction which results in an increase of velocity in the stern boundary-layer region, as shown in Figure 1. A typical stream surface moves inward from radius r to r_p while the velocity is increased from the nominal axial velocity u_x to u_p. The resultant axial velocity u_p in front of an operating propeller is called the apparent velocity distribution. The velocity distribution actually experienced by the propeller blade in developing thrust and torque is called the effective velocity distribution. The effective velocity, which is to be used for the design of a wake-adapted propeller, is the apparent velocity minus the circumferential-mean propeller-induced axial velocity, u_a. The propeller-induced velocity can be computed from the propeller field-point velocity program developed by Kerwin and Leopold,[2] if the loading and geometry of the propeller are known. However, sometimes only the propeller geometry is known; then an interactive procedure to compute the loading (using a propeller inverse computer program such as the one developed by Cummings[3]), propeller-induced velocity (reference 2), and the present program are required. A detailed description of the theory, computation method, and iteration procedure is given in Reference 1.

---

[2] Kerwin, J.E. and R. Leopold, "A Design Theory for Subcavitating Propellers," Transactions of the Society of Naval Architects and Marine Engineers, Vol. 72 (1964), pp. 294-335.

[3] Cummings, D.E., "Numerical Prediction of Propeller Characteristics," Journal of Ship Research, Vol. 17, Part 3 (1973), pp. 12-18.

The input of the present computer program is the nominal axial velocity (u_x/V_s) profiles at the plane of propeller. The present program then computes the apparent (u_p/u_x) and the effective ($u_e/V_s = (u_p-u_a)/V_s$) axial velocity profiles based on the following assumptions:

(a) The flow is axisymmetric, the fluid is incompressible, and upstream of the propeller, the mean circumferential velocity is identically equal to zero with and without the propeller in operation.

(b) The interaction of propeller and stern boundary layer is considered to be inviscid in nature. Thus, propeller-induced viscous losses and turbulent Reynolds stresses are neglected.

(c) The conventional boundary-layer assumption of $\partial v_r/\partial x \ll \partial u_x/\partial r$ is assumed to be valid for the boundary layer in the absence of a propeller; and

(d) Upstream of the propeller, no energy is added to the fluid by the propeller, and the propeller-induced velocity field upstream of the propeller is assumed to be irrotational.

Based on the above assumptions, two equations governing the propeller/stern boundary-layer interaction have been derived in reference 1, i.e.,

$$r u_x dr = r_p u_p dr_p \,, \tag{1}$$

$$u_x du_x = u_p d(u_p - u_a) \,. \tag{2}$$

Since u_x and u_p can be approximated locally by linear functions of r and r_p, the mass flux within the stream annuli given by $dr = r_{i+1} - r_i$ and $dr_p = r_{p_{i+1}} - r_{p_i}$ can be integrated from Equation (1). Integrating Equations (1) and (2), one obtains the finite-difference forms of the governing equations,

$$(r_{i+1}^2 - r_i^2)\left[(2u_{x_{i+1}} + u_{x_i}) - (u_{x_{i+1}} - u_{x_i})\frac{r_i}{r_{i+1} + r_i}\right]$$

$$= (r_{p_{i+1}}^2 - r_{p_i}^2)\left[(2u_{p_{i+1}} - u_{p_i}) - (u_{p_{i+1}} - u_{p_i})\frac{r_{p_i}}{r_{p_{i+1}} + r_{p_i}}\right] \quad (3)$$

$$(u_{x_{i+1}}^2 - u_{x_i}^2) = (u_{p_{i+1}} - u_{p_i})(u_{p_{i+1}} - u_{p_i} - u_{a_{i+1}} - u_{a_i}) \quad (4)$$

This program computes the values of u_p at various values of r_p from the input values of $u_x(r)$ and $u_a(r)$ by a simple iteration procedure. The numerical scheme developed for solving Equations (3) and (4) was found to converge rapidly.

NUMERICAL PROCEDURE

If the loading and geometry of the propeller are known, the lifting-surface computer program developed by Kerwin and Leopold[2] can be used to calculate the values of u_a at arbitrary points in the boundary layer. The following procedure is used to compute the values of u_p from Equations (3) and (4) at various radial locations r_p, given calculated values $u_a(r_p)$.

