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Summary

A computer program (WIND) has been developed that numerically solves an exact, full-potential equation (FPE) for three-dimensional, steady, inviscid flow through an isolated wind turbine rotor. The program automatically generates a three-dimensional, boundary-conforming grid and iteratively solves the FPE while fully accounting for both the rotating cascade and Coriolis effects. The numerical techniques incorporated involve rotated, type-dependent finite differencing, a finite volume method, artificial viscosity in conservative form, and a successive line overrelaxation combined with the sequential grid refinement procedure to accelerate the iterative convergence rate. Consequently WIND is capable of accurately analyzing incompressible and compressible flows, including those that are locally transonic and terminated by weak shocks. WIND can also be used to analyze the flow around isolated aircraft propellers and helicopter rotors in hover as long as the total relative Mach number of the oncoming flow is subsonic.

Introduction

An exact, full-potential equation (FPE) that governs three-dimensional steady, inviscid, potential flow through the wind turbine rotor can be expressed in the following vector form (refs. 1 and 2):

$$a^2\Delta^2\varphi - (\Delta\varphi\cdot\Delta)\frac{1}{2}(\Delta\varphi\cdot\Delta\varphi) + 2(\Delta\varphi\cdot\Delta)((\Omega\times r)\cdot\Delta\varphi)$$

$$- ((\Omega\times r)\cdot\Delta)((\Omega\times r)\cdot\Delta\varphi) = 0 \qquad (1)$$

where $V = \Delta\varphi$ is the absolute velocity vector defined as

$$V = V_r + \Omega\times r \qquad (2)$$

Here V_r is the relative velocity vector of the fluid with respect to the rotating blade, Ω is the angular rotor speed, and r is the position vector in the rotor plane.

Equation (1) is a second-order, quasi-linear, partial differential equation of mixed elliptic-hyperbolic type. For the particular set of boundary conditions the solution of FPE can be composed of locally hyperbolic regions (supersonic relative flow) that neighbor regions where FPE is locally of an elliptic type (i.e., where the local relative flow is subsonic). The boundary surfaces separating these regions can be of a continuous parabolic type (sonic surfaces) or of a mathematically discontinuous type (isentropic shocks). This means that the FPE can govern flow regimes varying from incompressible (when the FPE reduces to a simple Laplace's equation) through the transonic, accepting mathematical discontinuities in the "weak solution" form. These discontinuities are then interpreted as weak isentropic shocks (refs. 3 and 2).

The FPE cannot be solved analytically, and therefore a numerical method will be used. This method, called the finite-volume method (refs. 4 and 5), represents a combination of finite difference and finite element techniques. Because of the exceedingly large number of mathematical operations that will be performed and the large amount of computer storage required, an iterative, successive line overrelaxation (SLOR) technique is used. The details of the numerical scheme have been presented in other references (refs. 6, 7, and 2) and will not be repeated in this users manual. To make the computer program suitable for computers with a limited central memory, the program was written in such a way that a number of disks or tapes will accommodate the excessive storage requirements.

Applicability of Computer Program WIND

The computer program WIND is capable of numerically analyzing the flow field about a given blade shape of the wind turbine rotor (horizontal-axis type).

The rotor hub is defined as a doubly infinite circular cylinder having the x coordinate as its axis. An arbitrary number of blades can be attached to the hub. The blades can have arbitrary spanwise distribution of taper and of the twist, sweep, and dihedral angles. An arbitrary number of different airfoil section shapes can be used along the span, although the spanwise variation of all the geometric parameters must be reasonably smooth.

The results of the numerical analysis are given in the form of a computer printout. At a number of spanwise stations along the blade the output gives the chordwise distribution of the coefficient of pressure,

the Mach number, the density, and the relative velocity vector components. In addition, the results specify local values of the lift coefficient and tangential and axial aerodynamic force components. These are also given in an integrated form expressing the total torque on the shaft and the total axial force on the shaft.

As stated in reference 8, WIND numerically solves an exact, full-potential equation for a three-dimensional, steady, homentropic flow of an inviscid, compressible, homocompositional, nonradiating, and nonconducting fluid. The practical implications of this mathematical model are the following:

(1) The wind is blowing at a steady speed. Gusts lasting for a period of time long enough to change the loading of the blade significantly should be analyzed as separate test cases at different wind speeds, each speed treated as a different constant.

(2) The axis of the rotor is always alined with the wind.

(3) The atmospheric turbulence is of negligible intensity.

(4) The tower and all other obstacles are placed downwind from the rotor.

(5) The entire rotor is placed above the ground shear layer; that is, the wind speed is uniform.

(6) Vertical and horizontal variations of atmospheric density and temperature are negligible.

(7) The rotor rotates at constant angular speed.

(8) There is no separation of the airstream from the blades or the rotor hub.

(9) The rotor hub has the shape of an infinitely long, circular cylinder.

(10) Atmospheric impurities (rain, snow, ice, sand, dust, and industrial air pollutants) are uniformly distributed throughout the air mass.

It is important to explicitly warn the users of the WIND code that this program cannot account for possible flow separations and subsequent heavy losses due to poor aerodynamic design of rotor blades.

In its present form WIND is capable of calculating flow fields that could become locally supersonic and terminate with weak shocks. Although this situation is not desirable, it can easily occur in the case of a strong gust or a malfunction of the blade twisting (pitching) mechanism. The consequences include an unacceptably high level of noise and possibly serious damage to the blade and tower structure as the result of an aerodynamic load that was not accounted for during the blade design process.

With increasing rotor diameter and angular speed the outer portions of the blades will operate in a flow regime where the compressibility effects cannot be neglected. The compressibility effects, combined with blade shapes incorporating advanced shockless airfoil shapes, are capable of significantly increasing the aerodynamic efficiency of the rotor without increasing the noise level. The theories for this approach have already been developed (refs. 9 and 10) and successfully tested numerically (ref. 11).

Besides being capable of calculating flows ranging from the incompressible through the transonic regime, WIND fully accounts for the effect of the Coriolis force and the mutual blade interference (cascade) effect. Compressibility and Coriolis effects will be important in the outer portion of the blade; the three-dimensional rotating cascade effects become important in the blade root region.

Global Structure of Program

A computer program called WIND numerically solves the FPE. The program is written in FORTRAN IV and consists of about 2200 computer cards. Wind automatically generates the computational grids and performs the iterative solution of the FPE. Thus user intervention is unnecessary once the program has begun execution.

While developing and testing the program it was observed that the computational grid-generating portion of the code uses about 50 percent of the total high-speed memory required by WIND but consumes less than 2 percent of the total central processing unit time required by WIND. Therefore, to save computer storage and at the same time provide the designer with an opportunity to separately analyze the geometry, WIND was divided into two separate programs (fig. 1).

