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High Wind Speed Performance of AeroMINE at Pilot-Scale

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Abstract. AeroMINEs consist of a mirrored pair of foils that have no external moving parts. A low-pressure region is created between the foils. The foils are hollow and the low-pressure side skins contain orifices (air-jets) that allow air to flow from the interior of the foil to the exterior flow, driven by the suction between the mirrored pair. This flow is ducted to an internal turbine and generator, producing electricity. A series of pilot-scale field (1-m chord) demonstrations were performed on AeroMINEs. These included both low wind speed tests (<5 m/s) and high wind speed tests (>9 m/s) at the Sandia National Laboratories Scaled Wind Farm Technology site in Lubbock, Texas, USA. Here the performance in high wind speed conditions is studied while varying the air-jet area. An efficiency of 25%, or 42% of Betz limit, was achieved for the maximum air-jet area.

1. Nomenclature

A_{duct} = cross-sectional area of AeroMINE inlet duct
A_{exit} = exit area of AeroMINE defined by a rectangle enclosing the trailing edges of the foils
A_{jet} = total area of air-jets (orifices) in foil surface
AoA = angle-of-attack of each foil (or half-angle between foils)
C_p = power coefficient for the device
ΔP_{jet} = pressure-drop across the jets from inside to outside the foils
ΔP_{choke} = pressure-drop across choke in the inlet duct
L = chord length of foils
LCOE = levelized-cost-of-electricity
$Power$ = mechanical power of the AeroMINE unit
PIV = particle image velocimetry
PV = photovoltaic
ρ = air density
Re = Reynolds number based on chord
u_{duct} = average flow velocity in the inlet duct
u_{jet} = flow velocity at the air-jets
U_∞ = freestream velocity
V_{jet} = total volume flow through all air-jets

2. Introduction
Rooftop-scale distributed wind power devices have suffered from three major weaknesses. First, they typically sweep a relatively small area and thus produce proportionally small power. Second, they often have many moving components at height, often exposed to harsh environments, leading to vibrations and mechanical failures. Third, they typically incorporate fast moving external blades which require large standoff distances for human safety and can produce significant aero-acoustic noise. Because of these weaknesses, point-of-use wind power has seen little market penetration. For example, in the United States, the point-of-use market is dominated by solar photovoltaics (PV), while distributed wind is almost non-existent [1], and has decreased in recent years [2, 3]. Because they have no external parts, AeroMINE (Motionless, INtegrated Extraction) wind harvesters can be made very large to safely sweep a large area. This overcomes all of the weakness listed above, allowing AeroMINEs to achieve a potentially market-viable levelized-cost-of-electricity (LCOE). This would allow rooftop-scale distributed wind to substantially add to distributed green energy generation.

3. Objectives
The objectives of the field tests described were to evaluate the performance of AeroMINEs at pilot-scale in real-world conditions with wind speeds of 9 m/s and greater, with turbulence and shifting wind directions. The performance was compared to both previous scaled wind tunnel tests [4] and low-speed pilot-scale tests [5]. The previous wind tunnel tests were carried out at the National Wind Institute (NWI) at Texas Tech University. All pilot-scale testing was performed at the Sandia National Laboratories (SNL) Scaled Wind Farm Technology (SWiFT) site in Lubbock, Texas, USA. The AeroMINE foil design is based on an S1210 airfoil, selected for its excellent lift characteristics over a wide range of freestream velocities [6].

4. Methodology
An AeroMINE with angle-of-attack (AoA) of 10° and 1-m chord was constructed. The device was mounted on a trailer to allow alignment with the approximate dominant wind direction, as shown in Figure 1. More than 800 kg of ballast and guy-wires were used to ensure the safe operation during the field campaign. Moving the factors of safety from the device to the ballast allowed for modularly in the device geometry. This made it possible to change air-jet and foil sections during the test campaign, so that geometry modifications could be studied to better understand performance sensitivities.

The freestream wind velocity U_∞ and direction were measured upstream of the device at the approximate mid-height using a Davis wind speed and direction sensor. The cup anemometer has an accuracy of ±1.1 m/s for the wind speeds considered. The wind vane has a ±7° accuracy in wind direction. The lower manifold, which would house the internal turbine-generator in the production system, was removed and replaced with adjustable chokes in each intake duct. The average intake duct velocities u_{duct} were measured with hot wire anemometers (Onset HOBO T-DCI-F300-1C3). The pressure drops ΔP_{choke} across the chokes were also measured with differential pressure transducers (Veris Industries, T-VER-PX3UL). The locations of these measurements are shown in Figure 1, reproduced from [5]. Together these give an estimate of the potential aero-mechanical power at the intakes as described below. This allowed the performance of the foils and air-jets to be evaluated stand-alone, decoupled from the efficiency of the internal turbine. A final hot wire anemometer was placed between the foils at the minimum separation to measure the speedup between the foils and compare to previous PIV wind tunnel measurements [4].