(a) First, assume that $u_{p_i}(r_{p_i}) = u_{x_i}(r_{p_i}) = u_{a_i}(r_{p_i})$ for i=1,N (i = 1 on body surface, i = N outside the boundary layer).

(b) Use a least-squares fitting technique to obtain a polynomial representation of the measured values of $u_{x_i}(r_i)$ for i=1,N.

(c) Use Equation (3) to determine values of $u_{p_i}(r_{p_i})$, under the assumptions that the mass flux in the presence of the propeller, from r_{p_i} to $r_{p_{i+1}}$, is equal to the flux in the absence of the propeller, from r_i to r_{i+1}.

(d) Improve the values of $u_{p_i}(r_{p_i})$ by $u_{x_i}(r_i) + u_{a_i}(r_{p_i}) + u_{\xi_i}(r_{p_i})$ and use Equation (4) to obtain $u_{\xi_i}(r_{p_i})$. Since outside the boundary layer $u_{x_{N-1}}(r_{N-1}) = u_{x_N}(r_N) = V_s$, Equation (4) yields $u_{p_N}(r_{p_N}) = u_{a_N}(r_{p_N}) + V_s = u_{a_N}(r_{p_N}) + u_{x_N}(r_N)$. The correction velocity $u_{\xi_i}(r_{p_i})$ for the second approximation is zero outside the boundary layer, $u_{\xi_i}(r_{p_i} > \delta) = 0$. For $r_{p_i} < \delta$, Equation (4) can be used to solve for $u_{\xi_i}(r_{p_i} > \delta)$ step by step from the edge of the boundary layer where $u_i(r_{p_i} > \delta) = 0$ inwards down to the radius of the body surface.

(e) With the new set of $r_{p_i}(r_{p_i})$ repeat steps (c) and (d) until the distribution of u_p versus r_p converges.

EXAMPLE

Figure 2 shows (a) the measured nominal axial velocity profile, u_x/V_s, in the absence of a propeller (Afterbody 1 of Reference 1), (b) the final propeller nondimensional circulation distribution $G(r/R_p)$ calculated by the propeller inverse program,[3] (c) the final effective velocity (u_e/V_s) and apparent (u_p/V_s) axial velocity distributions computed by the present propeller/stern boundary-layer interaction program, and (d) the propeller-induced circumferential-mean axial velocity, u_a/V_s, computed by the propeller field-point program.[2] The final propeller thrust coefficient, $C_{TS} = T/(\frac{1}{2}\rho V_S^2 \pi R_p^2)$ is 0.371, and the advance ratio, $J = V_S/nD_p$, is 1.25 for this example. As discussed in Reference 1, the computed values of u_e/V_s and G have essentially converged to their final values after three iterations.

INPUT INSTRUCTION

INPUT STATEMENTS

The input statement by means of which data are entered into the program are as follows:

```
READ (5.1) NI

READ (5.7) (TITL(I), I = 1.8)

READ (5.1) N, NPRL

READ (5.5) (UX(I)) R(I), UAP(I), I = 1,N)
```

The corresponding format statements are as follows:

```
1     FORMAT (2I10)

7     FORMAT (8A10)

5     FORMAT (3F10.5)
```

DEFINITION OF INPUT VARIABLES

NI	Number of input sets or cases to be computed
TITL	Title
N	Total number of points from hub out to the edge of the boundary layer where nominal velocities are given
NPRL	Total number of points from hub out to the tip of propeller where nominal velocities are given; NPRL may be smaller than N

UX(I)	u_x/V_s, nominal axial velocity/ship speed
R(I)	Radius (use dimensionless radius r/R_p, R_p being the propeller radius
UAP(I)	u_a/V_s, propeller-induced axial velocity/ship speed

DEFINITION OF OUTPUT VARIABLES

The output variables are defined in the order that they appear in output listing.