The first portion of this code is called WIND-01. It reads its own input data, which contain all major geometric parameters. WIND-01 then generates the three-dimensional, body-fitted grid and stores it on disks or tapes.
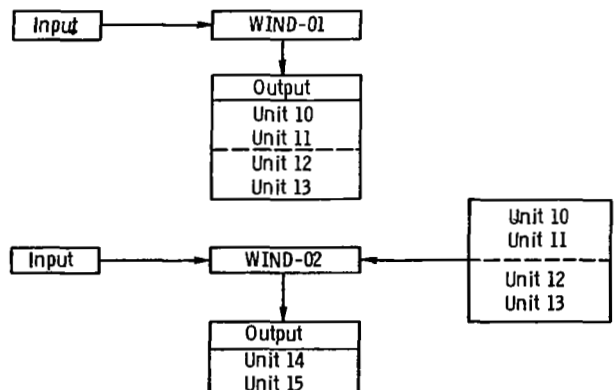

Figure 1. - Global flow chart.

The second portion of the program is called WIND-02. It reads the (x,y,z) coordinates that were previously generated by WIND-01 and thus reactivates units 10, 11, 12, and 13. WIND-02 also reads its own input, which defines the basic flow parameters, and then performs an interative solution of the FPE. The final results of WIND are thus the results of WIND-02. These results, representing values of the potential function, will remain stored on units 14 and 15.

Computer Program WIND-01

The grid generation performed by WIND-01 is based on an analytic function (refs. 12 and 2) that conformally maps a cascade of straight slits onto a cascade of unit circles with a slit in the middle (fig. 2). These circles are "unwrapped" by using elliptic polar coordinates. After additional coordinate stretching and shearing this deformed rhomboid is converted into a parallelepiped-shaped computational domain suitable for finite differencing. Several important geometric parameters and (x,y,z) coordinates of the coarse (first) grid are stored permanently on units 10 and 11, coordinates of the refined (second) grid are stored on unit 12, and coordinates of the fine (third) grid are stored on unit 13 so that each of them can be separately plotted and analyzed.

The computer program WIND-01 consists of seven routines and a separate input data operation (fig. 3). The input data are discussed in detail in the following section. The subroutine MAIN is the principal part
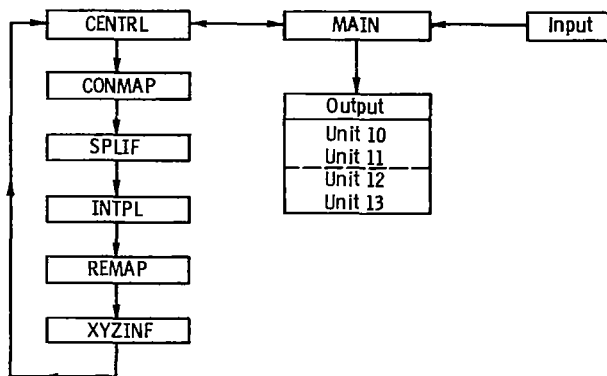

Figure 3. - Flow chart of WIND-01 computer program.

of WIND-01 in the sense that most of the other routines are called from that routine. MAIN reads the input data and rotates the airfoil to its actual stagger angle. MAIN also writes (x,y,z) coordinates of the first (coarse) grid on unit 11 and the values of the parameters XCELL, YCELL, ZCELL, RHUB RTIP, RINF, TIPCEL, and BLADE (explained in the following section) on unit 10. On the same unit 10, MAIN also writes the values of the normalized radii of the cylindrical computational surfaces (ref. 8) intersecting the blade. If the original coarse grid has to be refined in all three directions, the refined grid coordinates will automatically be written onto unit 12. The coordinates of the fine (third) grid will be written by MAIN on unit 13.

Subroutine CENTRL calculates the length of the central slit in the circle plane and calls routines SPLIF, INTPL, CONMAP, and REMAP in order to perform the conformal mapping and remapping.

Subroutine CONMAP iteratively performs the point-by-point conformal mapping from the (x,θ) plane onto the circle plane. Furthermore CONMAP "unwraps" the circle and calculates the elliptic polar coordinates (fig. 2).

Subroutine SPLIF fits a cubic spline through the lower boundary of the computational domain that corresponds to the surface of the airfoil.

Subroutine INTPL interpolates the values of the elliptic polar coordinates at points that are equidistantly spaced with respect to the image of the upstream infinity. This is a necessary step in obtaining a grid that is periodic in the θ-direction.

Subroutine REMAP analytically determines coordinates of the mesh points in the physical plane; that is, REMAP performs a backtransformation process from the computational plane to the (x,θ) plane.

The mesh points defining the axial infinities should be positioned along the line $x=$ constant (fig. 4). Because of the way the potential jump Γ will be enforced across the cut, the points at $x=+\infty$ should be
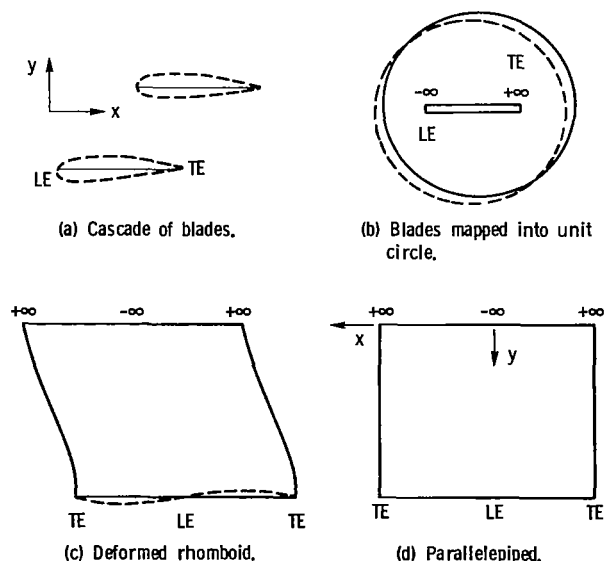

Figure 2. - Transformation from (x,θ) plane into computational plane, where TE denotes trailing edge and LE denotes leading edge.

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equidistantly positioned in the θ direction with respect to that cut.

Subroutine XYZINF determines the coordinates of the axial infinity points explicitly, because they cannot be obtained from the conformal mapping. XYZINF also determines the coordinates of points in the imaginary rows and columns outside the actual computational domain.

Input to WIND-01

All the input data for WIND-01 are combined in one data set (see appendix A). Following is a card-by-card description of that data set (see appendix B for the input format).

The first card contains an arbitrary text composed of up to 80 alphanumeric characters. Its purpose is to give a description or a name to the entire input defining the blade geometry. This same text will then appear at the beginning of the output of WIND-01.

The second card contains the following five parameters:

XCELL   number of computational mesh cells around surface of each blade cross section (fig. 4) when calculating on coarse (first) grid. XCELL must be an even number. The maximum suggested value is XCELL = 24.

YCELL   number of elliptic layers of mesh cells enveloping each local blade cross section (fig. 4) when calculating on a coarse grid. The suggested minimum value is YCELL = 5.

