A Vortex Model of the Darrieus Turbine: An Analytical and Experimental Study

J. H. Strickland, T. Smith, K. Sun
Texas Tech University
Lubbock, TX 79409

When printing a copy of any digitized SAND Report, you are required to update the markings to current standards.
ABSTRACT

Improvements in a vortex/lifting, line-based Darrieus wind turbine, aerodynamic performance/loads model are described. These improvements include consideration of dynamic stall, pitching circulation, and added mass. Validation of these calculations was done through water tow tank experiments. Certain computer run time reduction schemes for the code are discussed.
# TABLE OF CONTENTS

1.0 INTRODUCTION ................................................................. 1
   1.1 Purpose of Research ............................................. 1
   1.2 Summary of Previous Work ..................................... 2
   1.3 Research Objectives ........................................... 4

2.0 AERODYNAMIC MODEL ......................................................... 4
   2.1 Summary of the Vortex Model .................................. 5
   2.2 Dynamic Effects .................................................. 9
      2.2.1 Added mass effects ................................... 10
      2.2.2 Circulatory effects ................................13
      2.2.3 Dynamic stall ........................................... 15
      2.2.4 Computation of unsteady force, moment, and
            torque coefficients ................................ 16
   2.3 Methods for Reducing CPU Time ................................. 20
      2.3.1 Frozen lattice point velocities ..................... 21
      2.3.2 Fixed wake grid points ................................ 21
      2.3.3 Continuity considerations ........................... 26
      2.3.4 Vortex proximity ....................................... 28

3.0 TWO-DIMENSIONAL EXPERIMENT ............................................ 29
   3.1 Wake Velocity Profiles .......................................... 30
      3.1.1 Velocity transducer .................................. 32
      3.1.2 Calibration of hot-film probe ........................ 34
      3.1.3 Data acquisition and test matrix ................... 36
   3.2 Improved Blade Force Measurements ............................ 39
      3.2.1 Modified procedure to obtain forces ............... 40
      3.2.2 Signal processing ..................................... 42
4.0 COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS .......... 42
   4.1 Blade Forces .............................................. 43
   4.2 Wake Structure ............................................ 51
      4.2.1 Two-dimensional rotor ............................... 51
      4.2.2 Three-dimensional rotor ............................. 55
5.0 SUMMARY OF RESULTS ........................................ 63
   5.1 Summary .................................................. 63
   5.2 Conclusions ............................................... 65
   5.3 Recommendations .......................................... 66
6.0 BIBLIOGRAPHY ................................................ 67
7.0 APPENDIX ..................................................... 69
   7.1 VDART2 Computer Code Listing (FWG Version) ............... 70
   7.2 VDART3 Computer Code Listing (FWG Version) ............... 89
   7.3 Blade Force Data .......................................... 111
   7.4 Wake Velocity Data ........................................ 155
1.0 INTRODUCTION

A number of aerodynamic performance prediction models have been formulated for the Darrieus turbine in the past. In general, these models are based either upon simple momentum principles [1,2,3,4] or upon some form of vortex theory [5,6,7,8,9]. The major disadvantages of the simple momentum models are associated with their inability to adequately predict blade loadings and near-wake structure. They do, however, provide reasonable predictions of the overall rotor performance for situations where the rotor is not heavily loaded. The vortex model [9], on the other hand, appears to be capable of adequately predicting blade loading and wake structure, but previously required a large amount of computing time. Additional experimental work was needed to supplement that obtained from the study given by reference [9] to fully validate the vortex model.

1.1 Purpose of Research

This work is an extension of work performed under Sandia contract #06-4178, "A Three-Dimensional Aerodynamic Vortex Model for the Darrieus Turbine" [9]. Based on that study, it was ascertained that additional work should be performed with regard to both analysis and experiment.

The major need in the analysis area was found to be with regard to the sometimes excessive computer processing times required. For instance, it was found that computer processing times for the two- and three-dimensional vortex models were much longer than for their simple momentum counterparts. In some cases, the computer processing times for the three-dimensional vortex model were so long that a periodic solution could not be obtained in a reasonable time (less than one hour on the CDC 6600). The excessive computer processing time greatly limited the utility of these computer codes.
The major need with regard to experimental work was to obtain quantitative data which describes the wake region, in addition to the qualitative data already obtained from flow visualization studies. This new data is in the form of velocity profiles taken in the wake region at several streamwise locations behind the rotor. Another need with regard to experimental work was to obtain reliable blade force measurements. While normal blade forces predicted by the vortex model were found to be in good agreement with the original experimental data, this was not the case for tangential blade forces. Tangential blade forces predicted by the vortex model were found to agree rather poorly with the original experimental data. The tangential force is, in general, an order of magnitude smaller than the normal force. An uncertainty analysis revealed that with the previous experimental arrangement very large errors in the experimental data would likely exist.

Therefore, the purpose of this research was to enhance the utility and credibility of the present vortex model. The successful completion of this work provides a valuable analytical tool for Darrieus wind turbine designers.

1.2 Summary of Previous Work

Several aerodynamic performance prediction models have been formulated for the Darrieus turbine. The models of Templin [1], Wilson and Lissaman [2], Strickland [3], and Shankar [4] have all been used to predict the performance of three-dimensional Darrieus rotors. Each of these models (the latter three being virtually identical) are based upon equating the forces on the rotor blades to the change in streamwise momentum through the rotor. The overall performance can be predicted reasonably well with these models under conditions where the rotor blades are lightly loaded and the rotor tip to wind speed ratios are not high.
While these models are moderately successful at predicting overall performance trends, they are inadequate from several standpoints. Accurate performance predictions for large tip to wind speed ratios cannot be made because the momentum equations used in these models become invalid. This situation deteriorates with increasing rotor solidity. Predicted blade loads are inaccurate since these models assume a quasi-steady flow through the rotor, a constant streamwise velocity as a function of streamwise position in the vicinity of the rotor, and that the flow velocities normal to the freestream direction are zero. There has been some doubt in the past as to whether or not meaningful information concerning the near-wake structure of the rotor could be obtained from these models. This information may be important with regard to the placement of rotors in close proximity to each other and in making assessments of the environmental impact of large-scale rotors on downstream areas. Alteration of the simple momentum models to alleviate all of the listed objections presently appears to be unlikely.

Another class of prediction schemes are the "vortex models" which do not have the disadvantages associated with the simple momentum models. Several of these vortex models for vertical axis machines have been developed in the past. Models which typify previously developed vertical axis vortex models are those due to Fanucci [5], Larsen [6], Wilson [7], Holmes [8], and Strickland [10]. The vortex models of Fanucci [5], Wilson [7], and Holmes [8] are strictly two-dimensional models. The vortex model of Larsen [6] is not strictly two-dimensional if the vortices trailing from the rotor blade tips are considered. Both Fanucci [5] and Holmes [8] assumed that rotor blades were always at angles of attack sufficiently small such that aerodynamic stall was not encountered. The giromill [6,7]
has articulating blades which operate at angles of attack that are less than the stall threshold levels. The vortex model of Strickland [10] is formulated for three-dimensional rotors and considers aerodynamic stall.

Experimental work with regard to overall rotor performance has been conducted by several groups. Notable among these works are those conducted by Sandia Laboratories on small rotors placed in a wind tunnel [11] and large rotors operating in the natural wind environment [12,13]. The experimental work reported in [9] and summarized in [10] produced results with regard to details of the flow structure near the rotor, as well as instantaneous blade force measurements. Streak lines produced by fluid particles leaving the trailing edge of two-dimensional rotor blades were successfully visualized and instantaneous normal blade forces were successfully measured.

1.3 Research Objectives

The major research objectives for this work were as follows:
* The computer processing times required by the original vortex model were to be reduced by an order of magnitude.
* Spanwise velocity profiles were to be taken in the wake of the two-dimensional experimental rotor.
* Satisfactory measurement of the tangential blade forces on the two-dimensional experimental rotor was to be made.
* A user's guide for the two- and three-dimensional vortex model computer codes was to be written.

2.0 AERODYNAMIC MODEL

The basic vortex model developed prior to this work due to Strickland [9,10] will be described only briefly. The reader is referred to the
indicated references for more details. The original work was based upon quasi-steady aerodynamics which gives rise to some error in predicting blade forces and performance. Dynamic effects and their inclusion into the original model are discussed in section 2.2. Methods for reducing CPU time are discussed in section 2.3.

2.1 Summary of the Vortex Model

The general analytical approach requires that the rotor blades be divided into a number of segments along their span. The production, convection, and interaction of vortex systems springing from the individual blade elements are modeled and used to predict the "induced velocity" or "perturbation velocity" at various points in the flow field. The induced or perturbation velocity at a point is simply the velocity which is superimposed on the undisturbed wind stream by the wind machine. Having obtained the induced velocities, the lift and drag of the blade segment can be obtained using airfoil section data.

A simple representation of the vortex system associated with a blade element is shown in Figure 1. The airfoil blade element is replaced by a "bound" vortex filament sometimes called a "substitution" vortex filament [14] or a "lifting line" [15]. The use of a single line vortex to represent an airfoil segment is a simplification over the two-dimensional vortex model of Fanucci [5] which uses three to eight bound vortices positioned along the camber line. The use of a single bound vortex represents the flow field adequately at distances greater than about one chord length from the airfoil [14]. The strengths of the bound vortex and each trailing tip vortex are equal as a consequence of the Helmholtz theorems of vorticity [16]. As indicated in Figure 1, the strengths of the shed vortex
Figure 1. Vortex System for a Single Blade Element
systems have changed on several occasions. On each of these occasions, a spanwise vortex is shed whose strength is equal to the change in the bound vortex strength as dictated by Kelvin's theorem [16].

Each portion of a vortex filament making up the shed vortex system is convected in the flow at the local fluid velocity. Therefore, the vortex filament will be distorted in a number of ways as it moves through the fluid. As a first approximation, it can be assumed that the vortex filament may stretch, translate, and rotate as a function of time.

The fluid velocity at any point in the flow field is the sum of the undisturbed wind stream velocity and the velocity induced by all of the vortex filaments in the flow field. The velocity induced at a point in the flow field by a single vortex filament can be obtained from the Biot-Savart law, which relates the induced velocity to the filament strength. Referring to the case shown in Figure 2, for a straight vortex filament of strength $\Gamma$ and length $\ell$ the induced velocity $\mathbf{V}_p$ at a point $p$ not on the filament is given by [15]

$$\mathbf{V}_p = \hat{e} \frac{\Gamma}{4\pi \ell} (\cos \theta_1 + \cos \theta_2)$$

(1)

where the unit vector $\hat{e}$ is in the direction of $\hat{r} \times \hat{\ell}$. It should be noted that if point $p$ should happen to lie on the vortex filament, equation (1) yields indeterminate results, since $\hat{e}$ cannot be defined and the magnitude of $\mathbf{V}_p$ is infinite. The velocity induced by a straight vortex filament on itself is, in fact, equal to zero [17].

In order to allow closure of the vortex model, a relationship between the bound vortex strength and the velocity induced at a blade segment must be obtained. A relationship between the lift, $L$, per unit span on a blade
Figure 2. Velocity Induced at a Point by a Vortex Filament
segment and the bound vortex strength, $\Gamma_B$, is given by the Kutta-Joukowski law [16]. The lift also can be formulated in terms of the airfoil section lift coefficient, $C_L$. Equating these two expressions for lift yields the required relationship between the bound vortex strength and the induced velocity at a particular blade segment.

$$\Gamma_B = \frac{1}{2} C_L U_R$$

(2)

Here the blade chord is denoted by $C$, and $U_R$ is the local relative fluid velocity in the plane of the airfoil section. It should be noted that the effects of aerodynamic stall are automatically introduced into equation (2) through the section lift coefficient.

2.2 Dynamic Effects

Unsteady aerodynamic loading of an airfoil can arise due to several effects. In the absence of aerodynamic stall, these effects can be loosely categorized as those due to fluid inertia "added mass" and unsteady wake circulation "circulatory lift and moment." For conditions where boundary layer separation can occur, a combination of viscous, inertial, and unsteady wake effects give rise to "dynamic stall."

Added mass effects are normally small for the C/R values commonly used on full-scale Darrieus turbines (i.e., C/R $\approx 0.07$). For the present experiment where C/R = 0.15, added mass effects are important at the higher tip to wind speed ratios. These effects were unaccounted for in the original vortex model and should be added to more accurately predict aerodynamic loads.

The circulatory lift produced by the unsteady wake has been included in the vortex model in an approximate way. The effect of downwash and
upwash produced by discrete vortices models this effect. The pitching of the airfoil does require an adjustment in the bound vorticity in order to satisfy the Kutta condition. For small values of $C/R$, this adjustment is negligible. At larger values of $C/R$, this effect must be considered. While the original vortex model included the effect of steady stall, it did not include any dynamic stall model. Klimas [18] has included an approximate dynamic stall model in the Sandia version of VDART. It appears that dynamic stall may be an important phenomenon even in turbines with small values of $C/R$. Neglect of the dynamic stall effect makes small differences in the magnitude of the rotor power coefficient, but large differences in plots of power output versus windspeed.

2.2.1 Added mass effects

The added mass effect will be obtained by utilizing an analytical technique found in Milne-Thomson [19]. For simplicity, it is assumed that the airfoil can be approximated as a flat plate with a coordinate system as shown in Figure 3. The $x$-$y$ axes are fixed in the plate. The origin of this coordinate system (body coordinates) moves with a relative velocity, $U_R'$, with respect to an inertial reference frame fixed in the fluid at "infinity." The body reference frame rotates with an angular velocity of $\omega$ with respect to the inertial reference frame.

The complex potential for the flat plate undergoing the prescribed motion can be written in the following form with respect to the inertial reference frame:

$$F(Z) = \frac{4\pi}{2\pi} \log Z + \frac{a_1}{Z} + \frac{a_2}{Z^2} + \ldots$$  \hspace{1cm} (3)
Figure 3 Flat Plate Airfoil Motion
In particular from article 9.65 of reference [19], the complex potential for a flat plate rotating and translating with respect to an inertial reference frame is given by

\[
F(\zeta) + \frac{i \Gamma}{2\pi} \log \zeta + (i \frac{C}{2} U_R \sin \alpha') \zeta^{-1} + i \frac{C^2}{16} \omega \zeta^{-2}
\]  

(4)

where

\[
Z = \frac{C}{4} (\zeta + \frac{1}{\zeta}).
\]

(5)

For large values of \( Z \), the complex potential can be written as

\[
F(Z) = \frac{i \Gamma}{2\pi} \log \left( \frac{4}{C} Z \right) + [2i \left( \frac{C}{4} \right)^2 U_R \sin \alpha'] \zeta^{-1} + i \left( \frac{C}{4} \right)^4 \omega \zeta^{-2}.
\]

(6)

Following the procedure in article 9.53 of reference [19], the complex force on the flat plate can be written as

\[
X + iY = i \rho \Gamma (U + iV) - 2 \pi \rho (i \omega a_1 + \frac{dV}{dt}).
\]

(7)

Here \( X \) and \( Y \) are the forces along the body coordinate axes, and \( U \) and \( V \) are the velocities of the origin of the body coordinate system with respect to the inertial system. The velocities, \( U \) and \( V \), represent instantaneous velocities along the x and y axis, respectively. By comparing equations 3 and 4, it is seen that the value of \( a_1 \) required in equation 7 is given by

\[
a_1 = i \left( \frac{C}{4} \right)^2 U_R \sin \alpha' = i \left( \frac{C}{4} \right)^2 v.
\]

(8)

Inserting this expression into equation 7 yields

\[
X + iY = i \rho \Gamma (U + iV) = 4 \pi \rho \left( \frac{C}{4} \right)^2 (\omega V - i \frac{dv}{dt}),
\]

(9)
The added mass effects are seen to be those represented by the "non-circulatory" part of the solution. The forces arising due to the added mass effects can be given as

\[ X_{am} = \frac{\pi \rho C^2}{4} \omega V \]  
\[ Y_{am} = -\frac{\pi \rho C^2}{4} \frac{dV}{dt}. \]  

The pitching moment about the mid-chord can be obtained in a similar fashion by using the development in article 9.52 of reference [19]. The results are given as

\[ M = -\frac{\pi \rho U C^2}{4} V \]  

where the positive sense is counterclockwise.

