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Tow testing of Savonius wind turbine above a bluff body complemented by CFD simulation

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ABSTRACT

A simple way to improve its power coefficient (c_p) of a Savonius turbine is by its installation above a cuboidal building as the building will redirect the wind and increase its speed significantly. To determine the gain, a turbine was constructed and installed above a bluff body and tow tested. Detailed measurements of vehicle speed and turbine power were made. Tow test speeds were 8, 10 and 12 m/s, while TSR range was 0.6–1.1. Most importantly, wind speed at the position beside and slightly above the turbine was measured during test runs. The c_p calculated using this measured wind speed was used to validate CFD simulation results. Simulation results were also used to obtain the relationships between the wind speed of the free stream and at the anemometer position. Typically, wind speed at the anemometer position is about 9% higher than those of the free stream. These relationships were used to derive the free stream wind speed of each experimental run. The c_p calculated using these derived free stream wind speeds showed an increase of 25% at 12 m/s wind speed, compared to the c_p reported by previous researchers for a similar turbine operating in unmodified air flow.

1. Introduction

The Savonius turbine invented by Finnish engineer Sigurd Johannes Savonius is a simple machine that extracts energy from the wind using the principle of differential drag between the advancing (moving in the same direction as the wind) and returning halves of the rotor. In spite of its lower maximum power coefficient, it still finds application in circumstances where simplicity of construction, high torque at low wind speeds, ability to withstand extreme wind conditions and self-limiting characteristic are overriding considerations. A typical large axial flow wind turbine in the megawatt range has power coefficient (c_p) of more than 0.5 [1]. In contrast, the c_p of drag-based turbines does not exceed 0.2, according to a summary of various devices by Saha and Rajkumar [2]. For a three-bladed rotor, the c_p is even lower, at 0.16 [3,4].

Therefore many researchers have attempted to improve the performance of the Savonius turbine. A commonly employed principle is the shielding of the returning blade. Examples are the use of a shielding plate [5], a deflector plate [6], guide vanes [7], etc. These prior works all involve additional components, which detracts from the one of the advantages of the Savonius turbine: its simplicity.

The present research focuses on the installation of a Savonius turbine with its axis horizontal above a flat-roofed cuboidal building. Our prior computational fluid dynamics (CFD) simulation has shown that such a building standing in the presence of wind generates a circular flow field just behind the windward top edge due to flow separation. The upper part of this circular flow region has high local wind speed, typically up to 25% higher than the free stream wind speed [8]. Just adjacent to the roof surface, there is backflow, i.e., the direction of the air flow is opposite to the direction of the wind. Since a drag-based wind machine produces useful torque when its blade is moving in the same direction as the wind but at a slower speed, hence a rotary drag-based turbine would be the best machine to exploit the circular flow field. An axial flow turbine would derive no benefit from the back flowing region even though it would also benefit from the high local wind speed at the upper part of the circular flow region. This concept of improving the performance of a Savonius turbine does not require additional

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Abbreviations and nomenclature

TSR	tip speed ratio
A	frontal swept area of turbine (m^2)
C_D	drag coefficient
C_{DR}	drag coefficient of the returning blade
c_p	power coefficient
P	power output of turbine (W)
U	free stream wind velocity (m/s)
U_b	turbine blade velocity (m/s)
λ	speed ratio of the blade of a drag-based wind device, $= U_b \div U$
ρ	density of air (kg/m^3)
ω	Rotating speed (rad/s)

components. Furthermore, existing structures can be used to install and optimise the wind turbine, in particular in urban areas, where the produced electricity is needed.

In this study, we performed tow tests of a Savonius wind turbine. This was after initial tests in our University's wind tunnel produced unsatisfactory results. The wind tunnel had a limited test section size of 0.78 m wide and 0.72 m high, which meant that when a forward facing step was installed, the turbine size was limited to 0.1 m in diameter. Such a small turbine produced very low torque and thus the relative error in torque measurements were quite large. In contrast, tow testing offers an infinitely large 'test section' without the blockage effect found in a wind tunnel. However, tow testing is subject to prevailing wind which is beyond our control. Fortunately, by conducting the tests during the inter-monsoon season, such disturbances were minimised.