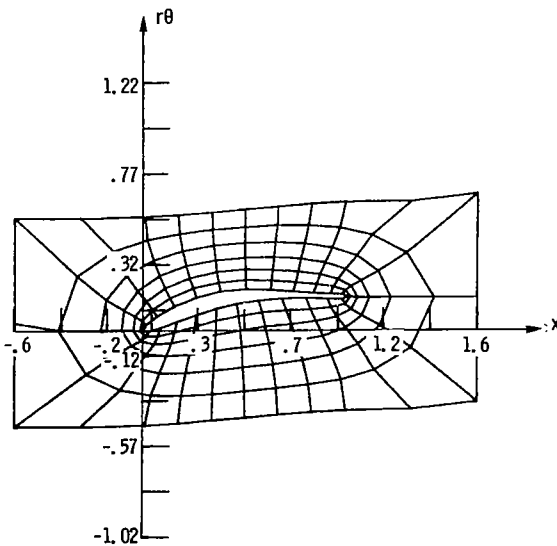ZCELL   number of mesh cells in spanwise direction (between hub and radial in-

Figure 4. - Computational mesh on (x, rθ) cylindrical surface.

finity cutoff boundary) when calculating on coarse grid. The minimum value for ZCELL that will still provide for a stable numerical scheme can be determined from the following expression:

$$ZCELL = 0.9\left(\frac{r_t - r_h}{c_t + c_h}\right) + 2.$$

where r_t is the rotor radius, r_h is the radius of the rotor hub, c_h and c_t are the blade chord lengths at the hub and the tip, respectively.

TIPCEL   number of mesh cells in spanwise direction (between hub and the tip of blade) when calculating on coarse grid. The maximum value for TIPCEL should be

TIPCEL = ZCELL − 2.

PMESH   total number of consecutively refined computational grids that should be generated and separately stored. The number of the mesh cells on the first (coarse) three-dimensional grid is defined by specifying XCELL, YCELL, ZCELL, and TIPCEL. Each following grid will be automatically generated with twice as many mesh cells·in each of the computational directions (X, Y, Z) as the previous grid had. The minimum value for PMESH is 1 and the maximum value is 3.

The third input card contains the following five parameters:

RINF   normalized radius of cylindrical outer boundary on which radial infinity boundary conditions will be applied (ref. 8). Normalization must be performed with respect to the rotor radius r_t (fig. 8).

RHUB   normalized radius of rotor hub. Again, the normalizing length is r_t.

RTIP   rotor radius r_t, ft

BLADE   number of rotor blades

SETANG   blade setting angle, deg. This is the angle between the pitching position of the blade as defined by the rest of the input data and any other blade pitching position (fig. 5).

The actual detailed shape of the blade without the hub is given on a number of (x,y) input planes (fig. 6). The innermost input plane must be positioned inside the hub; the outermost input plane should be positioned precisely at or beyond the blade tip.
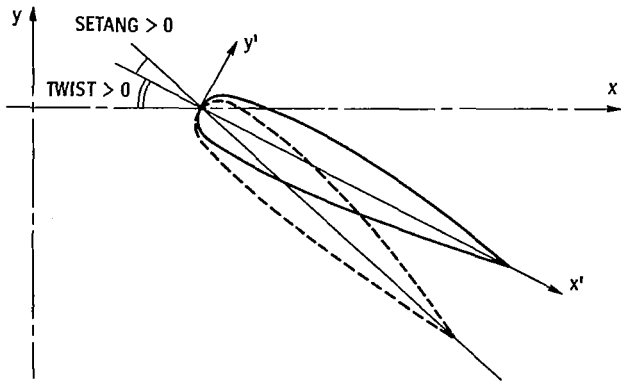
Figure 5. - Local blade section inclination.

The fourth input card contains eight parameters defining the relative position in space of the Nth local blade cross section. These parameters are

N
number of (x,y) input plane. The planes are numbered in the spanwise direction, starting with N = 1 for the most inward plane (fig. 6). The maximum number of input planes N = NP is 25.

RLEAD
radial distance from axis of rotation to leading edge of local airfoil defined on N^{th} plane. RLEAD is nondimensional; the normalizing length being the rotor radius RTIP.

CHORD
chord length of blade local cross section defined on N^{th} input plane. Chord length is defined as a maximum distance connecting the leading and trailing edges of the blade section. CHORD is nondimensionalized with respect to RTIP.

XLEAD
axial distance (sweep) from origin of (x,y,z) coordinate system to leading edge of the blade cross section defined on N^{th} plane. The origin should be placed on the axis of rotation (x axis) close to the point of intersection of an extrapolated leading edge and that axis (fig. 6). XLEAD is nondimensionalized with respect to the RTIP.

R01,R02
leading- and trailing-edge radii of blade local cross-section (airfoil) shape defined in N^{th} plane. R01 and R02 are nondimensionalized with respect to the actual local blade chord length on the Nth plane.

TLEAD
local dihedral angle between z axis and leading edge of blade cross section on N^{th} plane (fig. 6), deg

TWIST
local twist angle between x axis and line connecting leading and trailing edges of blade cross section defined on N^{th} plane (figs. 5 and 6), deg

The fifth input card, together with a number of following input cards, specifies pairs of (x',y') coordinates of the finite number of input points defining the shape of a local blade cross section on the Nth plane. These cards also specify the number of each point and a control parameter (explained below) assigned to each input point. Thus the input parameters appearing on the fifth card (and several consecutive input cards) are (appendix A):

I
number of particular point on local airfoil surface at N^{th} station. The input points are numbered starting from the trailing edge (I = 1) and proceeding clockwise until the trailing-edge point is reached again (I = MAXP). The maximum number of input points at each Nth station is MAXP = 65. By increasing the length of vector arrays in COMMON/BLK1/ and COMMON/BLK2/ of the WIND-01 code, the value of MAXP can be increased accordingly.

x'
x' coordinate of Ith input point on blade cross section at N^{th} spanwise station. The value of x' is normalized with respect to the local blade chord length. The range of possible x' values is

$$0 < x' < 1.$$

y'
y' coordinate of Ith input point on blade cross section at N^{th} spanwise station. The value of y' is normalized with respect to the local blade chord length.

It is emphasized that the (x',y') input system differs from the (x,y,z) coordinate system (fig. 5). The (x',y') system is attached to the local leading edge of the Nth blade cross section, with the x' axis passing through the blade leading- and trailing-edge points. The (x,y,z) system has its origin on the axis of rotation (x axis) and rotates with the blade.

As already mentioned, the fifth card and each number of the following input cards specify x' and y' coordinates of two input points (appendix A). The total number of input points on each Nth plane must be odd (counting the trailing-edge point twice, i.e.,
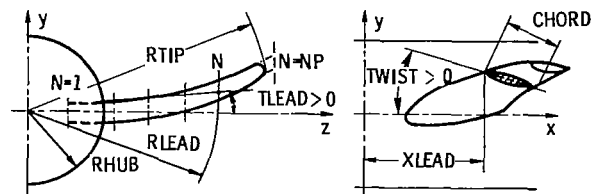

Figure 6. - Local spanwise input parameters.

accounting for it as I = 1 and I = MAXP) if the local airfoil shape is not symmetrical. If the local input airfoil shape is symmetrical, the total number of input points must be even, and only the points along the lower airfoil surface need be specified. WIND-01 will then automatically determine the symmetrically positioned remaining input points that are on the upper blade surface.

