Aeroelastic Effects in the Structural Dynamic Analysis of Vertical Axis Wind Turbines

D. W. Lobitz, T. D. Ashwill

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789
AEROELASTIC EFFECTS IN THE STRUCTURAL DYNAMIC ANALYSIS OF VERTICAL AXIS WIND TURBINES*

D. W. Lobitz and T. D. Ashwill
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

Aeroelastic effects impact the structural dynamic behavior of vertical axis wind turbines (VAWTs) in two major ways. First, the stability phenomena of flutter and divergence are direct results of the aeroelasticity of the structure. Secondly, aerodynamic damping can be important for predicting response levels, particularly near resonance, but also for off-resonance conditions. The inclusion of the aeroelasticity is carried out by modifying the damping and stiffness matrices in the NASTRAN finite element code. Through the use of a specially designed preprocessor, which reads the usual NASTRAN input deck and adds appropriate cards to it, the incorporation of the aeroelastic effects has been made relatively transparent to the user. NASTRAN flutter predictions are validated using field measurements and the effect of aerodynamic damping is demonstrated through an application to the Test Bed VAWT being designed at Sandia.

*This work performed at Sandia National Laboratories is supported by the U.S. Department of Energy under Contract Number DE-AC04-76DP00789.
INTRODUCTION

The aeroelastic analysis of wind turbines is entirely similar to that done for subsonic aircraft wing structures, and most of the theory that has been developed for those structures carries over directly. The essence of aeroelastic behavior is that the aerodynamic loads depend on motions of the structure which change the angle of attack. As an example, for a horizontal wing structure, wing velocities in the vertical direction change the angle of attack in such a way that the motion is resisted by the induced aerodynamic loads. This type of motion produces aerodynamic damping. Alternatively, for wing torsion, the induced loads generally act to increase the motion, leading to a possible divergence or flutter condition.

In the case of flutter the oscillatory motion of the blade necessitates the use of unsteady aerodynamic theory. This theory introduces complex valued coefficients, which are functions of the reduced frequency (Strouhal Number), in the expressions for the aerodynamic loads. These coefficients alter the phase relations between the blade motions and the resulting aerodynamic loads, and can be very important in the prediction of flutter. For the analysis of divergence, which is a static phenomenon, the same equations apply, but the reduced frequency must be set to zero. Generally for VAWTs, flutter and divergence instabilities have not been an issue. However, during the design stage of a new turbine, it is always prudent to establish the flutter and divergence boundaries to avoid the catastrophic consequences associated with these phenomena.

For frequency response analysis aeroelasticity is important in establishing the level of aerodynamic damping. For VAWTs with high tip speeds aerodynamic damping can be substantial, leading to significant reductions in even the off-resonance response. Additionally, with the advent of modeling atmospheric turbulence, analysis procedures will have to accommodate dynamic response at all frequencies rather than just the integer multiples of the operating speed. Thus, to obtain accurate response levels near the natural frequencies of the rotor some reasonable estimate of the damping will be required. Since aerodynamic damping is at least as significant as the low level of structural damping that generally exists in VAWTs, it is important that it also be accounted for in the analysis.
The inclusion of the aeroelasticity is carried out by modifying the damping and stiffness matrices in the NASTRAN finite element code (using NASTRAN's "DMIG" input option). These modifications are incorporated with the Coriolis and softening matrices required for modeling the rotating coordinate system effects. The stability and frequency response of the turbine are subsequently investigated using the appropriate NASTRAN solution procedure. Through the use of a specially designed preprocessor, which reads the usual NASTRAN input deck and adds appropriate cards to it, the incorporation of the aeroelastic effects has been made relatively transparent to the user.

A number of other investigators have addressed the issue of aeroelasticity in VAWTs [1,2,3] with good success. Although the approach is similar to the one used here, their work is based on a modal representation using generalized degrees of freedom. In addition, the phase relations between the structural motions and the induced aerodynamic loads are taken to be zero. The work presented here utilizes physical degrees of freedom, which simplifies the NASTRAN input of the aeroelasticity matrices. The phase relations between the structural motions and the induced loads, as prescribed by unsteady aerodynamic theory, are also retained.

The remainder of this paper includes sections which describe the theory used in the development of the aeroelasticity matrices, present and discuss specific results, and draw some conclusions.

