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UPSTREAM AND LATERAL WIND TURBINE WAKE EFFECTS ON NEARBY WIND TURBINE PERFORMANCE

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ABSTRACT

A selection of different 1:50 scale rotor blades were evaluated with dynamometers, force balances, and wake measurements to select a rotor model which correctly simulates the full-scale behavior of an actual wind mill. A wind-tunnel measurement program was then carried out on a set of five dynamic (operating) wind mills placed at various heights and orrientations to one another. The interdependence of wind-turbine performance on such spacing was determined.

INTRODUCTION

Wind turbine aerodynamics research is concerned with the dynamic interaction between atmospheric flow and the turbine's rotor. Design extrapolation from propeller, helicopter blade and airplane aerodynamics to the response of wind turbine blades in steady, uniform, low-turbulence wind flows is understood. The wind-turbine rotor, however, operates in the atmospheric surface layer, where wind shear, gustiness and upwind rotors change the operating environment. In particular upwind rotors perturb the approach winds resulting in localized flow accelerations, decelerations and secondary motions. These perturbations result in wind turbine performance and loading changes of un-resolved magnitude.

During early design studies of the efficacy of multiple wind turbine arrays engineers considered the actual availability of energy in the wind. Templin (1974) estimated the effective power reduction in a wind-turbine array due to the removal of upwind wind energy; however, the estimates were based on tenuous estimates of the restoration of wind energy from the surrounding atmosphere. A number of analytic and numeric programs have been developed to predict multiple array wind turbine wake effects (Taylor, 1980; Bate

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et al, 1981) by studying the flow field over model arrays represented by disks of wire and filter paper (Builtjes, 1978; Faxen, 1978; Riley et al, 1980). None of these model exercises actually used dynamic model wind-turbines; hence, they might represent some momentum characteristics of wind-turbines, but they did not actually remove kinetic energy or induce the appropriate vortex wakes. These studies resulted in recommendations for turbine separation ranging from 3 to 30 diameters.

Subsequently, various researchers measured the wakes downstream of MOD-OA, and MOD-2 wind turbines (Connell, 1984; Hadley and Tenne, 1983). Although valuable, these data are difficult to interpret due to the non-stationarity of the wind fields sampled. In addition the wake separations, turbine/turbine and turbine/obstacle configurations studied are very limited.

MODELING WIND TURBINES

Accurate simulation of field conditions in the laboratory requires that the values of dimensionless similarity parameters attained in the field be matched in the laboratory. These dimensionless parameters result from the need to attain geometric, kinematic and dynamic similarity. Geometric similarity requires that all geometric objects be scaled up or down proportionally. Kinematic similarity requires that the path lines of fluid particles move in geometrically similar patterns. This will occur if velocities and accelerations at geometrically similar points are scaled proportionally. Finally, dynamic simlilarity requires that all forces acting on fluid particles or turbine be scaled proportionally. If geometric and dynamic similitude are attained, then kinematic similarity is generally assured as a result of Newton's laws of motion.

The wake characteristics of full-size wind turbines are often predicted by examining the performance of intermediate size or miniature turbines. Reliable results require consideration of the simulation of both the flow characteristics of the approach wind and the response of the wind turbine. Simulation of the atmospheric boundary approach wind characteristics is extensively discussed by Meroney (1986). Riley et al. (1980) and Milborrow (1980) review studies which consider the dynamic simulation of both horizontal and vertical axis wind turbines.

Dimensional or inspectional analysis suggest that the important kinematic and dynamic parameters which control wake behavior are: Tip Speed, $\lambda = (R\Omega)/U$; Reynolds Number, $Re = (UL)/\upsilon$; Thrust Coefficient, $C_T = F/(\frac{1}{2}\rho AU^2)$; and Power Coefficient, $C_p = P/(\frac{1}{2}\rho AU^3)$. Many full-scale wind turbines produce power most efficiently when they are operated at a Tip Speed Ratio between four to eight. Since full-scale rotational speeds are usually from 50 to 100 rpm, then a model turbine constructed to a 1/50 scale must operate at 2500 to 5000 rpm for equivalent wind speeds. Thus, care must be taken that dynamic models are sufficiently strong to resist very high centrifugal forces.