The moment about the mid-chord does not depend upon the circulation strength and, thus, might be thought of as an added mass effect. Traditionally, the moment coefficient is based on the moment at the quarter-chord with the lift force assumed to act through that point. Adopting this tradition yields the following formulation for the moment at the quarter-chord:

\[ M_{c/4} = \frac{C}{4} Y - \frac{\pi \rho U C^2}{4} V. \]  

Since, for steady flow over a flat plate airfoil, the right-hand side of equation 12 is zero, this term in the unsteady case can be viewed as an added mass effect.

2.2.2 Circulatory effects

The pitching of the airfoil gives rise to changes in the bound
circulation strength as a result of required adjustments to satisfy the Kutta condition and as a result of the shed vortex sheet. As mentioned previously, the shed vortex sheet is modeled in an approximate way in the VDART model with a series of discrete vortices. It remains then to satisfy the Kutta condition for the pitching airfoil.

The Kutta condition will be satisfied if a stagnation point is forced to coincide with the sharp trailing edge of the airfoil. This can most easily be accomplished by considering the flow in the circle plane as given by equation 4. The complex velocity in the circle plane can be obtained by taking the derivative of the complex potential.

\[
\frac{dF(\zeta)}{d\zeta} = \frac{i \Gamma}{2\pi} \zeta^{-1} - i \frac{C}{2} U_R \sin \alpha' \zeta^{-2} - i \frac{C^2}{8} \omega \zeta^{-3}
\]  

(13)

From equation 5, it can be seen that for the trailing edge condition, \((Z = C/2), \zeta = 1\). It should be noted that this choice rather than \(Z = -C/2\) for the trailing edge condition limits the range of \(\alpha'\) to \(\pi/2 < \alpha' < 3\pi/2\). Since the stagnation condition requires that the complex velocity be equal to zero, then the bound circulation strength must be equal to

\[
\Gamma = \pi C U_R \sin \alpha' + \pi \frac{C^2}{4} \omega.
\]  

(14)

The last term represents the additional circulation due to the pitching motion. It should be noted that this same result is obtained if one calculates the circulation based on the motion of the three-quarter chord point.

From equation 9, the forces due to circulation are given by
2.2.3 Dynamic stall

Dynamic stall is a highly complex problem and will be handled in an approximate manner, using a modified Boeing-Vertol method [20]. The observed hysteresis in lift and moment coefficients is obtained in this method by utilizing two-dimensional static wind tunnel data, along with an empirically derived stall delay representation.

The method utilizes a modified blade angle of attack for use in entering two-dimensional force coefficient data. The modified angle of attack $\alpha_m$ is given by

$$\alpha_m = \alpha_b - K_1 \gamma (| \frac{C_b}{V_R} |)^{1/2} S_\alpha$$

(16)

where $\alpha_b$ is the effective blade angle of attack, $\gamma$ and $K_1$ are empirical constants, and $S_\alpha$ is the sign of $\alpha$. This modified angle of attack is used to calculate force coefficients in the following manner:

$$C_L = \frac{\alpha_b}{\alpha_m - \alpha_{b0}} C_L(\alpha_m)$$

$$C_M = C_M(\alpha_m)$$

$$C_d = C_d(\alpha_m).$$

(17)

Here $\alpha_{b0}$ is the effective blade angle of attack for zero lift and $C_L$, $C_M$, and $C_d$ are the coefficients of lift, moment, and drag, respectively.

For low Mach numbers and for airfoil thickness to chord ratios greater than 0.1, the value of $\gamma$ for lift stall ($\gamma_L$) and moment stall ($\gamma_M$) are
given by

\[ \gamma_L = 1.4 - 6(0.06 - t/c) \]  
\[ \gamma_M = 1.0 - 2.5(0.06 - t/c) \]  

where \( t \) is the maximum airfoil thickness. Therefore, the value of \( \alpha_m \) used to calculate the lift coefficient is obtained using \( \gamma_L \), whereas \( \alpha_m \) for the moment and drag coefficients is based on \( \gamma_M \). The empirical constant, \( K_l \), can be obtained from

\[ K_l = \frac{3}{4} + \frac{1}{4} S \dot{\alpha} \]  

Therefore, \( K_l \) is equal to 1.0 for \( \dot{\alpha} \) positive and 0.5 for \( \dot{\alpha} \) negative.

This formulation is applied when the angle of attack, \( \alpha_B \), is greater than the static stall angle or when the angle of attack is decreasing after having been above the stall angle. The stall model is turned off when the angle of attack is below the stall angle and increasing. Dynamic effects are accounted for, as outlined in the previous two sections, when the stall model is turned off.

2.2.4 Computation of unsteady force, moment, and torque coefficients

Use of the material developed in the preceding sections allows a rational method for computing force and moment coefficients, using airfoil section data corrected for dynamic effects. The idealized potential flow models can be used to suggest how the data should be corrected for dynamic effects.

The conventional nomenclature and positive sense for forces, angles, velocities, etc., are shown in Figure 4 for an airfoil blade on a Darrieus turbine. It should be noted that the attachment point, \( \xi \), is extremely
Figure 4 Blade Forces and Mounting Geometry
important when considering dynamic effects, since it introduces what some have referred to as "virtual angle of incidence" [21]. The forces and moment per unit length of blade can be defined in terms of thrust force, normal force, and moment coefficients as follows:

\[
\begin{align*}
F'_t &= \frac{1}{2} \ C_t \rho CV^2_R \\
F'_n &= \frac{1}{2} \ C_n \rho CV^2_R \\
M'_{c/4} &= \frac{1}{2} \ C_m \rho CV^2_R 
\end{align*}
\] (20)

For the idealized flat plate case neglecting terms containing \(dV/dt\), the three coefficients can be written as

\[
\begin{align*}
C_t &= \frac{2\pi}{U} V^2 = (2\pi \sin \alpha_{1/2}) \sin \alpha_{1/2} \\
C_n &= \frac{2\pi}{U} \left( V + \frac{C}{4} \omega \right) = (2\pi \sin \alpha_{3/4}) \cos \alpha_{3/4} \\
C_m &= \frac{\pi}{U} \frac{C}{8} \omega
\end{align*}
\] (21)

where the subscripts on \(\alpha\) indicate the fraction of the chord at which the angles are taken.

From equation 21, it can be deduced that if one calculates the thrust coefficient, \(C_t\), using the angle of attack at mid-chord, dynamic effects are included. The normal coefficient, \(C_n\), should be calculated based on the three-quarter chord angle of attack, since the velocities indicated in equation 21 occur at the three-quarter chord point. In order to clarify this last statement, it should be noted that the velocity, \(V + C\omega/4\), is the relative velocity normal to the airfoil at the three-quarter chord point and that the velocity, \(U\), is the relative velocity tangent to the airfoil at all chord points, as well as the three-quarter chord point.
An order of magnitude analysis shows that the term containing $dV/dt$ in equation 10 contributes little to the total normal force and, thus, can be justifiably neglected in constructing equation 21. It also should be noted that the moment coefficient given in equation 21 is on the order of $\pi C/8R$ and is, therefore, reasonably small for normal C/R values.

In conclusion, the following rules were followed in the calculation of the force and moment coefficients:

1) The tangential force coefficient was calculated using the mid-chord angle of attack to obtain airfoil section data.

2) The normal force coefficient was calculated using the three-quarter chord angle of attack to obtain airfoil section data.

3) The moment coefficient about the quarter chord was assumed to be negligible.

The steady state coefficients are to be evaluated at either the mid-chord or three-quarter chord angle of attack, which are given to first order in terms of the angle of attack at the attachment point, $\alpha_\xi$, as follows:

$$\alpha_{1/2} = \alpha_\xi + \left(\frac{1}{2} - \xi\right) \frac{\omega}{U_R}$$

$$\alpha_{3/4} = \alpha_\xi + \left(\frac{3}{4} - \xi\right) \frac{\omega}{U_R}$$

(22)

For cases where the airfoil is stalled, the method of section 2.2.3 is used to calculate $C_L$, $C_M$, and $C_d$ from which

$$C_t = C_L \sin \alpha_{1/2} - C_d \cos \alpha_{1/2}$$

$$C_n = -C_L \cos \alpha_{3/4} - C_d \sin \alpha_{3/4}$$

$$C_m = C_M$$

(23)
The effective blade angle of attack, $\alpha_b$, used in the method of section 2.2.3 is equal to $\alpha_{3/4}$ for calculation of $C_n$ in equation 23 and $\alpha_{1/2}$ for the calculation of $C_t$ and $C_m$.

The torque produced by a unit length of blade can be given in terms of a torque coefficient, $C_t$, which in turn can be defined in terms of the force and moment coefficients as follows:

$$\tau' = \frac{1}{2} C_T \rho CV^2$$

$$C_T = C_t + \left(\frac{1}{4} - \frac{r}{R}\right) C_n + \frac{C}{r} C_m$$

2.3 METHODS FOR REDUCING CPU TIME

Original computer processing times for the Vortex DARrieus Turbine (VDART) models were moderately long. The CPU time in minutes for the original model on the CDC 7600 computer were given approximately by

$$t = \left(\frac{NE}{2}\right)^2 \left(\frac{NT}{100}\right)^3, \text{ VDART3}$$

$$t = \frac{1}{3} \left(\frac{NB}{2}\right)^2 \left(\frac{NT}{100}\right)^3, \text{ VDART2}$$

where $NE$ is the number of blade element ends, $NB$ is the number of blades, and $NT$ is the total number of time steps. The VDART2 and 3 denote two- and three-dimensional models. A major portion of the CPU time was required for calculating the velocities of wake vortex lattice points. The subroutine FIVEL, which calculates induced velocities, had already been written in an efficient format and, thus, reduction in computational time was obtained by reducing the number of times the subroutine FIVEL is called. As an example of the number of times which FIVEL might be called, consider a two-bladed rotor with ten elements. If 20 time increments per revolution
are used and if the rotor rotates through seven revolutions, then FIVEL will be called $666 \times 10^6$ times. For a two-bladed rotor in two dimensions, this figure will drop to $3.66 \times 10^6$. Several methods for reducing CPU time are presented in the sections below. Some of these methods have been tried and found to be successful while others have not.

2.3.1 Frozen lattice point velocities

One approach which has been used in the VDART2 and VDART3 programs is to update lattice point velocities on a less periodic basis. It was assumed the lattice point moves with a velocity on the order of the free-stream velocity and that the perturbation velocity should be updated when the lattice point travels a distance equal to the distance traveled by the rotor blade in one time step. Using this criteria, the wake velocities should be updated after approximately every $\frac{U_T}{U_\infty}$ time step. Therefore, the CPU time given in equation 25 can be reduced by a factor of $\frac{U_T}{U_\infty}$. Obviously, a certain amount of risk is present with this method with regard to both numerical accuracy and stability. Several cases were run initially with and without this time-saving feature, and the power coefficients were in good agreement for low to moderate tip to wind speed ratios. One case was run at a very high tip to wind speed ratio ($\frac{U_T}{U_\infty} = 20$), and numerical instabilities were seen to result. This feature should be used with caution.

2.3.2 Fixed wake grid points

A method which has been used on the VDART2 and VDART3 programs to reduce CPU time utilizes a number of grid points arranged in the flow field as shown in Figure 5. Any number of grid points can be placed anywhere in the flow; however, the arrangement shown in Figure 5 has been used most
Figure 5. Arrangement of Grid Points in the Wake
extensively. Perturbation velocities are calculated at each of these grid points instead of at the vortex lattice points in the wake. The velocities at the vortex lattice points are then obtained by linear interpolation of the velocities at the 50 grid points (250 for VDART3). Potentially, this method can reduce the CPU time by a factor of \((NE)NT/NG\) where \(NG\) is the number of fixed grid points. In reality, the interpolation procedure reduces this factor to approximately \((NE)NT/2NG\). For cases where a vortex lattice point happens to fall outside the grid pattern, its velocity is calculated in the usual way. It also should be pointed out that the lattice point velocities are calculated in the usual way until 50 (250 for VDART3) vortex lattice points are shed into the wake.

A typical comparison of blade forces obtained from VDART2 by the standard vortex model method (SVM) and the fixed wake grid method (FWG) is shown in Figure 6. A similar plot using VDART3 is shown in Figure 7. The non-dimensional tangential and normal forces \(F_t^+\) and \(F_n^+\) are defined in terms of the tangential and normal forces per unit blade length, \(F'_t\) and \(F'_n\); the fluid density, \(\rho\); the airfoil chord length, \(C\); and the freestream velocity, \(U_\infty\), by

\[
\begin{align*}
F_t^+ &= \frac{F_t'}{1/2\rho C U_\infty^2} \\
F_n^+ &= \frac{F_n'}{1/2\rho C U_\infty^2}
\end{align*}
\]

As can be seen from these figures, the agreement between the two methods is reasonably good. The largest variations appear in the downstream portion of the blade traverse. For these particular examples, the number of time increments per revolution of the rotor NTI was chosen to be 24 for the VDART2 case and 20 for the VDART3 case. For 2040° of rotation,
Figure 6. Comparison of Calculated Blade Loads (VDART2)
(--- SVM model, --- FWG model, 
Re = 40,000, NB = 2, C/R = 0.15, 
$U_f/U_\infty = 5.0$, NTI = 24)
Figure 7 Comparison of Calculated Blade Loads (VDART3, mid plane, — SVM model, --- FWG model, Re = 0.3 x 10^6, NB = 2, C/R = 0.135, U_T/U_∞ = 6.0, NTI = 20)
the SVM method was found to require approximately three times more CPU time than the FWG method.

Power coefficients were calculated for a two-dimensional one-, two-, and three-bladed rotor at tip to wind speed ratios of 2.5, 5.0, and 7.5. Agreement between this method and the conventional method was reasonably good except for the three-bladed rotor operating at a tip to wind speed ratio of 7.5. The results are depicted in Figure 8. The solid and dashed lines are visual aids only with the symbols denoting the actual information obtained from the computer runs. In each case, the FWG method yields slightly lower values of $C_p$. The difference between the two methods is accentuated at higher tip to wind speed ratios and higher solidities.

In conclusion, this technique holds especially good promise, since it reduces the time dependence on the number of time steps from a cubic function to a square function. A variation of this method would allow the fixed grid point system to expand into the downstream region as the wake expands into the downstream area. It is planned to continue to investigate the advantages and disadvantages of the FWG method by running additional cases.

2.3.3 Continuity considerations

This technique was intended to be used in conjunction with the FWG method given in the previous section. Basically, this method was intended to take advantage of the continuity equation given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

(27)

to allow calculation of one of the velocity components in terms of the
Figure 8. Comparison of Calculated Power Coefficients (VDART2)
(○ SVM model, △ FWG model, solid line for visual aid, Re = 40,000, C/R = 0.15)
others. For example, in the two-dimensional case the lateral velocity, \( w \), can be obtained from a difference equation of the form

\[
\frac{\Delta w}{\Delta z} = -\frac{\Delta u}{\Delta x}
\]  

(28)

The values of \( u \) were to be calculated as usual at the fixed wake grid points, based on the cumulative perturbation velocities from vortices in the wake. The values of \( w \) along the wake centerline were also calculated in the same fashion. All other values of \( w \) were to be calculated efficiently using equation 28.

It was originally expected that the CPU time would be reduced by one-half for the two-dimensional case and by one-third for the three-dimensional case. The expected time savings did not materialize and, in fact, this feature appeared to be a time consumer. The reason is apparent when one examines the calculation procedure in the subroutine FIVEL, which calculates the induced velocities arising from an individual vortex filament. In this procedure, several parameters are calculated which are common to the calculation of each of the components of velocity. Each component of velocity is then calculated using a single multiplication of parameters common to the calculation of the other velocities. In other words, the calculation of the velocity component, which was to be obtained from continuity considerations, requires only a single multiplication in the original scheme. Therefore, this technique was considered to be unworthy of additional consideration.

2.3.4 Vortex proximity

A technique of combining vortices whose centers pass in close proximity to each other could be quite useful in the two-dimensional case. The
spatial coincidence of vortex filaments in the three-dimensional case is, perhaps, too rare an occurrence to consider. The occasional coincidence of vortex filaments ends might, on the other hand, justify their combination. Logic to "skip" the absorbed vortex when calculating perturbation velocities should be carefully developed to avoid loss of time due to excessive use of logic "if" statements.

Conversely, vortices whose centers are far away from the point at which perturbation velocities are being calculated could be neglected. Some criteria based on a combination of range and vortex strength could be used.