UX(I)	Nominal axial velocity ratio, u_x/V_s (input variable)
R(I)	Radius (input variable)
UPD(I)	Effective axial velocity ratio, u_e/V_s
UP(I)	Apparent axial velocity ratio, u_p/V_s, the resulting velocity with propeller in operation
UDF(I)	Velocity ratio different with and without propeller in operation $(u_p/V_s) - (u_x/V_s)$
UAP(I)	u_a/V_s (input variable)
WR(I)*	Volume-mean nominal axial velocity ratio, $[u_x]_v/V_s$
WPR(I)	Volume-mean effective axial velocity ratio, $[u_e]_v/V_s$
URT	WR(I)/WPR(I)

$$*\ \frac{[u_x]_v}{V_s} = \frac{\int_{r_h}^{R_p} 2\pi r\left(\frac{u_x}{V_s}\right) dr}{\int_{r_h}^{R_p} 2\pi r\, dr}, \qquad \frac{[u_e]_v}{V_s} = \frac{\int_{r_h}^{R_p} 2\pi r\left(\frac{u_e}{V_s}\right) dr}{\int_{r_h}^{R_p} 2\pi r\, dr}$$

FORTRAN IV COMPUTER LISTINGS

PROPELLER STERN BOUNDARY-LAYER INTERACTION COMPUTER PROGRAM

COMPUTE EFFECTIVE VELOCITY PROFILE FROM MEASURED NOMINAL VELOCITY PROFILE

```
PROGRAM MAIN        74/74    OPT=0 ROUND=*/ TRACE                FTN 4.6+420          02/09/77  13.59.07

                PROGRAM MAIN    (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
                 COMMON /UPD/ NI,N,NPRL,UX(40),R(40),UAP(40),UPD(40)
                DIMENSION UC(40),UP(40),U(40),RU(40)
                DIMENSION UIND(40),V(9),A(40),SUM(40),WR(40),WPR(40),URT(40)
                DIMENSION UAT(40),X(40),XUA(40),UDF(40),TITL(8),Y(40),B(40)
C NI=NUMBER OF INPUT SETS
C N=TOTAL NUMBER OF POINTS FROM HUB OUT WHERE NORMINAL VELOCITIES ARE GIVEN
C NPRL=TOTAL NUMBER OF POINTS FROM HUB OUT TO THE TIP OF PROPELLER
C ARE GIVEN. NPRL MAY BE LESS THAN OR EQUAL TO N
C UX(I)=NORMINAL VELOCITY AT R(I)
C R(I)=RADIUS
C UA(I)=PROPELLER INDUCED VELOCITY AT R(I)
      READ(5,1) NI
      DO 1000  KT=1,NI
      READ(5,7)(TITL(I),I=1,8)
    7 FORMAT(8A10)
    8 FORMAT(1H1,5X,8A10///)
      WRITE(6,8) (TITL(I),I=1,8)
      READ(5,1) N,NPRL
    1 FORMAT(2I10)
      READ(5,5) (UX(I),R(I),UAP(I),I=1,N)
    5 FORMAT(3F10.5)
       CALL CONVORT
 1000 CONTINUE
       STOP
       END
```

```
SUBROUTINE CONVORT     74/74    OPT=0 ROUND=*/ TRACE              FTN 4.6+420          02/09/77  13.59.07

               SUBROUTINE CONVORT
               COMMON /UPD/ NI,N,NPRL,UX(40),R(40),UAP(40),UPD(40)
              DIMENSION UC(40),UP(40),U(40),RU(40)
              DIMENSION UINO(40),V(9),A(40),SUM(40),WR(40),WPR(40),URT(40)
              DIMENSION UAT(40),X(40),XUA(40),UDF(40)
               DS(E,F,M)=2.*E(M+1)+E(M)+( E(M)-E(M+1) )/( 1.+F(M+1)/F(M) )
              UAT(1)=UAP(1)
              UC(1)=0.
              UA=UX(1)
              UB=UX(2)
               UP(1)=UAP(1) + UA
               UP(2)=UAP(2) + UB
               U(1)=UA
              RU(1)=R(1)
C LEAST SQUARES FIT
              NANCY=1
      101     DO 9  I=1,8
              X(I)=R(I)
      9       XUA(I)=UX(I)
               CALL POLY(X,XUA,A,V,SUM)
C BY CONTINUITY
              NT=1
              DO 80  J=2,N
              L=J-1
               IF(NANCY.LT.2) UC(J)=0.
              RUE=RU(L)+R(J)-R(L)
              DO 22  K=1,5
              UAT(J)=UAP(J)+UC(J)
C USE UC TO SATISFY THE CONSERVATION OF VORTICITY
              UAA=UA+UAT(L)
              UBB=UB+UAT(J)
               DR=(R(J)*R(J)-R(L)*R(L))
               DQ=DR*( 2.*UBB+UAA +(UAA-UBB)/(1.+R(J)/R(L)) )/3.
               UMN=(2.*UB+UA + (UA-UB)/(1.+RUE/RU(L)) )/3.
              R2=RU(L)*RU(L)+DQ/UMN
              RU(J)=SQRT(R2)
              U(J)=V(1)+(V(2)+(V(3)+(V(4)+V(5)*RU(J))*RU(J))*RU(J))*RU(J)