A Reynolds number for a model turbine based on chord length is often several orders of magnitude below the full-scale value. Yet the effect of Reynolds number on the turbine blade lift curve is indeed profound and often quite unpredictable. Unfortunately most "modern" wind turbine airfoils will yield embarrassingly poor results at low Reynolds numbers. These variations result from the tendency for flow to separate from the blade surface when operated at low Reynolds number.

Power and thrust coefficients are directly related to the lift and drag performance of a rotor blade. Previous attempts to study geometrically scaled blade shapes have always resulted in reduced power coefficients compared to full-scale performance data (Riley et al.,1980; Cao and Wentz, 1987). Many researchers did not attempt to geometrically scale blade shape, but they chose to work with blades redesigned to reduce stall (Vermeulen, 1978, 1979; Neff and Meroney, 1985). It is generally conceeded that wind turbine wake characterstics are strongly dependent upon the thrust perceived by the rotor disk; thus, an acceptable wake simulation approach would be to utilize a modified model rotor design in the laboratory experiment which produces an equivalent magnitude thrust coefficient.

DATA ACQUISITION AND ANALYSIS

The Colorado State Environmental Wind Tunnel (EWT) was used for all experiments except the drag force measurements. Models were located over the middle turntable and various grids were placed at the tunnel entrance to increase the turbulence level. The Colorado State Industrial Aerodynamics Wind Tunnel was used for all drag force measurements. For measurements in this tunnel the model wind turbine was placed over the downwind turntable. A turbulence grid similar that used in the EWT was installed upwind of the test site.

Pitot-static probe measurements documented the mean longitudinal wind velocities upwind and downwind of the model wind turbines. Typically one probe was located upwind of the turbines for an approach flow reference and a rake of seven other probes was moved to the different measurement locations. Pitot-static probe signals were digitized by a Data Translations DT2818 board within an IBM AT computer for sixty seconds and the mean velocities were calculated.

A survey of small DC generators and their power generation capabilities indicated that a generator capable of properly loading the model rotor would be two to three times larger than a properly scaled nacelle. To circumvent these difficulties a flexible belt drive was attached to the rear of the rotor shaft on all five model wind turbines. This belt drive was connected to either a dynamometer located under the tunnel floor for accurate power measurements (see Figure 1) or to a small Pittman 9414B589 permanent magnet DC motor/generator located on the model base plate (see Figure 2). The motor was operated as a generator to load the model turbine, and, thus, to insure that proper wake interaction occured with the turbine that was connected directly to the dynamometer. Whenever multiple turbine arrays were tested one of the towers was connected to the dynamometer and all the others were loaded by their DC generators.

The dynamometer, a Magtrol Model HO-400-2, allowed one to adjust the torque from 0.2 to 32 inch ounces and monitor angular velocity (rpm). The power developed at the dynamometer is the product of the torque setting and angular velocity. The power developed at the rotor is the power measured at the dynamometer divided by the drive train efficiency. The drive train efficiency was determined for a variety of drive speeds, loads and belt tensions.

Two different approaches were employed to obtain turbine thrust estimates. The first and the least accurate of the methods performed a momentum balance on a control volume that encapsulated the turbine rotor. The wind speed approaching the rotor was measured with a single pitot-static probe at an unperturbed location upwind of the turbine. The approach profile was assumed to be uniform. The wind speed downwind of the rotor was measured with pitot-static probes placed at several radial distances from the rotor's centerline. The mean longitudinal flow downwind of the rotor was assumed to be axisymmetric. Evaluating the momentum difference between these two sections yields the drag force on the air induced by the turbine rotor.

The second method measured the drag force on the turbine rotor directly using a strain-gage balance. The drag force on the rotor was obtained by subtracting the tower only drag force from the tower and rotor drag force. The thrust coefficient is the drag force divided by the total momentum in the wind approaching the rotor.