A bluff body was constructed and installed around a lorry. A three-bladed Savonius turbine was installed with its axis horizontal above the bluff body. Instruments to measure vehicle speed, turbine power and wind speed were installed. Tow tests at vehicle speeds of 8, 10 and 12 m/s were conducted, with the turbine TSR ranging from 0.6 to 1.1. Full details are given in Section 3 of this paper.

2. Analytical power estimate

Erich Hau [9] gives the fundamental derivation of the c_p of a drag-based wind machine. A blade subjected to wind experiences drag force proportional to its drag coefficient C_D. In a wind machine, the effective wind seen by the blade is the difference between the wind speed (using a stationary reference) and the blade speed. The drag force multiplied by the blade speed gives the power output of the blade. Hence:

$$P = C_D\left[\frac{1}{2}\rho A(U-U_b)^2\right]U_b \tag{1}$$

When the blade is loaded so heavily that it is stationary, it experiences the maximum possible drag force. However, since it is stationary, its power output is zero. On the other extreme, when the blade is moving at the same velocity as the wind, it experiences no force and again its power output is zero. Thus there must exist a blade velocity between these two extremes where the power is maximum. To obtain this velocity, we define the speed ratio:

$$\lambda = U_b/U \tag{2}$$

Expressing equation (1) in terms of λ and dividing by the power available in the wind gives the power coefficient:

$$c_p = C_D\frac{\frac{1}{2}\rho AU^3\lambda(1-\lambda)^2}{\frac{1}{2}\rho AU^3} = C_D(1-\lambda)^2\lambda \tag{3}$$

For a given C_D, to find the speed ratio λ at which maximum c_p occurs, equation (3) is differentiated with respect to λ and solved, giving the non-trivial root of λ = 1/3. Substituting this value into equation (3) gives the maximum c_p:

$$c_{p,max} = C_D\left(1-\frac{1}{3}\right)^2\frac{1}{3} = \frac{4}{27}C_D \tag{4}$$

Even with the ideal case of an infinitely long concave semi-cylinder with C_D of 2.3 [10], the c_p is only 0.34. In practical machines, this is reduced further by the negative torque produced by the returning blade. A similar derivation can be applied to the returning blade. In this case the effective wind seen by the blade is the sum of blade speed and wind speed. Thus the power absorbed by the returning blade is:

$$P = C_{DR}\left[\frac{1}{2}\rho A(U+U_b)^2\right]U_b \tag{5}$$

However, if it is attempted to find the net power by the difference between equation (1) and equation (5), an unrealistically low value would be obtained. This is because the returning blade diverts some of the wind to the advancing blade, thus causing its power output to deviate from that theoretically derived. Additionally, near the end of the return and at the start of the advance, air flow over the convex surface of the blade generates lift which also contributes to positive torque. These two phenomena are visible in the CFD wind vector diagrams reported by Zhou and Rempfer [11].

The present research employs a three-bladed Savonius turbine installed above a bluff body simulating a cuboidal building. The point of interest is whether the c_p of such an arrangement exceeds the value 0.16 reported by Sheldahl et al. [3] and Kumbernuss et al. [4].

3. Materials and methods

3.1. Design of the Savonius turbine

The Savonius turbine used in the present study is a three-bladed device with its axis of rotation installed horizontally. It has a

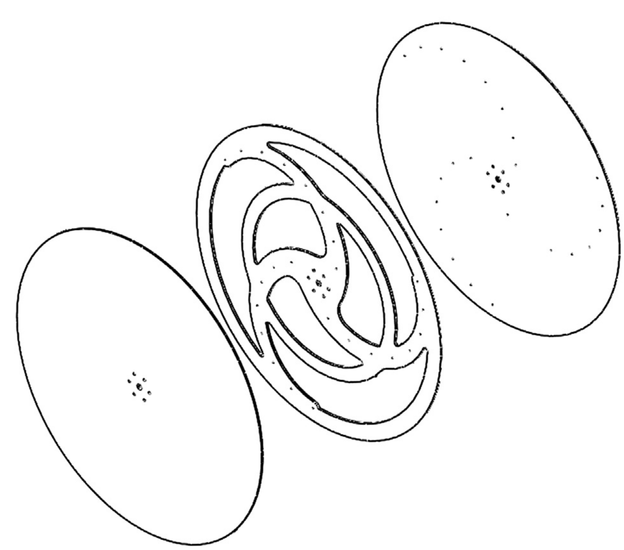

Fig. 1. Exploded view of laminated construction of end plate.