(54) Title: HIGH-EFFICIENCY VERTICAL AXIS WIND TURBINE BLADES FOR APPLICATION AROUND A CYLINDRICAL SURFACE
TITLE OF INVENTION:

High-efficiency Vertical Axis Wind Turbine Blades for Application Around a Cylindrical Surface

General Description

Vertical wind turbine blades mounted on the outside of cylinders have a significant power output increase at all wind speeds over blades without an interior cylinder for a given sweep area and same upwind wind speed ($V_u$). This benefit is due to the physics of fluid flow, specifically Bernoulli’s Law, where the wind speed increase at the cylinder sides parallel to wind direction is due to the need for the rate of mass transfer of air to be the same upstream and downstream from the pipe. The increase in wind speed can be as high as twice the upwind wind speed and asymptotically approaches $V_u$ as illustrated in Figure 1.

Traditional blade designs have been embodied on Horizontal Axis Wind Turbines (HAWT), which usually consist of three blades and sweep perpendicular to the wind, and traditional Vertical Axis Wind Turbines (VAWT) such as Darrius or Savonius types that sweep parallel (and at times anti-parallel) to the wind direction $^1$. The blades described in this disclosure are based on a unique and previously unknown blade configuration that has a streamline, low drag cross-sections in a headwind and large drag cross-section in a tailwind. Figure 2 is a possible embodiment of the blade cross-section. These blades are
specifically designed to maximize output power and torque when rotating in close proximity to a cylinder.

The blades are attached to a generator, possibly toroidal in shape and located concentric with the cylinder. If the cylinder is relatively large and tall, for example several meters in diameter and dozens of meters tall, a combination generators and/or mounts may be required. Figures 3 and 4 embody the general concept of the cylindrical wind turbine (CWT).

Discussion of Figures

Figure 1

By examining the steady, irrotational, incompressible potential flow around a cylinder, the wind speed increase on the outside surface of the pipe and orthogonal to the direction of flow shows a doubling of the prevailing wind speed. For example, if the wind speed upwind of the pipe is 10 m/s, very close to the pipe and orthogonal to it the wind speed is 20 m/s. This is a dramatic and substantial increase in the wind power potential of the cylindrical turbine, since wind power is proportional to the cube of wind speed. Another way to think about it is with the concept of Tip-Speed-Ratio (TSR). TSR is the ratio of the speed of the blade at the tip to the incoming wind speed. The cylindrical wind turbine (CWT) can potentially have a TSR approaching two (TSR~2) when referenced to the upwind wind speed. This is an unprecedented feature in drag based wind turbines, also
referred to as “panemones”\textsuperscript{2,3}. Increasing TSR is important in wind turbine design since the greater the TSR the more output power at increasing wind speeds.

The above describes the ideal case. There are two practical matters that affect the ideal performance to the cylindrical turbine. Firstly, the wind turbine blades must be located close to the cylinder in order to capture the speed up effect, but far enough away to not detrimentally affect the wind profile about the stack. As the blades are moved away from the cylinder, the speed up effect is reduced. The second correction to the ideal case deals with the potential flow equations, which do not include the effect of a boundary layer around the cylinder. If the boundary layer near the cylinder is taken into account i.e. the air just outside the cylinder is not moving since the cylinder is not moving, the wind speed profile around the cylinder will still show an increase relative to the upwind speed approximately 1.1 radius’s from the center of the cylinder, then exponentially decrease with greater radius. Figure 1 shows the wind speed orthogonal to the wind direction and moving radially from the cylinder.

Figure 2

In Figure 2 (a), a generic streamline body is shown in two-dimensions. It has been designed to provide a small drag coefficient when air passes from left to right. In Figure 2 (b), the streamline body has been modified to maximize the torque available from the tail wind side i.e. from right to left. The body has been hollowed out to catch the wind and provide high drag, while maintaining a minimize counter-torque from the headwind side.
Typical cup anemometers have headwind drag coefficients of approximately 0.4, while their tailwind drag coefficients are close to 1.4. This will provide positive torque around the cylinder but at a modest power coefficients of less than 5%. For CWT blades, the drag coefficients can be made < 0.1 and > 1.0, respectively, providing a much improved power coefficient. The CWT blades could also be made from an airfoil shape.