Implementation of this time-saving feature did not occur as part of this work, but has been used in one form by D.E. Berg [25] of Sandia Laboratories. In his use of the method, the vortices downstream of a certain streamwise position were simply neglected, since these vortices had very little effect in the vicinity of the rotor. This scheme was used in conjunction with the fixed wake grid technique and was easily applied by neglecting vortices downstream of the last set of grid points. The reported results were good.

3.0 TWO-DIMENSIONAL EXPERIMENT

In order to check the validity of the analytical model with regard to instantaneous blade loading and wake structure, an experiment was set up as described in reference [9]. Only a brief description of the experimental arrangement will be given herein, and the reader is referred to the indicated report for more details.

In general, a straight-bladed rotor with one, two, or three blades was built and operated in a water tow tank with a depth of 1.25 meters,
a width of 5 meters, and a length of 10 meters. The rotor blades extended to within 15 centimeters of the tank bottom. This simple rotor appears to be adequate for validating the major features of the analytical model. The use of water as a working fluid greatly facilitates the ability to visualize the flow structure while working at appropriate blade Reynolds numbers. In addition, blade forces are more easily measured. In order to use available section data for the NACA 0012 airfoil, the rotor blades are required to operate at a Reynolds number of 40,000 or greater. An airfoil chord length of 9.14 cm and a rotor tip speed of 45.7 cm/sec were chosen to yield a blade Reynolds number of 40,000. Three towing speeds of 18.3 cm/sec, 9.1 cm/sec, and 6.1 cm/sec were chosen to yield tip to wind speed ratios of 2.5, 5.0, and 7.5, respectively. The rotor diameter was chosen to be 1.22 meters, thus giving solidity values (NC/R) of 0.15, 0.30, and 0.45 for one-, two-, and three-bladed rotors, respectively.

Two types of measurements were to be made to obtain quantitative data useful in further evaluation of the analytical model. The first of these was the measurement of velocity profiles in the rotor wake using a hot-wire anemometer system. The second measurement involved a second attempt to accurately measure the tangential blade forces. Methodology associated with making these measurements is given in the following sections.

3.1 Wake Velocity Profiles

Velocity profiles were obtained in the rotor wake by towing a velocity transducer along behind the rotor as depicted in Figure 9. This was repeated a number of times with the probe being placed at various spanwise locations. The distance behind the rotor at which measurements were made is fully adjustable. Probe cables were suspended from the laboratory
Figure 9. Schematic of General Arrangement for Obtaining Wake Velocity Profiles
ceiling using surgical tubing and, thus, allowed the anemometer instrumentation to be placed in a fixed laboratory reference frame.

3.1.1 Velocity transducer

The total velocity was obtained by using a TSI model 1239W Quartz coated hot film probe which has a hemispherical sensing element mounted on the end of the probe support. When the probe support axis is vertical, the sensor measures the total velocity in the two-dimensional plane of interest. The probe was used with a DISA 55M hot-wire anemometer system. This probe was selected due to its rugged nature and its applicability for use in slightly contaminated water flows.

The direction of the flow was measured using a small vane mounted to a precision ultra low torque potentiometer, as shown in Figure 10. This potentiometer is a BOWMAR model PS 091-105 with a maximum starting and running torque of 0.005 oz. in. In order to ascertain the sensitivity of the direction indicator, it is appropriate to calculate the angle of attack of the vane with respect to the oncoming field which will produce the starting torque of the potentiometer. In terms of the given parameters, the torque can be expressed by

\[ \tau = \frac{1}{2} \rho C L C_L (a - 3/4 C) U_\infty^2 \]  

If the torque is maximized with respect to C, it is found that C = 2a/3. Assuming that the lift coefficient is given by C_L = 0.1a, then

\[ \alpha = \frac{26.7T}{\ell \rho C L^2 U_\infty^2} \]

By choosing C equal to 1 inch and \ell equal to 5 inches in equation 30, it can be shown that the flow direction should be measurable to within about
Figure 10 Vane Direction Indicator
± 0.3 degrees at a towing speed of 18.3 cm/sec and about ± 3.0 degrees at a towing speed of 6.1 cm/sec.

This method of measuring flow velocities appears to yield much more reliable results than the originally proposed method using a cross-wire, hot-wire anemometer probe. According to both prominent manufactures of hot-wire equipment (TSI and DISA), the calibration drift problems associated with small hot-wires in water make their use impractical. A calibration run would have been required over the complete range of velocities and angles normally encountered by the probes prior to each run lasting more than a few minutes had the hot-wire been used. Using the large cylindrical hot-film probe and direction indicator required that the hot-film probe and direction indicator be calibrated over the appropriate velocity range only occasionally. The calibration was checked during the course of each run by noting the zero velocity value of the anemometer voltage output and the towing speed velocity voltage which occurred prior to the probe's passage into the wake. While there is not enough information in these two measurements to construct a calibration curve, correlation of these two data points with previously obtained calibration curves provides a useful check.

3.1.2 Calibration of hot-film probe

The hot-film probe was calibrated in the probe calibrator shown in Figure 11. This calibrator was designed and constructed as part of this project and utilizes water from the towing tank. The water enters the calibrator through a valve which is used to control the inlet flow rate. Before flowing over the probe, the water passes through a short section of honeycomb with screens on the upstream and downstream sides. The
Figure 11  Probe Calibrator
hydrostatic pressure in the calibrator is measured with a simple glass tube manometer mounted into the top wall. An orifice plate is used to constrict the flow so that maximum readings on the manometer are on the order of 25 cm for the particular flow range of interest.

The calibrator itself is calibrated by closing the outlet valve and noting the fill rate of the calibrator calibration chamber as a function of the calibrator manometer reading. Curves for two different orifice plates are shown in Figure 12.

The calibration move for the TSI 1239W probe obtained from the calibrator is shown in Figure 13. In addition, data obtained by simply towing the probe in the tow tank at various speeds is shown in Figure 13. The agreement between these two sets of data is very good. As can be seen from this curve, the data can be represented by

\[ V = A(E^2 - E_0^2)^n \]

where \( E \) is the probe output voltage, \( V \) is the measured fluid velocity, and \( E_0 \) is the probe output voltage for no flow. By using a least-squares curve fit through the data, the constants were found to be \( A = 1.888 \times 10^{-6} \text{ ft/} (\text{sec volts}^2 \text{m}) \), \( n = 2.214 \), and \( E_0^2 = 177 \text{ volts}^2 \).

3.1.3 Data acquisition and test matrix

Data were acquired using the Mechanical Engineering Department HP9835A desktop computer coupled to a four-channel HP59313A analog to digital converter and a HP7225A plotter. The system is capable of acquiring analog signals from an experiment at rates of up to 200 Hz, which was quite adequate in light of the rotor rotational speed of 0.12 Hz. A real time clock, coupled with the A/D pace rate, provided adequate time monitoring.
Figure 12 Calibrator Calibration Data
Figure 13. Calibration Curve for TSI 1239W Hot Film Probe (overheat ratio = 1.1)
The synchronization of the rotor position for various runs was extremely important. The rotor has a transducer (Waters Mfg. Analyzer APT 55) mounted on the main shaft, which allowed the rotor angular position to be monitored and recorded along with whatever other parameter was being measured. Calibration and input data for each run was stored on magnetic tape cartridges which are compatible with the HP9835A. Each cartridge is capable of storing 256 K Bytes of information or about 128 K data points on 42 files.

The test matrix selected for the wake velocity measurements was a compromise between several factors, such as spatial resolution, time required to perform the experiment, data manipulation and storage, and compatibility with previous computer code output format.

More than 260 wake velocity runs consisting of five blade number tip to wind speed ratio combinations, two streamwise probe locations behind the rotor, and 13 spanwise probe locations were made. Forty-eight data points per revolution were acquired. The experiment was run for an average of ten revolutions. Three measurements were made each time data were acquired (rotor position, velocity, and flow angle). With this test matrix, more than 249,600 pieces of data were collected and placed on eight 256 K Byte data cartridges.

3.2 Improved Blade Force Measurements

The original experimental arrangement has been modified to allow more accurate measurements of the tangential blade forces to be made. In addition, more accurate measurements of the normal force have been made, although they were measured in a reasonably successfully manner at an earlier date.
3.2.1 Modified procedure to obtain tangential forces

Tangential forces are, in general, on the order of 0.01 lb maximum and are, thus, quite small. Experimental uncertainties for the original experiment were estimated to be on the order of ± 70 percent. Several experimental errors were responsible for this large uncertainty. Mechanical noise caused by the meshing of gear and sprocket teeth produces dynamic forces which are the same order of magnitude as the tangential force. Fortunately, this noise was successfully filtered out of the signal. The original placement of the strain gage bridges required that signals from two sets of bridges be summed in order to obtain the tangential force. This was previously done by hand, which introduced errors associated with the digitizing process and phase misalignment of the two signals. Signal levels from the strain gage circuits were on the order of 50 μV max. These signals were amplified by a factor of 1,000 before being passed through a set of slip rings. Thus, the signal level through the slip rings was only about 50 mV, which is felt to be relatively low considering that the slip rings were not of especially high quality. Some shifting and drifting of output signals was noted, which was thought to be caused by variations of the resistance in the slip rings.

Several modifications were made to address the above difficulties. A strain gage bridge was placed on a modified vertical support arm shown in Figure 14. This allowed the tangential forces to be obtained using a single bridge and, thus, eliminated the need to sum signals from two bridges. The strain gages used were 350 ohm gages, which allowed the bridge voltage to be increased from 5 volts to 15 volts with a corresponding factor of three increase in sensitivity. In addition, the cross section thickness at the point of measurement was decreased by a factor of two so that the
Figure 14. Blade Force Measurement

1. $F_t$ strain gage bridge
2. $F_n$ strain gage bridge
3. $M$ strain gage bridge
bridge output was increased by a factor of four. Therefore, the signal level was increased by a factor of 12. A new set of silver slip rings was obtained, which eliminated the oxide buildup problems associated with the old copper slip rings. The experiment was modified to accept the new slip ring assembly. The strain gage bridge amplifiers were also upgraded.

3.2.2 Signal processing

Force measurements at each of the three indicated positions were made using a Whetstone bridge with four active strain gage elements. The signals produced by the bridge circuits were amplified using CALEX model 176L amplifiers mounted on the rotor arm. A gain of approximately 1000 was used to amplify the millivolt signals into the 0.1 to 10 volt range. The amplified signals were passed through slip rings and monitored with the HP9835A data acquisition system mentioned in section 3.1.3. A KRONITE filter (model 335) was used to eliminate mechanical noise at approximately 2 Hz from the $F_t$ signal whose frequency content is approximately 0.1 to 0.2 Hz. The low-pass filter was set on 0.6 Hz.

Ten blade force runs consisting of five blade number tip to wind speed ratio combinations and two force measurements (normal and tangential) were made. Forty-eight data points per revolution were acquired for an average of ten revolutions per run. Three measurements were made each time data were acquired (time, force, rotor position). With this test matrix, 14,400 pieces of data were collected which required approximately 28,800 Bytes of memory on a data cartridge.

4.0 COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

The major purpose of this section is to present analytical and experimental results from the present work. Where applicable, these results will
be presented in light of previous analytical models and experimental data. A comparison of analytical and experimental results pertaining to blade forces on the two-dimensional rotor will be presented in the first section. Comparisons for both the two-dimensional rotor and a three-dimensional rotor will be made with respect to wake velocity profiles in the second section.

4.1 Blade Forces

Typical blade force measurements taken with the modified experimental setup are shown in Figure 15 and 16. The quality of these data appear to be much better than those data presented in reference [9]. Repeatability was found to be very good as evidenced by the very close agreement between data taken during two different runs. A complete set of data for the blade force measurements can be found in the appendix (section 7.3).

From preliminary comparisons of these data with VDART2 output, it became apparent that the dynamic effects discussed in section 2.2 were significant. At the lowest tip to wind speed ratio (2.5), dynamic stall was found to be important. At the highest tip to wind speed ratio (7.5), added mass effects and pitching circulation were found to be important, while at the moderate tip to wind speed ratio (5.0), both effects played a role.

It was also ascertained that the normal blade force data should be corrected by subtracting out the centrifugal forces induced in the experiment. This correction can be given approximately by

$$
\Delta F_n^+ = -1.34 \frac{\rho_B}{\rho_f} \frac{C}{t} \frac{\ell_{bt}}{\ell_{bf}} \left( \frac{U_T}{U_\infty} \right)^2
$$

where $\rho_B/\rho_f$ is the blade density to fluid density ratio, $t/C$ is the thickness to chord ratio, and $\ell_{bt}/\ell_{bf}$ is the total blade length to the blade length immersed in the fluid ratio. The numerical coefficient is equal
Figure 15  Normal Force Data From Two-Dimensional Experiment ($U_{f}/U_{\infty} = 7.5$, $C/R = 0.15$, $Re = 40,000$)
Figure 16 Tangential Force Data From Two-Dimensional Experiment
($U_T/U_\infty = 7.5$, $C/R = 0.15$, $Re = 40,000$)
to twice the airfoil cross sectional area divided by the thickness chord product. This correction is insignificant at the lower tip to wind speed ratios producing a downward shift in the $F_n^+$ curve of only 0.48 at a tip to wind speed of 2.5. At a tip to wind speed ratio of 7.5, the shift is equal to about 4.29.

Results at a tip to wind speed ratio of 7.5 are shown in Figure 17. At this tip to wind speed ratio, only the dynamic effects discussed in sections 2.2.1 and 2.2.2 are present; dynamic stall does not occur. As can be noted from this figure, these dynamic effects produce a significant downward shift in the $F_n^+$ curve and an amplification in the $F_t^+$ curve. It is apparent that these effects should be included in the analytical model.

The agreement between the VDART2 model and this experiment is reasonably good in light of the uncertainties. The hump seen in the experimental curve near $1080^\circ + 270^\circ$ may be partially due to misalignment errors in the blade mounting. Errors on the order of 1° in the blade angle of attack could cause this level of deviation from the analysis. A slight phase shift is also apparent between analysis and experiment. The exact cause of this shift is unknown, but may be partially due to the time step size used in the analytical model. Since calculations are smeared over a particular time step which represents about 15° of rotor rotation, the shift due to this cause could potentially be up to 15°.

Results at a tip to wind speed ratio of 2.5 are shown in Figure 18. At this tip to wind speed ratio, the dominant dynamic effects are those due to dynamic stall which was discussed in section 2.2.3. It is apparent from Figure 18 that some sort of correction to the quasi-steady analysis is required to adequately predict the experimental results. Strict application of the method suggested in section 2.2.3 yielded values of $F_t^+$ which were
Figure 17. Blade Force Data For a Two-Dimensional Rotor
(Re = 40,000, \( N_b = 2 \), \( U_r/U_\infty = 7.5 \), o tow tank data, --- quasi-steady model, — dynamic model)
Figure 18. Blade Force Data for a Two-Dimensional Rotor
(Re = 40,000, N_B = 2, U_T/U_0 = 2.5, θ = tow tank data, --- quasi-steady model, --- dynamic model)
on the order of 3.5. Several modifications were tried in an attempt to bring the results into closer agreement. These modifications were primarily aimed at adapting the time delay coefficients given in equation 18. Uniform adjustment of these coefficients, where the ratio, $\gamma_L/\gamma_M$, was held constant, could be used to produce a $F^+_n$ curve which was satisfactory, while $F^+_t$ was unsatisfactory or vice versa. The most satisfactory adjustment of the time delay coefficients is shown in Figure 18. In this case, $\gamma_L$ was used as given in equation 18, whereas $\gamma_M$ (used to calculate delay in drag coefficient) was set equal to zero. The reason that this adjustment yields better results is unclear. Even with this adjustment, the peak value of $F^+_t$ is overpredicted by 66 percent. Therefore, while the modified Boeing-Vertol dynamic stall model does appear to yield improvement in prediction of normal and tangential forces, the results are not totally satisfying.

Figure 19 represents data taken at a moderate tip to wind speed ratio (5.0), where each of the dynamic effects (added mass, pitching circulation, and dynamic stall) are important. In this case, the values of $\gamma_L$ and $\gamma_M$ used in the analysis are as given in equation 18. If $\gamma_M$ is set equal to zero as in the previous case, stall occurs prematurely and "chops off" the $F^+_t$ curve at about 2.0. The undershoot in the predicted $F^+_L$ curve at around \(1080^\circ + 150^\circ\) is a result of the hysteresis loop in the Boeing-Vertol dynamic stall model.

