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A COMPUTER SUBROUTINE FOR ESTIMATING AERODYNAMIC BLADE LOADS ON DARRIEUS VERTICAL AXIS WIND TURBINES

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A COMPUTER SUBROUTINE FOR ESTIMATING
AERODYNAMIC BLADE LOADS ON DARRIEUS VERTICAL AXIS
WIND TURBINES

W. N. Sullivan
T. M. Leonard

An important aspect of structural design of the Darrieus rotor is the determination of aerodynamic blade loads. This report describes a load generator which has been used at Sandia for quasi-static and dynamic rotor analyses. The generator is based on the single streamtube aerodynamic flow model and is constructed as a FORTRAN IV subroutine to facilitate its use in finite element structural models. Input and output characteristics of the subroutine are described and a complete listing is attached as an appendix.

Acknowledgement

The early versions of FORCE were initially constructed in 1976 by J. F. Banas, Division 4722. These early versions formed the basic framework for the subroutine described in this report.

A COMPUTER SUBROUTINE FOR ESTIMATING AERODYNAMIC BLADE LOADS ON DARRIEUS VERTICAL AXIS WIND TURBINES

Introduction

The Darrieus vertical axis wind turbine (VAWT) is a fixed pitch device, typically using curved blades as shown in Fig. 1. The structural response of the rotor during opera-

FIGURE 1: The DOE/Sandia 17-m 60 kW VAWT System in Albuquerque, New Mexico

tion is driven by the centrifugal, gravitational, and aerodynamic loads on the blades. While the computation of centrifugal and gravitational loads is straightforward, the aerodynamic loads are less widely understood. This report describes a computer program which has been used to compute aerodynamic blade loads.

The fluid mechanical behavior of the wind passing through a VAWT rotor governs the aerodynamic blade loads which vary in a complex manner as the rotor turns through the flow field. A variety of approximate schemes¹⁻⁴ have been developed to model the flow field and predict overall aerodynamic performance of the rotor. Any of these methods could conceivably be used to compute the time-dependent aerodynamic loads applied to the blades. The load package presented here utilizes the single streamtube model¹ first developed by the Canadian National Research Council (NRC). This model has the advantage of simplicity over other modeling approaches. The accuracy of the single streamtube model remains a research question, but operational experience⁵ indicates it adequately estimates the aerodynamic loads for most structural design applications. Of course, research efforts are continuing to identify the most suitable load models and the current package should not be considered as final.

The load computation is effected in a FORTRAN IV subroutine called FORCE. This subroutine computes the blade forces based on inputs describing the rotor geometry,

rotor rpm, windspeed, and blade chord. FORCE is not intended to be a stand-alone package. Rather, it is constructed to be used in conjunction with structural analysis programs developed by the user.

The following sections will describe the input/output characteristics of FORCE. Typical output results from the package are shown. A complete FORTRAN IV listing of the package is given in an appendix.

Load Subroutine FORCE

Brief Description -- Load computation takes place in the subroutine FORCE based on equations derived in detail in a NRC report.¹ Another subroutine called TAB is utilized by FORCE. TAB contains lift and drag aerodynamic data for the particular airfoil involved.

The single streamtube model assumes that the flow field inside the rotor is uniform and parallel to the ambient wind velocity. The flow velocity inside the rotor (the "disk" velocity, V_D) is ordinarily reduced in magnitude from the ambient windspeed because of the kinetic energy removed from the airstream by the turbine. The single streamtube model computes the disk velocity from a momentum balance in the direction parallel to the ambient wind. This balance relates the average downwind drag on the rotor to the change in flow velocity between the upwind and downwind sides of the rotor. The disk velocity is assumed to be equal to the average of the upwind and downwind windspeeds. Since the

rotor drag depends on the disk velocity, an iterative loop is used in FORCE to determine the disk velocity consistent with the momentum balance.

Once the disk velocity is determined, FORCE calculates the local angle of attack and airspeed for an observer fixed to an element of the blade. The elemental blade forces may then be calculated based on airfoil lift and drag data. The subroutine TAB serves this purpose using linear interpolation of tabular airfoil data supplied at discrete angles of attack.

Input/Output Arguments -- The following are the input/output arguments to FORCE: RPM, VMPH, ARHO, C, NBL, INIT, R, Z, NRZ, NT, II, FFL, IF, FLL, IL. Each of these arguments will be described below.

RPM, VMPH - Rotor speed (in rpm) and ambient windspeed (in mph).

ARHO - Ambient air density, in lbm/ft^3 .