TEST PROGRAM AND DATA

The test program consisted of several different developmental phases and measurement tasks. The first task involved the development of a dynamic wind turbine model that reproduced field scale performance characteristics. Next, five model-scale dynamic wind turbines were constructed, three mounted on scaled sixty foot towers and two mounted on scaled 140 foot towers. Then the disturbed flow field upwind and to the side of a single dynamic wind turbine model mounted on a scaled 60 foot tower were measured. Finally, the wake behavior and power performance changes of multiple turbine arrays for a variety of spacings were determined.

Dynamic Turbine Model Development

The USW 56-100 wind turbine modeled has variable pitch rotor blades. The ability to vary the rotor's pitch allows one to optimize the power performance of the wind turbine over a range of wind speeds. The model rotors studied were limited to a specific operating condition. USW personnel specified that the performance region of most interest was between 15 to 30 mph. At these wind speed the USW 56-100 wind turbine operates over a specific range of tip speeds, with associated power and thrust coefficients. A good model turbine rotor should reproduce all three of these dimensionless numbers; however, the larger thrust coefficient was selected to produce conservative wake effects on power production.

A series of different model turbine blade designs were constructed and tested to identify an acceptable model blade configuration. Two different basic blade patterns were tested. For each basic blade pattern a series of modifications to the twist angle and/or profile shape was studied. The first blade pattern tested was similar to a 1:50 scale field blade. The second design selected was similar to that used by Vermeulen (1979), here-after referred to as the TNO design.

USW Type Blade Design Test Series

Figure 3 describes the rotor design (Rotor # 4) for the field similar blade. Rotor # 4 was made of aluminum, and it had a blade chord variation similar to a 1:50 scaled USW 56-100 field blade, a linear blade twist angle of 0° at the tip and 10° at the base, a flat profile shape that was rounded at the leading edge and tapered at the trailing edge, and a constant thickness of 1/8".

Rotor # 4 was attached to the model 60 tower assembly and tested. It rotated slowly and produced negligible power. Rotor # 5 was similar to Rotor # 4, but it was made of steel and had a thickness of 1/16". Again this rotor's performance was poor. Rotor # 6 was similar to Rotor # 5, but the blade twist angle was changed to 10° at the tip and 20° at the base. Rotor # 6's power performance (see Figure 5) was still unsatisfactory; thus, further blade modifications were considered.

Rotor # 7 was similar to Rotor # 6, but the blade twist was changed to vary radially from the base at 40° to the tip at 5°. Its performance is presented as one of the curves in Figure 5. Rotor # 7 produced more power than any of the other USW type designs, but, unfortunately, the hub-blade connection fatigued, and it flew apart before any wake measurements could be made. Since modifications to the scaled field blade did not yield significant improvement in turbine performance, This blade design was abandoned, and a new blade design similar to a TNO design was constructed.

TNO Type Blade Design Test Series

Figure 4 describes the TNO rotor design. The first rotor similar to this design, Rotor # 8, made of steel, had a constant blade chord, a constant blade twist angle of 10°, a curved profile shape that was rounded at the leading edge and tapered at the trailing edge, and a constant thickness of 1/8".

Rotor # 8 was attached to the model 60 tower assembly and tested. Its power performance data is graphically presented as one of the curves in Figure 6. Figure 6 shows that Rotor # 8 produced peak power performance at low tip speed ratios. Rotor # 9 was similar to Rotor # 8, but there was a little less curvature in the profile shape and the twist was set at 6°. Unfortunately, during the pressure and velocity profile measurements this rotor slammed into the support tower and was destroyed. Thus no thrust coefficient data for this rotor was obtained.