It goes almost without saying that several anomalies exist with regard to the dynamic stall model presently being employed. A review of this and other dynamic stall models given by McCrosky [26] indicates that the inconsistencies in such models are rather commonplace. It is apparent that additional work needs to be done in this area. It should be noted that the effects of dynamic stall are strongly related to the chord to radius
Figure 19. Blade Force Data for a Two-Dimensional Rotor
(Re = 40,000, N = 2, U_p/U_∞ = 5.0, • tow tank data, --- quasi-steady model, — dynamic model)
ratio, C/R, as are other dynamic effects. In general, the effects are strongest for large C/R values. The two-dimensional experiment conducted in the present work represents a rather large C/R value equal to 0.15, as opposed to about 0.05 for most full-scale rotors. Therefore, the configuration studied in the present work represents a rather severe test with regard to dynamic effects.

4.2 Wake Structure

Results from the present two-dimensional tow tank experiment, as well as results from the wake measurements behind a three-dimensional Darrieus turbine made by Vermeulen [22], will be compared with analytical results in this section. The test conditions are vastly different for the two sets of experiments with the tow tank experiment representing a two-dimensional low turbulence level flow, while the measurements made by Vermeulen represent a three-dimensional high turbulence level atmospheric flow.

4.2.1 Two-dimensional rotor

Velocity profiles were taken at one and two rotor diameters downstream of the rotors used in the tow tank test series. These experimental data can be compared not only with the VDART analytical model, but also with the simple momentum model [3]. The simple momentum model can be used to estimate the fully developed wake by multiplying the velocity defect computed for the "actuator" disk by a factor of two. As will be shown in section 4.2.2, the wake behind a Darrieus turbine reaches a fully developed condition within about one rotor diameter downstream of its vertical axis.

Figures 20, 21, and 22 illustrate that the level of agreement between both analytical models and the experimental data is reasonably good so long as the perturbation velocities are small. However, the momentum model is
Figure 20. Comparison Between DART, VDART2 and Experimental Data at One Rotor Diameter Downstream
\( \text{NC/R} = 0.30, \text{U}_{\infty}/U_{\infty} = 2.5, \text{Re} = 40,000 \)
Figure 21. Comparison Between DART, VDART2 and Experimental Data at One Rotor Diameter Downstream
(NC/R = 0.15, UT/U_∞ = 5, Re = 40,000)
Figure 22. Comparison Between DART, VDART2 and Experimental Data at One Rotor Diameter Downstream (NC/R = 0.30, $U_T/U_\infty = 5$, Re = 40,000)
unable to predict a reasonable wake velocity profile for cases where the perturbation velocity approaches 1.0. It is well known that the momentum model breaks down for these cases. The perturbation velocity profile shown for the case in Figure 22 is completely unrealistic, since it indicates that the fluid in the wake is moving upstream into the rotor. Since the level of the perturbation velocity is a strong function of tip to wind speed ratio and rotor solidity (NC/R), it can be said, in general, that the simple momentum model will not predict a reasonable wake at high tip to wind speed ratios or for large rotor solidities.

The vortex model, on the other hand, continues to predict reasonable results for the average streamwise velocity perturbations at the higher tip to wind speed ratios and for larger rotor solidities as shown in Figure 22. The vortex model is also capable of predicting both instantaneous streamwise and lateral perturbation velocities as illustrated in Figure 23 and 24.

4.2.2 Three-dimensional rotor

Wake measurements on three-dimensional Darrieus turbines have been made by Blackwell [11] on a 2-meter turbine operating in a wind tunnel and by Vermeulen [22] on a 5.3-meter turbine operating in a natural wind environment. The results of Blackwell's measurements have been reported by Giles [23] and more recently by Sheldahl [24] and will not be presented herein.

The full-scale wake measurements obtained by Vermeulen [22] behind a 5.3-meter Darrieus turbine in a natural wind environment were chosen for the purposes of this report as a test case for the near-wake prediction capability of the VDART model. The work of Vermeulen allows the VDART model to be checked on a three-dimensional rotor of moderate size operating
Figure 23. Streamwise Perturbation Velocities (Re = 40,000, N_B = 3, U_T/U_∞ = 5.0, o tow tank data, — VDART2)
Figure 24. Lateral Perturbation Velocities (Re = 40,000,
N_B = 3, U_T/U_∞ = 5.0, • tow tank data, — VDART2)
in a turbulent natural wind environment. The measurements of Vermeulen consist of wake velocity profiles taken at 1.1, 3.0, 5.0, and 8.0 rotor diameters downstream at a few selected tip to wind speed ratios. All of these profiles were taken at "hub" height behind the rotor.

Calculations using the VDART computer code were performed for a two-bladed rotor operating at a tip to wind speed ratio, $U_T/U_\infty$, of 4.0. The chord to radius ratio, $C/R$, was selected to be equal to 0.10. Data for a NACA 0012 airfoil operating at a Reynolds number of $0.3 \times 10^6$ was used. These conditions match those reported by Vermeulen [22] reasonably well.

Predicted perturbation velocity profiles at six streamwise locations in the near wake are shown in Figure 25. As can be seen from this figure, the development of almost self similar velocity profiles occurs fairly quickly downstream of the rotor. There appears to be some broadening of the shear layers at the edges of the wake as one goes downstream. Based on the small number of data points used to define the profiles, this broadening may be somewhat the result of artistic license. The lack of symmetry is apparent with a greater velocity deficit occurring on the advancing side of the rotor.

The centerline velocity reaches a nearly constant value for points downstream of $X/D = 1.0$ as shown in Figure 26. The constant centerline velocity is, of course, characteristic of the near wake region of most bluff bodies. The centerline perturbation velocity increases linearly as a function of the streamwise distance $X/D$ in the immediate vicinity of the rotor. The reason for this latter occurrence is not apparent.

It is interesting, at this point, to note the velocity defect profile predicted by the simple momentum model [3]. This profile agrees most closely with the vortex model profile at $X/D = 0$ as shown in Figure 27.
Figure 25 Calculated Velocity Defect Profiles for a Three-Dimensional Two-Bladed Rotor
(C/R = 0.10, $U_T/U_\infty = 4.0$, Re = $0.3 \times 10^6$)
Figure 26 Calculated Center Line Velocity in the Near Wake of a Three-Dimensional Two-Bladed Rotor (same case as Figure 25)
Figure 27 Comparison between VDART and Simple Momentum Profiles (same case as Figure 25)
It is also interesting to note that if one doubles the magnitude of the velocity defect at $X/D = 0$, the velocity defect profiles downstream of $X/D = 1.0$ are approximated. This is not too surprising, since it is well known that one-half of the velocity deficit occurs as the flow "passes through" the rotor and the other half further downstream.

The VDART code presently does not have any turbulence model built into it and, therefore, the resulting velocity profiles must be corrected for those effects. The uncorrected profiles would be consistent with measurements made in a low turbulence wind tunnel. As Vermeulen [22] points out, the diffusion or broadening of the velocity defect in the wake will, in general, be a function of the wind direction fluctuations in the approach flow. The root mean square, $\sigma_\beta$, of the direction fluctuations were about eight degrees for the cases under study.

A relatively simple correction can be applied if one assumes that the direction fluctuations are Gaussian in nature and that the broadening can be calculated based on the average of a number of quasi-steady wakes produced by different upstream wind directions. The probability that the streamwise wake axis will deviate by an angle, $\beta_c$, from the mean angle and lie between $\beta_c - \delta \beta_c/2$ and $\beta_c + \delta \beta_c/2$ is given by

$$\gamma \delta \beta_c = \frac{\exp(-\beta_c^2/2 \sigma^2) \delta \beta_c}{\sigma_\beta \sqrt{2\pi}} \quad (33)$$

The corrected velocity defect profile as a function of the angle $\beta$ ($\beta$ is measured from the streamwise wake axis) can, therefore, be calculated from

$$U(\beta)_{\text{corr}} = \int_{-\infty}^{\infty} \gamma U(\beta - \beta_c) \, d\beta_c \quad (34)$$
Here \( U(\beta - \beta_c) \) is the uncorrected velocity defect profile evaluated at an angle, \( \beta - \beta_c \). The angle, \( \beta - \beta_c \), is also measured from the streamwise wake axis.

Corrected velocity profiles at \( X/D = 1.1 \) and 3.0 are shown in Figure 28, along with the experimental results due to Vermeulen [22]. It should be noted that the profile at \( X/D = 1.1 \) is modified very little by this correction, while there is a significant modification of the profile at \( X/D = 3.0 \). Figure 28 indicates that the corrected velocity profiles predicted by VDART are in some reasonable agreement with the experimental data.

Dynamic effects are not included in the analysis and may have a modifying effect. It is anticipated that these effects may be minimal at locations away from the immediate vicinity of the rotor.

5.0 SUMMARY OF RESULTS

In this section, a summary of the work which has been accomplished will be given, along with a list of conclusions that have been reached. In addition, recommendations for future work will be presented.

5.1 Summary

Experimental data have been taken in the following areas:

* Transient normal and tangential blade forces have been measured on a two-dimensional rotor for five different tip to wind speed ratio and rotor configuration combinations.

* Total velocity data were obtained at one and two rotor diameters downstream of a two-dimensional rotor. Data were taken at 13 spanwise positions across the wake. Five cases which represented three different rotor geometries (number of blades) and three different tip to wind speed ratios were run.
Figure 28 Comparison Between VDART and Experimental Data of Vermeulen [22] (- VDART data corrected for wind direction fluctuations, same case as Figure 25)
Flow direction measurements were obtained to coincide with each of the total velocity measurements made. The total velocity was then decomposed into its streamwise and lateral components.

Analytical work has been conducted along the following lines:

* Time saving methods in the form of FLP (frozen lattice point velocities) and FWG (fixed wake grid points) were incorporated into the two- and three-dimensional VDART codes.
* The effects of unsteady aerodynamics have been formulated and incorporated into the VDART codes.
* The VDART codes have been exercised in order to assess their agreement with experimental results.

5.2 Conclusions

Several statements can be made with regard to the analytical model, the experimental work, and comparisons between the analytical and experimental results.

* Use of the time-saving feature FWG yields good results in terms of maintaining accuracy, while reducing computer time by a factor of three for six revolutions and by a factor of six for 12 revolutions.
* Use of the time-saving feature FLP yields good results in general, but must be used with caution, especially at high tip to wind speed ratios and/or high rotor solidities.
* Use of continuity considerations as a time-saving feature is not justified as no savings can be realized.
* Dynamic effects are important at C/R values on the order of 0.1 or greater and are manifest in the form of stall delay, added mass effects, and circulation due to pitching.
* Good results are obtained in predicting the effects of added mass and pitching circulation on blade forces.

* Poor results were obtained in predicting the effect of dynamic stall on blade forces in that constants in the dynamic stall model (Boeing-Vertol) had to be adjusted in several cases to yield agreement between analysis and experiment.

* Reasonable results were obtained with regard to predicting the near wake velocity profiles behind a two-dimensional rotor operating in a uniform low-turbulence-level stream.

* Reasonable results were obtained with regard to predicting the near wake velocity profiles behind a three-dimensional rotor operating in a natural wind environment after simple wind direction fluctuation corrections were made.

5.3 Recommendations

* A better approach to the dynamic stall formulation should be undertaken.

* Additional blade force (or instantaneous rotor torque) data should be obtained on full-scale rotors.

* Additional wake velocity profiles behind full-scale rotors should be obtained.

* The role of freestream turbulence with respect to performance and near wake structure should be studied.

* The effects of the ground plane should be investigated.
6.0 BIBLIOGRAPHY


7.0 APPENDIX

Listings of the VDART2 and 3 computer codes, along with blade force data are given in this appendix.
7.1 VDART2 Computer Code Listing

