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A USER'S MANUAL FOR THE VERTICAL AXIS WIND TURBINE PERFORMANCE COMPUTER CODE DARTER

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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract AT(29-1)-789

Printed May 1980

Sandia Laboratories
energy report

Issued by Sandia Laboratories, operated for the United States Department of Energy by Sandia Corporation.

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Contents

Nomenclature

A_s	Turbine swept area
c	Blade chord
$C_{\ell,n}$	Blade section lift, normal force coefficient, $\frac{\ell,\ n}{1/2\ \rho_\infty V^2 c}$
$C_{d,a}$	Blade section drag, axial force coefficient, $\frac{d,\ a}{1/2\ \rho_\infty V^2 c}$
C_m	Blade section moment coefficient, $\frac{m}{1/2\ \rho_\infty V^2 c^2}$
C_{d_o}	Zero wind drag coefficient
C_D	Turbine drag coefficient, $\frac{D}{1/2\ \rho_\infty V_{CL}{}^2 A_s}$
C_p	Power coefficient, $\frac{Q\omega}{1/2\ \rho_\infty V_{CL}{}^3 A_s}$
C_Q	Turbine torque coefficient, $\frac{Q}{1/2\ \rho_\infty V_{CL}{}^2 A_s R}$
D	Turbine drag
J	Advance ratio, $\frac{V_\infty}{R\omega}$
K_p	Power coefficient, $\frac{Q\omega}{1/2\ \rho_\infty A_s (R\omega)^3}$
L	Blade length
N	Number of blades
P	Wind shear exponent
Q	Turbine aerodynamic torque
R	Turbine maximum radius

Re_c	Chord Reynolds number, $\frac{\rho_\infty R\omega c}{\mu_\infty}$
V_{CL}	Average freestream velocity at turbine centerline
V_∞	Average freestream velocity at reference height
X	Turbine tipspeed ratio, $\frac{R\omega}{V_\infty}$
Z_{max}	Turbine height
α	Blade section angle of attack
μ_∞	Freestream viscosity
ν	Freestream kinematic viscosity
ρ_∞	Freestream density
ω	Turbine rotational speed
σ	Solidity, $\frac{NcL}{A_s}$

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Introduction

The computer code DARTER (DARrieus Turbine, Elemental Reynolds number) is an aerodynamic performance/loads prediction scheme based upon the conservation of momentum principle. It is the latest evolution in a sequence which began with a model developed by Templin[1] of NRC, Canada and progressed through the Sandia National Laboratories-developed SIMOSS[2] (SImple MOmentum, Single Streamtube) and DART[3] (DARrieus Turbine) to DARTER.

Program Theory

The basic theory upon which DARTER is based was first reported[1] in a model which takes the rotor to be enclosed in a single streamtube. Wind velocity across the area swept by the rotor is assumed constant. By choosing some value of this velocity, a combination of the simple actuator-disc momentum model and blade-element theory will give the far-field windspeed, turbine power, torque and drag for a turbine with given blade characteristics, rotational speed, and geometry. In SIMOSS[2] an iteration is incorporated which allows the (upstream) far-field windspeed to be treated as an input while wind velocity across the rotor-swept area is calculated. DART[3] differs from SIMOSS in that a multiple streamtube system is used; i.e., the swept area is modeled by an arbitrary number of adjacent and aerodynamically independent areas over which the conservation of momentum principle is applied. Advantages gained by this more detailed modeling stem from allowing disc-area-windspeeds to vary from section to section. DARTER is an extension of DART which has the capability of using airfoil data based upon elemental Reynolds numbers. When combined with the ability of treating the effects of wind shear, DARTER represents the most detailed momentum based Darrieus turbine aerodynamic model reported to date. Comparisons between measured performance and that predicted by DARTER and certain other models are reported in Ref. 4.

Program Usage

DARTER is a reasonably versatile code and possesses options which are intended to make it useful to users with varied requirements. It allows selection of one of three constant chord blade planforms: 1) straight line/circular arc troposkien approximation, 2) parabolic, or 3) straight-blade geometries. Any symmetrical blade profile may be chosen, providing sufficient section data are available. Any number of blades may be treated. Varying degrees of atmospheric wind shear may be included through stipulation of a power law profile. Up to 24 different operating conditions may be examined at any one time by setting one value of any of turbine angular velocity, ambient windspeed or equatorial tipspeed ratio and varying either one of the remaining two parameters over a prescribed range. Logarithmic or linear blade airfoil section data interpolation with Reynolds number may be chosen. The blade section data may be either in the form or normal and axial force coefficients vs angle-of-attack or lift and drag coefficients vs angle-of-attack. These may be input via cards or from disc.

The following quantities are required inputs to DARTER:

Description	Symbol	Units
Number of blades	NUMB	None
Number of azimuthal integration steps, upwind half of rotor	NTH	None
Number of vertical integration steps, lower half of rotor	NZBAR	None
Turbine maximum radius	RMAX	m
Turbine height	ZMAX	m
Blade Chord	CHORD	m
Kinematic viscosity	NU	m^2/sec
Atmospheric density	RHO	kg/m^3
Shear exponent	P	None

Vertical distance from ground plane to rotor bottom	ZGC	m
Reference anemometer* height above ground plane	ZR	m
Turbine angular velocity, ω	RPM	rev/min
Ambient windspeed at reference height, V_∞	VINF	m/sec
Equatorial tipspeed ratio, $R\omega/V_\infty$	XCL	None
Number of conditions to be calculated in a single code running	NXCL	None
Tabulated blade section angle of attack, α	TAA	Degrees
Tabulated blade section normal or lift coefficient	TCN	None
Tabulated blade section axial or drag coefficient	TCA	None
Tabulated blade section moment coefficient	TCM	None

*The effects of wind shear are calculated according to

$$V/V_\infty = ([Z + ZGC]/[ZR + ZGC])^P$$

where V is the ambient air speed corresponding to a given height, Z.

The required input data take the following form:

Card	Description
1,2,3	Title cards, 80 columns/card
4	NUMB, NTH, NZBAR, IFLG(I), I = 21, 28

I5 format is used for the first three quantities. I1 format is used for the IFLG(I) array. This array keys various options and is defined as follows.

- IFLG(21) ≠ 0 will cause each iteration on streamtube velocity to be printed.

- IFLG(22) is used to select blade planform geometry. For IFLG(22) = 1, the blades will be of the straight line circular arc troposkien approximation. If IFLG(22) = 2, the planform will be parabolic. Straight blades are chosen if IFLG(22) = 3.

- IFLG(23) selects the angular velocity-freestream velocity tipspeed ratio combination

	Parameter		
IFLG(23)	Single Fixed	Incremented	Calculated
0	RPM	X	V_∞
1	RPM	V_∞	X
2	V_∞	X	RPM
3	V_∞	RPM	X

- IFLG(24) sets the H/D ratio for straight line-circular arc straight line troposkien approximation blade planform. For IFLG(24) = 0, H/D = 1.0 and for IFLG(24) = 1, H/D = 1.5.