C - Blade chord (in inches).

NBL - Number of blades (integer).

INIT - Initialization variable (integer). If INIT = 0, the disk velocity is calculated. If INIT $\neq$ 0, the disk velocity is retained from the last call to FORCE when INIT was equal to zero. The disk velocity depends on RPM, VMPH, C, NBL, R, and Z and need not be recalculated for multiple calls to FORCE with these same

input variables. INIT is supplied to allow the user to save computation time when making multiple calls to FORCE. INIT also affects the interpretation of the output variables IF and IL discussed below.

$R(I)$ and $Z(I)$ - These arrays define the blade radial and axial coordinates shown in Fig. 2. These coordinates

FIGURE 2: Blade Geometry and Nomenclature for FORCE

must describe the entire blade and be in order, proceeding from one end of the blade ($I = 1$) to the other ($I = NRZ$). The coordinates should be in units of inches. For multiple blade rotors, only the coordinates of one blade

should be defined. Subroutine FORCE assumes the origin of the R,Z coordinate system is on the axis of rotation.

- NRZ - The length of the R and Z arrays.
- NT - Forces are output for an individual blade as a function of its azimuthal angle, θ (Fig. 2). The variable NT governs the angular resolution of the output data. Output data are given in angular increments of $\Delta\theta = 360^\circ/\text{NT}$, i.e., for $\text{NT} = 72$, $\Delta\theta = 5^\circ$.
- II - On any particular call to FORCE, output forces are only given for a blade node at the position $R(\text{II}), Z(\text{II})$.
- FFL - This output array (dimension of $\text{NT} + 1$) gives the flatwise aerodynamic forces (in lbs/ft) at blade node II. $\text{FFL}(1)$ is the force at blade azimuthal angle, $\theta = 0^\circ$; $\text{FFL}(\text{NT} + 1)$ is the force at $\theta = 360^\circ$. The sign convention and orientation of FFL is shown in Fig. 2.
- IF - IF is the θ index for which the force FFL reaches its maximum absolute value. IF is only calculated if $\text{INIT} = 0$. Should $\text{INIT} \neq 0$, the value of IF is left at its value from the last call to FORCE for which $\text{INIT} = 0$.
- FLL, IL - These variables are analogous to FFL and IF, respectively, only they refer to lead/lag

forces. The sign convention for FLL is shown in Fig. 2.

Airfoil Performance Data -- The subroutine TAB is called by FORCE and contains the basic airfoil section performance data. These data are in the form of the coefficients C_N and C_T as a function of the local angle of attack. The C_N and C_T coefficients are dimensionless representations of the blade forces (per unit length) which are normal (flatwise) and tangential (lead/lag) to the blade chord line, respectively. The C_N and C_T coefficients are related to the more traditional lift and drag coefficients through

$$C_N = C_L \cos \alpha + C_D \sin \alpha$$

$$C_T = C_L \sin \alpha - C_D \cos \alpha$$

where C_L is the lift coefficient, C_D is the drag coefficient, and α is the local angle of attack.

Subroutine TAB computes C_N and C_T from linear interpolation of tabular data supplied at discrete angles of attack. These tabular data are given in three data arrays at the beginning of the subroutine. Array TA gives the discrete angles of attack for which C_N and C_T data are supplied. Arrays TCN and TCT are the C_N and C_T values corresponding to the angles in TA.

The appended listing for TAB has airfoil data for a NACA 0015 blade at a Reynolds number of approximately 3 million. This is a symmetric airfoil and thus array TA

only contains angles from 0 to 180°. For calls to TAB with negative angles, the absolute value of the angle of attack is used and the sign of C_N reversed. This procedure is only valid for symmetric airfoils. To model an asymmetric airfoil, the data arrays must cover the angle of attack range from -180 to +180 degrees and the enforced symmetry statements eliminated.

The C_T tabular data supplied in the array for angles of attack below 15° actually has the value of C_{D0} (zero angle of attack drag) added to it. Thus, C_{D0} must be subtracted from the interpolated value of C_T if the angle of attack is less than 15°. The magnitude of C_{D0} is given in a data statement at the beginning of TAB.

Example Results

Figure 3 shows typical flatwise and edgewise loads at the blade equator as a function of azimuthal angle, θ . This particular computation is for the DOE/Sandia 17-m research turbine operated at 50 rpm in 30 mph winds. This plot is normalized to the maximum flatwise load. Figure 4 shows similar results for a higher windspeed (60 mph). The irregular characteristics of the force are due to blade stall which occurs as the windspeed increases.