This appendix contains the VDART2 computer code listing with the FWG option. The Fortran code is suitable for execution on the Texas Tech University ITEL AS6 computer.
COMMON/XWAKE/XFW(10),ZFW(5),FWKFW
COMMON/UWAKE/UFW(10,5),FWW(10,5)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/VEL/U(3,400),W(3,400)
COMMON/VEO/UO(3,400),WO(3,400)
COMMON/GAM/GS(3,400),GB(14),OGB(14),OALP(14)
COMMON/CLTAB/TA(30),TCL(30),TCD(30),NTBL,ASTAL,TCR
DIMENSION NPT(5),NPP(5),SPP(5),XO(5),ZO(5)
NR=12
NTI=24
NSW1=2
NSW2=2
READ(5,1) NB,CR,UT,XIP,TCR
1 FORMAT(I1,4F10.4)
READ(5,2) NTBL,RE,ASTAL
2 FORMAT(I2,2F10.3)
DO 10 I=1,NTBL
READ(5,3) TA(I),TCL(I),TCD(I)
3 FORMAT(3F10.4)
10 CONTINUE
INTEGER PSW1,PSW2,PSW3
READ(5,16) PSW1,PSW2,PSW3
16 FORMAT(3I1)
PRINT 60,PSW1,PSW2,PSW3
60 FORMAT(3I2)
READ(5,55) NPR
55 FORMAT(I2)
IF(NPR.EQ.0) GO TO 23
DO 12 I=1,NPR
READ(5,13) NPT(I),NPP(I),SPP(I),XO(I),ZO(I)
13 FORMAT(2I3,3F7.3)
12 CONTINUE
23 CONTINUE
DELT=6.2832/NTI
NT=1
DO 50 I=1,NB
GS(I,1)=0.0
OGB(I)=0.0
OALP(I)=0.0
50 CONTINUE
PRINT 4,NB,UT,CR,XIP,RE,TCR,ASTAL
4 FORMAT(30X,'ROTOR DATA',/27X,'NUMBER OF BLADES=',I2,/27X,'TIP TO WIND SPEED RATIO=',F4.1,/27X,'2-DIMENSIONAL ROTOR'
$,/27X,'CHORD TO RADIUS RATIO=',F4.3,/27X,'BLADE MOUNTING'
$,/27X,'LOCATION=',F6.3,' CHORDS',/27X,'AIRFOIL DATA',/27X,'RE=',F5.2,' MILLION',/27X,'THICKNESS TO CHORD RATIO=',F5.2,'/27X,'STATIC STALL ANGLE=',F5.2,' DEG',/27X,'ALPHA',5X,'$C L$,8X,'CD')
DO 15 I=1,NTBL
PRINT 5,TA(I),TCL(I),TCD(I)
5 FORMAT(20X,F10.1,2F10.4)
15 CONTINUE
CPSUM=0.0
DO 20 I=1,NTI
CALL BGEOM(NT,NB,CR,DELT,XIP)
CALL BVEL(NT,NB,NTI)
CALL BVORT(NT,NB,CR,UT,NTI,XIP)
CALL BVEL(NT,NB,NTI)
CALL PERF(NT,NB,CR,UT,NTI,CPL,XIP,PSW2)
CPSUM=CPSUM+CPL
NPW=NT*NB
NFPW=IFW*KFW
IF(NFW.LE.NFPW) GO TO 42
CALL SWIVEL(NT,NB,UT,NSW1,NTI,PSW3)
GO TO 43
CALL WIVEL(NT,NB,UT,NSW1,NTI)
CONTINUE
IF(NSW2.EQ.NT) GO TO 9
GO TO 11
CONTINUE
IF(NPR.EQ.0) GO TO 24
DO 14 J=1,NPR
CALL PROFIL(NT,NB,NPT(J),NPP(J),SPP(J),XO(J),ZO(J),NTI)
CONTINUE
DO 45 M=1,NB
DO 45 N=1,NRI,5
PRINT 8,M,N,X(M,N),Z(M,N),U(N,N),W(H,N)
CONTINUE
END
BLOCK DATA
COMMON/XWAKE/XFW(10), ZFW(5), IFW, KFW
DATA IFW/10/, KFW/5/
DATA XFW/-1.0, -0.5, 0.0, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 7.0/
DATA ZFW/-1.5, -0.75, 0.0, 0.75, 1.5/
END
SUBROUTINE BGEOM(NT,NB,CR,DELT,XIP)
COMMON/LOC/X(3,400),Z(3,400)
THET=(NT-1)*DELT
DTB=6.2832/NB
DO 10 I=1,NB
THETA=THET+(I-1)*DTB
X(I,NT)=-SIN(THETA)-(XIP-.25)*COS(THETA)*CR
Z(I,NT)=-COS(THETA)+(XIP-.25)*SIN(THETA)*CR
10 CONTINUE
RETURN
END
SUBROUTINE BIVEL(NT, NB, NTI)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/VEL/U(3,400),W(3,400)
COMMON/GAM/GS(3,400),GB(14),OGB(14),OALP(14)
DO 11 I=1,NB
J=NT
USUM=0.0
WSUM=0.0
DO 10 K=1,NB
DO 10 L=1,NT
CALL FIVEL(X(K,L),X(I,J),Z(K,L),Z(I,J),GS(K,L),UU,WW,NTI)
USUM=USUM+UU
WSUM=WSUM+WW
10 CONTINUE
U(I,J)=USUM
W(I,J)=WSUM
11 CONTINUE
RETURN
END
SUBROUTINE BVORT(NT,NB,CR,UT,NTI,XIP)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/VEL/U(3,400),W(3,400)
COMMON/GAM/GS(3,400),GB(14),OGB(14),OALP(14)
COMMON/CLTAB/TA(30),TCL(30),TCD(30),NTEL,ASTAL,TCR
REAL K
DO 10 I=1,NB
URDN=-(U(I,NT)+1.0)*X(I,NT)-W(I,NT)*Z(I,NT)
URDN=URDN-(XIP-.25)*CR*UT
URDC=-(U(I,NT)+1.0)*Z(I,NT)+W(I,NT)*X(I,NT)+UT
UR=SQRT(URDN**2+URDC**2)
ALPHA=ATAN2(URDN,URDC)
K=CR*UT/(2.0*UR)
CADOT=K*NTI*(ABS(ALPHA)-ABS(OALP(I)))/(2.0*3.1416)
URDNN=URDN+0.5*CR*UT
ALPN=ATAN2(URDNN,URDC)
CALL ALDNT(ALPN,CADOT,CL,CD,CN,CT)
GB(I)=CL*CR*UR/2.0
GS(I,NT)=GB(I)
10 CONTINUE
RETURN
END
SUBROUTINE PERF(NT, NB, CR, UT, NTI, CPL, XIP, PSW2)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/VEL/U(3,400),W(3,400)
COMMON/GAN/GS(3,400),GB(14),OGB(14),OALP(14)
COMMON/CLTAB/TA(30),TCL(30),TCD(30),NTBL,ASTAL,TCR
REAL K
INTEGER PSW2
IF (PSW2.NE.1) GO TO 4
PRINT 1
1 FORMAT (//,3X,'THETA',2X,'BLADE',2X,'ALPHA',8X,'FN',11X,
$'FT',11X,'T',11X,'U',9X,'W')
4 TR=0.0
CPL=0.0
DO 10 I=1,NB
TH=(NT-1)*360.0/NTI+(I-1)*360.0/NB
URDN=-(U(I,NT)+1.0)*X(I,NT)-W(I,NT)*Z(I,NT)
URDN=URDN-(XIP-.25)*CR*UT
URDC=-(U(I,NT)+1.0)*Z(I,NT)+W(I,NT)*X(I,NT)+UT
UR=SQRT(URDN**2+URDC**2)
ALPHA=ATAN2(URDN,URDC)
AL=57.296*ALPHA
K=CR*UT/(2.0*UR)
CADOT=K*NTI*(ABS(ALPHA)-ABS(OALP(I)))/(2.0*3.1416)
OALP(I)=ALPHA
URDNN=URDN+0.5*CR*UT
URDNT=URDN+.25*CR*UT
ALPN=ATAN2(URDNN,URDC)
ALPT=ATAN2(URDNT,URDC)
call ALDNT(ALPN, CADOT, CL, DUMCD, CN, DUMCT)
CALL ALDNT(ALPT, CADOT, DUMCL, DUMCD, DUMCN, CT)
GB(I)=CL*CR*UR/2.0
GS(I, NT):GB(I)
FN=CN*UR**2
FT=CT*UR**2
TE=FT*CR/2.0-FN*CR*(XIP-.25)*CR/2.0
IF (PSW2.NE.1) GO TO 5
PRINT 2, TH, I, AL, FN, FT, TE, U(I, NT), W(I, NT)
2 FORMAT (F8.1,I6,F7.1,3X,E10.3,3X,E10.3,3X,E10.3,3X,E10.3,3X,E10.3,3X,E10.3,3X)
5 TR=TR+TE
CPL=CPL+TE*UT
10 CONTINUE
IF (PSW2.NE.1) GO TO 6
PRINT 3, TR, CPL
3 FORMAT (/10X,'ROTOR TORQUE COEFFICIENT=',E10.3,/,10X,
$'ROTOR POWER COEFFICIENT=',E10.3)
6 RETURN
END
SUBROUTINE WIVEL(NT,NB,UT,NSW1,NTI)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/VEL/U(3,400),W(3,400)
COMMON/VEO/UO(3,400),WO(3,400)
COMMON/GAM/GS(3,400),GB(14),OGB(14),OALP(14)
IF(NT.LE.1) GO TO 12
NT1=NT-1
DO 11 I=1,NB
DO 11 J=1,NT1
UO(I,J)=U(I,J)
WO(I,J)=W(I,J)
IF(NT.EQ.NSW1)GO TO 30
GO TO 11
30 CONTINUE
CALL PIVEL(NT,NB,X(I,J),Z(I,J),U(I,J),W(I,J),NTI)
11 CONTINUE
IF(NT.EQ.NSW1) NSW1=NT+UT
12 CONTINUE
RETURN
END
SUBROUTINE SWIVEL(NT, NB, UT, NSW1, NTI, PSW3)

COMMON/XWAKE/XFW(10), ZFW(5), IFW, KFW
COMMON/UWAKE/UFW(10, 5), WFW(10, 5)
COMMON/LOC/X(3, 400), Z(3, 400)
COMMON/VEL/U(3, 400), W(3, 400)
COMMON/VEO/UO(3, 400), WO(3, 400)
COMMON/GAM/GS(3, 400), GB(14), OGB(14), CALP(14)

INTEGER PSW3
THETA = (NT-1)*360.0/NTI
XMIN = XFW(1)
ZMIN = ZFW(1)
XMAX = XFW(IFW)
ZMAX = ZFW(KFW)
IF(NT.EQ.NSW1) GO TO 5
GO TO 13

5 CONTINUE
IF(PSW3.NE.1) GO TO 2
PRINT 1, THETA
1 FORMAT(11, 5X, 'VELOCITIES AT FIXED WAKE POINTS', /8X, '(ROTOR AN' 

DO 10 IW = 1, IFW
    DO 10 KVJ = 1, KFW
        CALL PIVEL(NT, NB, XFV(IW), ZFW(KVJ), UFVJ(IW, KVJ), 
$'FW(IW, KVJ), NTI)
        IF(PSW3.NE.1) GO TO 16
        PRINT 15, XFW(IW), ZFW(KVJ), UFW(IW, KVJ), 
$'FW(IW, KVJ)
15 FORMAT(4F7.3)

16 CONTINUE

10 CONTINUE

13 CONTINUE
NT1 = NT-1
DO 11 I = 1, NB
    DO 11 J = 1, NT1
        UO(I, J) = U(I, J)
        WO(I, J) = W(I, J)
        IF(NT.EQ.NSW1) GO TO 30
        GO TO 11
11 CONTINUE

30 CONTINUE
IF(X(I, J).LT.XMIN.OR.X(I, J).GT.XMAX) GO TO 40
IF(Z(I, J).LT.ZMIN.OR.Z(I, J).GT.ZMAX) GO TO 40
GO TO 41

40 CALL PIVEL(NT, NB, X(I, J), Z(I, J), U(I, J), W(I, J), NTI)
GO TO 11

41 CONTINUE
CALL INTERP(X(I, J), Z(I, J), U(I, J), W(I, J))

11 CONTINUE
IF(NT.EQ.NSW1) NSW1 = NT+UT

12 CONTINUE
RETURN
END
SUBROUTINE PROFIL(NT,NB,NPT,NPP,SPP,X0,Z0,NTI)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/GAM/GS(3,400),GB(14),OGB(14),OALP(14)
THETA=(NT-1)*360.0/NTI
PRINT 1,THETA
 1 FORMAT(///,10X,'WAKE VELOCITY PROFILE',/11X,'(ROTOR ANGLE='
$\$F6.1,'DEG.)',/11X,'X',/11X,'Z',/11X,'U',/11X,'W')
DO 10 I=1,NPP
  2 XP=X0+SPP*(I-1)*(2-NPT)*(3-NPT)/2.0
  3 ZP=Z0+SPP*(I-1)*(NPT-1)*(NPT-2)/2.0
  4 CALL PIXEL(NT,NB,XP,ZP,UP,WP,NTI)
  5 PRINT 2,XP,ZP,UP,WP
 10 CONTINUE
RETURN
END
SUBROUTINE PIVEL(NT,NB,XP,ZP,UP,WP,NTI)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/GAM/GS(3,400),GB(14),OGB(14),OALP(14)
USUM=0.0
WSUM=0.0
DO 20 K=1,NB
DO 20 L=1,NT
CALL FIVEL(X(K,L),XP,Z(K,L),ZP,GS(K,L),UU,WW,NTI)
USUM=USUM+UU
WSUM=WSUM+WW
20 CONTINUE
UP=USUM
WP=WSUM
RETURN
END
SUBROUTINE INTERP(XP,ZP,UIN,WIN)
COMMON/XWAKE/XFW(10),ZFV(5),IFW,KFW
COMMON/UWAKE/UFW(10,5),WFW(10,5)
DIMENSION UX(2),WX(2),UQ(2,2),WQ(2,2)
IW=1
KW=1
2 IF(XP.LE.XFW(IW)) GO TO 6
   IW=IW+1
   GO TO 2
6 IF(ZP.LE.ZFW(KW)) GO TO 8
   KW=KW+1
   GO TO 6
8 CONTINUE
IW=IW-1
KW=KW-1
HX=XFW(IW+1)-XFW(IW)
HZ=ZFW(KW+1)-ZFW(KW)
DO 50 IQ=1,2
   DO 50 KQ=1,2
      IS=IW+IQ-1
      KS=KW+KQ-1
      UQ(IQ,KQ)=UFW(IS,KS)
      WQ(IQ,KQ)=WFW(IS,KS)
50 CONTINUE
DHX=(XP-XFW(IW))/HX
DHZ=(ZP-ZFW(KW))/HZ
DO 10 J=1,2
   UX(J)=UQ(1,J)*(1.0-DHX)+UQ(2,J)*DHX
   WX(J)=WQ(1,J)*(1.0-DHX)+WQ(2,J)*DHX
10 CONTINUE
UIN=UX(1)*(1.0-DHZ)+UX(2)*DHZ
WIN=WX(1)*(1.0-DHZ)+WX(2)*DHZ
RETURN
END
SUBROUTINE CONLP(NT,NB,DELT,UT)
COMMON/LOC/X(3,400),Z(3,400)
COMMON/VEL/U(3,400),W(3,400)
COMMON/VEO/UC(3,400),WO(3,400)
DT=DELT/UT
NT1=NT-1
DO 20 I=1,NB
  IF(NT.LE.1)GO TO 11
  DO 10 J=1,NT1
    X(I,J)=X(I,J)+(3.0*U(I,J)-UO(I,J)+2.0)*DT/2.0
    Z(I,J)=Z(I,J)+(3.0*W(I,J)-WO(I,J))*DT/2.0
  CONTINUE
11 CONTINUE
X(I,NT)=X(I,NT)+(U(I,NT)+1.0)*DT
Z(I,NT)=Z(I,NT)+W(I,NT)*DT
20 CONTINUE
RETURN
END
SUBROUTINE SHEDVR(NT,NB)
COMMON/GAN/GS(3,400),GB(14),OGB(14),OALP(14)
NT1=NT-1
DO 10 I=1,NB
   GS(I,NT)=GB(I)
   GS(I,NT1)=OGB(I)-GB(I)
   OGB(I)=GB(I)
10 CONTINUE
RETURN
END
SUBROUTINE FIVEL(X1,X3,Z1,Z3,GAMMA,UU,WW,NTI)
  DELT=6.2832/NTI
  RLIM=2.0/NTI
  CX=X1-X3
  CZ=Z1-Z3
  CCAV=CX*CX+CZ*CZ
  SRLIM=RLIM*RLIM
  IF(CCAV.LT.SRLIM) GO TO 10
  VF=GAMMA/(6.283185*CCAV)
  GO TO 11
10  VF=(3.1416*GAMMA)/(2.0*DELT*DELT)
11  UU=-CZ*VF
    WW=CX*VF
    RETURN
END
SUBROUTINE ALDNT(ALPHA, CADOT, CL, CD, CN, CT)
COMMON/CLTAB/TA(30), TCL(30), TCD(30), NTBL, ASTAL, TCR
REAL K
PI=ARCOS(-1.0)
ASTR=ASTAL*PI/180.0
IF(ABS(ALPHA).GE.ASTR) STALL=1.0
IF(CADOT.GE.0.0.AND.ABS(ALPHA).LE.ASTR) STALL=0.0
IF(STALL.EQ.1.0) GO TO 1
GO TO 2
CONTINUE
SALPH=SIGN(1.0, ALPHA)
SADOT=SIGN(1.0, CADOT)
K=0.25*SADOT*SALPH*(3+SADOT)
CHEATL=1.0
CHEATD=1.0
GL=CHEATL*(1.4-6.0*(0.06-TCR))
GD=CHEATD*(1.0-2.5*(0.06-TCR))
ADL=(ALPHA-K*GL*SQRT(ABS(CADOT)))*180.0/PI
ADD=(ALPHA-K*GD*SQRT(ABS(CADOT)))*180.0/PI
CALL ATAB(ADL, CL, DUM)
CALL ATAB(ASTAL, CLS, DUM)
SL=(CL-TCL(1))/(ADL-TA(1))
SLM=(CLS-TCL(1))/(ASTAL-TA(1))
IF(SL.GT.SLM) SL=SLM
CL=TCL(1)+SL*(ALPHA*180.0/PI-TA(1))
CALL ATAB(ADD, DUM, CD)
GO TO 3
2
AD=ALPHA*180.0/PI
CALL ATAB(AD, CL, CD)
CONTINUE
CN=-CL*COS(ALPHA)-CD*SIN(ALPHA)
CT= CL*SIN(ALPHA)-CD*COS(ALPHA)
RETURN
END
SUBROUTINE ATAB(ALD,CL,CD)
COMMON/CLTAB/TA(30),TCL(30),TCD(30),NTBL,ASTAL,TCR
AD=ALD
NTBL1=NTBL-1
IF(AD.LE.0.0) AD=AD+360.0
IF(AD.GE.0.0) AL=AD
IF(AD.GE.180.0) AL=360.0-AD
IF(AD.GE.360.0) AL=AD-360.0
DO 10 I=1,NTBL1
  J=I
  IF(AL.GE.TA(I).AND.AL.LE.TA(I+1)) GO TO 20
10 CONTINUE
20 XA=(AL-TA(J))/(TA(J+1)-TA(J))
   CL=TCL(J)+XA*(TCL(J+1)-TCL(J))
   CD=TCD(J)+XA*(TCD(J+1)-TCD(J))
IF(AD.GT.180.0.AND.AD.LT.360.0) CL=-CL
RETURN
END
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.15</td>
<td>8.0</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0.04</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0000</td>
<td>0.0180</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0.2500</td>
<td>0.0188</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>0.5675</td>
<td>0.0236</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>0.7300</td>
<td>0.0355</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.7800</td>
<td>0.0880</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.0</td>
<td>0.7650</td>
<td>0.1080</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>0.7175</td>
<td>0.1905</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18.0</td>
<td>0.7000</td>
<td>0.2580</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.0</td>
<td>0.6975</td>
<td>0.2855</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.0</td>
<td>0.9546</td>
<td>0.6666</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>1.1200</td>
<td>1.0100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50.0</td>
<td>1.1000</td>
<td>1.3700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60.0</td>
<td>0.9700</td>
<td>1.7000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70.0</td>
<td>0.7100</td>
<td>1.9300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80.0</td>
<td>0.4100</td>
<td>2.0500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90.0</td>
<td>0.0900</td>
<td>2.0700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>-0.2300</td>
<td>2.0400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>110.0</td>
<td>-0.5300</td>
<td>1.8900</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120.0</td>
<td>-0.8000</td>
<td>1.6900</td>
<td></td>
</tr>
<tr>
<td></td>
<td>130.0</td>
<td>-0.9800</td>
<td>1.4100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>140.0</td>
<td>-1.0500</td>
<td>1.0900</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150.0</td>
<td>-0.9400</td>
<td>0.7200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>154.0</td>
<td>-0.8400</td>
<td>0.5600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160.0</td>
<td>-0.7000</td>
<td>0.3700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>164.0</td>
<td>-0.6800</td>
<td>0.2700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>168.0</td>
<td>-0.7100</td>
<td>0.2100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>170.0</td>
<td>-0.7400</td>
<td>0.1800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>172.0</td>
<td>-0.8400</td>
<td>0.1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>175.0</td>
<td>-0.5000</td>
<td>0.0800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>180.0</td>
<td>0.0000</td>
<td>0.0300</td>
<td></td>
</tr>
</tbody>
</table>