- IFLG(25) chooses the type of interpolation on Reynolds number used in the section data lists. If IFLG(25) = 0, logarithmic interpolation follows. For IFLG(25) ≠ 0, linear interpolation is used.

- IFLG(26) selects the proper form of the blade airfoil section coefficients. If the section data lists are in the C_n, C_a vs α form, set IFLG(26) = 0. If of the form C_ℓ, C_d vs α, set IFLG(26) ≠ 0.

- IFLG(27) depends upon the manner in which the blade airfoil section data are read. If IFLG(27) = 0, the data lists are read on a card-by-card basis. When IFLG(27) ≠ 0, the data are attached from a permanent file.

- IFLG(28). If IFLG(28) = 0, the blade section data are printed. For IFLG(28) ≠ 0, the data are not printed.

5 RMAX, ZMAX, CHORD, NU, RHO, P, ZGC, ZR. The format here is F10.0.

6 NXCL and, depending upon the value of IFLG(23), either RPM or V_∞. If IFLG(23) is 0 or 1, RPM is input. For IFLG(23) = 2 or 3, V_∞ is input.

Format for NXCL is I10, that for RPM or V_∞ is F10.0. NXCL cannot exceed 24.

7,(8),(9) Input here are values of X, V_∞, X or RPM, if IFLG(23) = 0, 1, 2 or 3, respectively. The format is F10.0, and there can be up to 8 values/card.

8 (or 9) (or 10) These are the blade airfoil section data inputs. Data for up to 15 different values of Reynolds number (Re) can be accommodated. The first card in any of the up to 15 sets has the appropriate value of Re in a F10.0 format. The last 70 columns are used for a title. The remaining cards in any Re set each have I, TAA, TCN, TCA, and TCM in a I1, F10.0 format. Data for up to 182 values of TAA can be used. I is either 0, 1, or 2 depending upon whether the data card is not the last card in a Re set, the last card in an intermediate Re set, or the last card in the last Re set, respectively.

The following are DARTER output quantities.

Description	Symbol	Units
Advance Ratio, $V_\infty/R\omega$	1/XCL	None
Power coefficient based on rotational speed, $K_p \times 10^3$	KPE3	None
Tipspeed ratio, $R\omega/V_\infty$	XCL	None
Power coefficient based on ambient windspeed, C_p	CP	None

Turbine (average) drag coefficient, C_D	CT	None
Turbine (average) torque coefficient, C_Q	CQ	None
Turbine angular velocity, ω	RPM	revolutions/ minute
Reference ambient windspeed, V_{ref}	VREF	meters/sec
Blade equatorial Reynolds number, Re_c	REC	None
Average turbine torque	TORQUE	Newton-meters
Average turbine power	POWER	Kilowatts
Average turbine drag	DRAG	Newtons

References

1. R. J. Templin, "Aerodynamic Performance Theory for the NRC Vertical-Axis Wind Turbine," Report LTR-LA-160, National Aeronautical Establishment of Canada, June 1974-

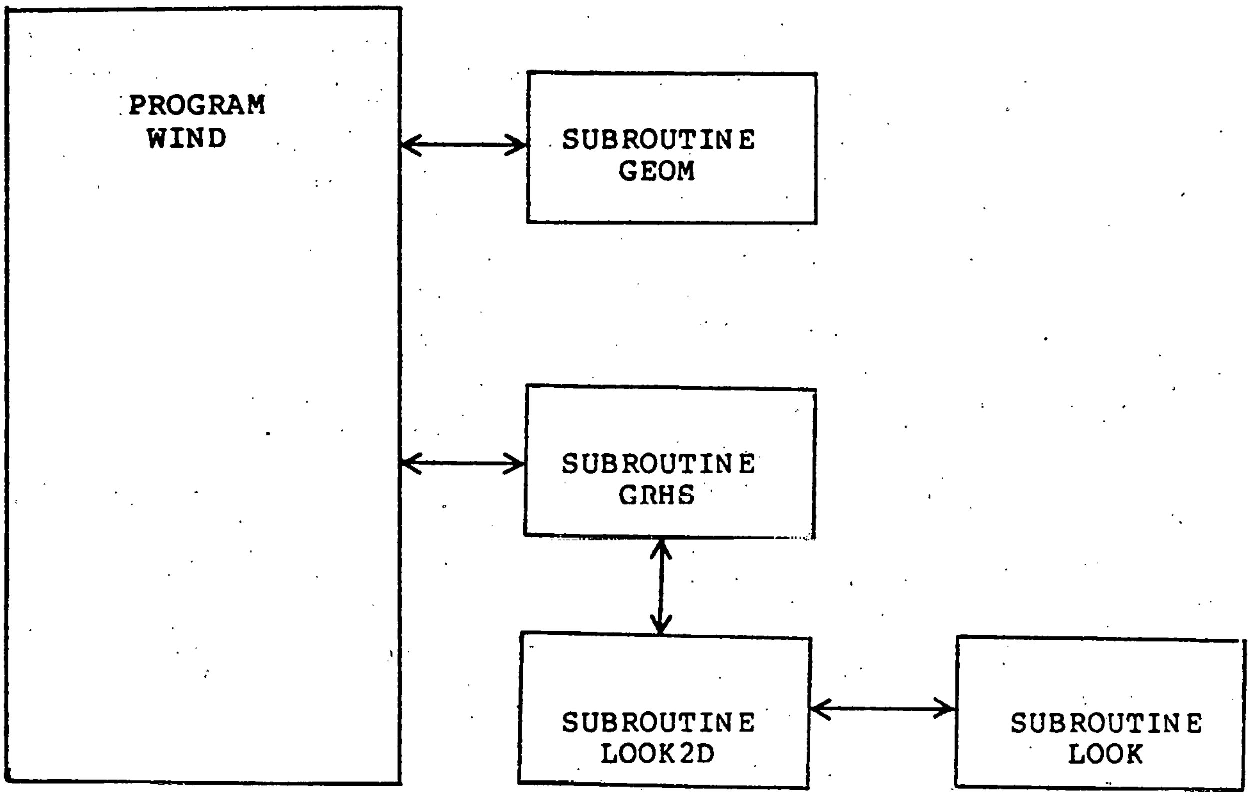
2. User's Manual for SIMOSS, Sandia National Laboratories (to be published).

3. J. H. Strickland, The Darrieus Turbine: A Performance Prediction Model Using Multiple Streamtubes, SAND75-0431, Sandia National Laboratories, Albuquerque, NM, October 1975.

4. P. C. Klimas, R. E. Sheldahl, Four Aerodynamic Prediction Schemes for Vertical Axis Wind Turbines: A Compendium, SAND78-0014, Sandia National Laboratories, Albuquerque, NM, June 1978.

APPENDIX A

Module Diagram



Module Description

Program WIND

Wind functions as the main calling program performing all input and output operations. WIND also handles the aerodynamic performance calculations.

Subroutine GEOM

GEOM evaluates all the blade geometry.

Subroutine GRHS

GRHS evaluates local angle of attack, relative wind speed, blade Reynolds number, and thrust forces. Also, GRHS serves as caller to subroutine LOOK2D.

