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Structural Effects of Unsteady Aerodynamic Forces on Horizontal-Axis Wind Turbines

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ABSTRACT

Due to its renewable nature and abundant resources, wind energy has the potential to fulfill a large portion of this nation's energy needs. The simplest means of utilizing wind energy is through the use of downwind, horizontal-axis wind turbines (HAWT) with fixed-pitch rotors. This configuration regulates the peak power by allowing the rotor blade to aerodynamically stall. The stall point, the point of maximum coefficient of lift, is currently predicted using data obtained from wind tunnel tests. Unfortunately, these tests do not accurately simulate conditions encountered in the field. Flow around the tower and nacelle coupled with inflow turbulence and rotation of the turbine blades create unpredicted aerodynamic forces. Dynamic stall is hypothesized to occur. Such aerodynamic loads are transmitted into the rotor and tower causing structural resonance that drastically reduces the design lifetime of the wind turbine. The current method of alleviating this problem is to structurally reinforce the tower and blades. However, this adds unneeded mass and, therefore, cost to the turbines. A better understanding of the aerodynamic forces and the manner in which they affect the structure would allow for the design of more cost effective and durable wind turbines.

Data compiled by the National Renewable Energy Laboratory (NREL) for a downwind HAWT with constant chord, untwisted, fixed-pitch rotors is analyzed. From these data, the actual aerodynamic characteristics of the rotor are being portrayed and the potential effects upon the structure can for the first time be fully analyzed. Based upon our understanding, solutions to the problem of structural resonance are emerging.

BACKGROUND

Wind Rotor Background

Fossil fuels currently supply a vast majority of the world's energy needs. Unfortunately, these non-renewable resources are not only being quickly depleted, but many pollute the environment. Developing cost-effective energy options will be crucial for the United States since it is estimated that by 2010, electricity demand will exceed generating capacity by more than 200,000 megawatts (Brown, 1991). Thus, the development of alternative energy sources, such as renewable energy, is mandatory.

One such alternative energy resource, wind energy, is a renewable and abundant resource which has the potential to significantly enhance the nation's electrical generating capabilities. The Pacific Northwest Laboratory (PNL) concluded that 0.6% of the contiguous United States contains sufficient wind resources to generate 20% of U.S. electricity demand using today's wind turbine technology (Elliott *et al.*, 1991). For instance, winds sweeping across one ridge in southwestern Minnesota could provide enough electricity to meet 86% of the state's electrical needs (Swisher *et al.*, 1991). More advanced machines, such as those being developed at the National Renewable Energy Laboratory (NREL), could increase this potential by as much as 10 times (Elliott *et al.*, 1991).

Wind energy's major advantages over other power sources, besides its enormous electrical generating capabilities, are that it is renewable, economical, and environmentally sound. Since wind energy is renewable, there is no danger of depletion. However, wind is an intermittent resource so the selection of a

wind power plant site at which winds remain constant year-round is important. Wind energy's economic benefits include that among all commercially available fossil fuels and renewable energy technologies evaluated for utility power plants, wind technology had the lowest levelized costs at 4.8 cents/kWh (Rashkin, 1991). Also, wind energy provides more jobs per dollar invested than any other energy technology, more than five times that from coal or nuclear power (Swisher *et al.*, 1991). Wind rotors are environmentally sound because they do not pollute the environment and more than 90% of the land in wind power plants remains available for compatible uses, such as ranching, farming, or recreation (Brown, 1991).

The two main types of turbines used to harness the wind's power are the vertical-axis wind turbine (VAWT) and the horizontal-axis wind turbine (HAWT). After many years of testing, downwind HAWTs have been determined to be best suited to generate electrical power, based primarily on the fact that they are more economical. Consequently, most American and foreign wind turbine manufacturers only design and build downwind HAWTs. Thus, since one of NREL's primary objectives is to engage in research which benefits the industrial community, a downwind HAWT was chosen as the type of wind turbine to study.

Although wind turbines have the potential to supply large amounts of clean, cost effective power, improvements can still be made. Operational and manufacturing costs may be lowered through the elimination of over-design and equipment loss due to fatigue. Likewise, increasing the operational lifetime of the turbine would lower long-term costs. The only way to accomplish these design goals is to understand the underlying mechanisms that cause unpredicted, unsteady forces on wind turbines.