AEROELASTICITY THEORY FOR VAWTS

In this analysis, a VAWT blade is visualized as a series of straight airfoil sections joined together to form the desired shape. The theory for the aeroelasticity of a wing structure is assumed to be applicable to each segment. An excellent presentation of the physics and the governing equations of subsonic aeroclaslicity for wing structures can be found in [4]. The equations below are reproduced from that reference. As indicated above, unsteady aerodynamic theory is used in their development.
For subsonic flutter, the lifting force, L, and the moment about the center of twist, M, resulting from the motion of a blade segment, are given by

\[
L = a_0 \rho V^2 b \left\{-\frac{c}{V} \dot{u} + C \theta + [C(1-2a)+1] \frac{b \dot{\theta}}{2V} - \frac{b}{2V^2} \ddot{u} - \frac{ab^2}{2V^2} \dot{\theta} \right\}
\]

\[
M = a_0 \rho V^2 b \left\{ d_1 \left[-\frac{c}{V} \dot{u} + C \theta + C(1-2a) \frac{b \dot{\theta}}{2V} \right] + d_2 \frac{b \dot{\theta}}{2V} - \frac{ab^2}{2V^2} \ddot{u} - \left( \frac{1}{8} a^2 \right) \frac{b^3}{2V^2} \dot{\theta} \right\}
\]

where, referring to Figure 1,

- \(a_0\) is the coefficient of lift (per radian),
- \(\rho\) is the air mass density,
- \(V\) is the air speed,
- \(b\) is the half chord length,
- \(a\) is the fraction of \(b\) that the center of twist is behind the half chord point,
- \(d_1\) is the distance the center of pressure is ahead of the center of twist,
- \(d_2\) is the distance the rear aerodynamic center of pressure is ahead of the center of twist,
- \(C\) is the Theodorsen function,
- \(u\) is the vertical wing motion,
- \(\theta\) is the rotational wing motion about the center of twist.

The terms which are proportional to the second time derivatives of \(u\) and \(\theta\) represent "apparent mass" effects (additional mass due to air entrainment by the blade). Since the air mass density is so much smaller than that of the blade, these terms have been neglected in this analysis. Also, the half chord point and center of twist of the blade section are taken to be colinear, rendering the quantity, \(a\), to be zero. Incorporating these considerations, the equations for \(L\) and \(M\) become
Equation (2) can be specialized further by replacing \( V \) with \( RQ \), where \( R \) is the radial distance from the tower to the blade location of interest, and \( Q \) is the rotational speed of the turbine. With this approximation, only the relative air speed corresponding to the rotation of the rotor is taken into account in this aeroelasticity model. The free stream wind velocity is neglected. Also, for these computations, \( d_1 \) and \( d_2 \) are taken to be \( b/2 \) and \(-b/2\), respectively. This places the center of pressure and rear center of pressure at the quarter chord and three quarter chord points, respectively.

The Theodorsen function, \( C \), is of great importance for accurately predicting flutter in wing structures, but less so in VAWTs. It is a complex valued function of the reduced frequency, \( k \), and therefore affects the phase relationships between the wing motions and the resulting aerodynamic loads. It is usually found in tabular form but can be reasonably approximated by
\[ C(k) = \left[ 1 - \frac{0.165k^2}{k^2 + (0.0455)^2} - \frac{0.335k^2}{k^2 + (0.3)^2} \right] \]

\[ -i \left[ \frac{0.165 \cdot 0.0455k}{k^2 + (0.0455)^2} - \frac{0.335 \cdot 0.3k}{k^2 + (0.3)^2} \right] \]

where

\[ k = \frac{\omega_b}{V} \text{ is the reduced frequency,} \]

\[ \omega \text{ is the oscillatory frequency of the wing, i.e., the flutter frequency.} \]

For flutter calculations, the value of \( \omega \) used in the evaluation of the Theodorsen function should be set at the flutter frequency. As this frequency is not precisely known at the outset, some amount of manual iteration is required. To establish divergence conditions \( \omega \) should be set to zero since divergence is a static phenomenon. For providing aerodynamic damping in frequency response computations, \( \omega \) should be set to some characteristic frequency anticipated in the response, i.e. 3/rev.