Subroutine LOOK2D

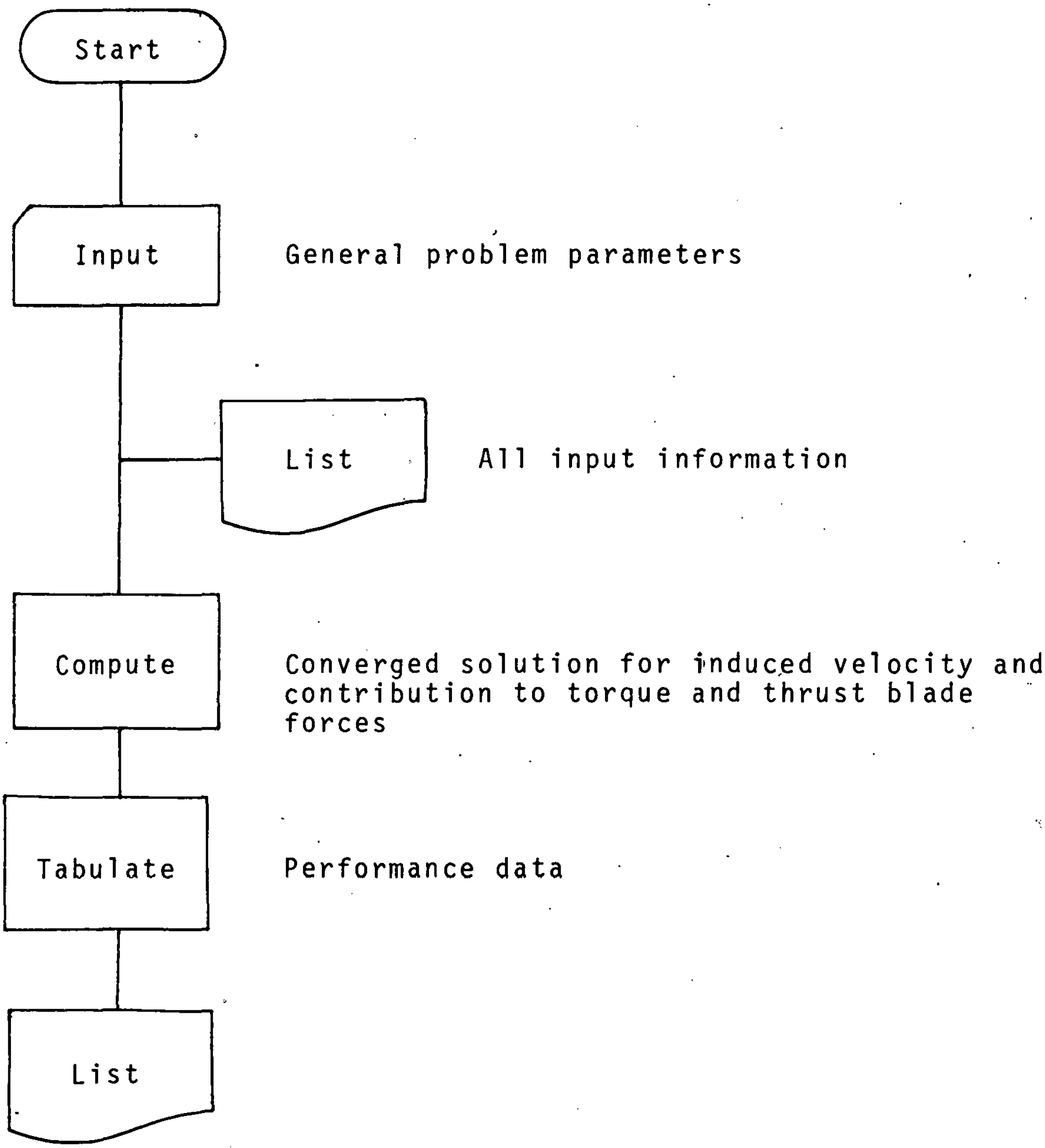
LOOK2D performs a two-dimensional linear interpolation on a two-dimensional matrix and calls subroutine LOOK.

Subroutine LOOK

LOOK does 1-D interpolation computations.