Rotor # 10 was similar to Rotor # 9 except that a sharper taper on the trailing edge was incorporated to make the blade profile similar to that used by Vermeulen (1979). Its power performance data is graphically presented as one of the curves in Figure 6. Thrust coefficients were calculated by the momentum deficit method and are presented in Table 1. Direct measurements with a force balance in the IWT found the unloaded and loaded Rotor # 10 thrust coefficient were equal to 1.12 and 0.93, respectively.

Rotors # 9 or 10 produce power coefficient performance similar to the USW rotor at acceptable tip speeds. Therefore, these model rotors were considered acceptable for scale model turbine construction.

Multiple Turbine Construction

Three new model 60 foot towers and two new model 140 foot towers were constructed at a model length scale ratio of 1 to 50. The model 60 foot towers were 14.4 inches tall and were made of 0.2 inch diameter brass rods brazed together. The model 140 foot towers were 33.6 inches tall and were made of square brass rods brazed together. A top plate was attached to these rod frames and a shaft-bearing housing scaled to nacelle size was bolted to each top plate. Each tower had a belt drive that connected the rotor shaft to a small generator on the tower base plate.

Five model turbine rotors (Rotors # 11 to # 15) similar to the TNO Rotor design # 9 were constructed and mounted on the towers. All rotors performed quite similarly, but not quite as well as the rotor constructed earlier for the rotor test program. This demonstrates that small differences in blade shape can lead to significant differences in performance.

Multi-Turbine Far Wake Tests

During this task mean velocity profiles were measured at several locations downwind of five model wind turbines for a variety of different turbine spacings. There were three scaled sixty foot towers and two scaled 140 foot towers. The measurement locations were between 6 to 30 rotor diameters downwind.

A velocity profile was obtained at each measurement location with both the turbines removed from the tunnel and with the turbines in the tunnel but not operating. Velocity values were normalized by their turbine-off condition to remove wind tunnel spatial velocity variations from the data set. When the turbines were running they were always fully loaded by the small generators at the base of the towers.

Multi-Turbine Power Performance Tests

The purpose of these tests was to measure the magnitude of turbine performance changes due to the proximity of other operating turbines. The turbine of central interest was connected to the dynamometer for accurate power performance measurements. For each turbine spacing arrangement power performance data was measured both when all other turbines were off and when they were fully loaded.

DISCUSSION OF RESULTS

The test program produced documentation on model wind turbine behavior for three different configurations. These were single turbine wakes, multi-turbine wakes, and multi-turbine power performance interactions.

Single Wind Turbine Wake Behavior

Measurements of velocity deficits were obtained for a variety of different model wind turbines. Figure 7 presents the radial velocity deficit profiles at the downwind distance X/D = 1 for rotors 2, 6, 8, 10. Rotor # 10 produced the greatest velocity deficit at all radial distances.

Multiple Wind Turbine Wake Behavior

Measurements of wake velocity deficits were obtained for six different multiple wind turbine spacings. Figure 8 displays typical centerline profiles for three sixty foot turbines spaced eighty feet apart symmetric to tunnel centerline. The velocity deficit at Z/D = 1 decreases with increasing downwind distance, X/D, and the wake expands (look at 0 % crossing) in height with increasing X/D. Continuity of mass requires that the low speed wake region immediately downwind of the rotor disk induces a narrowing of streamlines and an acceleration of velocity at larger radial distances from the turbine axis. Thus, negative deficits (larger velocities) of -2 to -3 % exist at Z/D = 3 at all downwind distances. The deficit near the ground at Z/D = 0.5 was greater at all downwind stations than the deficit at Z/D = 1.5.

Run 4 (shown in Figure 9) also had eighty foot lateral spacing but two 140 foot towers were placed 50 foot downwind of the three 60 foot tower-turbines. The wake deficit of the two off-centerline 140 foot tower (Z/D = 2.25) turbines is as strong as the on-centerline 60 foot tower (Z/D = 1) turbine at a downwind distance X/D = 6.67.