In order to incorporate Equations (2) into NASTRAN, they are cast in a finite element form. This is accomplished using a Galerkin procedure. For the beam elements of which the VAWT blades are composed, the transverse and torsional degrees of freedom are assumed to vary linearly from one end of the element to the other. In the local element coordinate system, these motions are represented by

\[
\begin{align*}
\{u\} &= \begin{bmatrix} 1-s & 0 & s & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ \theta_1 \\ u_2 \\ \theta_2 \end{bmatrix} \\
\{\theta\} &= \begin{bmatrix} 0 & 1-s & 0 & s \end{bmatrix} \begin{bmatrix} u_1 \\ \theta_1 \\ u_2 \\ \theta_2 \end{bmatrix}
\end{align*}
\]

where the subscripts denote the motions at either end of the element, and \( s \) is the arc length measured along the element and normalized by the element length.
Inserting this approximation into Equations (2), premultiplying by the same linear shape functions, and integrating over the length of the beam element, the contributions to the element damping and stiffness matrices are obtained as shown below

**Damping Matrix**

\[
\begin{pmatrix}
-C(1-s)^2 & (1+C)^2(1-s)^2 \\
-d_1C(1-s)^2 & (d_2+d_1C)^2(1-s)^2 \\
-Cs(l-s) & (1+C)^2s(l-s) \\
-d_1Cs(l-s) & (d_2+d_1C)^2s(l-s)
\end{pmatrix}
\]

\[
\int_0^1 \frac{B}{v} \frac{1}{v} \left[
\begin{array}{c}
-Cs(l-s) \\
-d_1Cs(l-s) \\
-Cs^2 \\
-d_1Cs^2
\end{array}
\right] (1+C) \frac{b_2}{s} \frac{(1-s)^2}{s(l-s)} ds
\]

**Stiffness Matrix**

\[
\begin{pmatrix}
0 & (1-s)^2 & 0 & s(l-s) \\
0 & d_1(l-s)^2 & 0 & d_1s(l-s) \\
0 & s(l-s) & 0 & s^2 \\
0 & d_1s(l-s) & 0 & d_1s^2
\end{pmatrix}
\]

\[
\int_0^1 \frac{1}{BC} \left[
\begin{array}{c}
0 \\
0 \\
0 \\
0
\end{array}
\right] ds
\]

where

\[B = a_0 \rho V^2 bL,\]

\[L\] is the length of the element.
Note that the quantities, $V$, $b$, $d_1$, $d_2$, and $C$, may all be functions of $s$. The integrals are numerically evaluated using two-point Gaussian integration.

As NASTRAN's DMIG input option only allows one matrix to be input for each of the structural matrices, it is necessary to assemble all of the element contributions prior to NASTRAN input. Before this can be carried out, however, all of the individual element matrices must be transformed from the local frames in which they have been developed, to the global coordinate system.

Having provided these matrices to NASTRAN, flutter and divergence calculations are carried out using one of NASTRAN's complex eigenvalue solvers. Modes which are fluttering have negative damping coefficients, and divergent modes have null or negative frequencies. Frequency response analysis is accomplished in the usual manner using NASTRAN's frequency response solver.

**PRESENTATION AND DISCUSSION OF RESULTS**

To validate the analysis technique for predicting the onset of flutter, two test cases have been completed. First, the predicted flutter speed for a straight, uniform, cantilevered wing was compared to that obtained from an exact solution, and nearly perfect agreement was attained. Secondly, the flutter speed was computed for a specific configuration of the Sandia two meter VAWT, for which experimental flutter data has been obtained. The flutter prediction of 680 RPM is in good agreement with the observed value of 745 RPM, especially since the predicted result does not include any structural damping. The flutter mode was also correctly predicted.

