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ELEVATION AND VEGETATION CONSIDERATIONS ON WIND POWER AVAILABILITY: A WIND TUNNEL STUDY

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INTRODUCTION

Forested hills and ridges pose a number of significant technical and environmental issues for siting wind turbines. The change in the wind profile across the top of the hill due to the presence or absence of trees and differences in roughness characteristics must be understood in order to develop accurate energy estimates.

To address these issues, KENETECH/Windpower undertook a wind tunnel study to understand and examine windflow over tree covered hills and ridges. The first phase of this work was a thorough review of the known effects on windflow due to individual trees, forest stands, and clearings within the forest. The second and third phases of the work involved wind tunnel measurements of hill-top wind speed profiles as a function of surface roughness, hill shape, and hill slope. The wind tunnel testing involved in the second phase of the work and the evaluation of the wind flow over forested and cleared two-dimensional ridges are described in this paper.

PROGRAM DESIGN

A physical model was used to estimate wind speed profiles over two dimensional ridges with various forest clearings, ridge shapes, and slopes. The experiments were performed in the Meteorological Wind Tunnel at Colorado State University.

A combination of tests was specified to meet our objectives. Two-dimensional sinusoidal and triangular ridge shapes 200 feet high at a model scale of 1:1000 were selected. Measurements of wind speed profiles at 40, 80, 120, 160, 200, 300, 423, 600, 800, and 1000 feet were obtained for each model run. Four slopes were specified for each ridge shape: 1:2, 1:3, 1:5, 1:10.

The effects of three different tree heights, 20 feet, 40 feet, and 60 feet, and four different forest configurations were included in the modeling. The four different forest clearings included 1) no tree removal (No Cut), 2) the highest tree top being level with hill top ground level (Top Cut), 3) highest tree top being 100 feet lower than the hill top ground level(-100'), and 4) all trees completely removed to the base of the hill (Full Cut).

The combination of 2D ridges, ridge slopes, tree heights, and forest clearings resulted in a total of 96 different run conditions.

EXPERIMENTAL SETUP

Model Specifications

Eight model ridges were constructed out of wood and plastic products; four sinusoidal and four triangular ridges at ridge slopes of 1:2, 1:3, 1:5 and 1:10 (height:half-base). The full width of the 1:2, 1:3, 1:5 and 1:10 sloped ridges were 24.4, 36.6, 61.0 and 122.0 cm respectively. The wind tunnel into which these model ridges were placed limited all ridge lengths to 183 cm. Modeling 200 foot high ridges at a 1:1000 length scale ratio resulted in 6.1 cm high model ridges. The aspect ratio, i.e. ridge length to ridge full width, for each of these ridge slopes was 7.5, 5.0, 3.0 and 1.5.

The tree cover was simulated with an Astroturf product manufactured by Monsanto for door mats and walkways. The Astroturf, made of polyethylene, consisted of vertical bristle groups 1.8 cm tall, connected to flexible matting, 0.15 cm thick. At a length scale ratio of 1:1000 these 1.8 cm tall bristles are representative of 60 foot tall trees. To simulate 40 and 20 foot tall trees, the bristles were trimmed to 1.2 cm and 0.6 cm respectively. Measurements of the original and cut bristles of the three forest cover mats at several places found that the mean tree heights were within a few percent of the design heights of 20′, 40′ and 60′. The bristles, however, were always perpendicular to the mat backing; thus when the matting was stapled to the model ridge contour, the simulated trees were not in a vertical position.

Wind Tunnel Configuration

The experiments were performed in the Meteorological Wind Tunnel facility at Colorado State University's Engineering Research Center. This wind tunnel has a speed range of 0 to 40 m/s, a test section length of 26.8 m, and a test section area of 3.34 m^2. The 9:1 contraction ratio upwind of the test section produces a stable, uniform flow with low turbulence. The test section length upwind (≈20 meters) of the model site area has sufficient fetch for the natural development of simulated atmospheric boundary layer winds. The test section has a cross-sectional size of 183 cm x 183 cm. The model ridges, both sinusoidal and triangular, were always 6.1 cm tall and the wind tunnel flow blockage ratio was approximately 3 percent.