Multiple Wind Turbine Power Performance Interaction

The homogeneity of the wind tunnel mean turbulent velocity field approaching the wind turbines was approximately ± 4 percent. Thus when comparing power coefficients in and between these different data sets it should be remembered that a 3.3 percent error in the measurement of mean turbulent velocity would cause a 10 percent error in the power coefficient. Figure 10 compares the power performance data for runs 1 through 6. This sequence of tests was designed to look at the effect of two upwind 140 foot tower-turbine structures on the performance of a downwind 60 foot tower-turbine. Runs 1 and 2 are reference data points for the cases of 3-60 foot tower-turbines with only the middle turbine on and 3-60 foot tower-turbines all on. Runs 3 and 5 show the influence of the 140 foot tower with the turbine off for positions 50 foot directly upwind and 50 foot upwind but offset laterally 20 feet. These data points show a marked decrease (-15 %) in performance due to the presence of the upwind 140 foot tower structure. Runs 4 and 6 show the influence of these same two positions but with the upwind turbines on. They show that the downwind 60 foot tower-turbines gain a benefit from flow accelerations around and below the 140 foot tower-turbines but only for the 20 foot laterally offset case is this benefit enough to compensate for losses due to the tower's wake. The offset lateral position produced about a 5 to 6 % better power performance than the directly upwind case.

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Table 1 TASK 2 Rotors # 2, 6, 8, 10 Thrust Coefficient Data

ROTOR No. =	# 2	# 2	# 6	# 6	# 8	# 8	# 10	# 10
Desc. =	Graupner	Graupner	USWP 10-20	USWP 10-20	TNO 10	TNO 10	TNO 6	TNO 6
Uref (m/s) =	9.4	9.4	9.3	9.3	9.4	9.4	9.2	9.2
LOAD (in-oz) =	0.3	6.5	1.5	1.5	0.3	6.5	0.3	5.5
Speed (rpm) =	2700.0	1900.0	2750.0	2750.0	2600.0	1700.0	3850.0	2750.0
Position X/D =	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0
Ct (r/R=1) =		0.632	0.372	0.349			0.983	0.710
Ct (r/R=2) =								
Ct (r/R=3) =		0.362	0.370	0.370			1.350	0.860
Ct (direct) =	0.280				0.690		1.120	0.930