               IF(U(J).GE.1.) U(J)=1.
              RUE=RU(J)
      22      UB=U(J)
              UA=UB
              RPP=RU(J)+(R(J+1)-R(J))*(RU(J)-RU(L))/(R(J)-R(J-1))
              UB=       V(1)+(V(2)+(V(3)+(V(4)+V(5)*RPP)*RPP)*RPP)*RPP
C MOVING LEAST SQUARES FIT
               M=J-4
               IF(M.LT.0.OR.N.LT.J+5) GO TO  80
              DO 113  KK=1,8
               KM=KK+M
              X(KK)=R(KM)
      113     XUA(KK)=UX(KM)
               CALL POLY(X,XUA,A,V,SUM)
   80         UP(J)=U(J)+UAT(J)
              NANCY=NANCY+1
               IF(NANCY.GT.5) GO TO 742
               UC(N)=0.
C CONSERVATION OF VORTICITY CORRECTION
              NI=N-1
```

```
SUBROUTINE CONVORT     74/74   OPT=0 ROUND=*/ TRACE             FTN 4.6+420         02/09/77  13.59.07

              DO 194  I=1,N1
              IB=N-I
               IA=IB+1
              FTH=1.-(U(IA)+U(IB))/(UP(IA)+UP(IB))
        194   UC(IB)=UC(IA)+(U(IA)-U(IB))*FTH
              UAT(1)=UAP(1)+UC(1)
              UAT(2)=UAP(2)+UC(2)
              GO TO 101
          742 UDF(1)=(UAP(1)+UC(1))
              UIND(1)= UC(1)
              UPD(1)=UX(1)+UC(1)
              DOO=0.
              DOP=0.
              SDA=0.
              DO 276 I=2,N
              UDF(I)=UP(I)-UX(I)
               UIND(I)=UDF(I)-UAP(I)
              UPD(I)= UX(I)+UIND(I)
               IP=I-1
              DA=R(IP+1)*R(IP+1)-R(IP)*R(IP)
               AD=DA/3.
              SDA=SDA+DA
               DOO=DOO+AD*DS(UX,R,IP)
               DOP=DOP+AD*DS(UPD,R,IP)
              WR(IP+1)=DOO/SDA
              WPR(IP+1)=DOP/SDA
          276 URT(IP+1)=WPR(IP+1)/WR(IP+1)
              WRITE(6,303)
        303     FORMAT(4X,*NOMINAL*,5X,*RADIUS*,6X,*EFFECTIVE*,4X,*TOTAL*,5X,*DI
             *FFERENCE PROP INDUCED  VLM AV UX VLM AV UPD  VLM UPD/UX*,/,7X,*UX*
             S,10X,*R*,11X,*UPD*,8X,*UP*,9X,*UDF*,11X,*UA*,11X,*WR*,11X,*WRR*,10
             SX,*URT*)
              UP(1)=UPD(1)+UAP(1)
              WRITE(6,300)UX(1),R(1),UPD(1),UP(1),UDF(1),UAP(1)
              DO  286  I=2,NPRL
        286   WRITE(6,300) UX(I),R(I),UPD(I),UP(I),UDF(I),UAP(I),WR(I),WPR(I),UR
             ST(I)
        300   FORMAT(9F12.6)
               RETURN
              END
```

```
SUBROUTINE POLY          74/74   OPT=0 ROUND=*/ TRACE          FTN 4.6+420        02/09/77  13.59.07

                SUBROUTINE POLY(X,Y,A,V,SUM)
               DIMENSION X(40),Y(40),A(40),V(9),SUM(40),B(40)
                SUM(1)=0.
                DO 4 J=2,9
          4     SUM(J)=0.
                DO 12 J=1,5
         12     V(J)=0.
                DO 30 I=1,8
                V(1)=V(1)+Y(I)
                P=1.
                DO 20 J=2,5
                P=P*X(I)
                SUM(J)=SUM(J)+P
         20     V(J)=V(J)+Y(I)*P
                DO 30 J=6,9
                P=P*X(I)
         30     SUM(J)=SUM(J)+P
                DO 45 K=1,5
                IT=5*(K-1)
                DO 45 I=1,5
                J=I+K-1
                MNO=IT+I
         45     A(MNO)=SUM(J)
                CALL ENXN(A,V)
                RETURN
                END
```

```
SUBROUTINE ENXN        74/74   OPT=0 ROUND=*/ TRACE              FTN 4.6+420            02/09/77  13.54.07

                  SUBROUTINE ENXN(A,B)
                  DIMENSION A(40),B(40)
                  ID=1
                  DO 39 I=1,4
                  H=A(ID)
                  IF(H.NE.0.) GO TO 10
                  WRITE(6,66)
            66    FORMAT(//,5X,*DIAGONAL ELEMENT EQUAL TO ZERO*)
                  STOP 77776