From appendix A it can be seen that after each pair of (x',y') coordinates specifying an input point on the Nth station, there is a three-digit parameter. Its description follows:

NEXT   input reading parameter. The value NEXT = 111 at the end of each input card specifying (x',y') input coordinates means that the following input card has the same format and that the reading of input data of the same type can be continued. The value NEXT = 000 acknowledges the end of the set of input cards specifying (x',y') coordinates and consequently the end of all the data that are needed at the Nth station. Such a set involves input card 4 and all the following cards, including a card with NEXT = 000. A value of NEXT = 222 at the end of such a set of cards instead of NEXT = 000 means that the airfoil shape at the $(N+1)^{th}$ station will be the same as it was at the Nth station.

An entire set of (x',y') input coordinates has to be formed for each of the N spanwise input stations. Only when the last parameter on the Nth station input set is NEXT = 222 will the set for the $(N+1)^{th}$ station consist of a single input card having the format of the fourth input card.

The very last card in the input deck for the WIND-01 code is the same as card 4, but with N specified as N = 0. The rest of the parameters on that card are arbitrary (appendix A).

Output of WIND-01

The results of the WIND-01 program are partially given in written form on a single page of standard computer output (appendix C). This output lists the name of the programmer, the name of the program, and the institution where it was developed. These statements are followed by a listing of major geometric input parameters defining each Nth spanwise station. This listing is helpful in debugging the input deck. The next portion of printed output gives the following parameters, obtained after the spanwise interpolation has been performed:

K   number of cylindrical computational surface (fig. 8)

RADII   radii of Kth cylindrical computational surface divided by rotor radius (RTIP).

TWIST   twist angle of intersection contour (profile) obtained by intersecting blade with K^{th} cylindrical computational surface, deg

CHORD   chord length of the contour at K^{th} station. CHORD is normalized with respect to RTIP.

XL   axial distance between origin of (x,y,z) coordinate system and leading edge of contour on K^{th} cylindrical surface. XL is normalized with respect to RTIP.

TL   tangential distance between z axis and leading edge of contour on K^{th} cylindrical surface, deg

The major portion of the output from WIND-01 will be permanently stored on disks or tapes (fig. 3). For example, the parameters XCELL, YCELL, ZCELL, RHUB, RTIP, RINF, TIPCEL, and BLADE and the normalized radii of the K computational cylindrical surfaces will be stored on unit 10. The (x,y,z) coordinates defining every mesh point on the coarse three-dimensional grid will always be stored on unit 11. The (x,y,z) coordinates of the next (refined) three-dimensional grid will be automatically defined and stored on unit 12 (if PMESH = 2). If PMESH = 3 in the input data, the (x,y,z) coordinates of the fine (third) grid will be automatically generated and stored on unit 13. A message will appear on the printout sheet each time a separate storage device has been successfully used.

Computer Program WIND-02

The second part of the program WIND, called WIND-02, is executed separately after the (x,y,z) coordinates of the body-conforming grid have been generated by the first part, WIND-01. The purpose of WIND-02 is to actually solve the exact fullpotential equation and to calculate important aerodynamic parameters characterizing the flow field. WIND-02 was written in a modular form, separating the main steps in the solution process of the governing equation (fig. 7).

The main program, which reads input data that are written on cards as well as the (x,y,z) coordinates of the computational grid generated by WIND-01, is called MAIN. The same routine calls other routines and refines the potential field after the iteration process on a particular mesh has converged (when PMESH is greater than 1).
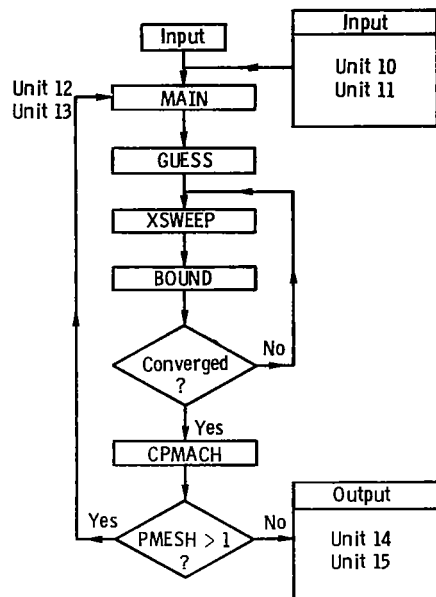
Figure 7. - Flow chart of WIND-02 computer program.

Figure 8. - Cylindrical computational planes.

In order to generate an improved initial guess for the potential field calculation on a first (coarse) mesh, subroutine GUESS is called. GUESS iteratively solves an exact two-dimensional full potential equation of the form (ref. 13)

$$\left(a^2 - \varphi_{,x}^2\right)\varphi_{,xx} + \left(a^2 - \varphi_{,\bar{y}}^2\right)\varphi_{,\bar{y}\bar{y}}$$

$$- 2\varphi_{,x}\varphi_{,\bar{y}}\varphi_{,x\bar{y}} = 0 \qquad (3)$$

Here the x coordinate corresponds to the x coordinate in the (x,y,z) space, and the $\bar{y}$ coordinate represents an arc length; that is

$$\bar{y} = r\theta \qquad (4)$$

where r is the radius of the Kth cylindrical surface and θ is the angle between the z axis and the point in question (fig. 8). The maximum number of K cylindrical surfaces is 24 in the present version of WIND.

Subroutine XSWEEP iteratively performs the actual flow calculation by using the SLOR technique. XSWEEP uses type-dependent rotated finite differencing and the artificial time concept in order to evaluate coefficients of the tridiagonal correction to the potential matrix. The residues are evaluated by using the finite area technique. The artificial viscosity is added explicitly in conservative form.

Subroutine BOUND applies boundary and periodicity conditions after each complete sweep through the flow field performed by XSWEEP. BOUND is also called after each mesh refinement.

Subroutine CPMACH calculates the chordwise distribution of the coefficient of pressure, the local relative Mach number, the density, and the relative velocity components at each Kth spanwise station. CPMACH also integrates the coefficient of pressure and gives the force and moment distribution along the blade.

Input to WIND-02

The input to WIND-02 is composed of two separate parts. The first part of the input consists of the following four computer cards (appendix D):

The first input card is the so-called title card, meaning that the name of the test case or some other text not longer than 80 alphanumeric characters can be written on that card (see appendix E for formatting).