Having established some credibility for the method, flutter predictions for the Sandia 34-m Test Bed VAWT design shown in Figure 2 have been made. A key innovation in this design is the variable blade section, which causes the rotor to stall at higher tip speeds. This permits higher operating speeds which reduce gear box loads and cost.
In Figure 3 the damping coefficient for the various modes of the turbine is plotted versus rotor RPM. The modes, which are characterized by their dominant behavior at 0 RPM, are identified by the labels to the right of the figure. The Pr or propeller modes are characterized by twisting motion of the rotor about the axis which is colinear with the tower. The F or flatwise modes primarily involve blade motion in the plane of the rotor with very little, if any, tower participation. The subscript, S, denotes symmetry in the motion of the two blades, and A, asymmetry. The B or butterfly modes consist of blade motion out of the plane of the rotor, which resembles the flapping of butterfly wings. This is usually coupled with some out-of-plane tower motion. And finally, the TI modes, or tower in plane modes, primarily involve tower motion in plane of the rotor.
The damping coefficients shown in this figure correspond to percent of critical structural, rather than viscous damping. However, they derive totally from aeroelastic effects, i.e., no structural damping has been included. In computing these curves the oscillatory frequency, $\omega$, was set at 4 Hz, which corresponds to the frequency of the $2F_s$ mode as it crosses the axis at 82 RPM. Generally the flatwise modes are substantially damped over a large range of RPMs and eventually become unstable as they cross the axis. Other modes, such as the $1B$ and $1T1$, become unstable at a relatively low RPM and remain modestly so out to higher rotational speeds. These are not as crucial as they might seem since, as will be shown, a small amount of structural damping stabilizes them. The mode that actually establishes the flutter speed is the flatwise mode that first goes unstable. As shown in Figure 3, this corresponds to the $2F_s$ mode and, consequently, the flutter speed for the Test Bed is predicted to be approximately 82 RPM. This is well above the operating speed range of 28 to 40 RPM.
In Figure 4 damping coefficients similar to those of Figure 3 are shown, except that in Figure 4, structural damping at a level of 2 percent of critical has been included. This level is consistent with values reduced from data taken from Sandia's two-meter VAWT [5]. In general, the primary effect of including the structural damping is that the curves for the various modes are raised by approximately the amount of damping specified. This tends to stabilize the 1B and 1TI modes and increases the flutter speed to 89 RPM.

![Diagram showing damping coefficients versus RPM for the 34-m Test Bed, Aerodynamic Plus Structural Damping.](image)

Figure 4. Damping Coefficients Versus RPM for the 34-m Test Bed, Aerodynamic Plus Structural Damping.

In an attempt to discern the role of the Theodorsen function in analyzing the aeroelastic behavior of VAWTs, \( \omega \) was set to zero. For this value, the Theodorsen function is real rather than complex and has a value of unity. In this case, the predicted flutter speed becomes 84 RPM rather than 82, a modest difference.
However, damping factors are approximately 20 percent greater than previous values, which may lead to some degree of unconservatism in the predicted structural response.

To investigate the divergence characteristics of the Test Bed, the fanplot shown in Figure 5 was produced using a value of zero for $\omega$. Actually the fanplot proved to be relatively insensitive to the value of $\omega$ used. The dashed P lines denote the forcing frequencies that are present at each RPM as a result of the rotor turning in a steady wind. Recalling that divergence is indicated by a natural frequency dropping to zero, there is no indication of divergence or even its onset from this figure. The descent of the frequency of the 1B mode is a result of the whirl instability rather than aeroelastic divergence.

![Fanplot for the 34-m Test Bed.](image)
The effect of aerodynamic damping on the off-resonance response of a VAWT was determined by computing the response of the 34-m Test Bed with and without the aeroelasticity, at a rotational speed of 40 RPM. Results for the blade flatwise RMS stress versus vertical location are provided in Figure 6. The curves shown correspond to a wind speed of 20.11 m/s (45 MPH). As indicated, the aerodynamic damping provides an RMS peak stress reduction of approximately 20 percent. If the flatwise vibratory stresses happen to drive the fatigue life of the blade, this reduction would substantially increase its life.

![Figure 6. Effect of Aerodynamic Damping on Flatwise RMS Vibratory Stresses for the 34-m Test Bed.](image)
CONCLUSIONS

Aeroelasticity can produce unstable behavior in VAWTs associated with the phenomena of flutter and divergence. The occurrence of divergence, however, is unlikely because of the additional torsional stiffness afforded the blade by its attachment to the tower at each end, in contrast to the cantilever design of an aircraft wing. Additionally, it is anticipated that the whirl instability point would always occur prior to the onset of divergence. The possibility of flutter is not as remote as divergence. However, predicted flutter speeds tend to be two to three times that of the operating speed. In any case, for a new turbine design, it is always prudent to establish the flutter speed in order to avoid the serious consequences of flutter, should it occur. The method described here provides a relatively simple and accurate means of accomplishing this.