The pneumatically transmitted mechanical power of the air flow in the internal ducts is given by

$$Power = \Delta P_{choke} A_{duct} u_{duct} \,. \tag{1}$$

The largest area of the AeroMINE, A_{exit}, is defined by a rectangular perimeter outlined by the trailing edges of the foils, the top plate above the foils, and the base plate to which the foils are mounted. The power coefficient was calculated based on this maximum swept area to provide a fair comparison with a horizontal or vertical axis wind turbine. The power available in the wind flowing through this largest area is the maximum possible power that could be extracted by AeroMINE, defined as

$$Wind\ Potential\ Power = 0.5\rho A_{exit} U_\infty^3\ . \tag{2}$$

Thus the aero-mechanical power coefficient of AeroMINE is given by

$$Cp = \frac{Power}{Wind\ Potential\ Power}\ . \tag{3}$$

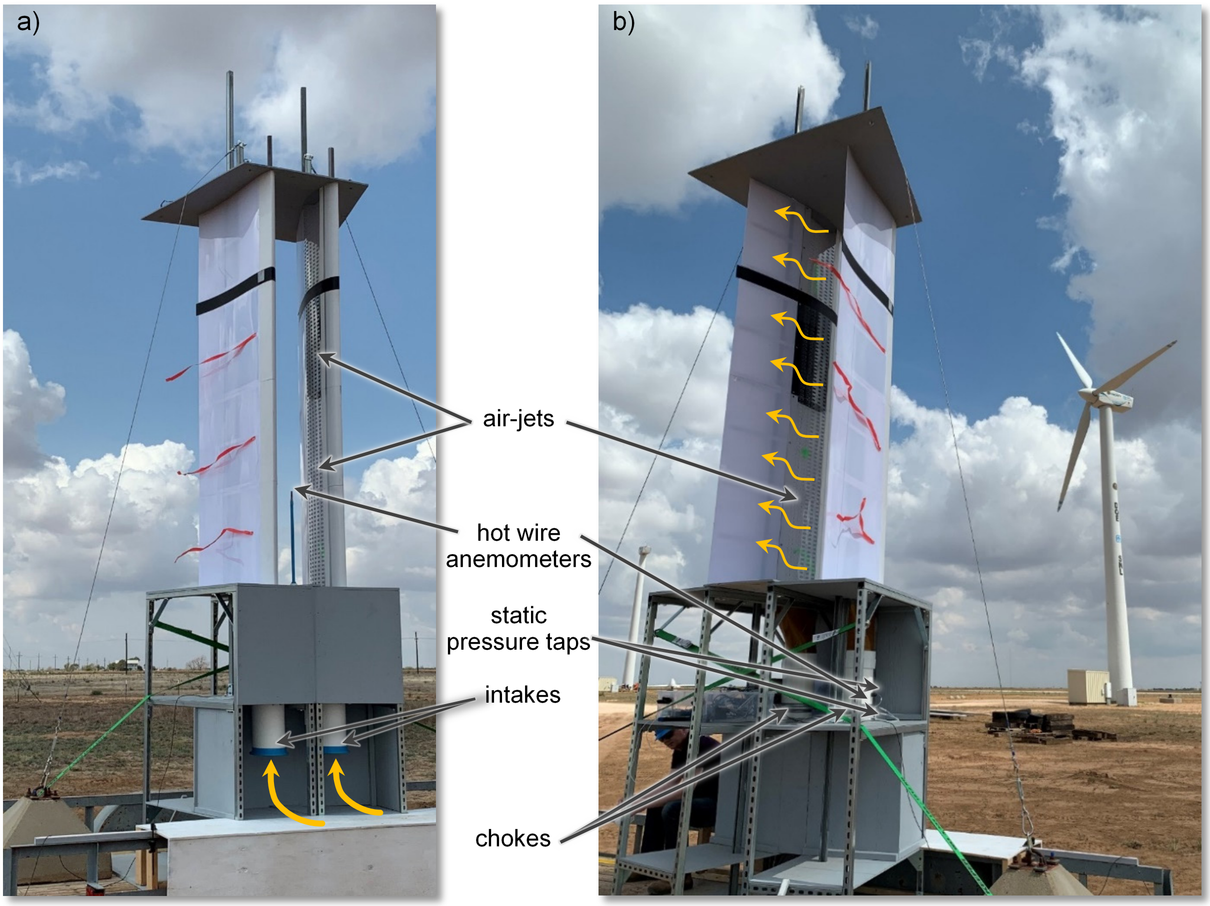

Figure 1. Pilot-scale (3-m tall, 1-m chord) AeroMINE test at SWiFT shown from a) the front and b) behind. The power producing flow is indicated by the yellow arrows, entering at the bottom through the two intakes and exiting from the air-jets along the foils [5]. This flow is driven by suction at the air-jet orifices, which is created on the low-pressure surfaces of the opposing foils.