APPENDIX B

Program Flow Diagram



APPENDIX C

Program Listing

```
      PROGRAM WIND(INPUT,TAPE5=INPUT,OUTPUT,TAPE6=OUTPUT,TAPE7,TAPE10,
     1   TAPE20,TAPE39,TAPE33)
      COMMON/TABLES/ ILO(200),IHI(200),IR(200), DEN, IEX,
     1         VR
      COMMON/GEOM/BETA,BETA2,ZBAR(101),RBAR(101),ASORZ,SINGAM(101)
     1 ,ASOS2
      DIMENSION ERR(3),TVCL(40),TRPM(40),TXCL(40)
      COMMON/STRUT/VFSOVCL(101),VCL,NU,IRE,TRE(15),TAA(182,15),
     1 TCN(182,15),TCA(182,15),TCM(182,15),DIM,X(4),DX(4),
     2 DEGTR,K,IFLG(20),KOUT,VBLADE,IFTA,ITER
      DIMENSION LHEAD(24),TITC(7,9)
      DIMENSION VFS(2),CQF(2),CTF(2),AI(2,3),VOVFS(2),A(2)
      REAL NCOR,NU,LHS
      DATA DEGTR/57.29577951/
      DATA PI /3.1415926535898/
      DATA KIN,KOUT/5,6/
      NMOD(I) = 1 + I - (I/3)*3
C***********************************************************************
C     INPUT GENERAL PROBLEM PARAMETERS
C***********************************************************************
      ICNT = 0
   10 CONTINUE
      ICNT = ICNT + 1
      READ(KIN,1000)(LHEAD(I),I=1,24)
 1000 FORMAT(8A10)
      IF(EOF(KIN)) 9999,20
   20 CONTINUE
      READ(KIN,1020) NUMB,NTH,NZBAR,IDUM,(IFLG(I),I=1,20)
 1020 FORMAT(4I5,20I1)
      KAD = KIN
      IF(IFLG(7).NE.0) KAD = 10
      IHD = IFLG(4)
      READ(KIN,1010) RMAX,ZMAX,CHORD,NU,RHO,P,ZGC,ZR
      IF(ZGC.LT.1.0E-06) ZGC = 1.0E-06
      ZCL = ZGC + ZMAX
      IF(ZR.LT.1.0E-08) ZR = 1.
      VCLOVR = (ZCL/ZR)**P
 1010 FORMAT(8F10.0)
      ISHEAR = 0
      IF(P.GT.1.0E-08) ISHEAR = 1
      NCOR = FLOAT(NUMB)*CHORD/RMAX
      IGEOM = IFLG(2)
      IIN = IFLG(3) + 1
      GO TO (30,40,50,60) IIN
C***********************************************************************
C     FIXED RPM WITH RANGE OF TIP SPEED RATIOS
C***********************************************************************
   30 CONTINUE
      READ(KIN,3000) NXCL,RPM
 3000 FORMAT(I10,7F10.0)
      READ(KIN,3010) (TXCL(I),I=1,NXCL)
 3010 FORMAT(8F10.0)
      DO 35 I=1,NXCL
      TXCL(I) = TXCL(I)/VCLOVR
      TRPM(I) = RPM
      TVCL(I) = RMAX*RPM*2.*PI/(60.*TXCL(I))
   35 CONTINUE
```

```
      GO TO 70
C***********************************************************************
C     FIXED RPM WITH RANGE OF FREE STREAM VELOCITIES
C***********************************************************************
   40 CONTINUE
      READ(KIN,3000) NXCL,RPM
      READ(KIN,3010) (TVCL(I),I=1,NXCL)
      DO 45 I=1,NXCL
      TVCL(I) = TVCL(I)*VCLOVR
      TRPM(I) = RPM
      TXCL(I) = RMAX*RPM*2.*PI/(60.*TVCL(I))
   45 CONTINUE
      GO TO 70
C***********************************************************************
C     FIXED VFS FOR A RANGE OF TIP SPEED RATIOS
C***********************************************************************
   50 CONTINUE
      READ(KIN,3000) NXCL,VCL
      READ(KIN,3010) (TXCL(I),I=1,NXCL)
      VCL = VCL*VCLOVR
      DO 55I=1,NXCL
      TXCL(I) = TXCL(I)/VCLOVR
      TVCL(I) = VCL
      TRPM(I) = VCL*TXCL(I)*60./(2.*PI*RMAX)
   55 CONTINUE
      GO TO 70
C***********************************************************************
C     FIXED FREE STREAM VELOCITY FOR A RANGE OF ROTATIONAL SPEEDS
C***********************************************************************
   60 CONTINUE
      READ(KIN,3000) NXCL,VCL
      READ(KIN,3010) (TRPM(I),I=1,NXCL)
      VCL = VCL*VCLOVR
      DO 65 I=1,NXCL
      TVCL(I) = VCL
      TXCL(I) = RMAX*TRPM(I)*2.*PI/(60.*VCL)
   65 CONTINUE
   70 CONTINUE
C***********************************************************************
C     READ IN NORMAL AND TANGENTIAL FORCE COEFFICIENTS AS A FUNCTION OF
C     ANGLE OF ATTACK FOR A SERIES OF CHORD REYNOLDS NUMBERS.
C     THE TABULAR LIMITS FOR THE FORCE COEFFICIENT DATA ARE STORED IN
C     THE FOLLOWING ORDER-- REYNOLDS NUMBER IFTA + 10
C                           ANGLE OF ATTACK IFTA + 1 THRU IFTA + 9
C***********************************************************************
      IF(ICNT.NE.1) GO TO 125
      IFTA = 0
      J = 0
  100 CONTINUE
      J = J + 1
      JJ = IFTA + J
      ILO(JJ) = IR(JJ) = 1
      READ(KAD,1100) TRE(J),(TITC(I,J),I=1,7)
 1100 FORMAT(F10.0,7A10)
      I = 0
  110 CONTINUE
      I = I + 1
      READ(KAD,1110) IFLAG,TAA(I,J),TCA(I,J),TCN(I,J),TCM(I,J)
 1110 FORMAT(I1,F9.0,7F10.0)
C***********************************************************************
```

```
C     THE PARAMETER IFLAG DETERMINES WHAT ADDITIONAL FORCE AND MOMENT
C     DATA SHOULD BE READ IN
C     IFLAG = 0, READ ANOTHER ANGLE OF ATTACK CARD FOR GIVEN RE
C     IFLAG = 1, LAST ANGLE OF ATTACK CARD FOR GIVEN RE BUT AT LEAST
C                ONE ADDITIONAL RE TABLE WILL FOLLOW
C     IFLAG = 2, LAST CARD OF FORCE AND MOMENT DATA
C***********************************************************************
      DEGTR = 57.29577951
      IF(IFLG(6).EQ.0) GO TO 115
      TCL=TCA(I,J)
      TCD=TCN(I,J)
      AA = TAA(I,J)/DEGTR
      SALP = SIN(AA)
      CALP = COS(AA)
      TCN(I,J) = TCL*CALP + TCD*SALP
      TCA(I,J) = TCL*SALP - TCD*CALP
  115 CONTINUE
      IHI(JJ) = I
      IFP1 = IFLAG + 1
      GO TO (110,100,120,117) IFP1
 117  IFLAG=1
      GO TO 100
  120 CONTINUE
      IRE=IFTA+15
      NRE = IHI(IRE) = J
      ILO(IRE) = IR(IRE) = 1
  125 CONTINUE
C***********************************************************************
C     PRINT OUT ALL OF THE INPUT INFORMATION
C***********************************************************************
      WRITE(KOUT,2000)
 2000 FORMAT(1H1)
      WRITE(KOUT,2002)(LHEAD(I),I=1,24)
 2002 FORMAT(10X,8A10)
      WRITE(KOUT,2005)