The data for either Fig. 3 or 4 are contained in the output from a single call to FORCE. These plots are a graphic representation of the arrays FFL and FLL. Figure 5 shows a distribution of flatwise and edgewise loads on

FIGURE 3

FIGURE 4

FIGURE 5

a turbine blade at a particular azimuthal angle, θ . The data for Fig. 5 are obtained from multiple calls to FORCE at the various nodal positions defining the blade geometry.

Summary and Conclusions

The subroutine FORCE provides a computationally rapid technique for determining aerodynamic blade loads on the Darrieus rotor. The package is readily adaptable for use with analytical structural models which require information on blade loading.

The basis for FORCE is the single streamtube aerodynamic model. This model uses a very simple, approximate representation of the rotor flowfield. Limited experience in applying the FORCE model indicates that its accuracy is acceptable for estimating the nature and magnitude

of structural loads on the blade. However, structural designers should recognize the developmental nature of the package. Research efforts are continued to quantify the limitations of FORCE and to provide more suitable methods where appropriate.

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APPENDIX

FORTRAN IV LISTING OF SUBROUTINES FORCE AND TAB

```

SUBROUTINE FORCE(RPM,VMPH,ARHO,C,NBL,INIT,
>               R,Z,NRZ,NT,
>               II,FFL,IF,FLL,IL)
  DIMENSION D(81),DS(80)
  DIMENSION FFL(73),FLL(73),R(81),Z(81)
  FG(III,THJ,CNX,CTX)=((R(III)/RMAX*XMU+COS(THJ))**2
*+(SIN(THJ)*COS(D(III)))**2)*(CNX*COS(D(III))*SIN(THJ)-
*CTX*COS(THJ))
  IF(INIT)52,61
61  CONTINUE
  PI=ACOS(-1.)
  W=RPM*PI/30.
  V=VMPH*22./15.
  AS=0.
  CFT=C/12.
  AIRHO=ARHO/32.17
  NN=NRZ
  RMAX=0.
C    COMPUTE BLADE GEOMETRY FACTORS NEEDED FOR
C    INTEGRATIONS BELOW
  DO 2000 IN=1,NN
    N1=IN-1
    N2=IN+1
    IF(N1.LT.1)N1=1
    IF(N2.GT.NN)N2=NN
    IF(R(IN).GT.RMAX)RMAX=R(IN)
    DR=R(N2)-R(N1)
    DZ=Z(N1)-Z(N2)
    D(IN)=ATAN(DR/DZ)
    IF(IN.EQ.NN)GOTO 2000
    DR=R(IN)-R(N2)
    DZ=Z(N2)-Z(IN)
    DS(IN)=SQRT(DR**2+DZ**2)
    AS=AS+ABS(DZ)*(R(IN)+R(N2))/144.
C    AS IS THE ROTOR DISC AREA
2000 CONTINUE
    RFT=RMAX/12.
    XNU=RFT*W/V
    NTP1=NT+1
    FI=0.

```

```

C      ITERITIVE LOOP TO COMPUTE INTERFERENCE FACTOR ↑FI↑
C      FI IS RELATED TO DISC VELOCITY, VD/VMPH=1-FI
7777  CONTINUE
      XMU=XNU/(1.-FI)
      SUM=0.
      NN=NRZ-1
      NT02=NT/2
      DO 3001 J=1,NT02
      TJ=FLOAT(J-1)*PI/LOAT(NT02)
      TJP1=FLOAT(J)*PI/LOAT(NT02)
      DT=TJP1-TJ
      SX=SIN(TJ)
      CX=COS(TJ)
      SXP=SIN(TJP1)
      CXP=COS(TJP1)
      DO 3000 IN=1,NN
      CSD=COS(D(IN))
      CSA=R(IN)/RMAX*XMU+CX
      CSAP=R(IN)/RMAX*XMU+CXP
      SNA=CSD*SX
      SNAP=CSD*SXP
      ALPD=180.*ATAN2(SNA,CSA)/PI
      ALPDP=180.*ATAN2(SNAP,CSAP)/PI
      IF(ALPD.GT.180.)ALPD=ALPD-360.
      IF(ALPDP.GT.180.)ALPDP=ALPDP-360.
      CALL TAB(ALPD,CN,CT)
      CALL TAB(ALPDP,CNP,CTP)
3000  SUM=SUM+.25*(FG(IN,TJ,CN,CT)+FG((IN+1),TJ,CN,CT)
      *+FG(IN,TJP1,CNP,CTP)+FG((IN+1),TJP1,CNP,CTP))
      *(DS(IN)*DT)/12.
3001  CONTINUE
      CDD=FLOAT(NBL)*C/12./PI/AS*SUM
      FIN=(1.-FI)*CDD/4.
C      CDD IS THE DIMENSIONLESS DISC DRAG COEFFICIENT
      IF(ABS(FI-FIN).LE.1.E-4)GOTO 4000
      FI=FIN
      GOTO 7777
4000  CONTINUE
C      ITERATION ON INTERFERENCE FACTOR IS COMPLETE
      FI=(FI+FIN)/2.
      NT1=1 $ NT2=NTP)
      CONX=AIRHO*CFT*(V*(1.-FI))**2/2.