            10    DO 30 J=1,4
                  IB=5*J+I
            30    A(IB)=A(IB)/H
                  B(I)=B(I)/H
                  IT=5*(I-1)
                  DO 38 K=1,5
                  IF(K.EQ.I) GO TO 38
                  NL=K+IT
                  DO 35 J=I,4
                  IS=J*5+K
                  IJK=IS+I-K
            35    A(IS)=A(IS)-A(IJK)*A(NL)
                  B(K)=B(K)-A(I)*A(NL)
            38    CONTINUE
            39    ID=6*I+1
                  B(5)=B(5)/A(25)
                  DO 40 I=1,4
            40    B(I)=B(I)-A(20+I)*B(5)
                  RETURN
                  END
```

```
MODEL 5225-1  J=1.25  X/L=0.954

 NOMINAL     RADIUS      EFFECTIVE    TOTAL    DIFFERENCE PROP INDUCED  VLM AV UX VLM AV UPD  VLM UPD/UX
   UX          R            UPD        UP         UDF           UA           WR          WPR          URT
 .345000     .238500     .370811     .392811    .047811      .022000
 .460000     .278500     .480656     .502456    .042456      .021800     .403983     .427150     1.057346
 .534000     .318500     .556114     .576914    .042914      .020800     .454274     .476495     1.048915
 .595000     .358500     .611446     .631746    .036746      .020300     .496167     .517255     1.042502
 .643000     .398500     .657052     .677052    .034052      .020000     .532786     .552133     1.036313
 .685000     .438500     .699284     .717784    .032784      .018500     .565313     .583380     1.031959
 .725000     .478500     .737109     .755109    .030109      .018000     .595150     .612176     1.028607
 .763000     .518500     .772659     .788959    .025959      .016300     .623204     .639071     1.025460
 .794000     .558500     .804316     .819816    .025816      .015500     .649468     .664343     1.022902
 .824000     .598500     .832033     .846033    .022033      .014000     .673997     .687994     1.020767
 .850000     .638500     .857675     .870675    .020675      .013000     .697009     .710139     1.018838
 .875000     .678500     .882507     .894507    .019507      .012000     .718632     .731039     1.017265
 .900000     .718500     .905068     .916068    .016068      .011000     .739189     .750850     1.015775
 .920000     .758500     .925048     .935048    .015048      .010000     .758665     .769573     1.014379
 .937000     .798500     .940730     .949730    .012730      .009000     .776887     .787095     1.013141
 .950000     .838500     .953145     .961145    .011145      .008000     .793775     .803297     1.011996
 .960000     .878500     .962866     .969866    .009866      .007000     .809268     .818164     1.010993
 .970000     .918500     .968122     .974122    .004122      .006000     .823499     .831626     1.009869
 .969000     .958500     .971769     .976769    .007769      .005000     .836218     .843677     1.008920
 .972000     .998500     .976760     .980760    .008760      .004000     .847400     .854552     1.008440
 .987000    1.038500     .983940     .986940   -.000060      .003000     .857940     .864587     1.007748
 .990000    1.078500     .991806     .993806    .003806      .002000     .867934     .874026     1.007019
 .995000    1.118500     .997803     .999303    .004303      .001500     .877102     .882916     1.006628
 .999000    1.158900     .997411     .998411   -.000589      .001000     .885680     .891120     1.006142
1.000000    1.198900     .984388     .984888   -.015112      .000500     .893456     .897934     1.005012
```