Unlike in previous low wind speed tests [5], during this high wind speed test series it became clear that the flow was detached at the base plate. Thus, a front nose and trailing rear flap were installed on the device and were observed to significantly improve attachment along the bottom plate as shown in Figure 2.

The impact of wind misalignment with performance is an important consideration. In previous low-speed pilot scale tests [5], negligible impact of misalignment was observed up to ±30°. Even at 45° misalignment, performance was reduced by only 20%. The flow conditions considered here were binned at ±10° to approximate perfectly aligned flow. This was determined by the wind speed and direction sensor shown in Figure 2.

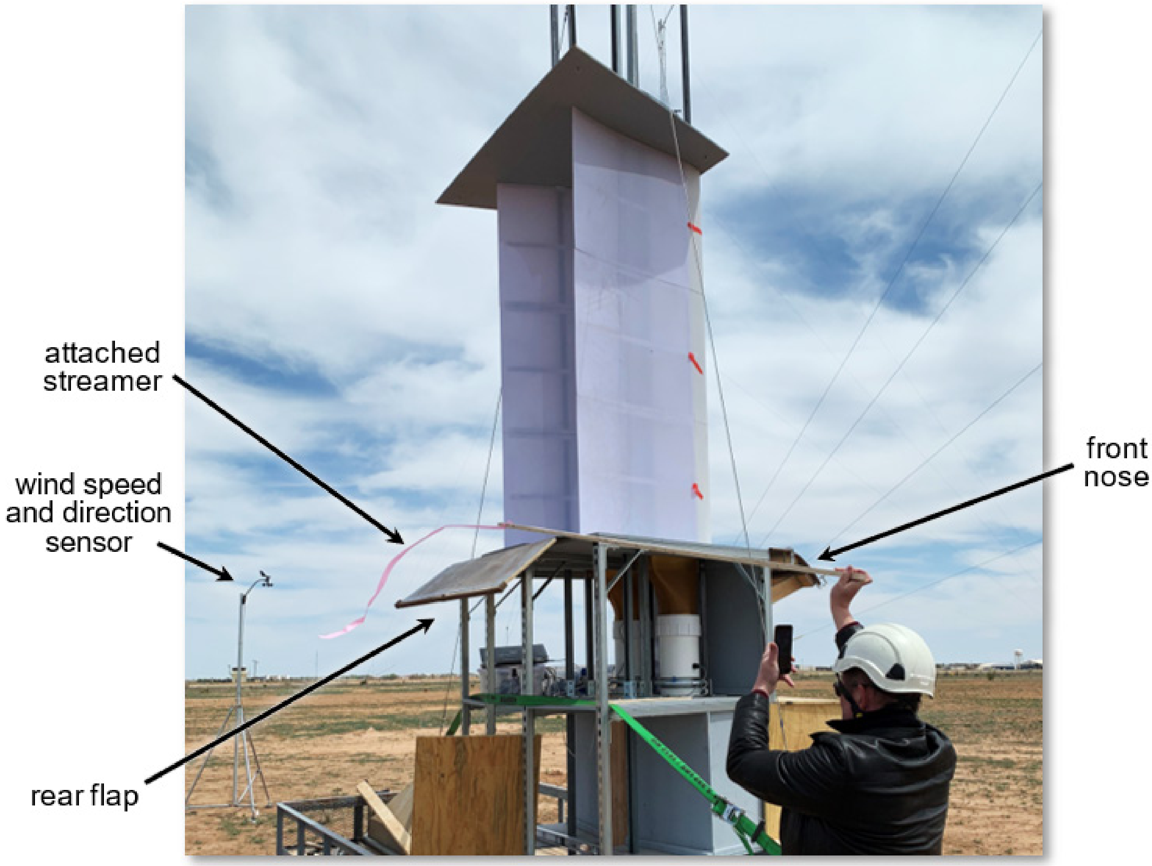

Figure 2. Improved flow attachment demonstrated by a streamer held at the front nose.