The upstream twelve meters of the test section floor was covered with thin carpet type roughness, this was followed by six meters of Commercial Grade Astroturf with a bristle height of ≈1.2 cm (40 foot trees). These sections of ground roughness were present during all test measurements. Following these fixed ground roughness conditions, two tree-height-specific roughness mats of 183 cm wide by 152 cm long were placed end to end on the tunnel floor. The different model ridges were placed underneath and centered in-between these two mats. These roughness mats were secured to the floor of the tunnel and model ridge to ensure they followed the surface contour of the different model ridges.

Wind Speed Profiles

Single-hot-film (TSI 1210 Sensor) measurements were used to document the longitudinal mean velocities and the longitudinal turbulence levels for all velocity profiles in this test program. The hot-film-probe was mounted on a vertical traverse and positioned over the desired profile location in the wind tunnel. The anemometer's output voltages were digitized and stored within an IBM computer. The vertical positioning of the probe was controlled by the IBM computer. The computer system would move the velocity probe to a vertical position, acquire and reduce the data, then move on to the next vertical position, thus obtaining an entire vertical velocity profile automatically. The velocity time series was then analyzed for pertinent statistical quantities, such as mean velocity and root-mean-square turbulent velocity fluctuations.

Wind tunnel reference velocities, one at the top of each profile and one at an upwind location, were obtained via a pitot-static probe for each hot film velocity measurement point. These reference velocities were used to normalize any wind tunnel speed variations that existed among the different runs and during the acquisition of individual vertical profiles.

WIND TUNNEL DATA

Mean Wind Speed

The velocity data collected by the hot wire anemometer at each of the 10 points in the profile is normalized by the velocity measured at the reference point. This reference point is the pitot tube at 30.5 cm height (scale height of 1000') above the top of the 2D ridge. The normalized velocity values are presented in Table 1 for the triangular 1:10 ridge for the 20-foot tree case. The influence of the presence of the trees can be seen in the profile for the "No Cut" option and the "Top Cut" option at the 40 foot scale measurement level. For the sinusoidal 1:10 ridge, shape is shown to have a greater influence on the profiles. The normalized velocity values were less at both the 40 foot and 80 foot scale heights for the sinusoidal ridge than the triangular ridge.

TABLE 1

	1:10 Triangular Ridge				1:10 Sinusoidal Ridge			
Scale Height (ft)	No Cut	Top Cut	-100'	Full	No Cut	Top Cut	-100'	Full
300	.84	.82	.84	.84	.84	.82	.84	.83
200	.79	.79	.81	.80	.80	.78	.79	.81
160	.79	.76	.79	.79	.77	.77	.78	.80
120	.76	.75	.78	.79	.76	.75	.76	.78
80	.72	.72	.75	.78	.69	.71	.73	.75
40	.51	.62	.72	.75	---	.58	.67	.68

Model ridge normalized velocity profiles at the crest of the ridge (1:10, triangular and sinusoidal) for the four forest cut options (20 foot trees).

A review of the normalized velocity data yielded some interesting comparisons between the different ridge shapes, slopes, and tree heights. For the steeper ridges (1:2, 1:3), the normalized wind speed profiles across the crest of the sinusoidal ridges show that higher wind speeds occur here than over the triangular ridges. Over the 1:5 and 1:10 slope ridges the normalized velocity profiles are similar for both ridge slopes except at the measurement levels close to the ground for the "No Cut" option. For example, the normalized velocity profiles for the 1:5 ridge show a 16% lower wind speed value at 80 feet for the sinusoidal ridge versus the same measurement height on the triangular ridge. This difference becomes more pronounced with the 1:10 ridge and affects the measurements up to scale heights of 120 feet.