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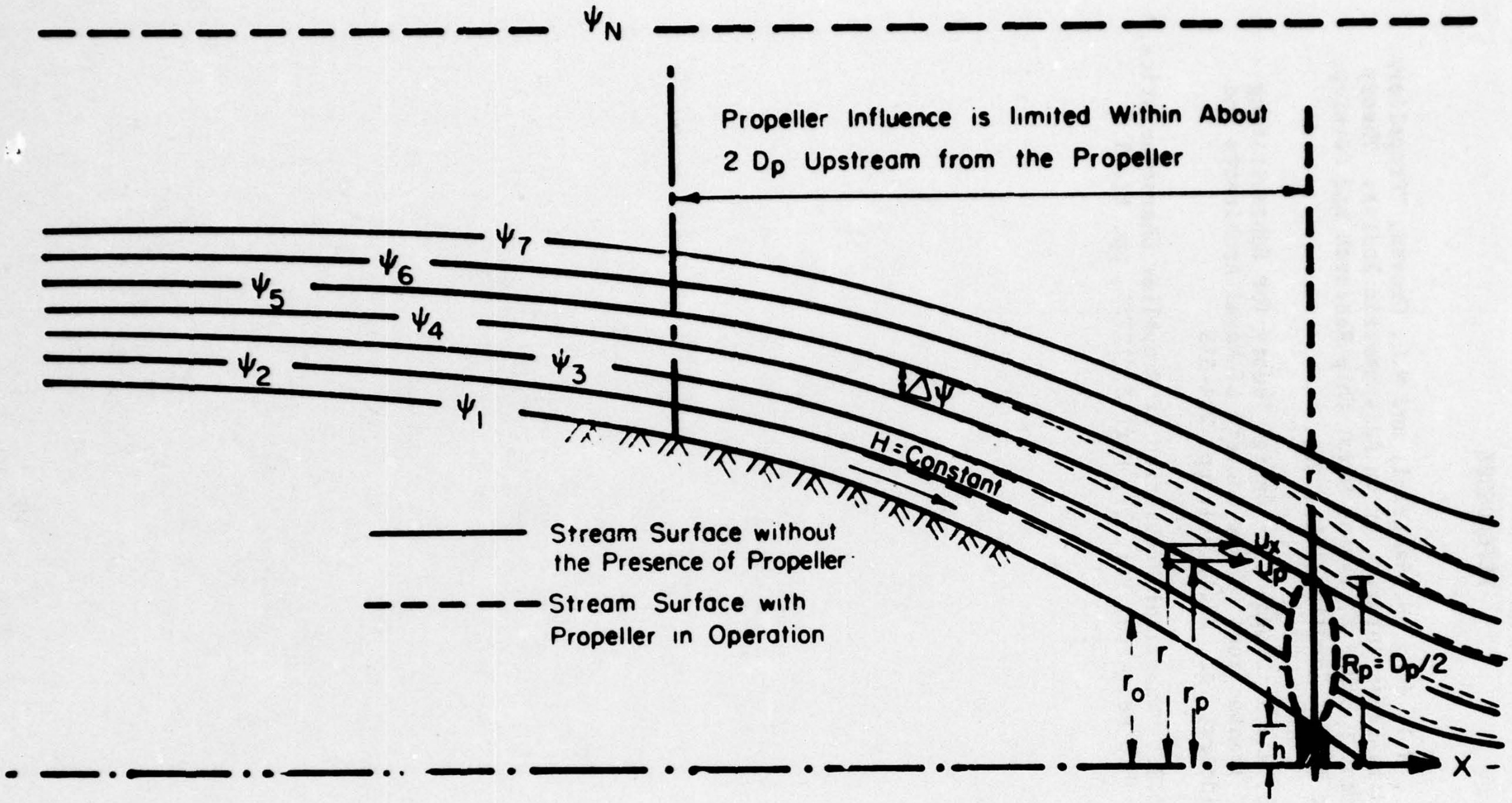