Experimental Rationale

One of NREL's major goals is to predict

the loads on wind turbines accurately enough so that the blades, hub, and remaining support structure can be designed to achieve a 30-year life (Butterfield *et al.*, 1992). The performance capabilities of downwind HAWTs are normally obtained through wind tunnel performance data measurements. However, this method does not accurately predict the aerodynamic loads placed upon wind turbines in the field. Usually the loads experienced by the turbine are significantly higher than the predicted loads. This causes severe problems. For instance, there is an occasional tendency for the blades to break off the turbine due to loads above their design limitations. Therefore, in order to better understand the aerodynamics loads and the effects of these loads on turbines, it is necessary to further understand and quantify the operating conditions encountered in the field.

HYPOTHESIS

The most likely reason that the HAWT performance can not be accurately determined from the wind tunnel performance data is that unsteady aerodynamics effects are produced during most or all of the turbine's operational lifetime. Problems with predictions of aerodynamic loads might occur when turbines use stall to regulate peak power and loads. Stall performance of the airfoils used for rotating wings will probably be affected by three-dimensional flow effects not yet fully determined even in controlled wind tunnel data. Another possibility is that dynamic stall, a condition that would increase both the normal and tangential force coefficients, might be occurring.

Such unsteady effects have been the subject of much study by the Air Force (cf., Francis and Lutges, 1984; Helin *et al.*, 1988). Unsteady flows have been shown to produce peak transient loads on airfoils up to 10 times those experienced in steady state tests. Such large brief loads could be a major problem if

experienced by wind rotor blades. For instance, Figure 1 depicts a pressure coefficient (C_p) spike when a wing was pitched rapidly through static stall. Dynamic motions of wind rotors can produce similar pitching motions. Similar pressure fluctuations also occur when an airfoil interacts with coherent vortices shed from other bodies.

TEST SET-UP

A detailed description of the NREL test apparatus can be found in Butterfield (1986). The test platform, called the Combined Experiment, is a Grumman Wind Stream 33 turbine. This turbine is a 10.1 meter diameter, three-bladed, downwind horizontal-axis wind turbine. The turbine rotates at a constant rate of 1.2 Hz and is capable of producing 20 kW of power. An overall view of the test platform is shown in Figure 2. A few of the general dimensions of the wind turbine are as follows:

- 1) The height from the ground to the center of the hub is approximately 17.0 meters.
- 2) The width of the cylindrical post is 0.46 meters in diameter until 4.57 meters above the ground. At this point the tower necks down to 0.406 meters.
- 3) The nacelle is 0.79 meters high, 2.79 meters long, and 0.91 meters deep.

Figure 1: Pressure coefficient distribution with a vortex above an airfoil (Robinson et al., 1987).

The blades used are NREL S809 airfoils which are specifically designed for wind turbine use. For instance, these blades are designed to reduce the effects of leading edge roughness so that bug accumulation will not effect the airfoil performance. Figure 3 shows the shape of the S809 airfoil. These blades are 5.05 meters long and have a constant 0.45 meter chord with no twist. This simplified geometry enables the understanding of the turbine aerodynamics without the complications of an excessive number of variables. With the aerodynamic and structural loadings for this simple case known, more complicated cases involving twisted and tapered blades can be studied.

The turbine blades are constructed of extremely stiff fiberglass composites to limit load induced blade deflections. Two of the blades are standard turbine blades while the third blade has instrumentation. Four sets of chordwise pressure taps are located at 30%, 47%, 63%, and 80% blade spans; pressure taps at 4% chord and 36% chord are located at approximately 35.5%, 41%, 52%, 57.5%, 68.5%, and 74% blade spans; and four total pressure probes are located at 34%,

COMBINED EXPERIMENT TEST SETUP

Figure 2: Front and side views of the Grumman Wind Stream 33 Horizontal Axis Wind Turbine utilized in the Combined Experiment.

52%, 67%, and 84% blade spans. Examining Figure 3, the top picture shows the chordwise pressure tap distribution while the bottom picture indicates the span location of the pressure sampling stations. The heavy dashed lines indicate the full distribution of taps, the light dashed lines locate the 4% and 36% taps only, and the lines protruding from the leading edge of the airfoil are the total pressure probes. There are four ESP-32 pressure transducers inside the blade near the chordwise distributed taps. ESP-32 transducers were chosen since they can be calibrated by remote control, and thus can be calibrated while the turbine is rotating. Each of the transducers is electrically scanned at a tap-to-tap frequency of 16,672 Hz. Thus, each pressure channel is sampled at 521 Hz (Butterfield, 1990).

Figure 3: Rotor blade schematic showing the different span locations for the pressure sampling stations and the individual transducers at the 30%, 47%, 63%, and 80% station (Butterfield, 1990).