The same method also provides a simple way to incorporate aerodynamic damping in frequency response analyses. As shown, aeroelasticity can produce damping factors associated with flatwise blade motion as high as 20 percent of critical. At these levels, even the off-resonance response can be significantly reduced. This suggests that an additional benefit of VAWT designs with higher tipspeeds may be a reduction in flatwise blade response due to higher damping levels.
REFERENCES


West Wind Industries
Attn: K. Jackson
PO Box 1705
Davis, CA 95617

McAllester Financial
Attn: M. Jackson
1816 Summit
W. Lafayette, IN 47906

Kaiser Aluminum and Chemical Sales, Inc.
Attn: A. A. Hagman
14200 Cottage Grove Avenue
Dolton, IL 60419

Kaiser Aluminum and Chemical Sales, Inc.
Attn: D. D. Doerr
6177 Sunol Blvd.
PO Box 877
Pleasanton, CA 94566

Kansas State University
Electrical Engineering Department
Attn: Dr. G. L. Johnson
Manhattan, KS 66506

R. E. Kelland
The College of Trades and Technology
PO Box 1693
Prince Philip Drive
St. John's, Newfoundland, A1C 5P7
CANADA

KW Control Systems, Inc.
Attn: R. H. Klein
RD#4, Box 914C
South Plank Road
Middleton, NY 10940

Kalman Nagy Lehoczky
Cort Adelers GT. 30
Oslo 2, NORWAY

L. Liljidahl
Building 005, Room 304
Barc-West
Beltville, MD 20705

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

R. Lynette & Assoc., Inc.
Attn: Robert Lynette
15921 SE 46th Way
Bellevue, WA 98006

Massachusetts Institute of Technology (2)
Attn: Professor N. D. Ham
W. L. Harris, Aero/Astro Dept.
77 Massachusetts Avenue
Cambridge, MA 02139

Pioneering R&D Laboratories
Composite Materials Laboratory
Attn: H. S. Matsuda
Toray Industries, Inc.
Sonoyama, Otsu, Shiga, JAPAN 520

US Wind Power
Attn: G. M. McNerney
1600 Wheeler Road
Burlington, MA 01803

Michigan State University
Division of Engineering Research
Attn: O. Krauss
East Lansing, MI 48825

Napier College of Commerce and Technology
Tutor Librarian, Technology Faculty
Colinton Road
Edinburgh, EH10 5DT
ENGLAND

NASA Lewis Research Center (2)
Attn: D. Baldwin
J. Savino
21000 Brookpark Road
Cleveland, OH 44135

National Rural Electric Cooperative Assn.
Attn: Wilson Prichett, III
1800 Massachusetts Avenue NW
Washington, DC 20036
Rockwell International (2)
Rocky Flats Plant
Attn: A. Trenka
PO Box 464
Golden, CO 80401

Dr. Ing. Hans Ruscheweyh
Institut fur Leichbau
Technische Hochschule Aachen
Wullnerstrasse 7
FEDERAL REPUBLIC OF GERMANY

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

National Atomic Museum
Librarian
Attn: Gwen Schreiner
Albuquerque, NM 87185

Arnan Seginer
Professor of Aerodynamics
Technion-Israel Institute of Technology
Department of Aeronautica Engineering
Haifa
ISRAEL

Wind Energy Abstracts
Attn: Farrell Smith Seiler, Editor
PO Box 3870
Bozeman, MT 59772-3870

Queen Mary College
Dept. of Aeronautical Engineering
Attn: David Sharpe
Mile End Road
London, E1 4NS
UNITED KINGDOM

Instituto Technologico Costa Rico
Attn: Kent Smith
Apartado 159 Cartago
COSTA RICA

Bent Sorenson
Roskilde University Center
Energy Group, Bldg. 17.2
IMFUFA
PO Box 260
DK-400 Roskilde
DENMARK

ADECON
Attn: Peter South
32 Rivalda Road
Weston, Ontario, M9M 2M3
CANADA

Southern California Edison
Research & Development Dept., Rm 497
Attn: R. L. Scheffler
PO Box 800
Rosemead, CA 91770

The University of Reading
Department of Engineering
Attn: G. Stacey
Whiteknights, Reading, RG6 2AY
ENGLAND

Stanford University
Dept. of Aeronautics and Astronautics Mechanical Engineering
Attn: Holt Ashley
Stanford, CA 94305

Dr. Derek Taylor
Alternative Energy Group
Walton Hall
Open University
Milton Keynes, MK7 6AA
UNITED KINGDOM

Low Speed Aerodynamics Laboratory (3)
NRC-National Aeronautical Establishment
Attn: R. J. Templin
Montreal Road
Ottawa, Ontario, K1A OR6
CANADA

Texas Tech University (2)
Mechanical Engineering Dept.
Attn: J. W. Oler
PO Box 4289
Lubbock, TX 79409
Tulane University  
Dept of Mechanical Engineering  
Attn: R. G. Watts  
New Orleans, LA 70018