Turbulence Intensity

Turbulence intensity (TI), derived from the hot film measurements, were also prepared for each of the 96 model runs. A sample of the turbulence intensity profiles for the 1:10 triangular and sinusoidal ridges for the 20 foot tree case and the four forest configurations are presented in Table 2.

TABLE 2

	1:10 Triangular Ridge				1:10 Sinusoidal Ridge			
Scale Height (ft)	No cut	Top Cut	-100′	Full	No Cut	Top Cut	-100′	Full
300	12.7	12.2	12.5	12.3	12.3	12.6	12.4	12.5
200	13.2	13.4	13.5	13.2	13.3	14.1	13.6	13.3
160	13.5	14.4	13.5	13.8	13.2	14.0	13.7	13.6
120	13.8	14.1	13.5	13.4	14.0	13.9	14.3	13.3
80	15.5	15.4	14.3	13.2	16.0	15.3	14.4	14.1
40	22.7	19.3	13.9	13.6	---	19.9	16.1	15.4

Turbulence intensity profiles at the crest of the ridge 1:10, triangular and sinusoidal) for the four forest cut options (20 foot trees).

These measurements show that TI is, as expected, a function of the upwind tree height. The effect of ridge shape is also evident. The TI measurements are sightly higher for the sinusoidal ridge than the triangular ridges.

The shallower slopes (1:10, 1:5) have a deeper turbulence layer than the steeper slopes. This is true for both the sinusoidal and triangular ridge. For the 20 foot trees, the "-100 foot" option and the "full cut" option exhibit the same TI values for the 20 foot trees. As the trees become taller, the "-100 foot" option becomes much more effective than the "Top Cut" option at minimizing TI.

Fractional Speedup

Fractional speed-up ratios were also calculated from the wind speed profile measurements at the crest of the ridge. Fractional speed-up is calculated as:

$$\text{Delta } S(z) = (U(z) - U_o(z))/ U_o(z)$$

where U(z) is the normalized velocity ratio at height z above the ridge crest;
$U(z_o)$ is the normalized velocity ratio at height z at an upwind reference location.

Table 3 presents the percent fractional speed-up for the 1:5 triangular and sinusoidal hills for the 20 foot trees. The amount of speed-up at the 80 foot or 120 foot scale height is relatively uniform for all four cut options. For taller trees, the fractional speed-up increases dramatically from the "no cut" option to the "full cut" option. In general, the percent fractional speed-up values show their greatest increase from the "no cut" to the "-100 foot" option while the change from "-100 foot" to "full cut" is small.

TABLE 3

	1:5 Triangular Ridge				1:5 Sinusoidal Ridge			
Scale Height (ft)	No Cut	Top Cut	-100′	Full	No Cut	Top Cut	-100′	Full
1000	7	7	7	7	7	7	6	5
800	9	9	9	10	10	9	9	7
600	12	12	12	12	12	12	11	11
420	17	16	16	16	18	16	17	16
300	20	22	21	25	23	22	22	21
200	27	27	30	31	30	30	31	29
160	31	32	33	36	33	34	33	33
120	39	40	44	45	43	42	45	43
80	57	60	65	64	63	62	62	65
40	98	122	135	146	82	121	135	136

Percent fractional speedup profile at the crest of the ridge (1:5 triangular and sinusoidal) for the four forest cut options (20 foot trees).

CONCLUSIONS

The wind tunnel testing yielded a large amount of information on windflow over simple forested ridges. The information provides an objective design basis for the innovative use of selecting turbine tower heights and forest clearing strategies. The potential energy impacts of these tradeoffs can be used in the site design process to balance site design and environmental issues.

The removal of vegetation at and upwind from the ridge crest will substantially increase the wind speed, reduce turbulence, and reduce the potential for flow separation. Models based on linear perturbation theory have been applied to predicting the wind speed profile at the ridge crest. There are also linear models available which predict the effects of sudden roughness changes on the wind speed profile. This data set will be used to assess the suitability of these combined models for predicting the changes in the wind speed profiles as a function of both the ridge dimensions and roughness changes.