The second input card specifies the following three input parameters:
UNIF   wind speed, mph
OMEGA   angular speed of rotor, rpm
TEMP   temperature of air, °F

The third input card specifies CONVER, RLX, and PMESH, where
CONVER   circulation rate of convergence criteria in case of lifting flows

$$\text{CONVER} = \frac{\Gamma^{n+1} - \Gamma^n}{\Gamma^n}$$

where Γ^n is the value of the circulation at the particular spanwise sta-

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tion. The suggested input value for CONVER is CONVER = 1.0D − 05.

RLX iterative overrelaxation factor in regions of locally subsonic relative flow. If the calculation is going to be performed on more than one grid, the value of RLX will automatically be increased by 5 percent on each following (refined) grid. Suggested value is RLX = 1.65.

PMESH total number of computational grids used. Minimum value is PMESH = 1. With the common region presently existing in WIND-01 and WIND-02, the *maximum value for PMESH is PMESH = 3*. This means that the calculation can be performed on a coarse grid consisting of (24 × 6 × ZCELL) mesh cells and then automatically continued on two more consecutively three-dimensionally refined grids. Calculation on a single coarse grid (PMESH = 1) usually gives quite satisfactory results.

The fourth input card contains values for ITER1, ITER2, and PRESS, where

ITER1 maximum number of iterations to be performed on first (coarse) grid. The suggested value is ITER1 = 50.

ITER2 maximum number of iterations to be performed on second grid (if PMESH > 1). The suggested value is ITER2 = 30. *If three grids are to be used (PMESH = 3), the maximum value of iterations on the third grid will be automatically determined as ITER3 = ITER2/2.*

PRESS atmospheric pressure, lb/in^2, usually about PRESS = 14.7

The second portion of the input to the WIND-02 program consists of the (x,y,z) coordinates previously generated by WIND-01 and stored on units 10, 11, and possibly 12 and 13. These units of permanent storage will be used during the entire execution of WIND-02.

Output from WIND-02

The results of the iterative solution of an exact full-potential equation as obtained by WIND-02 are given in printed form. The (x,y,z) coordinates of the computational grid (or grids, if PMESH > 1) will remain saved on units 10 and 11 (and possibly 12 and 13). Thus, if WIND-02 is run again for the same blade geometry, but with different input parameters (UNIF, OMEGA, TEMP, and PRESS), the time and

money for executing WIND-01 can be saved. Besides saving (x,y,z) coordinates of the computational grid, the values of the reduced potential $G(x,y,z)$ defined as

$$\varphi(x,r,\theta) = \frac{1}{(q_r^t)_{-\infty}} (UINF*x + OMEGA*r)$$
$$+ G(x,y,z) \qquad (5)$$

will remain saved on units 14 and 15, which were used during the execution of WIND-02.

These values of $G(x,y,z)$ can be used later for computing various flow parameters at any point in the flow field if there is any need for analyzing them. For that purpose an extension of WIND-02 will be needed. *This extension is not presently included but* can be easily developed by the user according to his needs.

The most important output parameters, as mentioned earlier, will appear in a printed form. The first part of the printed output of WIND-02 will give the name of the programmer, the name of the institution where the program was developed, and the name of the program. This will be followed by the listing of input data to WIND-02.

Results of the two-dimensional cascade calculations performed by subroutine GUESS will appear next. They will include the following parameters:

K number of spanwise position of two-dimensional cylindrical surface $(r\theta,x)$(fig. 8)

R/RTIP radial distance of Kth cylindrical surface normalized with respect to rotor radius r_t

ALREL angle between axial and rotational component of relative free-stream vector at upstream infinity, deg

TWIST angle between chord line at K^{th} station and axis of rotation, deg

ALPHA angle of attack at K^{th} station, deg, that is,

ALPHA = TWIST − ALREL

CL-2D local coefficient of lift at K^{th} station (obtained by solving two-dimensional, full-potential equation on K^{th} surface)

NSUP *total number of mesh points on K^{th} surface where relative flow was locally supersonic*

The values of CL-2D could serve for comparison with the standard aerodynamic results for the isolated two-dimensional airfoils in incompressible flow (ref. 14, e.g.).

Two-dimensional cascade results of subroutine GUESS are then used as an improved initial guess for the potential field in the actual three-dimensional iterative solution process of the full potential equation performed by the routine XSWEEP. For the purpose of monitoring this process the output listing from WIND-02 continues by listing the following parameters:

ITER — number of iteration sweep

K — number of spanwise station, that is, the number of the particular cylindrical surface intersecting the blade

IR,JR — (X,Y) coordinates of point where residue had largest absolute value on K^{th} surface during last iteration sweep

MAX.RESIDUE — maximum residue on entire two-dimensional K^{th} cylindrical surface. Its location is at the point (IR,JR,K).

IC,JC — (X,Y) coordinates of a point where correction to potential had maximum absolute value on K^{th} cylindrical surface during last iteration sweep

MAX.CORRECT — maximum value of calculated correction to potential. This correction was introduced at the point (IC, JC).

CIRCULATION — value of circulation Γ at K^{th} station

RELAX.COEF — value of relaxation factor RLX used in last iteration sweep at subsonic points

ISTG — number of leading-edge stagnation point. From that point the next iteration sweep will start proceeding along the airfoil suction surface to the trailing edge and then again from ISTG along the pressure surface to the trailing edge. In such a way the problems of marching upstream in the locally supersonic flow and the consequent introduction of negative artificial viscosity are avoided.

NSUP — total number of supersonic points on K^{th} surface

When the absolute value of the normalized convergence rate

$$(\Gamma^{n+1} - \Gamma^n)/\Gamma^n$$

becomes smaller than CONVER, the iterative process on that particular grid will terminate. For $\Gamma = 0$ (when the flow is nonlifting) the iterative process on each grid will terminate after ITER = ITRMAX on that particular grid.

The printout will then be continued by listing the following values on the blade surface:

I — number (index) of point on blade surface at K^{th} station. The points are numbered clockwise starting from the trailing edge.

X — x coordinate of point on airfoil surface at K^{th} station

Y — y coordinate of point on airfoil surface at K^{th} station

XNORM — x' coordinate normalized with local chord at K^{th} station

MACH — local value of relative Mach number calculated from

$$MACH = q_r/a$$

where q_r is local value of relative speed and a is local speed of sound

Q/QINF — ratio of local value of relative speed and value of relative speed measured at rotor tip radius

$$Q/QINF = q_r / \left(UINF^2 + OMEGA^2 \cdot RTIP^2\right)^{1/2}$$

U0,V0,W0 — components of local relative velocity vector along x, y and z directions, respectively

DENS — local fluid density normalized with density at upstream infinity

CPMACH also integrates the C_p distribution along the local blade sections and lists the results at each Kth station. The results are

FTANG — local value of aerodynamic force in θ direction, lb

FAXIAL — local value of aerodynamic force in x direction, lb

CL-3D — three-dimensional results for sectional lift coefficient

RADIUS — radius of Kth station, ft

K — number (or index) of Kth station

CPMACH also integrates FTANG and FAXIAL in the spanwise direction and lists the total aerodynamic torque on the shaft and the total axial force on the shaft.