```

```

52 CONTINUE
C      IF INIT NE 0, FORCE COMPUTATION ENTRY IS HERE
C      TO AVOID RECOMPUTATION OF INTERFERENCE FACTOR FI.
C      IN THIS CASE, VALUE OF FI FOR LAST CALL FOR WHICH
C      INIT EQ 0 IS USED
      RX=R(II)/RMAX
      CSD=COS(D(II))
      DO 53 IT=NT1,NT2
      T=PI*FLOAT(IT-1)/FLOAT(NT)*2.
      SX=SIN(T)
      CX=COS(T)
      C4=(RX*XMU+CX)**2+(SX*CSD)**2
      C3=SQRT(C4)
      CSA=(RX*XMU+CX)/C3
      SNA=SX*CSD/C3
      ALPD=180.*ATAN2(SNA,CSA)/PI
      IF(ALPD.LT.-180.)ALPD=ALPD+360.
      IF(ALPD.GT.180.) ALPD=ALPD-360.
      IF(INIT.EQ.2)ZZ(IT,2)=ALPD
      CALL TAB(ALPD,CN,CT)
      FFL(IT) = CN*CONX*C4
      FLL(IT) = CT*CONX*C4
53 CONTINUE
      IF(INIT.NE.0)RETURN
      FFLMAX = 0.
      FLLMAX = 0.
      NT02P1=NT02+1
      DO 49 IT = 1, NT02P1
      IF(FLL(IT) .LT. FLLMAX) GO TO 101
      FLLMAX = FLL(IT)
      IL = IT
101 IF(FFL(IT) .LT. FFLMAX) GO TO 49
      FFLMAX = FFL(IT)
      IF = IT
49 CONTINUE
      RETURN
      END

```



```

C      SUBROUTINE TAB(AD,CN,CT)
C      SBR. TAB IS AN INTERPOLATIVE ROUTINE TO COMPUTE
C      AERODYNAMIC NORMAL AND TANGENTIAL
C      FORCE COEFFICIENTS AS A FUNCTION OF
C      ANGLE OF ATTACK FROM TABULAR DATA.
C
      DIMENSION TA(50),TCN(50),TCT(50)
      DATA RE,XCD0,NTBL1/3000000.,.0081,29/
      DATA (TA(I),I=1,30)/0.,.2.,.5.,.10.,.15.,.17.5,18.,.20.,.25.,.30.,.40.,.50.,
160.,.70.,.80.,.90.,.100.,.110.,.120.,.130.,.140.,.150.,.154.,.160.,.164.,.168.,
2170.,.172.,.175.,.180./
      DATA (TCN(I),I=1,30)/0.,.2.,.498,.987,1.396,1.497,1.326,1.136,
11.042,1.16,1.5,1.75,1.95,2.05,2.08,2.06,2.04,1.95,1.85,1.7,1.5,
21.17,1.,.78,.72,.74,.76,.85,.5,0./
      DATA (TCT(I),I=1,30)/0.,.0066,.0421,.167,.356,.432,.189,.094,
1-.011,-.05,-.05,-.03,-.01,.01,.05,.09,.125,.15,.15,.15,.15,.14,
2.125,.1,.06,.045,.04,.025,.025,.025/
      A=ABS(AD)
      DO 1 I=1,NTBL1
      J=I
      IF(A.GE.TA(I).AND.A.LE.TA(I+1)) GO TO 2
1      CONTINUE
2      X=(A-TA(J))/(TA(J+1)-TA(J))
      CN=TCN(J)+X*(TCN(J+1)-TCN(J))
      CT=TCT(J)+X*(TCT(J+1)-TCT(J))
      IF(A.LE.15.) CT=CT-XCD0
      IF(AD.LT.0.) CN=-CN
      RETURN
      END

```

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