 2005 FORMAT(10X,8A10)
      WRITE(KOUT,2010) NCOR,RMAX,ZMAX,CHORD,NU,RHO
 2010 FORMAT(12X*NC/R*4X*RMAX*5X*ZMAX*4X*CHORD*7X*NU*10X*RHO*/
     1 10XF6.3,2(2XF7.2),2XF7.3,2(2XE10.3))
      WRITE(KOUT,2015) P,ZGC,ZR
 2015 FORMAT(11X*EXP*6X*ZGC*7X*ZR*/10XF6.3,2XF7.2,2XF7.2/)
      WRITE(KOUT,1030) NUMB,IGEOM,NTH,NZBAR
 1030 FORMAT(//10X*NUMB  IGEOM  NDTH  NDZ*/11XI2,5XI1,4XI3,3XI2)
      WRITE(KOUT,1035) (I,I=21,40)
 1035 FORMAT(10X,20(1X,I2))
      WRITE(KOUT,1035) (IFLG(I),I=1,20)
      IF(IFLG(8).EQ.0) GO TO 127
      WRITE(KOUT,1000) (TITC(I,1),I=1,7)
      GO TO 136
  127 CONTINUE
      DO 135 J=1,NRE
      WRITE(KOUT,1040) TRE(J),(TITC(I,J),I=1,7)
 1040 FORMAT(//10X*RE = *E10.3,5X7A10//12X*ALPHA*5X*CN*7X*CA*7X*CM*/)
      II = IHI(J)
      DO 130 I=1,II
      WRITE(KOUT,1050) TAA(I,J),TCN(I,J),TCA(I,J),TCM(I,J)
 1050 FORMAT(10XF7.2,3(2XF7.4))
  130 CONTINUE
  135 CONTINUE
  136 CONTINUE
```

```
      IF(IFLG(5).NE.0.OR.ICNT.NE.1) GO TO 138
      DO 137 J=1,NRE
      TRE(J) = ALOG(TRE(J))
  137 CONTINUE
  138 CONTINUE
      BETA = RMAX/ZMAX
      BETA2 = BETA**2
      EPS = 0.0
      KMAX = NZBAR + 1 + ISHEAR*(NZBAR - 1)
      DZBAR = 1./FLOAT(NZBAR)
      ZBARCL = ZCL/ZMAX
      DO 140 K=1,KMAX
      ZBAR(K) = FLOAT(K-1)*DZBAR-1.0
      VFSOVCL(K) = (1. + ZBAR(K)/ZBARCL)**P
  140 CONTINUE
      CALL GEOM(IGEOM,KMAX,IHD)
      AS = ASORZ*RMAX*ZMAX
      S = SQRT(AS/ASOS2)
      SIG = FLOAT(NUMB)*CHORD*S/AS
      WRITE(6,2040) SIG
 2040 FORMAT(10X*SOLIDITY = *F8.4)
      WRITE(KOUT,2020)
 2020 FORMAT(3X*M*,2X*1/XCL*,2X*KP E3*,3X*XCL*,6X*CP*,5X*CT*,6X*CQ*,
     1 4X*RPM*,4X*VREF*,6X*REC*,6X*TORQUE*,6X*POWER*,5X*DRAG*)
      KP1 = KP1 - ISHEAR
C***********************************************************************
C     BEGIN TIP SPEED RATIO LOOP
C***********************************************************************
      DO 600 M=1,NXCL
      RPM = TRPM(M)
      VCL = TVCL(M)
      XCL = TXCL(M)
      VBLADE = RMAX*RPM*2.*PI/60.
      XCL = VBLADE/VCL
      REC = VBLADE*CHORD/NU
      CQ = CT = 0.0
      SINEPS = SIN(EPS)
      COSEPS = COS(EPS)
      NTHP1 = NTH + 1
      DTH = PI/FLOAT(NTH)
      TH = -DTH
      IERR = 0
C***********************************************************************
C     BEGIN THETA INTEGRATION LOOP
C***********************************************************************
      DO 500 L=1,NTHP1
      CTSUM = CQSUM = CLLSUM = CFSUM = 0.0
      A(1) = A(2) = 0.0
      AFST = 0.0
      TH = TH + DTH
      THD = TH*DEGTR
      SINTH = SIN(TH)
      COSTH = COS(TH)
C***********************************************************************
C     BEGIN ZBAR INTEGRATION LOOP
C***********************************************************************
      DO 400 K=2,KMAX
      IF(IFLG(1).NE.0) WRITE(KOUT,6000) THD,RBAR(K),ZBAR(K),SINGAM(K)
 6000 FORMAT(1X,*THETA = *F6.1* RBAR = *F6.3* ZBAR = *F6.3* SINGAM = *
     1 F6.3/2X*ITER*,1X*ALPHA*,6X*RE*,5X*W/VT*,6X*CN*,6X*CA*,7X*CM*,
```

```
     2 6X*ANEW*,5X*AOLD*,7X*ERR*,7X*RHS*,5X*LHS*,7X*VFSL*,4X*V/VFSL*
     3 2X*W/VFSLSQ*)
      CQF(2) = CTF(2) = 0.0
      VFS(1) = VFSOVCL(K)*VCL
      VFSR2 = VFSOVCL(K)**2
      XFS = XCL/VFSOVCL(K)
      JJ = 1
C************************************************************************
C     BEGIN ITERATION LOOP ON INTERFERENCE FACTOR AI(J,N)--J=1, UPWIND
C************************************************************************
      DO 300 J = 1,JJ
      ERRMIN = 10000.
      ITER = 0
      IF(K.EQ.2) AI(J,1) = AFST
      AI(J,1) = A(J)
      AI(J,2) = AI(J,1) + 0.05
  200 CONTINUE
      N = NMOD(ITER)
      IM1 = ITER - 1
      NM1 = NMOD(IM1)
      ITER = ITER + 1
      NP1 = NMOD(ITER)
      IF(ABS(SINTH).LE.1.0E-10) AI(J,N) = 0.0
      VOVFS(J) = 1. - AI(J,N)
      LHS = 4.*AI(J,N)*VOVFS(J)
C************************************************************************
C     IF(AI(J,N).GT.0.5) LHS = 1.0
C************************************************************************
      CALL GRHS(0,SINTH,SINGAM(K),RBAR(K),COSTH,SINEPS,COSEPS,CHORD,
     1 ALPHAD,CN,CA,CM,WOVFS2,RHS,VFS(J),VOVFS(J))
      IF(ABS(SINTH).LT.1.0E-10) GO TO 220
      RHS = RHS*NCOR/PI
      ERR(N) = RHS - LHS
C************************************************************************
C     APPLY MODIFIED REGULA-FALSI METHOD TO FORCE ERROR TERM TO ZERO
C************************************************************************
      IF(ITER.LT.2) GO TO 200
      FP = (ERR(N) - ERR(NM1))/(AI(J,N) - AI(J,NM1))
      DERR = ERR(N)/FP
      AI(J,NP1) = AI(J,N) - DERR
      IF(AI(J,NP1).GT.1.0) AI(J,NP1) = AI(J,N) - 0.05*DERR/ABS(DERR)
      ERRF = ABS(DERR)
      IF(ABS(ERRMIN).LT.ABS(ERR(N))) GO TO 220
      ERRMIN = ERR(N)
      ASAVE = AI(J,N)
  220 CONTINUE
      IF(IFLG(1).NE.0) WRITE(KOUT,5000) AI(J,NP1),AI(J,N),ERR(N),RHS,
     1 LHS,VFS(J),VOVFS(J),WOVFS2
 5000 FORMAT(1H+,57X,2(2XF7.4),2XE10.3,2(1XF7.4),2XF7.2,2XF7.4,2XF8.3)
      IF(ABS(SINTH).LT.1.0E-10) GO TO 230
      IF((ERRF.GT.1.0E-03).AND.(ITER.LE.10)) GO TO 200
      IF(AI(J,N).LE.0.5) GO TO 225
      AI(J,NP1) = 0.5- 1.0E-10
      ITER = ITER + 30
      GO TO 200
  225 CONTINUE
      IF(ITER.NE.11) GO TO 230
      FFF = - 1.0
      IF(ASAVE.LT.0.5) FFF = 1.0
      AI(J,NP1) = ASAVE + FFF*1.0E-06
```

```
      IERR = IERR + 1
      GO TO 200
  230 CONTINUE
      IF(K.EQ.2) AFST = AI(1,N)
      A(J) = AI(J,N)
C***********************************************************************
C     WE NOW HAVE A CONVERGED SOLUTION FOR THE INDUCED VELOCITY
C     COMPUTE THE CONTRIBUTION TO TORQUE AND THRUST