Results

WIND was tested against the numerical results obtained by NASA Lewis for their ERDA-NASA

100-kilowatt Mod-0 wind turbine (refs. 15 and 16). These results were obtained for OMEGA = 40 rpm and UNIF = 18 mph by using a code called MOSTAB (refs. 17 and 18). The blade geometry is explained in reference 15. For these same flow conditions and blade geometry WIND was tested on a single grid having XCELL = 24, YCELL = 6, ZCELL = 8, and TIPCEL = 6 cells. Three-dimensional results obtained after only 50 iterations are presented in figure 9. It is obvious that serious errors could be made if the designer decided to use lift coefficients obtained for an isolated airfoil in free air. Even the two-dimensional cascade results (obtained by subroutine GUESS) are not acceptable for the design of wind turbine rotor blades. Two- and three-dimensional results agree very well only in the blade midspan region where the flow is essentially two dimensional. This part of the flow field is uninhibited by the three-dimensional and compressibility effects present in the blade tip region and by the rotating cascade effects and the presence of the hub dominating the flow in the blade root region. To avoid problems and the uncertainty of dealing with the blade root effects, most designers retreat to an unimaginative method called root-cutout. It would be more beneficial to avoid such techniques in favor of using more advanced airfoils with a high critical angle of attack. In this way the aerodynamic efficiency of the rotor could be increased even for low-speed wind turbine rotors. At the same time vibration and fatigue problems caused by the flow separation in the root region could be eliminated. The three-dimensionality of the flow in the blade tip region is not inevitable if one adds properly designed winglets to the blade tip.

It is pointed out that (at least for this particular test case) the total torque on the shaft calculated by WIND was $M_x = 24\,680$ foot-pounds. This result agrees very well with the results for steady loading reported in references 15 and 16. The experimentally measured value of the torque was reported (ref. 16, table I(b)) to be $M_x = 21\,000$ foot-pounds.

An inexplicable decision by the designers of Mod-0 to place the rotor in the tower wake and consequent serious separation-induced vibrations might be a partial cause of the discrepancy between the results of WIND and the measured results in this test case.

Concluding Remarks

A user-oriented computer program called WIND has been developed for the numerical analysis of the three-dimensional flow field about the propeller type of wind turbine rotor. WIND is an accurate and efficient computer program that is suitable for application on all nonvectorized computers. Besides final three-dimensional results, WIND also provides the results of the two-dimensional calculation so that the user can easily locate the areas of possible improvement in aerodynamic design of the blade shape. WIND is capable of reliably predicting flows that range from locally incompressible to locally supersonic, including the presence of weak shock waves.

Lewis Research Center,
National Aeronautics and Space Administration,
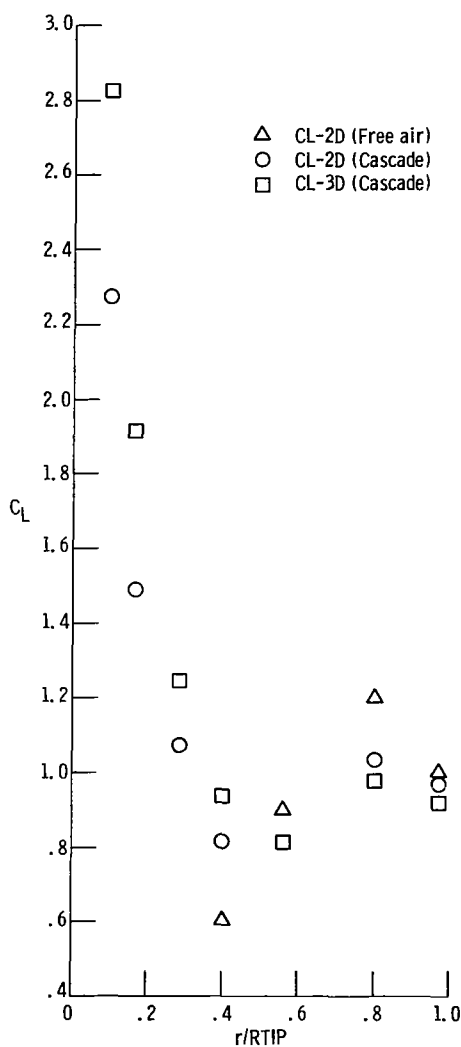Cleveland, Ohio, May 30, 1980,
505–32.

Figure 9. - Sectional values of lift distribution.