Tumac Industries, Inc.  
6400 Ford Street  
Attn: J. R. McConnell  
Colorado Springs, CO 80915

Terrestrial Energy Technology  
Program Office  
Energy Conversion Branch  
Aerospace Power Division/  
Aero Propulsion Lab  
Attn: J. M. Turner  
Air Force System Command (AFSC)  
Wright-Patterson AFB, OH 45433

United Engineers and Constructors, Inc.  
Attn: A. J. Karalis  
PO Box 8223  
Philadelphia, PA 19101

University Data Systems  
Attn: C. W. Dodd  
5000 Bradford Drive  
Huntsville, AL 35805

University of California  
Institute of Geophysics  
and Planetary Physics  
Attn: Dr. P. J. Baum  
Riverside, CA 92521

University of Colorado  
Dept. of Aerospace Engineering Sciences  
Attn: J. D. Fock, Jr.  
Boulder, CO 80309

University of Massachusetts  
Mechanical and Aerospace  
Engineering Dept.  
Attn: Dr. D. E. Cromack  
Amherst, MA 01003

University of New Mexico  
New Mexico Engineering  
Research Institute  
Attn: G. G. Leigh  
Campus PO Box 25  
Albuquerque, NM 87131

University of Oklahoma  
Aero Engineering Department  
Attn: K. Bergey  
Norman, OK 73069

University of Sherbrooke (2)  
Faculty of Applied Science  
Attn: A. Laneville  
P. Vittecoq  
Sherbrooke, Quebec, J1K 2R1  
CANADA

The University of Tennessee  
Dept. of Electrical Engineering  
Attn: T. W. Reddoch  
Knoxville, TN 37916

USDA, Agricultural Research Service  
Southwest Great Plains Research Center  
Attn: Dr. R. N. Clark  
Bushland, TX 79012

Utah Power and Light Co.  
Attn: K. R. Rasmussen  
51 East Main Street  
PO Box 277  
American Fork, UT 84003

W. A. Vachon & Associates  
Attn: W. A. Vachon  
PO Box 149  
Manchester, MA 01944

VAWTPOWER, Inc.  
Attn: P. N. Vosburgh  
134 Rio Rancho Drive  
Rio Rancho, NM 87124

Washington State University  
Dept. of Electrical Engineering  
Attn: F. K. Bechtel  
Pullman, WA 99163

West Texas State University  
Government Depository Library  
Canyon, TX 79015  
Number 613

West Texas State University  
Department of Physics  
Attn: V. Nelson  
PO Box 248  
Canyon, TX 79016
West Virginia University
Dept of Aero Engineering
Attn:  R. Walters
1062 Kountz Avenue
Morgantown, WV  26505

Central Lincoln People's Utility
District
Attn:  D. Westlind
2129 North Coast Highway
Newport, OR 97365-1795

Wichita State University (2)
Aero Engineering Department
Attn:  M. Snyder
W. Wentz
Wichita, KS  67208

Windy Energy Abstracts
Attn:  Farrell Smith Seiler
PO Box 3870
Bozeman, MT  59772

Wind Power Digest
Attn:  Michael Evans
PO Box 700
Bascom, OH  44809

Wisconsin Division of State Energy
Attn:  Wind Program Manager
8th Floor
101 South Wesbter Street
Madison, WI  53702

1520  D. J. McCloskey
1522  R. C. Reuter, Jr.
1523  J. H. Biffle
1524  D. W. Lobitz
1600  R. G. Clem
1630  R. C. Maydew
1636  J. K. Cole
2525  R. P. Clark
2542  W. N. Sullivan
3160  J. E. Mitchell (15)
3161  P. S. Wilson
6000  E. H. Beckner
6200  V. L. Dugan
6220  D. G. Schueler
6225  H. M. Dodd (50)
6225  T. D. Ashwill
6225  D. E. Berg
6225  L. R. Gallo
6225  R. D. Grover
6225  P. C. Klimas
6225  D. S. Oscar
6225  M. E. Ralph
6225  M. H. Worstell
6256  H. J. Sutherland
7111  J. W. Reed
7544  D. R. Schafer
7544  T. G. Carne
7544  J. Laufer
8024  P. W. Dean
3141  S. A. Landenberger (5)
3151  W. L. Garner (3)
3154-3  C. H. Dalin (28)
for DOE/OSTI (Unlimited Release)