2
3 10 .3333 2.0 -1.5
3 10 .3333 4.0 -1.5
7.2 VDART3 Computer Code Listing

This appendix contains the VDART3 computer code listing with the FWG option. The Fortran code is suitable for execution on the Texas Tech University ITEL AS6 computer.
COMMON/XWAKE/XFW(10), YFW(5), ZFW(5), IFW, JFW, KFW
COMMON/UNAKE/UFW(10,5,5), VFW(10,5,5), WFW(10,5,5)
COMMON/LOC/X(11,200), Y(11,200), Z(11,200)
COMMON/VEL/U(11,200), V(11,200), W(11,200)
COMMON/VEO/UO(11,200), VO(11,200), WO(11,200)
COMMON/GAM/GI(11,200), GS(11,200), GB(14), OGB(14), OALP(14)
COMMON/CLTAB/TA(30), TCL(30), TCD(30), NTBL, ASTAL, TCR
DIMENSION NPT(5), NPP(5), SPP(5), X0(5), Y0(5), Z0(5)
NR=12
NBE=5
NTI=16
NSW1=2
NSW2=2
READ(5,1) NB, CR, HR, UT, XIP, TCR
  FORMAT(I1,5F10.4)
READ(5,2) NTEL, RE, ASTAL
  FORMAT(2F10.3)
DO 10 I=1, NTEL
  READ(5,3) TA(I), TCL(I), TCD(I)
  FORMAT(3F10.4)
CONTINUE
  INTEGER PSW1, PSW2, PSW3
READ(5,16) PSW1, PSW2, PSW3
  FORMAT(3I1)
PRINT 60, PSW1, PSW2, PSW3
  FORMAT(3I1)
READ(5,55) NPR
  FORMAT(I2)
IF(NPR.EQ.0) GO TO 23
DO 12 I=1, NPR
  READ(5,13) NPT(I), NPP(I), SPP(I), X0(I), Y0(I), Z0(I)
  FORMAT(2I3,4F7.3)
CONTINUE
  DIELT=6.2832/NTI
NE=NBE*NB+1
NE1=NE-1
NT=1
DO 50 I=1, NE1
  GS(I,1)=0.0
  OGB(I)=0.0
  OALP(I)=0.0
CONTINUE
  CALL AREA(NE, NB, HR, AT)
  PRINT 4, NB, UT, HR, CR, XIP, RE, TCR, ASTAL
  FORMAT(30X,'ROTOR DATA',/27X,'NUMBER OF BLADES=',I2,/27X,'TIP TO WIND SPEED RATIO=',F4.1,/27X,'HEIGHT TO RADIUS RATIO=',F4.1,/27X,'CHORD TO RADIUS RATIO=',F4.3,/27X,'BLADE MOUNTING LOCATION=',F6.3,'CHORDS',/30X,'AIRFOIL DATA',/27X,'RE=',F5.2,'MILLION',/27X,'THICKNESS TO CHORD RATIO=',F5.2,
/27X,'STATIC STALL ANGLE=',F5.2,'DEG',/27X,'ALPHA',5X,
/CL',8X,'CD')
DO 15 I=1, NTEL
PRINT 5,TA(I),TCL(I),TCD(I)
5 FORMAT(20X,F10.1,2F10.4)
15 CONTINUE
DO 40 K=1,NR
CPSUM=0.0
DO 20 I=1,NTI
CALL BGEOM(NT,NE,NB,CR,HR,DELT,XIP)
CALL BIVEL(NT,NE,NTI)
CALL BVORT(NT,NE,NB,CR,UT,MTI,XIP)
CALL BIVEL(NT,NE,NTI)
CALL PERF(NT,NE,NB,CR,UT,AT,MTI,CPL,XIP,PSW2)
CP=CP+CPUM
NPW=NT*NE
NFPW=IFW*JFW*KFW
IF(NPW.LE.NFPW) GO TO 42
41 CALL SWIVEL(NT,NE,UT,NSW1,NTI,PSW3)
GO TO 43
42 CALL WIVEL(NT,NE,UT,NSW1,NTI)
43 CONTINUE
CALL CONLP(NT,NE,DELT,UT)
IF(NSW2.EQ.NT) GO TO 9
GO TO 11
9 CONTINUE
IF(NPR.EQ.0) GO TO 24
DO 14 J=1,NPR
CALL PROFIL(NT,NE,NPT(J),NPP(J),SPP(J),XO(J),YO(J),ZO(J),NTI)
14 CONTINUE
24 CONTINUE
NSW2=NT+UT
11 CONTINUE
NT=NT+1
CALL SHEDVR(NT,NE)
20 CONTINUE
CP=CPSUM/NTI
PRINT 6,CP,K
6 FORMAT(10X, F5.4, ' FOR REVOLUTION NUMBER', I2)
IF(PSW1.NE.1) GO TO 22
PRINT 7
7 FORMAT(12X, F5.4, F5.4, F5.4, F5.4, F5.4, F5.4, F5.4, F5.4, F5.4)
NRI=NTI*K
DO 45 M=1,NRI,5
PRINT 8,M,N,X(M,N),Y(M,N),Z(M,N),U(M,N),V(M,N),W(M,N)
45 CONTINUE
22 CONTINUE
40 CONTINUE
END
BLOCK DATA
COMMON/XWAKE/XFW(10),YFW(5),ZFW(5),IFW,JFW,KFW
DATA IFW/10/, JFW/5/, KFW/5/
DATA XFW/-1.0,-0.5,0.0,0.5,1.0,2.0,4.0,6.0,10.0,16.0/
DATA YFW/-0.5,0.25,1.0,1.75,2.5/
DATA ZFW/-1.5,-0.75,0.0,0.75,1.5/
END
SUBROUTINE AREA(NE,NB,HR,AT)
NBE=(NE-1)/NB
DELY=HR/NBE
RRSUM=0.0
H=0.0
NBE1=NBE-1
DO 10 I=1,NBE1
  H=H+DELY
  RR=1-4*(H/HR-0.5)**2
  RRSUM=RRSUM+RR
10 CONTINUE
AT=2.0*RRSUM*DELY
RETURN
END
SUBROUTINE BGEOM(NT, NE, NB, CR, HR, DELT, X1P)
COMMON/LOC/X(11,200), Y(11,200), Z(11,200)
THET=(NT-1)*DELT
NBE=(NE-1)/NB
DELY=HR/NBE
DTB=6.2832/NB
DO 10 I=1,NB
    THETA=THET+(I-1)*DTB
    X(1,NT)=-(X1P-.25)*CR*COS(THETA)
    Y(1,NT)=0.
    Z(1,NT)=(X1P-.25)*CR*SIN(THETA)
NEI=1+(I-1)*NBE
DO 10 J=1,NBE
    NEJ=NEI+J
    NEJ1=NEJ-1
    Y(NEJ,NT)=Y(NEJ1,NT)-DELY*(-1.0)**I
    RR=1-4*(Y(NEJ,NT)/HR-0.5)**2
    X(NEJ,NT)=-RR*SIN(THETA)-(X1P-.25)*CR*COS(THETA)
    Z(NEJ,NT)=-RR*COS(THETA)+(X1P-.25)*CR*SIN(THETA)
10 CONTINUE
RETURN
END
SUBROUTINE BIVEL(NT,NE,NTI)
COMMON/LOC/X(11,200),Y(11,200),Z(11,200)
COMMON/VEL/U(11,200),V(11,200),W(11,200)
COMMON/GAM/GT(11,200),GS(11,200),GB(14),OGB(14),OALP(14)
NT1=NT-1
DO 11 I=1,NE
J=NT
VSUM=0.0
USUM=0.0
WSUM=0.0
IF(NT.LE.1) GO TO 21
DO 20 K=1,NE
DO 20 L=1,NT1
L1=L+1
CALL FIVEL(X(K,L),X(K,L1),X(I,J),Y(K,L),Y(K,L1),Y(I,J),
$Z(K,L),Z(K,L1),Z(I,J),GT(K,L),UU,VV,WW,NTI)
USUM=USUM+UU
VSUM=VSUM+VV
WSUM=WSUM+WW
20 CONTINUE
21 CONTINUE
NE1=NE-1
DO 10 K=1,NE1
DO 10 L=1,NT
K1=K+1
CALL FIVEL(X(K,L),X(K1,L),X(I,J),Y(K,L),Y(K1,L),Y(I,J),
$Z(K,L),Z(K1,L),Z(I,J),GS(K,L),UU,VV,WW,NTI)
USUM=USUM+UU
VSUM=VSUM+VV
WSUM=WSUM+WW
10 CONTINUE
9 CONTINUE
U(I,J)=USUM
V(I,J)=VSUM
W(I,J)=WSUM
11 CONTINUE
RETURN
END
SUBROUTINE BVORT(NT, NE, NB, CR, UT, NTI, XIP)
COMMON/LCC/X(11,200), Y(11,200), Z(11,200)
COMMON/VEL/U(11,200), V(11,200), W(11,200)
COMMON/GAM/GT(11,200), GS(11,200), GB(14), OGB(14), OALP(14)
COMMON/CLTAB/TA(30), Tcl(30), Tcd(30), NTBL, ASTAL, TCR
REAL K
NBE=(NE-1)/NB
DO 10 I=1, NBE
NEI=1+(I-1)*NBE
DO 10 J=1, NBE
NEJ=NEI+J
NEJ1=NEJ-1
RR1=SQR(T(X(NEJ1, NT)**2+Z(NEJ1, NT)**2))
RR2=SQR(T(X(NEJ, NT)**2+Z(NEJ, NT)**2))
DX=X(NEJ, NT)-X(NEJ1, NT)
DY=Y(NEJ, NT)-Y(NEJ1, NT)
DZ=Z(NEJ, NT)-Z(NEJ1, NT)
EL=SQR((RR1-RR2)**2+DY**2)
SINT=-(X(NEJ, NT)+X(NEJ1, NT))/(RR1+RR2)
COST=-(Z(NEJ, NT)+Z(NEJ1, NT))/(RR1+RR2)
UTAVE=UT*(RR1+RR2)/2.0
UAVE=(U(NEJ, NT)+U(NEJ1, NT))/2.0
VAVE=(V(NEJ, NT)+V(NEJ1, NT))/2.0
WAVE=(W(NEJ, NT)+W(NEJ1, NT))/2.0
URDN=((1.0+UAVE)*SINT-VAVE*(DX*SINT+DZ*COST)+WAVE*DY*COST)/EL
URDN=URDN-(XIP-.25)*CR*UT*DY/EL
URDC=(1.0+UAVE)*COST-WAVE*SINT+UTAVE
UR=SQR(URDN**2+URDC**2)
ALPHA=ATAN2(URDN, URDC)
K=CR*UT/((2.0*UR)
CADOT=K*NTI*(ABS(ALPHA)-ABS(OALP(NEJ1)))/(2.0*3.1416)
URDNN=URDN+0.5*CR*UT*DY/EL
ALPN=ATAN2(URDNN, URDC)
CALL ALDNT(ALPN, CADOT, CL, CD, CN, CT)
GB(NEJ1)=CL*CR*UR/2.0
GS(NEJ1, NT)=GB(NEJ1)
10 CONTINUE
RETURN
END
SUBROUTINE PERF(NT, NE, NB, CR, UT, AT, NTI, CPL, XIP, PSW2)
COMMON/LOC/X(11,200), Y(11,200), Z(11,200)
COMMON/VEL/U(11,200), V(11,200), W(11,200)
COMMON/GAM/CT(11,200), GS(11,200), GB(14), OGB(14), OALP(14)
COMMON/CLTAB/TA(30), TCL(30), TCD(30), NTBL, ASTAL, TCR
REAL K
INTEGER PSW2
IF(PSW2.NE.1) GO TO 4
PRINT 1
4 NBE=(NE-1)/NB
TR=0.0
CPL=0.0
DO 10 I=1,NB
TH=(NT-1)*360.0/NTI+(I-1)*360.0/NB
NEI=1+(I-1)*NBE
DO 10 J=1,NBE
NEJ=NEI+J
NEJ1=NEJ-1
RR1=SQRT(X(NEJ1,NT)**2+Z(NEJ1,NT)**2)
RR2=SQRT(X(NEJ,NT)**2+Z(NEJ,NT)**2)
DX=X(NEJ,NT)-X(NEJ1,NT)
DY=Y(NEJ,NT)-Y(NEJ1,NT)
DZ=Z(NEJ,NT)-Z(NEJ1,NT)
EL=SQRT((RR1-RR2)**2+DY**2)
SINT=-(X(NEJ,NT)+X(NEJ1,NT))/CRR1+RR2)
COST=-(Z(NEJ,NT)+Z(NEJ1,NT))/CRR1+RR2)
UTAVE=UT*CRR1+RR2)/2.0
UAVE=(U(NEJ,NT)+U(NEJ1,NT))/2.0
VAVE=(V(NEJ,NT)+V(NEJ1,NT))/2.0
WAVE=(W(NEJ,NT)+W(NEJ1,NT))/2.0
URDN=((1.0+UAVE)*DY*SINT-VAVE*(DX*SINT+DZ*COST)+WAVE*DY*COST)/EL
URDN=URDN-(XIP-.25)*CR*UT*DY/EL
URDC=((1.0+UAVE)*COST-WAVE*SINT+UTAVE
UR=SQRT(URDN**2+URDC**2)
ALPHA=ATAN2(URDN,URDC)
AL=57.296*ALPHA
K=CR*UT/(2.0*UR)
CADOT=K*NTI*(ABS(ALPHA)-ABS(OALP(NEJ1)))/(2.0*3.1416)
OALP(NEJ1)=ALPHA
URDN=URDN+.5*CR*UT*DY/EL
URDT=URDN+.25*CR*UT*DY/EL
ALP=ATAN2(URDN,URDC)
ALPT=ATAN2(URDN,URDC)
CALL ALDNT(ALP, CADOT, CL, DUMCD, CN, DUMCN, CT)
CALL ALDNT(ALPT, CADOT, CL, DUMCD, CN, DUMCN, CT)
GB(NEJ1)=CL*CR*UR/2.0
GS(NEJ1,NT)=GB(NEJ1)
FN=CN*UR**2
FT=CT*UR**2
TE=FT*CR*EL*(RR1+RR2)/(2.0*AT)-FN*CR*DY*(XIP-.25)*CR/AT
IF(PSW2.NE.1) GO TO 5
97
PRINT 2, TH, NEJ1, AL, FN, FT, TE, UAVE, VAVE, WAVE
2 FORMAT(F7.1, I7, F7.1, 3E10.3, 3F7.3)
5 TR=TR+TE
   CPL=CPL+TE*UT
10 CONTINUE
   IF(PSW2.NE.1) GO TO 6
   PRINT 3, TR, CPL
3 FORMAT(/10X, 'ROTOR TORQUE COEFFICIENT=', E10.3, /10X,
   $'ROTOR POWER COEFFICIENT=', E10.3)
6 RETURN
END
SUBROUTINE WIVEL(NT, NE, UT, NSW1, NTI)
COMMON/LOC/X(11,200), Y(11,200), Z(11,200)
COMMON/VEL/U(11,200), V(11,200), W(11,200)
COMMON/VELO/UO(11,200), VO(11,200), WO(11,200)
COMMON/GAM/GT(11,200), GS(11,200), GB(14), OGS(14), CALP(14)
IF(NT.LE.1) GO TO 12
NT1=NT-1
DO 11 I=1, NE
  DO 11 J=1, NT1
    UO(I,J)=U(I,J)
    VO(I,J)=V(I,J)
    WO(I,J)=W(I,J)
  IF(NT.EQ.NSW1) GO TO 30
  GO TO 11
30 CONTINUE
CALL PIVEL(NT, NE, X(I,J), Y(I,J), Z(I,J), U(I,J), V(I,J), W(I,J), NTI)
11 CONTINUE
IF(NT.EQ.NSW1) NSW1=NT+UT
12 CONTINUE
RETURN
END
SUBROUTINE SWIVEL(NT, NE, UT, NSW1, NTI, PSW3)