Appendix A
Input Data for Mod-0 Wind Turbine

```
0000100    NASA 100KW MOD-0 WIND TURBINE ; AIRFOIL NACA 2300 SERIES
0000200    XCELL =   24.000YCELL =    6.000ZCELL =    8.000TIPCEL=    6.000PMESH =    1.000
0000300    RINF  =    1.200RHUB  =    0.100RTIP  =   62.500BLADE =    2.000SETANG=    0.000
0000400      1        0.050000  0.072000   0.006139  0.180000   0.025000      0.0000   58.0000
0000500     1 1.00000D+00  .00000D+00   111   2  .95036D+00-0.03008D+00   111
0000600     3  .90064D+00-0.05346D+00   111   4  .80116D+00-0.09606D+00   111
0000700     5  .70162D+00-0.13328D+00   111   6  .60202D+00-0.16484D+00   111
0000800     7  .50235D+00-0.18964D+00   111   8  .40256D+00-0.20556D+00   111
0000900     9  .30265D+00-0.20908D+00   111  10  .25262D+00-0.20446D+00   111
0001000    11  .20253D+00-0.19406D+00   111  12  .15001D+00-0.17704D+00   111
0001100    13  .09423D+00-0.15294D+00   111  14  .06601D+00-0.13720D+00   111
0001200    15  .03853D+00-0.11724D+00   111  16  .01331D+00-0.08864D+00   111
0001300    17  .00277D+00-0.06606D+00   111  18  .00000D+00-0.00000D+00   111
0001400    19  .00277D+00 0.08034D+00   111  20  .01331D+00 0.11528D+00   111
0001500    21  .03853D+00 0.16344D+00   111  22  .06601D+00 0.19688D+00   111
0001600    23  .09423D+00 0.22098D+00   111  24  .15001D+00 0.25056D+00   111
0001700    25  .20253D+00 0.26474D+00   111  26  .25262D+00 0.27070D+00   111
0001800    27  .30265D+00 0.27092D+00   111  28  .40256D+00 0.25856D+00   111
0001900    29  .50235D+00 0.23380D+00   111  30  .60202D+00 0.20016D+00   111
0002000    31  .70162D+00 0.15976D+00   111  32  .80116D+00 0.11374D+00   111
0002100    33  .90064D+00 0.06230D+00   111  34  .95036D+00 0.03448D+00   111
0002200    35 1.00000D+00 0.00000D+00   111  35 1.00000D+00 0.00000D+00   000
0002300      2        0.160000  0.072000   0.019645  0.120000   0.015000      0.0000   69.0000
0002400     1 1.00000D+00  .00000D+00   111   2  .95000D+00-0.02180D+00   111
0002500     3  .90000D+00-0.03880D+00   111   4  .80000D+00-0.06960D+00   111
0002600     5  .70000D+00-0.09620D+00   111   6  .60000D+00-0.11880D+00   111
0002700     7  .50000D+00-0.13620D+00   111   8  .40000D+00-0.14740D+00   111
0002800     9  .30000D+00-0.14940D+00   111  10  .25000D+00-0.14540D+00   111
0002900    11  .20000D+00-0.13720D+00   111  12  .15000D+00-0.12360D+00   111
0003000    13  .10000D+00-0.10440D+00   111  14  .07500D+00-0.09200D+00   111
0003100    15  .05000D+00-0.07600D+00   111  16  .02500D+00-0.05420D+00   111
0003200    17  .01250D+00-0.03660D+00   111  18  .00000D+00-0.00000D+00   111
0003300    19  .01250D+00 0.08180D+00   111  20  .02500D+00 0.10580D+00   111
0003400    21  .05000D+00 0.13840D+00   111  22  .07500D+00 0.16020D+00   111
0003500    23   10000D+00 0.17660D+00   111  24  .15000D+00 0.19720D+00   111
0003600    25  .20000D+00 0.20720D+00   111  26  .25000D+00 0.21120D+00   111
0003700    27  .30000D+00 0.21100D+00   111  28  .40000D+00 0.20080D+00   111
0003800    29  .50000D+00 0.18100D+00   111  30  .60000D+00 0.15500D+00   111
0003900    31  .70000D+00 0.12360D+00   111  32  .80000D+00 0.08800D+00   111
0004000    33  .90000D+00 0.04780D+00   111  34  .95000D+00 0.02640D+00   111
0004100    35 1.00000D+00 0.00000D+00   111  35 1.00000D+00 0.00000D+00   000
0004200      3        0.240000  0.072000   0.029468  0.090000   0.009000      0.0000   75.5000
0004300     1 1.00000D+00  .00000D+00   111   2  .95000D+00-0.01800D+00   111
0004400     3  .90000D+00-0.03180D+00   111   4  .80000D+00-0.05660D+00   111
0004500     5  .70000D+00-0.07820D+00   111   6  .60000D+00-0.09620D+00   111
0004600     7  .50000D+00-0.11000D+00   111   8  .40000D+00-0.11840D+00   111
0004700     9  .30000D+00-0.11920D+00   111  10  .25000D+00-0.11560D+00   111
0004800    11  .20000D+00-0.10820D+00   111  12  .15000D+00-0.09680D+00   111
0004900    13  .10000D+00-0.08180D+00   111  14  .07500D+00-0.07220D+00   111
0005000    15  .05000D+00-0.06080D+00   111  16  .02500D+00-0.04500D+00   111
0005100    17  .01250D+00-0.03080D+00   111  18  .00000D+00-0.00000D+00   111
0005200    19  .01250D+00 0.06680D+00   111  20  .02500D+00 0.08880D+00   111
0005300    21  .05000D+00 0.11780D+00   111  22  .07500D+00 0.13800D+00   111
0005400    23  .10000D+00 0.15280D+00   111  24  .15000D+00 0.17040D+00   111
0005500    25  .20000D+00 0.17840D+00   111  26  .25000D+00 0.18160D+00   111
0005600    27  .30000D+00 0.18100D+00   111  28  .40000D+00 0.17180D+00   111
0005700    29  .50000D+00 0.15480D+00   111  30  .60000D+00 0.13220D+00   111
0005800    31  .70000D+00 0.10500D+00   111  32  .80000D+00 0.07460D+00   111
0005900    33  .90000D+00 0.04080D+00   111  34  .95000D+00 0.02240D+00   111
0006000    35 1.00000D+00 0.00000D+00   111  35 1.00000D+00 0.00000D+00   000
0006100      4        0.350000  0.065333   0.042974  0.063300   0.005000      0.0000   81.0000
0006200     1 1.00000D+00  .00000D+00.  111   2  .95036D+00-0.01504D+00   111
0006300     3  .90064D+00-0.02673D+00   111   4  .80116D+00-0.04803D+00   111
0006400     5  .70162D+00-0.06664D+00   111   6  .60202D+00-0.08242D+00   111
```

```
0006500    7  .50235D+00-0.09482D+00  111  8  .40256D+00-0.10278D+00  111
0006600    9  .30265D+00-0.10454D+00  111 10  .25262D+00-0.10223D+00  111
0006700   11  .20253D+00-0.09703D+00  111 12  .15001D+00-0.08852D+00  111
0006800   13  .09423D+00-0.07647D+00  111 14  .06601D+00-0.06860D+00  111
0006900   15  .03853D+00-0.05862D+00  111 16  .01331D+00-0.04432D+00  111
0007000   17  .00277D+00-0.03303D+00  111 18  .00000D+00-0.00000D+00  111
0007100   19  .00277D+00 0.04017D+00  111 20  .01331D+00 0.05764D+00  111
0007200   21  .03853D+00 0.08172D+00  111 22  .06601D+00 0.09844D+00  111
0007300   23  .09423D+00 0.11049D+00  111 24  .15001D+00 0.12528D+00  111
0007400   25  .20253D+00 0.13237D+00  111 26  .25262D+00 0.13535D+00  111
0007500   27  .30265D+00 0.13546D+00  111 28  .40256D+00 0.12928D+00  111
0007600   29  .50235D+00 0.11690D+00  111 30  .60202D+00 0.10008D+00  111
0007700   31  .70162D+00 0.07988D+00  111 32  .80116D+00 0.05687D+00  111
0007800   33  .90064D+00 0.03115D+00  111 34  .95036D+00 0.01724D+00  111
0007900   35 1.00000D+00 0.00000D+00  111 35 1.00000D+00 0.00000D+00  000
0008000    5       0.670000  0.038666  0.082265  0.035600  0.002500    0.0000    89.0000
0008100    1 1.00000D+00  .00000D+00  111  2  .95000D+00-0.01090D+00  111
0008200    3  .90000D+00-0.01940D+00  111  4  .80000D+00-0.03480D+00  111
0008300    5  .70000D+00-0.04820D+00  111  6  .60000D+00-0.05940D+00  111
0008400    7  .50000D+00-0.06810D+00  111  8  .40000D+00-0.07370D+00  111
0008500    9  .30000D+00-0.07470D+00  111 10  .25000D+00-0.07270D+00  111
0008600   11  .20000D+00-0.06860D+00  111 12  .15000D+00-0.06180D+00  111
0008700   13  .10000D+00-0.05220D+00  111 14  .07500D+00-0.04600D+00  111
0008800   15  .05000D+00-0.03800D+00  111 16  .02500D+00-0.02710D+00  111
0008900   17  .01250D+00-0.01830D+00  111 18  .00000D+00-0.00000D+00  111
0009000   19  .01250D+00 0.04090D+00  111 20  .02500D+00 0.05290D+00  111
0009100   21  .05000D+00 0.06920D+00  111 22  .07500D+00 0.08010D+00  111
0009200   23  .10000D+00 0.08830D+00  111 24  .15000D+00 0.09860D+00  111
0009300   25  .20000D+00 0.10360D+00  111 26  .25000D+00 0.10560D+00  111
0009400   27  .30000D+00 0.10550D+00  111 28  .40000D+00 0.10040D+00  111
0009500   29  .50000D+00 0.09050D+00  111 30  .60000D+00 0.07750D+00  111
0009600   31  .70000D+00 0.06180D+00  111 32  .80000D+00 0.04400D+00  111
0009700   33  .90000D+00 0.02390D+00  111 34  .95000D+00 0.01320D+00  111
0009800   35 1.00000D+00 0.00000D+00  111 35 1.00000D+00 0.00000D+00  000
0009900    6       1.000000  0.024000  0.122784  0.015800  0.001000    0.0000    92.0000
0010000    1 1.00000D+00  .00000D+00  111  2  .95000D+00-0.00700D+00  111
0010100    3  .90000D+00-0.01230D+00  111  4  .80000D+00-0.02160D+00  111
0010200    5  .70000D+00-0.03000D+00  111  6  .60000D+00-0.03670D+00  111
0010300    7  .50000D+00-0.04170D+00  111  8  .40000D+00-0.04480D+00  111
0010400    9  .30000D+00-0.04460D+00  111 10  .25000D+00-0.04280D+00  111
0010500   11  .20000D+00-0.03970D+00  111 12  .15000D+00-0.03500D+00  111
0010600   13  .10000D+00-0.02920D+00  111 14  .07500D+00-0.02610D+00  111
0010700   15  .05000D+00-0.02260D+00  111 16  .02500D+00-0.01710D+00  111
0010800   17  .01250D+00-0.01230D+00  111 18  .00000D+00-0.00000D+00  111
0010900   19  .01250D+00 0.02670D+00  111 20  .02500D+00 0.03610D+00  111
0011000   21  .05000D+00 0.04910D+00  111 22  .07500D+00 0.05800D+00  111
0011100   23  .10000D+00 0.06430D+00  111 24  .15000D+00 0.07190D+00  111
0011200   25  .20000D+00 0.07500D+00  111 26  .25000D+00 0.07600D+00  111
0011300   27  .30000D+00 0.07550D+00  111 28  .40000D+00 0.07140D+00  111
0011400   29  .50000D+00 0.06410D+00  111 30  .60000D+00 0.05470D+00  111
0011500   31  .70000D+00 0.04360D+00  111 32  .80000D+00 0.03080D+00  111
0011600   33  .90000D+00 0.01680D+00  111 34  .95000D+00 0.00920D+00  111
0011700   35 1.00000D+00 0.00000D+00  111 35 1.00000D+00 0.00000D+00  000
0011800    0       0.000000  0.000000  0.000000  0.000000  0.000000    0.0000     0.0000
```