C***********************************************************************
      CQF(J) = RBAR(K)*WOVFS2*(CA*COSEPS - CN*SINEPS)/SINGAM(K)
      CTF(J) = WOVFS2*(COSEPS*(CN*SINTH*SINGAM(K) - CA*COSTH)
     1 + SINEPS*(CA*SINTH*SINGAM(K) + CN*COSTH))/SINGAM(K)
      CQF(J) = CQF(J)*VFSR2
      CTF(J) = CTF(J)*VFSR2
      VFS(2) = VFS(1)*(1. - 2.*A(1))
      VFS(2) = AMAX1(VFS(2),0.0)
      IF(IFLG(1).NE.0) WRITE(KOUT,5010) CTF(J),CQF(J)
 5010 FORMAT(82X,4(1XE11.4))
C***********************************************************************
C     COMPUTE THE BLADE FORCES WHEN APPLICABLE
C***********************************************************************
      DYNP =       0.5*RHO*VFS(J)**2
      CLLLOC - WOVFS2*(CA*COSEPS - CN*SINEPS)
      CFLOC = WOVFS2*(CN*COSEPS + CA*SINEPS)
  300 CONTINUE
      VFSRAT = (1. - 2.*A(1))**2
      CQLOC = CQF(1) + CQF(2)*VFSRAT
      CTLOC = CTF(1) + CTF(2)*VFSRAT
      KM1 = K - 1
      KP1 = K + 1
      IF(K.EQ.1) KM1 = KM1 + 1
      IF(K.EQ.KMAX) KP1 = KP1 - 1
      FACTOR = 0.5*(ZBAR(KP1) - ZBAR(KM1))
      CTSUM = CTSUM + CTLOC*FACTOR
      CQSUM = CQSUM + CQLOC*FACTOR
      CFSUM = CFSUM + CFLOC*FACTOR
      CLLSUM = CLLSUM + CLLLOC*FACTOR
C***********************************************************************
C     THIS COMPLETES THE INTEGRATION OVER THE UPPER HALF OF THE ROTOR
C     SWEPT AREA
C***********************************************************************
  400 CONTINUE
      IF(IFLG(1).NE.0) WRITE(KOUT,5010) CLLSUM,CFSUM,CTSUM,CQSUM
      IF(L.EQ.1.OR.L.EQ.NTHP1) CQSUM = 0.5*CQSUM
      IF(L.EQ.1.OR.L.EQ.NTHP1) CTSUM = 0.5*CTSUM
      CQ = CQ + CQSUM
      CT = CT + CTSUM
  500 CONTINUE
      FF = NCOR*DTH/(2.*PI*ASORZ)
      CQ = CQ*FF
      CT = CT*FF
C***********************************************************************
C     MULTIPLY BY A FACTOR TO ADD IN THE UPPER HALF AND DOWNWIND
C     PORTION OF THE ROTOR
C***********************************************************************
      FF= 2.*FLOAT(2-ISHEAR)
      CQ = FF*CQ
      CT = FF*CT
      CP = CQ*XFS
      TORQUE = 0.5*RHO*RMAX*AS*CQ*VCL**2
```

```
      POWER = TORQUE*RPM*2.*PI/(60.*1000.)
      THRUST = 0.5*RHO*AS*CT*VCL**2
      VREF = VCL/VCLOVR
      ADVR = 1./XCL
      RKP = CP*1000./(XCL)**3
      WRITE(KOUT,5020) M,ADVR,RKP,XCL,CP,CT,CQ,RPM,VREF,REC,TORQUE,
     1 POWER,THRUST,IERR
 5020 FORMAT(2XI2,1XF6.3,2(1XF6.2),1XF7.4,1XF6.3,1XF7.4,1XF6.1,1XF7.2,
     1 4(1XE10.3),I5)
  600 CONTINUE
      GO TO 10
 9999 CONTINUE
      END



      SUBROUTINE GEOM(IGEOM,KP1,IHD)
C*************************************************************************
C     THIS SUBROUTINE EVALUATES ALL OF THE BLADE GEOMETRY
C     IGEOM = 1 , STRAIGHT LINE-CIRCULAR ARC
C     IGEOM = 2 , PARABOLA
C     IGEOM = 3, STRAIGHT BLADE
C*************************************************************************
      COMMON/GEOM/BETA,BETA2,ZBAR(101),RBAR(101),ASORZ,SINGAM(101)
     1 ,ASOS2
      IGP1 = IGEOM + 1
      GO TO(10,20,30,40) IGP1
   10 CONTINUE
   20 CONTINUE
C*************************************************************************
C     STRAIGHT LINE-CIRCULAR ARC
C*************************************************************************
      IF(IHD.EQ.1) GO TO 22
      RJOZM = 0.672103
      RJORM = RJOZM/BETA
      ZJOZM = 0.565406
      GO TO 23
   22 RJOZM = 0.413
      RJORM = RJOZM/BETA
      ZJOZM = 0.604
   23 CONTINUE
      RORM = RJORM - ZJOZM*(1. - ZJOZM)/(RJORM*BETA2)
      ASORZ = (1. - ZJOZM)*RJORM + 2.*RORM*ZJOZM + ZJOZM*SQRT
     1 ((1. - RORM)**2 - (ZJOZM/BETA)**2) + BETA*(1. - RORM)**2
     2 *ASIN(ZJOZM/(BETA*(1. - RORM)))
      ASORZ = 2.*ASORZ
      TH = ASIN(ZJOZM/(BETA*(1. - RORM)))
      SOZM = BETA*(1. - RORM)*TH + ((1. - ZJOZM)**2 + (BETA*RORM
     1 + SQRT(BETA2*(1. - RORM)**2 - ZJOZM**2))**2)**0.5
      SOZM = 2.*SOZM
      ASOS2 = BETA*ASORZ/SOZM**2
      DO 28 K=1,KP1
      ZBARA = ABS(ZBAR(K))
      IF(ZBARA.LT.ZJOZM) GO TO 24
      RBAR(K) = RJORM*(1. - ZBARA  )/(1. - ZJOZM)
      GAM = ATAN((1. - ZJOZM)/(RJORM*BETA))
      SINGAM(K) = SIN(GAM)
      GO TO 28
   24 CONTINUE
      RBAR(K) = RORM + SQRT((1. - RORM)**2 - (ZBAR(K)/BETA)**2)
```

```
      COTGAM = ZBAR(K)/((RBAR(K) - RORM)*BETA)
      SINGAM(K) = 1./SQRT(1. + COTGAM**2)
   28 CONTINUE
      GO TO 50
   30 CONTINUE
C***********************************************************************
C     PARABOLA
C***********************************************************************
      ASORZ = 8./3.
      ASOS2 = 32.*BETA2/(3.*(2.*BETA*SQRT(1. + 4.*BETA2) + ALOG(2.*
     1 BETA + SQRT(1. + 4.*BETA2)))**2)
      DO 35 K=1,KP1
      SINGAM(K) = 1./SQRT(1. + 4.*BETA2*ZBAR(K)**2)
      RBAR(K) = 1. - ZBAR(K)**2
   35 CONTINUE
      GO TO 50
C***********************************************************************
C     STRAIGHT VERTICAL BLADE
C************************************************************************
   40 CONTINUE
      ASORZ = 4.
      DO 45 K=1,KP1
      SINGAM(K) = RBAR(K) = 1.0
   45 CONTINUE
   50 CONTINUE
      RETURN
      END


      SUBROUTINE GRHS(ISTRUT,SINTH,SINGAM,RBAR,COSTH,SINEPS,COSEPS,
     1 CHORD,ALPHAD,CN,CA,CM,WOVFS2,RHS,VFSL,VOVFS)
      COMMON/STRUT/VFSOVCL(101),VCL,NU,IRE,TRE(15),TAA(182,15),
     1 TCN(182,15),TCA(182,15),TCM(182,15),DIM,X(4),DX(4),
     2 DEGTR,K,IFLG(20),KOUT,VBLADE,IFTA,ITER
      REAL NU
C***********************************************************************
C     THIS SUBROUTINE EVALUATES LOCAL ANGLE OF ATTACK, RELATIVE WIND
C     SPEED, BLADE REYNOLDS NUMBER, AND THRUST FORCES FOR A GIVEN