COMMON/XAKE/XFW(10), YFW(5), ZFW(5), IFW, JFW, KFW
COMMON/WEAKE/UFW(10, 5, 5), VFW(10, 5, 5), WFW(10, 5, 5)
COMMON/LOC/X(11, 200), Y(11, 200), Z(11, 200)
COMMON/VEL/U(11, 200), V(11, 200), W(11, 200)
COMMON/VEL/VO(11, 200), VO(11, 200), WO(11, 200)
COMMON/VEL/VO(11, 200), GS(11, 200), GB(14), OGB(14), OALP(14)
INTEGER PSW3

THETA=(NT-1)*360.0/NTI
XMIN=XFW(1)
YMIN=YFW(1)
ZMIN=ZFW(1)
XMAX=XFW(IFW)
YMAX=YFW(JFW)
ZMAX=ZFW(KFW)
IF(NT.EQ.NSW1) GO TO 5
GO TO 13
5 CONTINUE
IF(PSW3.NE.1) GO TO 2
PRINT 1, THETA
1 FORMAT(///,5X,'VELOCITIES AT FIXED WAKE POINTS',/6X,'(ROTOR AN' $,'GLE=',F6.1,'DEG.)',//,3X,'X',6X,'Y',6X,'Z',6X,'U',6X,'V',6X,'W')
2 DO 10 IW=1, IFW
    DO 10 JW=1, JFW
    DO 10 KW=1, KFW
    CALL PIVEL(NT, NE, XFW(IW), YFW(JW), ZFW(KW), UFW(IW, JW, KW),
               VFW(IW, JW, KW), WFW(IW, JW, KW), NTI)
    IF(PSW3.NE.1) GO TO 16
    PRINT 15, XFW(IW), YFW(JW), ZFW(KW), UFW(IW, JW, KW), VFW(IW, JW, KW),
           WFW(IW, JW, KW)
    15 FORMAT(6F7.3)
    CONTINUE
10 CONTINUE
13 CONTINUE
NT1=NT-1
DO 11 I=1, NE
    DO 11 J=1, NT1
    UO(I, J)=U(I, J)
    VO(I, J)=V(I, J)
    WO(I, J)=W(I, J)
    IF(NT.EQ.NSW1) GO TO 30
    GO TO 11
30 CONTINUE
IF(X(I, J).LT.XMIN.OR.X(I, J).GT.XMAX) GO TO 40
IF(Y(I, J).LT.YMIN.OR.Y(I, J).GT.YMAX) GO TO 40
IF(Z(I, J).LT.ZMIN.OR.Z(I, J).GT.ZMAX) GO TO 40
GO TO 41
40 CALL PIVEL(NT, NE, X(I, J), Y(I, J), Z(I, J), U(I, J), V(I, J), W(I, J), NTI)
    GO TO 11
41 CONTINUE
CALL INTERP(X(I, J), Y(I, J), Z(I, J), U(I, J), V(I, J), W(I, J))
11 CONTINUE
IF(NT.EQ.NSW1) NSW1=NT+UT
CONTINUE
RETURN
END
SUBROUTINE PROFIL(NT, NE, NPT, NPP, SPP, XO, YO, ZO, NTI)
COMMON/LOC/X(11,200), Y(11,200), Z(11,200)
COMMON/GAM/GT(11,200), GS(11,200), GB(14), OGB(14), OALP(14)
THETA=(NT-1)*360.0/NTI
PRINT 1,THETA
1 FORMAT(///,10X,'WAKE VELOCITY PROFILE',/11X,'(ROTOR ANGLE=', $,F6.1,'DEG.)',//,3X,'X',6X,'Y',6X,'Z',6X,'U',6X,'V',6X,'W')
DO 10 I=1,NPP
XP=XO+SPP*(I-1)*(2-NPT)*(3-NPT)/2.0
YP=YO+SPP*(I-1)*(NPT-1)*(3-NPT)
ZP=ZO+SPP*(I-1)*(NPT-1)*(NPT-2)/2.0
CALL PIVELC(NT,NE,XP,YP,ZP,UP,VP,WP,NTI)
PRINT 2,XP,YP,ZP,UP,VP,WP,WP
2 FORMAT(6F7.3)
10 CONTINUE
RETURN
END
SUBROUTINE PIVEL(NT, NE, XP, YP, ZP, UP, VP, WP, NTI)
COMMON/LOC/X(11,200), Y(11,200), Z(11,200)
COMMON/GAM/GT(11,200), GS(11,200), GB(14), OGB(14), OALP(14)
NT1=NT-1
USUM=0.0
VSUM=0.0
WSUM=0.0
DO 10 K=1, NE
DO 10 L=1, NT1
L1=L+1
CALL FIVEL(X(K,L), X(K,L1), XP, Y(K,L), Y(K,L1), YP, $Z(K,L), Z(K,L1), ZP, GT(K,L), UU, VV, WW, NTI)
USUM=USUM+UU
VSUM=VSUM+VV
WSUM=WSUM+WW
10 CONTINUE
NE1=NE-1
DO 20 K=1, NE1
DO 20 L=1, NT
K1=K+1
CALL FIVEL(X(K,L), X(K1,L), XP, Y(K,L), Y(K1,L), YP, $Z(K,L), Z(K1,L), ZP, GS(K,L), UU, VV, WW, NTI)
USUM=USUM+UU
VSUM=VSUM+VV
WSUM=WSUM+WW
20 CONTINUE
UP=USUM
VP=VSUM
WP=WSUM
RETURN
END
SUBROUTINE INTERP(XP,YP,ZP,UIN,VIN,WIN)
COMMON/XWAKE/XFW(10),YFW(5),ZFV(5),IFW,JFW,KFW
COMMON/UWAKE/UFW(10,5,5),VFV(10,5,5),WFV(10,5,5)
DIMENSION UX(2,2),VX(2,2),WX(2,2),UQ(2,2,2),VQ(2,2,2),WQ(2,2,2)
DIMENSION UY(2),VY(2),WY(2)
IW=1
JW=1
KW=1
2 IF(XP.LE.XFW(IW)) GO TO 4
   IW=IW+1
   GO TO 2
4 IF(YP.LE.YFW(JW)) GO TO 6
   JW=JW+1
   GO TO 4
6 IF(ZP.LE.ZFW(KW)) GO TO 8
   KW=KW+1
   GO TO 6
8 CONTINUE
   IW=IW-1
   JW=JW-1
   KW=KW-1
   HX=XFW(IW+1)-XFW(IW)
   HY=YFW(JW+1)-YFW(JW)
   HZ=ZFW(KW+1)-ZFW(KW)
   DO 50 IQ=1,2
      DO 50 JQ=1,2
         DO 50 KQ=1,2
            IS=IW+IQ-1
            JS=JW+JQ-1
            KS=KW+KQ-1
            UQ(IQ,JQ,KQ)=UFW(IS,JS,KS)
            VQ(IQ,JQ,KQ)=VFW(IS,JS,KS)
            WQ(IQ,JQ,KQ)=WFW(IS,JS,KS)
      50 CONTINUE
   DHX=(XP-XFW(IW))/HX
   DHY=(YP-YFW(JW))/HY
   DHZ=(ZP-ZFW(KW))/HZ
   DO 10 J=1,2
      DO 20 I=1,2
         UX(I,J)=UQ(1,I,J)*(1.0-DHX)+UQ(2,I,J)*DHX
         VX(I,J)=VQ(1,I,J)*(1.0-DHX)+VQ(2,I,J)*DHX
         WX(I,J)=WQ(1,I,J)*(1.0-DHX)+WQ(2,I,J)*DHX
      20 CONTINUE
   UY(J)=UX(1,J)*(1.0-DHY)+UX(2,J)*DHY
   VY(J)=VX(1,J)*(1.0-DHY)+VX(2,J)*DHY
   WY(J)=WX(1,J)*(1.0-DHY)+WX(2,J)*DHY
10 CONTINUE
   UIN=UY(1)*(1.0-DHZ)+UY(2)*DHZ
   VIN=VY(1)*(1.0-DHZ)+VY(2)*DHZ
   WIN=WY(1)*(1.0-DHZ)+WY(2)*DHZ
RETURN
END
SUBROUTINE CONLP(NT,NE,DELT,UT)
COMMON/LOC/X(11,200),Y(11,200),Z(11,200)
COMMON/VEL/U(11,200),V(11,200),W(11,200)
COMMON/VEO/UO(11,200),VO(11,200),WO(11,200)
DT=DELT/UT
NT1=NT-1
DO 20 I=1,NE
  IF(NT.LE.1)GO TO 11
  DO 10 J=1,NT1
     X(I,J)=X(I,J)+(3.0*U(I,J)-UO(I,J)+2.0)*DT/2.0
     Y(I,J)=Y(I,J)+(3.0*V(I,J)-VO(I,J))*DT/2.0
     Z(I,J)=Z(I,J)+(3.0*W(I,J)-WO(I,J))*DT/2.0
  10 CONTINUE
  11 CONTINUE
  X(I,NT)=X(I,NT)+(U(I,NT)+1.0)*DT
  Y(I,NT)=Y(I,NT)+V(I,NT)*DT
  Z(I,NT)=Z(I,NT)+W(I,NT)*DT
20 CONTINUE
RETURN
END
SUBROUTINE SHEDVR(NT, NE)
COMMON/GAM/GT(11,200), GS(11,200), GB(14), OGB(14), OALP(14)
NT1 = NT - 1
NE1 = NE - 1
DO 10 I = 1, NE1
   GS(I, NT) = GB(I)
   GS(I, NT1) = OGB(I) - GB(I)
   OGB(I) = GB(I)
10   CONTINUE
   GT(1, NT1) = GB(1)
   GT(NE, NT1) = -GB(NE1)
   DO 20 I = 2, NE1
      I1 = I - 1
      GT(I, NT1) = GB(I) - GB(I1)
20   CONTINUE
RETURN
END
SUBROUTINE FIVEL(X1,X2,X3,Y1,Y2,Y3,Z1,Z2,Z3,GAMMA,UU,VV,WW,NTI)
    AX=X2-X1
    AY=Y2-Y1
    AZ=Z2-Z1
    BX=X2-X3
    BY=Y2-Y3
    BZ=Z2-Z3
    CX=X1-X3
    CY=Y1-Y3
    CZ=Z1-Z3
    CCAX=CY*AZ-AY*CZ
    CCAY=AX*CZ-CX*AZ
    CCAZ=CX*AY-AX*CY
    CCAV=CCAX*CCAX+CCAY*CCAY+CCAZ*CCAZ
    IF(CCAV.LT.0.0001) GO TO 10
    B=SQRT(BX*BX+BY*BY+BZ*BZ)
    C=SQRT(CX*CX+CY*CY+CZ*CZ)
    ADB=AX*BX+AY*BY+AZ*BZ
    ADC=AX*CX+AY*CY+AZ*CZ
    VF=(ADB/B-ADC/C)*GAMMA/(12.56637*CCAV)
    UU=CCAX*VF
    VV=CCAY*VF
    WW=CCAZ*VF
9 GO TO 11
10 UU=0.0
    VV=0.0
    WW=0.0
11 CONTINUE
RETURN
END
SUBROUTINE ALDNT(ALPHA,CADOT,CL,CD,CN,CT)
COMMON/CLTAB/TA(30),TCL(30),TCD(30),NTBL,ASTAL,TCR
REAL K
PI=ARCOS(-1.0)
ASTR=ASTAL*PI/180.0
IF(ABS(ALPHA).GE.ASTR) STALL=1.0
IF(CADOT.GE.0.0.AND.ABS(ALPHA).LE.ASTR) STALL=0.0
IF(STALL.EQ.1.0) GO TO 1
GO TO 2
CONTINUE
SALPH=SIGN(1.0,ALPHA)
SADOT=SIGN(1.0,CADOT)
K=0.25*SADOT*SALPH*(3+SADOT)
CHEATL=1.0
CHEATD=1.0
GL=CHEATL*(1.4-6.0*(0.06-TCR))
GD=CHEATD*(1.0-2.5*(0.06-TCR))
ADL=(ALPHA-K*GL*SQRT(ABS(CADOT)))*180.0/PI
ADD=(ALPHA-K*GD*SQRT(ABS(CADOT)))*180.0/PI
CALL ATAB(ADL,CL,DUM)
CALL ATAB(ASTAL,CLS,DUM)
SL=(CL-TCL(1))/(ADL-TA(1))
SLM=(CLS-TCL(1))/(ASTAL-TA(1))
IF(SL.GT.SLM) SL=SLM
CL=TCL(1)+SL*(ALPHA*180.0/PI-TA(1))
CALL ATABCADD,DUM,CD)
GO TO 3
2 AD=ALPHA*180.0/PI
CALL ATAB(AD,CL,CD)
3 CONTINUE
CN=-CL*COS(ALPHA)-CD*SIN(ALPHA)
CT= CL*SIN(ALPHA)-CD*COS(ALPHA)
RETURN
END
SUBROUTINE ATAB(ALD, CL, CD)
COMMON/CLTAB/TA(30), TCL(30), TCD(30), NTBL, ASTAL, TCR
AD = ALD
NTBL1 = NTBL - 1
IF (AD .LE. 0.0) AD = AD + 360.0
IF (AD .GE. 0.0) AL = AD
IF (AD .GE. 180.0) AL = 360.0 - AD
IF (AD .GE. 360.0) AL = AD - 360.0
DO 10 I = 1, NTBL1
   J = I
   IF (AL .GE. TA(I) .AND. AL .LE. TA(I + 1)) GO TO 20
   10 CONTINUE
20 XA = (AL - TA(J)) / (TA(J + 1) - TA(J))
    CL = TCL(J) + XA * (TCL(J + 1) - TCL(J))
    CD = TCD(J) + XA * (TCD(J + 1) - TCD(J))
    IF (AD .GT. 180.0 .AND. AD .LT. 360.0) CL = -CL
RETURN
END
<table>
<thead>
<tr>
<th>2</th>
<th>0.1000</th>
<th>2.0</th>
<th>4.0</th>
<th>0.25</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.30</td>
<td>10.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.0000</td>
<td>0.0085</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>0.2000</td>
<td>0.0094</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.5000</td>
<td>0.0125</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>0.7700</td>
<td>0.0177</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.9</td>
<td>0.8500</td>
<td>0.0465</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.0</td>
<td>0.8600</td>
<td>0.0935</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td>0.8200</td>
<td>0.1705</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>0.7900</td>
<td>0.2335</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.0</td>
<td>0.7500</td>
<td>0.3285</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>0.9800</td>
<td>0.6300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td>1.1200</td>
<td>1.0100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50.0</td>
<td>1.1000</td>
<td>1.3700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>0.9700</td>
<td>1.7000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70.0</td>
<td>0.7100</td>
<td>1.9300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80.0</td>
<td>0.4100</td>
<td>2.0500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90.0</td>
<td>0.0900</td>
<td>2.0700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.0</td>
<td>-0.2300</td>
<td>2.0400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110.0</td>
<td>-0.5300</td>
<td>1.8900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120.0</td>
<td>-0.8000</td>
<td>1.6900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130.0</td>
<td>-0.9800</td>
<td>1.4100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>140.0</td>
<td>-1.0500</td>
<td>1.0900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150.0</td>
<td>-0.9400</td>
<td>0.7200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>154.0</td>
<td>-0.8400</td>
<td>0.5600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160.0</td>
<td>-0.7000</td>
<td>0.3700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>164.0</td>
<td>-0.6800</td>
<td>0.2700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>168.0</td>
<td>-0.7100</td>
<td>0.2100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>170.0</td>
<td>-0.7400</td>
<td>0.1800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>172.0</td>
<td>-0.8400</td>
<td>0.1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>175.0</td>
<td>-0.5000</td>
<td>0.0800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180.0</td>
<td>0.0000</td>
<td>0.0300</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