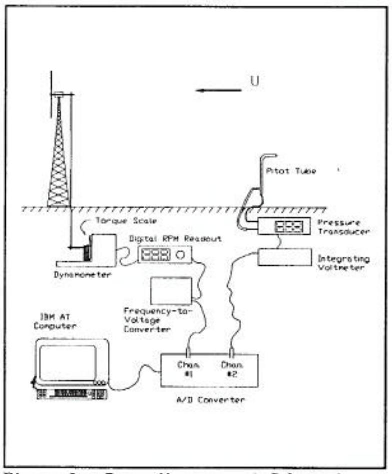

Figure 1 Power Measurement Schematic

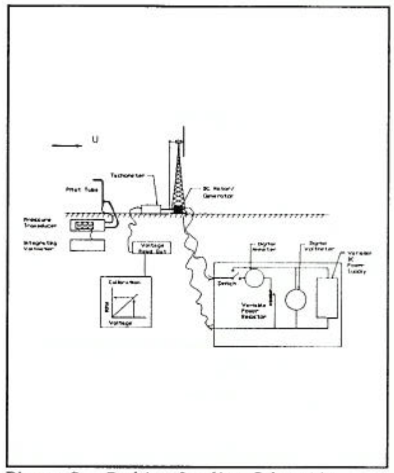

Figure 2 Turbine Loading Schematic

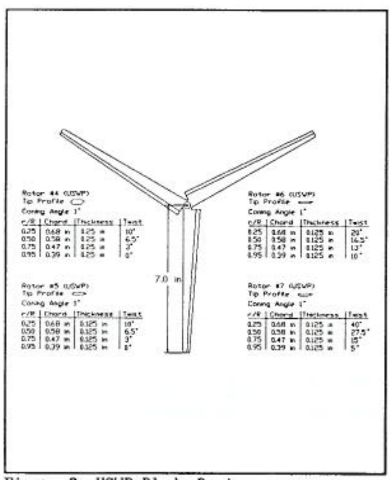

Figure 3 USWP Blade Design

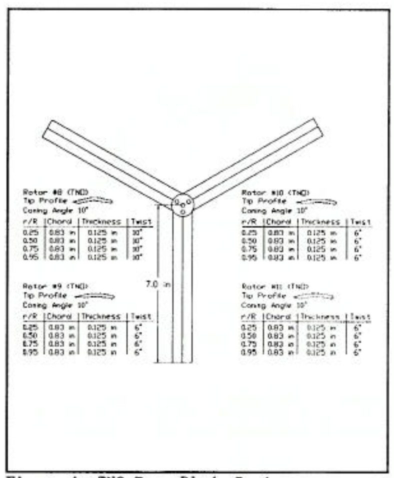

Figure 4 TNO Type Blade Design

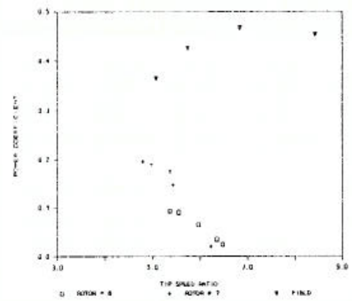

Figure 5 USWP Type Rotor Power Performance Comparisons

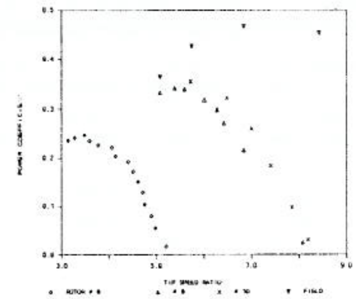

Figure 6 TNO Type Rotor Power Performance Comparisons

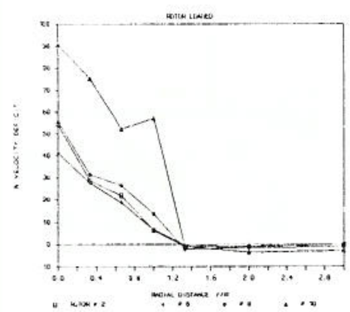

Figure 7 Single Turbine Wakes : Velocity Deficit vs. Radial Distance at X/D=1 for Rotors #2, #6, #8, #10 Loaded

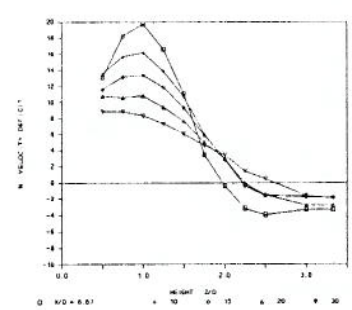

Figure 8 Multiple Turbine Wakes: Velocity Deficit vs. Height at Different Downwind Distances for Run 2 (Y/D=0)

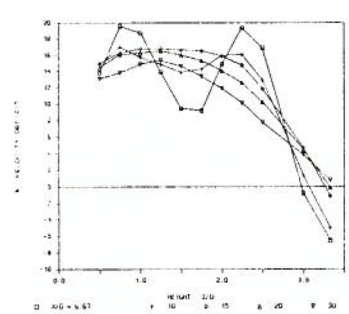

Figure 9 Multiple Turbine Wakes: Velocity Deficit vs. Height at Different Downwind Distances for Run 4 (Y/D=0)

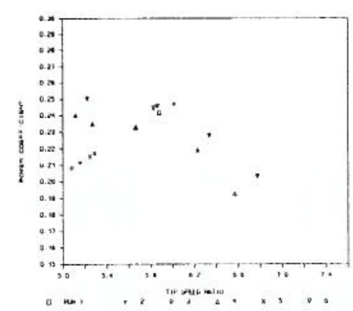

Figure 10 Multiple Turbine Power Interaction : Power Coefficient vs. Tip Speed Ratio for Run Numbers 1, 2, 3, 4, 5, 6