Figure 3

A sample embodiment of the CWT is illustrated in Figure 3. In this configuration, the blades provide torque to the generator in a direct-drive configuration (no gearbox). The generator can be constructed from permanent magnet (PM) technology, but could also be an induction generator. If the cylinder is made longer, another collar can be fitted for mechanical stability. The generator collar can be placed at the bottom or top and several collars and/or generators spanning long blades can be implemented. The number of blades required would depend on the application, but at a minimum two blades would be necessary.

Another aspect of the CWT is that the generator and blades do not have to be concentric with the cylinder. The blades could rotate on a collar that is offset from the cylinder, but would require a tail or fin in order to align into the wind. The advantage of this configuration is the downstream blade capturing wind energy would not be compromised, but the upwind movement of the blade would have even less negative torque, since its path is moved away from the cylinder.
Figure 4

By combining Figure 4 with Figure 1, the startup scenario for the CWT can be described. The initial condition has the blades stationary. The incoming wind is captured by the blade in the 6 o’clock position. This blade provides the positive torque so that the CWT can rotate. The blade at the 3 o’clock position is at a stagnation point (no net torque). The blade in the 12 o’clock position provides a negative torque, but since it’s streamlined in this direction the detrimental contribution is relatively small. The blade in the 9 o’clock position is also at a stagnation point and contributes no net torque. The total positive torque provided by the 6 o’clock blade is less than 50% of the total circumference at startup i.e. the flow lines push the 6 o’clock blade for less than 180 degrees of rotation. Note the cavity side of the blades are directed towards the cylinder.

Figure 5

In Figure 5, a sketch of the Magnus Effect is shown. It is well established that rotating cylinders exhibit this effect. If we combine a CWT of Figure 4 with Figure 5, the CWT after startup will exhibit the same phenomena, since the boundary layer near the cylinder is being modified in the same way. This effect increases the CWT output power since the blades being pushed have a longer path (thus increasing the total positive torque per rotation) while the blades moving upwind have a reduce path (thus reducing the total negative torque per rotation). Note that the total positive torque provided by the 6 o’clock
blade in Figure 4 after startup is greater than 50% of the total circumference i.e. the flow lines push the 6 o'clock blade for more than 180 degrees of rotation.

Figure 6

Figure 6 illustrates one application, although many applications can be realized. What is shown is a CWT located at the top of a utility pole and tied through a three-phase inverter to the power lines. This unique idea then transforms the transmission line into a power source and, depending on the wind speed, provides additional power to make up for line losses. In strong winds extra power will be supplied into the grid. In effect, this embodiment is the first truly distributed wind power source since a CWT could theoretically be placed on every power pole across a nation.

One of the major benefits of the CWT is the low noise and vibration developed from the blades. In conventional HAWTs, the majority of the noise comes from two sources: 1) the blades sweeping by the tower, and 2) the turbulence generated at the blade tips. In the CWT case, there is no major discontinuity in the fluid flow so the noise from the blades sweeping the tower is greatly reduced. In addition, the CWT runs at a lower TSR than conventional turbines, therefore the turbulent flow around the blade tips is reduced and consequently the noise. In addition, the visual impact is significantly reduced over that of HAWTs, since the sweep area is smaller and the blades are not cantilevered in the form of a long protrusion from a nacelle. This makes the CWT ideal for roof mounted...
applications in urban areas. They can also be electrically tied together along roof lines to multiply the output power for larger applications.

Another significant benefit to CWTs is that a tower may not be required. By using a low-cost pipe or pole, the turbine can be mounted virtually anywhere. In addition, VAWTs do not need to be turned into the wind i.e. they are well suited for turbulent environments, which makes them especially practical for urban deployment.
Figure 1. Fluid flow and wind speeds around a stationary cylinder.

Figure 2. A typical streamline body (a) made of solid material and (b) a streamline body hollowed for cylindrical wind turbine blades.
Figure 3. Generic CWT embodiment (left) and example PM generator (right) cross-section.

Figure 4. Generic CWT in action. In this case the cylinder is stationary and the blades are rotating.
Figure 5. Magnus effect observed on rotating cylinders. The same effect is seen for CWT after startup.
Figure 6. CWT applied to a power line utility pole.
Generic CWT embodiment (left) and example PM generator (right) cross-section.