5. Results

Based on equation 3, an efficiency of 25%, or 42% of Betz limit, was achieved for wind speeds at or above 9 m/s for AoA = 10° with the largest air-jet area, and wind with no more than 10° misalignment. This data point is shown in Figure 3, along with data from past wind tunnel tests on scaled versions of the device. This efficiency was calculated based on velocity and pressure measurements across variable chokes, placed internally just downstream of the location where the turbine-generator would sit. Additional losses associated with this internal turbine-generator would exist in the real system. As in previous wind tunnel tests [4], maximizing the exit air-jet area while still maintaining a sufficient skin was shown to be critical to performance. When this was achieved, the high wind speed field tests extrapolated as expected from previous scaled (0.5-m chord) wind tunnel tests as shown in Figure 3. Due to the internal to external nature of the power producing flow, AeroMINE cannot be maintained completely self-similar with scale. For example, in past wind tunnel tests with 0.5-m chord foils, the velocity was doubled to recover the same *Re* as for the 1-m chord field test. However, the hydraulic diameter of the internal flow inside the scaled airfoils used in the wind tunnel is much smaller than that of the 1-m chord pilot-scale foils, increasing frictional losses. Similarly, the velocity of the internal flow in the wind tunnel is higher, increasing losses associated with the flow inside the foils. Thus, as the scale of the device increases, an increase in efficiency as observed is expected because frictional effects of the internal flow are disproportionally reduced.

Good symmetry was generally maintained in the velocity and pressure response across the two foils, as expected for this relatively low AoA. It was expected that at high wind speeds some further increased power could be achieved with slightly higher AoA while still avoiding asymmetry.

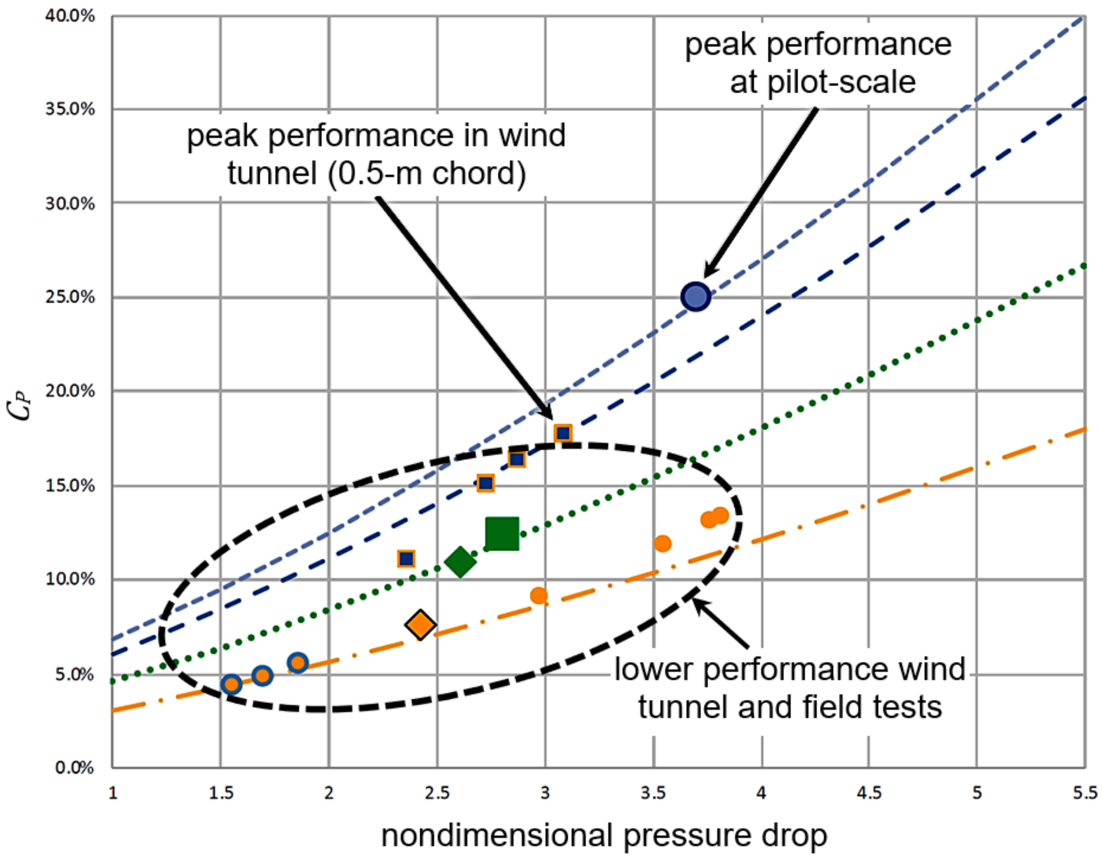

Figure 3. A 25% aero-mechanical efficiency based on equation 3 was achieved for high wind speed pilot-scale tests.

6. Conclusions and Future Work

In high wind speed tests above 9 m/s a peak efficiency of 25% was achieved for AeroMINE. It is estimated that further design optimization could achieve efficiencies of well over half of the Betz limit. At such efficiencies, AeroMINE becomes competitive with rooftop solar PV for point-of-use power generation. Because AeroMINE is designed to sit on the leading edge of large buildings, it is complementary to rooftop solar PV in that it only requires a small fraction of the area of the roof.

The next phase will focus on designing and optimizing the turbine-generator to extract as much of the potential aero-mechanical power as possible. A controller must be designed to maximize the performance and minimize detrimental effects of turbulence.

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