Strain gages mounted on the blades and low-speed shaft are used to measure the rotor loads. Flapwise bending loads are measured at seven spanwise stations and the root of the blade. Torsional loads are measured at the root of the blade and one spanwise location. Edgewise loads are measured at the root of the blade and five spanwise locations.

The camera boom holds a 10 lb, high-speed video camera. This camera has a shutter speed of 1/200 of a second and a frame speed of 30 per second. The resolution is a standard 512 x 512 pixel density. The boom is mounted on the hub and extends downwind 3.05 meters on the rotation axis. The boom length allows a view angle of 30 degrees at the tip of the blade and 45 degrees at 66% span. The boom also holds 11 tungsten halogen 120 V spotlights to illuminate the blade for flow visualization studies at night.

There are several other smaller details incorporated into this turbine design. The tower can be tilted down to the ground to allow for ease in instrumentation checkout and calibration. A yaw lock is provided to allow various yaw positions to be set. Dynamically balanced tufts are attached to the blade in order to indicate local wind flow direction.

Several different types of anemometers are placed in an instrumentation mount near the wind turbine to measure the incoming flow. There are 9 U-V-W anemometers, one hot-wire anemometer, and one triaxial sonic anemometer, 10.1 meters to the west-northwest of the turbine. These anemometers are strategically located on meteorological towers so as to obtain relevant data points.

When the environmental conditions desired for data taking occur, all data is taken for 5 minutes at 521 Hz using a time coding that assures time-locked data for all channels.

AERODYNAMIC LOADING

The forces present on a wind turbine are caused by the pressure distributions over the rotating blades. A pressure gradient from the upper to the lower surface gives rise to a force (i.e. lift, drag, normal, and tangential forces). A cycle averaged plot of the total pressure change experienced by the passing blade is shown in Figure 4. Although not shown, the pressure is relatively constant over a majority of a cycle. However, in general, it varies greatly between the azimuth angles of 150 to 210 degrees. This limited azimuth change occurs when the blade is roughly behind the tower in the tower wake.

Cycle average pressure plots (Figure 4) do not accurately reflect the pressure change from cycle to cycle. Figure 5 contains the total pressure profiles for 23 consecutive cycles between the azimuth angles of 150 to 210 degrees. These show that single cycle profiles can differ radically from the average. Yawed operation also causes dramatic deviations from the mean. In effect, the average plots smooth out the large fluctuations misrepresentative of the total pressure change. Therefore, structural loads predicted using averaged conditions are generally either under or overestimated.

The pressure profiles correlate over a majority of the cycle. However, large variations occur in the region behind the

Figure 4: Averaged pressure profile over 10 cycles for the 34% span total pressure probe.

tower. These transients are caused by the flow separation from the tower. This wake gives rise to a number of unsteady aerodynamic effects that influence the rotor blades. For instance, Butterfield *et al.* (1992) have shown that the velocity deficit in this wake induces dynamic stall over large portions of the rotor blades.

A second effect is due to the presence of an unsteady vortex sheet in the tower wake. All cylindrical bodies give rise to a periodic shedding of vorticity called a Karman vortex street (Roshko, 1954; Schlichting, 1979). As shown in Figure 6, vortices are alternately released from either side of the cylinder and are convected downstream by the flow. The shedding frequency can be calculated from the Strouhal number, $S = nd/V_o$, where n is the shedding frequency, d is the cylinder diameter, and V_o is the freestream velocity. Roshko (1954) found that the Strouhal number is approximately equal to 0.2 for Reynolds numbers (Re) on the order of 2×10^5 .

Figure 5: Pressure profiles between 150-210 degree azimuth angles for 23 consecutive cycles.

Therefore the shedding frequency for the test wind turbine varies from 2.5 Hz at $V_o = 5$ m/s to 12.5 Hz at $V_o = 25$ m/s.

The presence of a Karman vortex street is not enough in itself to cause the pressure profile variations seen in Figure 5. However, the differences may be attributed to the manner in which the rotor blade passes through the vortex street. The rotational frequency of 1.2 Hz is equivalent to the blade making one complete cycle every 0.833 seconds. In contrast, a vortex is shed from the tower every 0.4 seconds at $V_o = 5$ m/s to every 0.08 seconds at $V_o = 25$ m/s. The blade intercepts two vortices in exactly the same manner only if the equation $pn = 0.833m$ is true, where p is the vortex shedding period and n and m are any integers. The value of m indicates the number of cycles the blade must pass through before repetition occurs. This repetition is illustrated in Figure 5. Notice that the pressure data for cycles 7 and 8 is nearly identical to that for cycles 21 and 22.