Appendix B
Input Data Format for Program WIND-01

Card	Format
1	20A4
2 and 3	2X, 5(7X, F8.3)
4	I5, 5X, 5F10.6, 2F10.4
5 to m	I3, 2D12.5, I5, I3, 2D12.5, I5
(m + 1)	Same as card 4
. . .	Same as card 4 if NEXT = 222 on card m; otherwise, format is the same as on cards 5 to m
n	Same as card 4

Appendix C
Output Listing of Program WIND-01 for Mod-0 Case

NASA 100KW MOD-0 WIND TURBINE ; AIRFOIL NACA 2300 SERIES

XCELL	YCELL	ZCELL	TIPCEL	PMESH
24.00000	6.00000	8.00000	6.00000	1.00000
RHUB	RTIP	RINF	BLADE	SETANG
0.10000	62.50000	1.20000	2.00000	0.00000

LOCAL GEOMETRIC INPUT PARAMETERS

N	RLEAD	CHORD	XLEAD	RO1	RO2	TLEAD	TWIST
1	0.050000	0.072000	0.006139	0.180000	0.025000	0.0000	58.0000
2	0.160000	0.072000	0.019645	0.120000	0.015000	0.0000	69.0000
3	0.240000	0.072000	0.029468	0.090000	0.009000	0.0000	75.5000
4	0.350000	0.065333	0.042974	0.063300	0.005000	0.0000	81.0000
5	0.670000	0.038666	0.082265	0.035600	0.002500	0.0000	89.0000
6	1.000000	0.024000	0.122784	0.015800	0.001000	0.0000	92.0000

CYLINDRICAL SURFACES

K	RADII	TWIST	CHORD	XL	TL
2	0.100000E 00	0.645720E 02	0.749081E-01	0.122780E-01	0.0000
3	0.166709E 00	0.701317E 02	0.731283E-01	0.204688E-01	0.0000
4	0.286018E 00	0.786656E 02	0.709638E-01	0.351183E-01	0.0000
5	0.396563E 00	0.811770E 02	0.620590E-01	0.466227E-01	-0.0371
6	0.560923E 00	0.873103E 02	0.474956E-01	0.688719E-01	0.0000
7	0.803537E 00	0.911525E 02	0.306003E-01	0.986613E-01	0.0000
8	0.969867E 00	0.922053E 02	0.246055E-01	0.119084E 00	0.0000

DATA STORED ON UNIT NO. 10

X-Y-Z COORDINATES STORED ON UNIT 11

Appendix D
Input Data Program WIND-02 for Mod-0 Case

```
0000100    NASA 100KW WIND TURBINE - NACA 2300 SERIES BLADE
0000200    UINF  = 0.18000D+02OMEGA = 0.40000D+02TEMP  = 0.32000D+02
0000300    CONVER= 1.00000D-05RLX   = 1.65000D+00PMESH = 1.00000D+00
0000400    TITR1 = 0.50000D+02TITR2 = 0.10000D+02PRESS = 0.14700D+02
```

Appendix E
Input Data Format for Program WIND-02

Card	Format
1	20A4
2, 3, and 4	2X, 3(7X, D12.5)

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16. Abstract

A computer program (WIND) has been developed that numerically solves an exact, full-potential equation (FPE) for three-dimensional, steady, inviscid flow through an isolated wind turbine rotor. The program automatically generates a three-dimensional, boundary-conforming grid and iteratively solves the FPE while fully accounting for both the rotating cascade and Coriolis effects. The numerical techniques incorporated involve rotated, type-dependent finite differencing, a finite volume method, artificial viscosity in conservative form, and a successive line overrelaxation combined with the sequential grid refinement procedure to accelerate the iterative convergence rate. Consequently WIND is capable of accurately analyzing incompressible and compressible flows, including those that are locally transonic and terminated by weak shocks. WIND can also be used to analyze the flow around isolated aircraft propellers and helicopter rotors in hover as long as the total relative Mach number of the oncoming flow is subsonic.

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