Fig. I – Definition Sketch for Propeller–Stern–Boundary–Layer Interaction

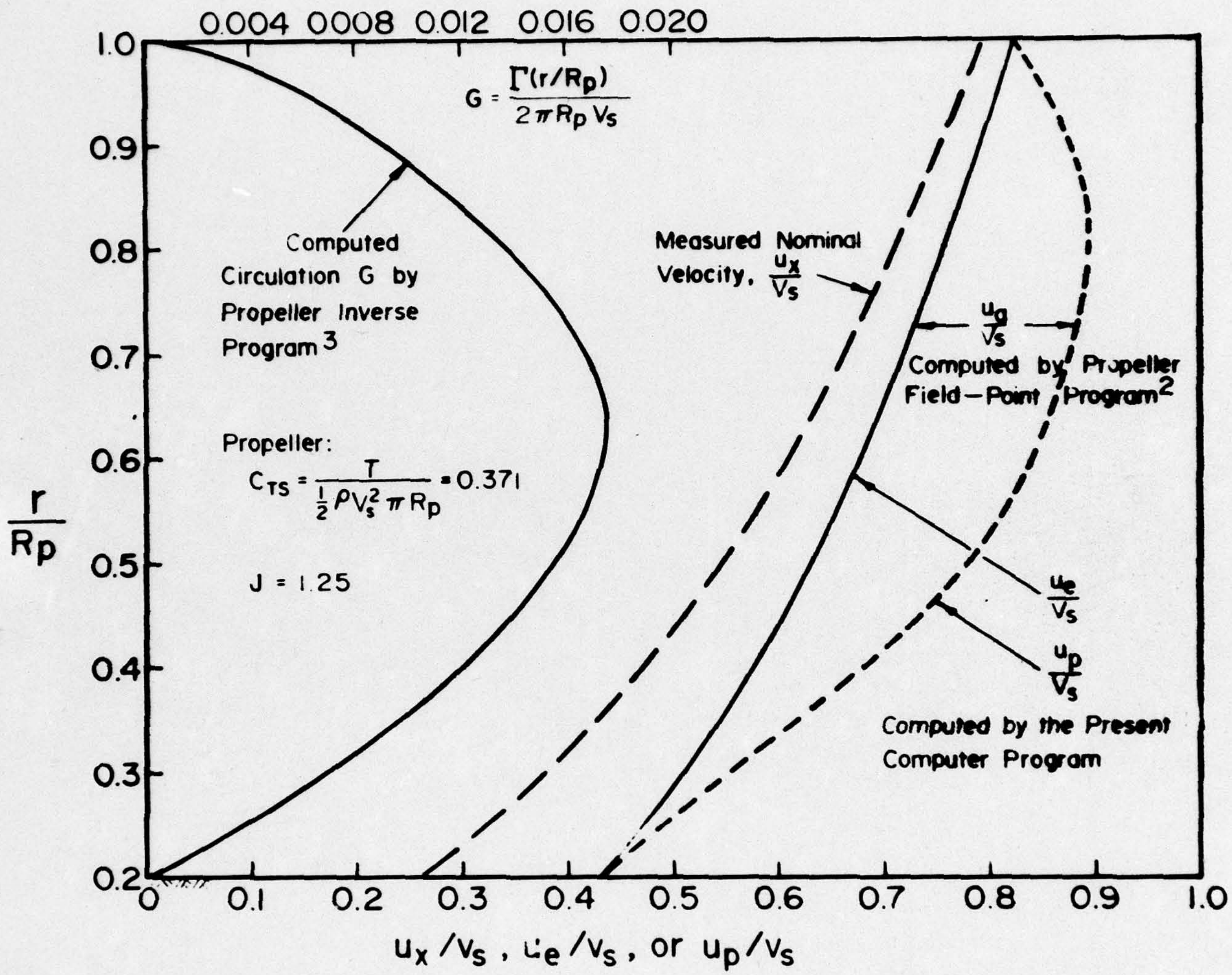

Figure 2—Computed Nondimensional Circulation and Effective and Apparent Axial Velocity Profiles after Four Iterations for a Typical Propeller Operated in a Measured Nominal Axial Velocity Profile of a Typical Axisymmetrical Body

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