C     VALUE OF THE INDUCED VELOCITY FIELD.
C***********************************************************************
      X1 = VOVFS*SINTH*SINGAM
      X2 = VOVFS*COSTH + RBAR*VBLADE/VFSL
      WOVFS2 = X1**2 + X2**2
      WOVFS = SQRT(WOVFS2)
      EPS = ASIN(SINEPS)
      ALPHA = EPS + ATAN2(X1,X2)
      ALPHAD = ALPHA*DEGTR
      ALPHA = ABS(ALPHA)
      WOV = WOVFS/VOVFS
      W = WOVFS*VFSL
      WOVT = W/VBLADE
      RE = W*CHORD/NU
      IF(IFLG(5).EQ.0) RE = ALOG(RE)
      CALL LOOK2D(IRE,RE,TRE,IFTA,ALPHAD,TAA,TCN,TCA,TCM,DIM,X,DX,3,182)
      CN = X(1)
      CA = X(2)
      CM = X(3)
      CN = CN*SIGN(1.,ALPHAD)
      ASINTH = ABS(SINTH)
```

```
      IF(ASINTH.LT.1.0E-10) GO TO 10
      F = SINTH/ASINTH
      F1 = COSTH/(SINGAM*ASINTH)
      F2=COSEPS*(ABS(CN)-CA*F1)
      F3 = 0.0
      IF(ABS(SINEPS).GT.1.0E-10) F3 = SINEPS*(CA*F + CN*F1)
      RHS = WOVFS2*(F2 + F3)/RBAR
   10 CONTINUE
      IF(IFLG(1).NE.0) WRITE(KOUT,1000) ITER,ALPHAD,RE,WOVT,CN,CA,CM
 1000 FORMAT(3XI2,F7.2,1XE10.3,1XF6.3,3(2XF7.4))
      RETURN
      END



      SUBROUTINE LOOK (II,XL,X,A,B,C,E,Y,D,IDN)
      COMMON/TABLES/ ILO(200),IHI(200),IR(200), DEN, IEX,
     1        VR
      DIMENSION X(1), A(1), B(1), C(1), E(1), Y(1), D(1)
      IH=IHI(II)
      IL=ILO(II)
      DO 5 J=1,IDN
      D(J) = 0.0
      Y(J) = 0.0
    5 CONTINUE
      VR = 0.0
      IEX=0
      IF (X(IH)-X(IL)) 10,10,30
 10   IEX=1
      IF (XL-X(IH)) 120,130,20
 20   IF (XL-X(IL)) 50,150,140
 30   IF (XL-X(IH)) 40,130,120
 40   IF (XL-X(IL)) 140,150,50
 50   I=IR(II)
      I=MINO(I,IH)
      I=MAXO(I,IL)
      IS=1
      IT=1
      GO TO 70
 60   I=I+1
      IS=0
 70   IF (IEX) 80,80,90
 80   IF (XL-X(I)) 100,160,110
 90   IF (XL-X(I)) 110,160,100
 100  I=I-1
      IT=0
      IF (IS) 160,160,70
 110  IF (IT) 160,160,60
 120  IEX=3
 130  I=IH-1
      GO TO 160
 140  IEX=2
 150  I=IL
 160  DEN=X(I+1)-X(I)
      IR(II)=I
      VR=XL-X(I)
      IF (IDN) 230,230,170
 170  GO TO (210,200,190,180), IDN
 180  Y(4)=E(I)
      D(4)=E(I+1)-E(I)
```

```
190    Y(3)=C(I)
       D(3)=C(I+1)-C(I)
200    Y(2)=B(I)
       D(2)=B(I+1)-B(I)
210    Y(1)=A(I)
       D(1)=A(I+1)-A(I)
       IF(DEN.EQ.0.0) RETURN
       DO 220 J=1,IDN
       D(J)=D(J)/DEN
220    Y(J)=Y(J)+D(J)*VR
230    VR=VR/DEN
       RETURN
       END


       SUBROUTINE LOOK2D(II,XL,X,IF,YL,Y,A,B,C,E,Z,DZ,NLOOK,ND)
C*********************************************************************
C      THIS SUBROUTINE PERFORMS A TWO DIMENSIONAL LINEAR INTERPOLATION
C      THE TABLES MUST BE ARRANGED SUCH THAT FOR A GIVEN VALUE OF THE
C      INDEPENDENT VARIABLE X(J), THEN ALL OF THE DEPENDENT VARIABLES
C      A(I,J), B(I,J), C(I,J), E(I,J) ARE TABULATED AS A FUNCTION OF
C      THE SECOND INDEPENDENT VARIABLE Y(I)--THIS MAY BE THOUGHT OF
C      CONCEPTUALLY AS "A IS A FUNCTON OF Y WITH X AS A PARAMETER"
C
C      II = INDEX OF THE TABULAR LIMITS OF THE TABULATED VARIABLE X(J)
C      XL = VALUE OF THE INDEPENDENT VARIABLE X FOR INTERPOLATION
C      IF , IF + 1 = INDEX OF THE TABULAR LIMITS OF THE TABLE A(I,1) ETC
C      YL = VALUE OF 2ND INDEPENDENT VARIABLE Y FOR INTERPOLATION
C      X = ARRAY IN WHICH XL IS SOUGHT
C      Y = ARRAY IN WHICH YL IS SOUGHT
C      A,B,C,E, TABULATED ARRAY OF DEPENDENT VARIABLES
C      Z = ARRAY CONTAINING VALUES INTERPOLATED FROM THE A,B,C,E, TABLES
C      NLOOK = NUMBER OF DEPENDENT VARIABLE TABLES SUPPLIED--NLOOK .LE. 4
C      IF NLOOK LT. 4, THEN DUMMY ARGUMENTS MUST BE SUPPLIED FOR D, C,
C      ETC
C      ND = DIMENSION SIZE OF Y, A, B, ETC
C*********************************************************************
       COMMON/TABLES/ ILO(200),IHI(200),IR(200), DEN, IEX,
      1          VR
       DIMENSION          X(1),      Y(ND,1),  A(ND,1),  B(ND,1),  C(ND,1),
      1          E(ND,1),  Z(4),      DZ(4),    ZL(4),    DZL(4),   ZR(4),
      2          DZR(4)
C*********************************************************************
C      IF THERE IS ONLY A SINGLE X TABLE (IHI(II) = 1) THEN WE WANT TO
C      DO ONLY A ONE DIMENSIONAL INTERPOLATION
C*********************************************************************
       VRS = 1.0
       J = 0
       DO 10 I=1,NLOOK
       Z(I) = DZ(I) = 0.0
   10  CONTINUE
       IF(IHI(II).EQ.1) GO TO 20
C*********************************************************************
C      DETERMINE THE INDEX J SUCH THAT X(J) .LE. XL .LE. X(J+1)
C*********************************************************************
       CALL LOOK(II,XL,X,0,0,0,0,Z,DZ,0)
       VRS = VR
       J = IR(II)
       JJ = IF + J
```

```
C*************************************************************************
C     INTERPOLATE IN TABLE J WITH YL AS INDEPENDENT VARIABLE
C*************************************************************************
      CALL LOOK(JJ,YL,Y(1,J),A(1,J),B(1,J),C(1,J),E(1,J),Z,DZ,NLOOK)
      DO 15 I=1,NLOOK
      ZL(I) = Z(I)
      DZL(I) = DZ(I)
   15 CONTINUE
   20 CONTINUE
      J = J + 1
      JJ = IF + J
C*************************************************************************
C     INTERPOLATE IN TABLE J+1 WITH YL AS INDEPENDENT VARIABLE
C*************************************************************************
      CALL LOOK(JJ,YL,Y(1,J),A(1,J),B(1,J),C(1,J),E(1,J),Z,DZ,NLOOK)
      DO 30 I=1,NLOOK
      ZR(I) = Z(I)
      DZR(I) = DZ(I)
   30 CONTINUE
      VRSP = 1. - VRS
      DO 40 I=1,NLOOK
      Z(I) = ZL(I)*VRSP  + ZR(I)*VRS
      DZ(I) = DZL(I)*VRSP + DZR(I)*VRS
   40 CONTINUE
      RETURN
      END
```