A blade passing close to a vortex causes a large fluctuation in pressure due to the increased or decreased local flow velocity. In contrast, passing far from a vortex or directly through one has little effect. In the latter case, the blade passes directly through the vortex and effectively cuts it in half, destroying the circulation. An analytical model was completed to determine the form of the pressure profile for each orientation. By superimposing a vortex onto a uniform flow and calculating the pressure along a line perpendicular to the freestream, an

Figure 6: Flow visualization of a Karman vortex street (Strykowski and Sreenivasan, 1990).

approximate pressure profile for the azimuth range of 150 to 210 degrees was calculated for each case (see Figure 7). In the future it will be possible to further expand upon this work and quantitatively determine the blade-vortex orientation that gives rise to the different types of profiles seen in Figure 5.

At higher Reynolds numbers ($Re \sim 1 \times 10^6$) the vortex street breaks down and a regular pattern no longer exists. The fact that wind turbines may operate at Reynolds numbers of over 1×10^6 means these effects may not be seen at the higher Reynolds numbers. Therefore, the largest pressure fluctuations may actually occur at lower velocities.

STRUCTURAL EFFECTS

Structural loads on the blades and tower are a direct consequence of the aerodynamic forces present on the HAWT. The data in Figures 8 and 9 was taken from the strain gage mounted on the blade root and represents the bending moment about the hub. A definite cyclic variation in strain load exists with a magnitude that varies with azimuth angle. This magnitude differs from cycle to cycle with preliminary evidence suggesting a relationship to the cycle pressure fluctuations.

Figure 7: Idealized pressure profiles for various blade-vortex orientations.

While the magnitude of the strain loads varies, the time that the peaks occur and their frequency remains relatively constant. Figures 8 and 9 show peak loads occurring at almost identical times throughout the test run, yielding a frequency of approximately 2.5 Hz. A fundamental frequency in this range may lead to structural resonance because it occurs within the range of the tower vortex shedding frequency. Perturbations on the order of the fundamental frequency can cause the structure to begin resonating. If continuously perturbed at the proper frequency, the wind turbine could basically shake itself to pieces. The resulting structural loads have a much greater magnitude than the steady state loads predicted in wind tunnel tests. This leads to structural fatigue and equipment failure long before the end of the turbines design lifetime. This problem can be overcome by either strengthening the HAWT or reducing the vortex shedding effects on the blades. Augmenting the structure can significantly add to the turbine mass and cost. Therefore, alternative methods of dealing with the problem are desired.

SOLUTIONS

Several methods exist to reduce the tower vortex shedding and its subsequent effects on the wind turbine structure. The most

obvious solution is to use upwind turbines in place of the downwind turbines discussed here. This alleviates the problem by placing the blades on the upwind side of the tower. Therefore, the blades never encounter the vortex street. Unfortunately, upwind turbines are far more complicated and costly than downwind turbines due to the need for a control mechanism to keep them pointed into the wind.

Alternatives to upwind turbines are to either destroy the shedding with diffusers or create blade conditions that are unresponsive to vortex passage. The first method involves placing screens upwind of the blades, breaking up the vortices. This creates turbulent conditions that lower the blade efficiency by increasing the drag. This is acceptable for wind turbines since the only effect of drag is to try to move the tower.

There are two methods for reducing the blade responsiveness. The first involves increasing the number of blades and positioning them closer together, effectively chopping up the vortices. The second method is to alter the blade geometry. For instance, twisted delta wings have been shown to be relatively unresponsive to vortex passage.

Figure 8: Root flap bending moment for cycles 70 to 74 showing 2.5 Hz frequency.

Figure 9: Root flap bending moment for cycles 50 to 54 showing 2.5 Hz frequency.

CONCLUSION

Wind energy has the potential to produce up to 20% of the nation's energy demands. However, to make wind energy competitive with conventional energy sources, improvements must be made in wind turbine design to further lower their cost and increase their operational lifetime. This requires accurate predictions of the structural loads encountered by the turbines. An analysis of the average pressure profiles over many blade cycles does not accurately represent the conditions present for any single cycle. Individual cycle pressure profiles are dependent upon the manner in which the blade passes through the vortex street created by air flow past the tower. Since aerodynamic loads are directly tied to the pressure, a blade-vortex interaction model will lead to an enhanced ability to predict the structural effects. Once the cause of the problem is completely understood, a variety of methods may be employed to alleviate it. Although the current analysis has been performed only on an untapered constant chord blade, a cooperative data-sharing agreement with the governments of Great Britain and Denmark will allow the evaluation of different blades and a quantification of the effect over a variety of conditions.

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