111

| 3 | 6 | 0.75 | 0.0 | 1.0 | -1.875 |
| 3 | 6 | 0.75 | 2.0 | 1.0 | -1.875 |
| 3 | 6 | 0.75 | 6.0 | 1.0 | -1.875 |
| 3 | 6 | 0.75 | 10.0 | 1.0 | -1.875 |
| 3 | 6 | 0.75 | 16.0 | 1.0 | -1.875 |
7.3 Blade Force Data

Blade force data from the two-dimensional experiment is presented in this appendix. A minimum of two runs for five different combinations of tip to wind speed ratio and blade geometry cases were made. The first set of data displays are non-dimensional normal and tangential forces taken during the fourth revolution. The second set of data displays are non-dimensional normal and tangential forces for each entire run. The resolution of these plots is, of course, low in comparison with the plots for a single revolution.
N=2
TSR=7.5
N=2

TSR=7.5

ROTOR ANGLE-1080°
N=3
TSR=5

ROTOR ANGLE - 1000°
N=1
TSR=5

NUMBER OF REVOLUTIONS

100  50  0  -50  -100

1  2  3  4  5  6  7  8  9  10  11  12  13  14  15
N=2
TSR=5

NUMBER OF REVOLUTIONS
7.4 Wake Velocity Data

Wake velocity data from the two-dimensional experiment are presented in this appendix. All of the data presented herein were taken at one rotor diameter downstream of the axis of rotation. Data for five different combinations of tip to wind speed ratio and blade geometries (number of blades) are presented. The first set of data displays the streamwise perturbation velocities measured during the fourth revolution of the rotor. The second set of data displays the lateral perturbation velocities measured during the fourth revolution of the rotor. Each set of data also contains a plot of the velocities predicted by VDART2.
ROTTER ANGLE = 1110° 1155° 1245°

1290° 1380° 1425°

U/U∞

TSR = 2.5

NB = 2

+ -- ANALYTICAL DATA, * -- EXPERIMENTAL DATA
ROTOR ANGLE

-1.0
-0.5
0
0.5
1.0

W/U_

-1.0
-0.5
0
0.5
1.0

TSR=5

-1.0
-0.5
0
0.5
1.0

NB=1

+ --ANALYTICAL DATA, * --EXPERIMENTAL DATA
+ --VDART2 DATA, * --EXPERIMENTAL DATA
Otto de Vries  
National Aerospace Laboratory  
Anthony Fokkerweg 2  
Amsterdam 1017  
THE NETHERLANDS

R. Walters  
West Virginia University  
Department of Aero Engineering  
1062 Kountz Avenue  
Morgantown, WV  26505

E. J. Warchol  
Bonneville Power Administration  
P.O. Box 3621  
Portland, OR  97225

D. F. Warne, Manager  
Energy and Power Systems  
ERA Ltd.  
Cleeve Rd.  
Leatherhead  
Surrey KT22 7SA  
ENGLAND

G. R. Watson, Project Manager  
The Energy Center  
Pennine House  
4 Osborne Terrace  
Newcastle upon Tyne NE2 1NE  
UNITED KINGDOM

R. J. Watson  
Watson Bowman Associates, Inc.  
1280 Niagara St.  
Buffalo, NY  14213

R. G. Watts  
Tulane University  
Department of Mechanical Engineering  
New Orleans, LA  70018

W. G. Wells, P.E.  
Associate Professor  
Mechanical Engineering Department  
Mississippi State University  
Mississippi State, MS  39762

T. Wentink, Jr.  
University of Alaska  
Geophysical Institute  
Fairbanks, AK  99701
Texas Tech University (3)  
P.O. Box 4389  
Lubbock, TX  79409  
Attn:  K. C. Mehta, CE Department  
        J. Strickland, ME Department  
        J. Lawrence, ME Department

Fred Thompson  
Atari, Inc.  
155 Moffett Park Drive  
Sunnyvale, CA  94086

J. M. Turner, Group Leader  
Terrestrial Energy Technology Program Office  
Energy Conversion Branch  
Aerospace Power Division  
Aero Propulsion Laboratory  
Department of the Air Force  
Air Force Wright Aeronautical Laboratories (AFSC)  
Wright-Patterson Air Force Base, OH  45433

United Engineers and Constructors, Inc.  
Advanced Engineering Department  
30 South 17th Street  
Philadelphia, PA  19101  
Attn:  A. J. Karalis

University of New Mexico (2)  
New Mexico Engineering Research Institute  
Campus, P.O. Box 25  
Albuquerque, N.M.  87131  
Attn:  G. G. Leigh

University of New Mexico (2)  
Albuquerque, NM  87106  
Attn:  K. T. Feldman  
        Energy Research Center  
        V. Sloglund  
        ME Department

Jan Vacek  
Eolienne experimentale  
C.P. 279, Cap-aux-Meules  
Iles de la Madeleine, Quebec  
CANADA

Irwin E. Vas  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401
Leo H. Soderholm  
Iowa State University  
Agricultural Engineering, Room 213  
Ames, IA 50010

Bent Sorensen  
Roskilde University Centre  
Energy JGroup, Bldg. 17.2  
IMFUFA  
P.O. Box 260  
DK-400 Roskilde  
DENMARK

Southwest Research Institute (2)  
P.O. Drawer 28501  
San Antonio, TX 78284  
Attn: W. L. Donaldson, Senior Vice President  
R. K. Swanson

Rick Stevenson  
Route 2  
Box 85  
Springfield, MO 65802

Dale T. Stjernholm, P.E.  
Mechanical Design Engineer  
Morey/Stjernholm and Associates  
1050 Magnolia Street  
Colorado Springs, CO 80907

G. W. Stricker  
130 Merchant St. #1104  
Honolulu, HI 96813

C. J. Swet  
Route 4  
Box 358  
Mt. Airy, MD 21771

John Taylor  
National Research Council  
ASEB  
2101 Constitution Avenue  
Washington, DC 20418

R. J. Templin (3)  
Low Speed Aerodynamics Section  
NRC-National Aeronautical Establishment  
Ottawa 7, Ontario  
CANADA K1A OR6
Arnan Seginer
Professor of Aerodynamics
Technion-Israel Institute of Technology
Department of Aeronautical Engineering
Haifa, ISRAEL

Dr. Horst Selzer
Dipl.-Phys.
Wehrtechnik und Energieforschung
ERNO-Raumfahrttechnik GmbH
Hunefeldstr. 1-5
Postfach 10 59 09
2800 Bremen 1
GERMANY

H. Sevier
Rocket and Space Division
Bristol Aerospace Ltd.
P.O. Box 874
Winnipeg, Manitoba
CANADA R3C 2S4

P. N. Shankar
Aerodynamics Division
National Aeronautical Laboratory
Bangalore 560017
INDIA

David Sharpe
Kingston Polytechnic
Canbury Park Road
Kingston, Surrey
UNITED KINGDOM

D. G. Shepherd
Cornell University
Sibley School of Mechanical and Aerospace Engineering
Ithaca, NY 14853

Dr. Fred Smith
Mechanical Engineering Department Head
Colorado State University
Ft. Collins, CO 80521

Kent Smith
Instituto Technologico Costa Rica
Apartado 159 Cartago
COSTA RICA
Wilson Prichett, III  
National Rural Electric Cooperative Association  
1800 Massachusetts Avenue NW  
Washington, DC 20036

Dr. Barry Rawlings, Chief  
Division of Mechanical Engineering  
Commonwealth Scientific and Industrial Research Organization  
Graham Road, Highett  
Victoria, 3190  
AUSTRALIA

Thomas W. Reddoch  
Associate Professor  
Department of Electrical Engineering  
The University of Tennessee  
Knoxville, TN 37916

Ray G. Richards  
Atlantic Wind Test Site  
P.O. Box 189  
Tignish P.E.I.  
COB 2BO CANADA

A. Robb  
Memorial University of Newfoundland  
Faculty of Engineering and Applied Sciences  
St. John's Newfoundland  
CANADA A1C 5S7

J. R. Rodriguez  
Solarwind Energy Corporation  
1163 Pomona Road  
Unit A  
Corona, CA 91720

Dr. -Ing. Hans Ruscheweyh  
Institut fur Leichbau  
Technische Hochschule Aachen  
Wullnerstrasse 7  
GERMANY

Gwen Schreiner  
Librarian  
National Atomic Museum  
Albuquerque, NM 87185

Douglas B. Seely, P.E.  
U.S. Department of Energy  
P.O. Box 3621  
102 NE Holladay  
Portland, OR 97208
Roger O'Hara
Energy Times
909 NE 43rd
Suite 308
Seattle, WA 98105

Oklahoma State University (2)
Stillwater, OK 76074
Attn: W. L. Hughes
EE Department
D. K. McLaughlin
ME Department

Oregon State University (2)
Corvallis, OR 97331
Attn: R. E. Wilson
ME Department
R. W. Thresher
ME Department

Pat F. O'Rourke
Precinct 4
County Commissioner
City-County Building
El Paso, TX 79901

H. H. Paalman
Dow Chemical USA
Research Center
2800 Mitchell Drive
Walnut Creek, CA 94598

Dr. Y. H. Pao, Chairman
Flow Industries, Inc.
21414 68th Ave. South
Kent, WA 98031

Ion Paraschivoiu
IREQ
1800 montee Ste-Julie
Varennes, Quebec
CANADA JOL 2PO

R. A. Parmalee
Northwestern University
Department of Civil Engineering
Evanston, IL 60201

Helge Petersen
Riso National Laboratory
DK-4000 Roskilde
DENMARK
J. B. Longendyck
Siltex
7 Capitol Drive
Moonachie, NJ 07074

Los Alamos Scientific Laboratories
P.O. Box 1663
Los Alamos, NM 87544
Attn: J. D. Balcomb Q-DO-T

Beatrice de Saint Louvent
Establissement d'Etudes et de Recherches Meteorologiques
77, Rue de Serves
92106 Boulogne-Billancourt Cedex
FRANCE

Ernel L. Luther
Senior Associate
PRC Energy Analysis Co.
7600 Old Springhouse Rd.
McLean, VA 22101

L. H. J. Maile
48 York Mills Rd.
Willowdale, Ontario
CANADA M2P 1E4

E. L. Markowski
Motolola, Inc.
G.E.D.
Mail Drop 1429
8201 E. McDowell Rd.
P.O. Box 1417
Scottsdale, AZ 85252

Jacques R. Maroni
Ford Motor Company
Environmental Research and Energy Planning Director
Environmental and Safety Engineering Staff
The American Road
Dearborn, MI 48121

Frank Matanzo
Dardalen Associates
15110 Frederick Road
Woodbine, MD 21797

H. S. Matsuda, Manager
Composite Materials Laboratory
Pioneering R&D Laboratories
Toray Industries, Inc.
Sonoyama, Otsu, Shiga
JAPAN 520
Carol Lamb
2584 East Geddes Avenue
Littleton, CO 80122

Lawrence Livermore Laboratory
P.O. Box 808 L-340
Livermore, CA 94550
Attn: D. W. Dorn

M. Lechner
Public Service Company of New Mexico
P.O. Box 2267
Albuquerque, NM 87103

Kalman Nagy Lehoczky
Cort Adelers GT. 30
Oslo 2
NORWAY

George E. Lennox
Industry Director
Mill Products Division
Reynolds Metals Company
6601 West Broad Street
Richmond, VA 23261

J. Lerner
State Energy Commission
Research and Development Division
1111 Howe Avenue
Sacramento, CA 95825

L. Liljedahl
Building 303
Agriculture Research Center
USDA
Beltsville, MD 20705

P. B. S. Lissaman
Aeroenvironment, Inc.
660 South Arroyo Parkway
Pasadena, CA 91105

Olle Ljungstrom
FFA, The Aeronautical Research Institute
Box 11021
S-16111 Bromma
SWEDEN

T. H. Logan
U.S. Turbine Corporation
Olde Courthouse Building
Canfield, OH 44406
Indian Oil Corporation, Ltd.
Marketing Division
254-C, Dr. Annie Besant Road
Prabhadevi, Bombay-400025
INDIA

JBF Scientific Corporation
2 Jewel Drive
Wilmington, MA 01887
Attn: E. E. Johanson

Dr. Gary L. Johnson, P.E.
Electrical Engineering Department
Kansas State University
Manhattan, KS 66506

B. O. Kaddy, Jr.
Box 353
31 Union Street
Hillsboro, NH 03244

Kaman Aerospace Corporation
Old Windsor Road
Bloomfield, CT 06002
Attn: W. BATESOL

R. L. Katzenberg
2820 Upton St. NW
Washington, DC 20008

Robert E. Kelland
The College of Trades and Technology
P.O. Box 1693
Prince Philip Drive
St. John's, Newfoundland
CANADA A1C 5F7

S. King
Natural Power, Inc.
New Boston, NH 03070

Larry Kinnett
P.O. Box 6593
Santa Barbara, CA 93111

Samuel H. Kohler
272 Old Delp Road
Lancaster, PA 17602

O. Krauss
Michigan State University
Division of Engineering Research
East Lansing, MI 48824
A. A. Hagman
Kaiser Aluminum and Chemical Sales, Inc.
14200 Cottage Grove Avenue
Dolton, IL  60419

Martin L. Hally, Section Manager
Project Department
Electricity Supply
18 St. Stephen's Green
Dublin 2, IRELAND

Professor N. D. Ham
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA  02139

C. F. Harris
Wind Engineering Corporation
Airport Industrial Area
Box 5936
Lubbock, TX  79415

W. L. Harris
Aero/Astro Department
Massachusetts Institute of Technology
Cambridge, MA  02139

Terry Healy (2)
Rockwell International
Rocky Flats Plant
P.O. Box 464
Golden, CO  80401

Helion
P.O. Box 4301
Sylmar, CA  91342

Don Hinrichsen
Associate Editor
AMBI0
KVA
Fax, S-10405
Stockholm
SWEDEN

Sven Hugosson
Box 21048
S. 100 31 Stockholm 21
SWEDEN

O. Igra
Department of Mechanical Engineering
Ben-Gurion University of the Negev
Beer-Sheva, ISRAEL
Richard G. Ferreira, Chief
The Resources Agency
Department of Water Resources
Energy Division
1416 9th Street
P.O. Box 388
Sacramento, CA 95822

D. R. Finley
New England Geosystems
P.O. Box 128
East Derry, NH 03041

James D. Fock, Jr.
Department of Aerospace Engineering Sciences
University of Colorado
Boulder, CO 80309

Dr. Lawrence C. Frederick
Public Service Company of New Hampshire
1000 Elm Street
Manchester, NH 03105

H. Gerardin
Mechanical Engineering Department
Faculty of Sciences and Engineering
Universite Laval—Quebec
CANADA G1K 7P4

E. Gilmore
Amarillo College
Amarillo, TX 79100

Paul Gipe
Wind Power Digest
P.O. Box 539
Harrisburg, PA 17108

Roger T. Griffiths
University College of Swansea
Department of Mechanical Engineering
Singleton Park
Swansea SA2 8PP
UNITED KINGDOM

Professor G. Gregorck
Ohio State University
Aeronautical and Astronautical Department
2070 Neil Avenue
Columbus, OH 43210

Richard Haddad
101 Arizona
P.O. Box 530
El Paso, TX 79944
DOE Headquarters/WESD (20)
600 E Street NW
Washington, DC  20545
Attn: D. F. Ancona
      C. E. Aspliden
      L. V. Divone
      W. C. Reddick

C. W. Dodd
School of Engineering
Southern Illinois University
Carbondale, IL  62901

D. D. Doerr
Kaiser Aluminum and Chemical Sales, Inc.
6177 Sunol Blvd.
P.O. Box 877
Pleasanton, CA  94566

Dominion Aluminum Fabricating Ltd. (2)
3570 Hawestone Road
Mississauga, Ontario
CANADA L5C 2U8
Attn: L. Schienbein
      C. Wood

D. P. Dougan
Hamilton Standard
1730 NASA Boulevard
Room 207
Houston, TX  77058

J. B. Dragt
Nederlands Energy Research Foundation (E.C.N.)
Physics Department
Westerduinweg 3 Patten (nh)
THE NETHERLANDS

C. E. Elderkin
Battelle-Pacific Northwest Laboratory
P.O. Box 999
Richland, WA  99352

Frank R. Eldridge, Jr.
The Mitre Corporation
1820 Dolley Madison Blvd.
McLean, VA  22102

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA  94304
Attn: E. Demeo

180