APPENDIX D

Sample Control Stream

The following is an example of a LGO control stream in using DARTER at Sandia National Laboratories.

```
DARTER,T15.                                    R E FRENCH  ** BOX 1134 **
ACCOUNT,S432961153,D5636,612,A0518400,RT,KUNC.
ATTACH,TAPE10,KD-EPPLERCLCD-NACA-DEC78,CY=15.
ATTACH,DARTER,KLIMAS-DARTER-PROG,CY=02.
DARTER,PL=25000.
**END-OF-RECORD**
 SAMPLE RUN OF THE DARTER CODE
TWO BLADED SYSTEM

    2    18    10      01000111
8.3628    8.5        0.60975    0.000017911.001      0.1       4.82      13.32
        2450.6
1.0       1.5        2.0        2.5        3.0        3.5       4.0       4.5
5.0       5.5        6.0        6.5        7.0        7.5       8.0       8.5
9.0       9.5        10.0       10.5       11.0       11.5      12.0      12.5
**END-OF-INFORMATION**
```

APPENDIX E

Sample Output

The following output was generated by DARTER in response to the input shown in Appendix D.

SAMPLE RUN OF THE DARTER CODE
TWO BLADED SYSTEM

NC/R	RMAX	ZMAX	CHORD	NU	RHO
.146	8.36	8.50	.610	.179E-04	.100E+01
EXP	ZGC	ZR			
.100	4.82	13.32			

NUMB	IGEOM	NDTH	NDZ
2	1	18	10

21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0

NACA 0015 SECTION DATA, EPPLER MODEL, CL, CD, DEC 78
SOLIDITY = .1625

M	1/XCL	KP E3	XCL	CP	CT	CQ	RPM	VREF	REC	TORQUE	POWER	DRAG	
1	1.000	10.34	1.00	.0103	.088	.0108	50.6	44.31	.151E+07	.167E+05	.887E+02	.163E+05	0
2	.667	7.31	1.50	.0247	.120	.0172	50.6	29.54	.151E+07	.118E+05	.627E+02	.989E+04	0
3	.500	7.33	2.00	.0587	.168	.0307	50.6	22.16	.151E+07	.119E+05	.629E+02	.779E+04	0
4	.400	7.42	2.50	.1160	.233	.0485	50.6	17.73	.151E+07	.120E+05	.637E+02	.691E+04	0
5	.333	9.06	3.00	.2446	.340	.0853	50.6	14.77	.151E+07	.147E+05	.777E+02	.699E+04	0
6	.286	7.41	3.50	.3179	.455	.0950	50.6	12.66	.151E+07	.120E+05	.636E+02	.687E+04	0
7	.250	5.59	4.00	.3575	.538	.0935	50.6	11.08	.151E+07	.904E+04	.479E+02	.622E+04	0
8	.222	4.16	4.50	.3794	.603	.0882	50.6	9.85	.151E+07	.674E+04	.357E+02	.551E+04	0
9	.200	3.10	5.00	.3874	.657	.0811	50.6	8.86	.151E+07	.502E+04	.266E+02	.486E+04	0
10	.182	2.32	5.50	.3853	.701	.0733	50.6	8.06	.151E+07	.375E+04	.199E+02	.429E+04	0
11	.167	1.74	6.00	.3760	.740	.0655	50.6	7.39	.151E+07	.282E+04	.149E+02	.380E+04	0
12	.154	1.31	6.50	.3587	.774	.0577	50.6	6.82	.151E+07	.211E+04	.112E+02	.339E+04	0
13	.143	.97	7.00	.3336	.804	.0499	50.6	6.33	.151E+07	.157E+04	.834E+01	.304E+04	0
14	.133	.72	7.50	.3051	.835	.0425	50.6	5.91	.151E+07	.117E+04	.620E+01	.275E+04	0
15	.125	.53	8.00	.2736	.867	.0358	50.6	5.54	.151E+07	.865E+03	.458E+01	.251E+04	0
16	.118	.39	8.50	.2381	.901	.0293	50.6	5.21	.151E+07	.628E+03	.333E+01	.231E+04	0
17	.111	.27	9.00	.1996	.935	.0232	50.6	4.92	.151E+07	.443E+03	.235E+01	.214E+04	0
18	.105	.18	9.50	.1583	.972	.0174	50.6	4.66	.151E+07	.299E+03	.158E+01	.199E+04	1
19	.100	.11	10.00	.1130	1.009	.0118	50.6	4.43	.151E+07	.183E+03	.969E+00	.187E+04	1
20	.095	.05	10.50	.0615	1.047	.0061	50.6	4.22	.151E+07	.860E+02	.455E+00	.176E+04	2
21	.091	.00	11.00	.0043	1.085	.0004	50.6	4.03	.151E+07	.520E+01	.276E-01	.166E+04	3
22	.087	-.04	11.50	-.0605	1.124	-.0055	50.6	3.85	.151E+07	-.644E+02	-.341E+00	.157E+04	4
23	.083	-.08	12.00	-.1326	1.163	-.0115	50.6	3.69	.151E+07	-.124E+03	-.659E+00	.149E+04	3
24	.080	-.11	12.50	-.2109	1.203	-.0177	50.6	3.55	.151E+07	-.175E+03	-.926E+00	.142E+04	3

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