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VARIABLE GEOMETRY DARRIEUS WIND MACHINE

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ABSTRACT

A new variable geometry Darrieus wind machine is proposed. The joint attachment of the blades to the rotor can move freely up and down the axle, allowing the blades to change shape during rotation. Experimental data for a 17m diameter Darrieus turbine and a theoretical model for multiple streamtube performance prediction were used to develop a computer simulation process for studying parameters that affect the machine's performance. New structural and dynamic parameters were incorporated into the program and varied in order to simulate the machine's operation in a wide range of aerodynamic conditions. In conclusion, a parabolic blade was used to approximate a true troposkein shape. The computer simulation study shows that governor behavior of a Darrieus turbine cannot be attained by a standard turbine operating within normally occurring rotational velocity limits. These results are illustrated graphically and numerically. A second-generation variable geometry Darrieus wind turbine which uses a telescopic blade is proposed as a potential improvement on the studied concept.

KEYWORDS: Wind power; vertical-axis wind turbine; Darrieus wind turbine of variable geometry; theoretical analysis; computer simulation results.

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INTRODUCTION

Attached to the rotor at two ends, the Darrieus machine was reintroduced again in the mid-1960s by researchers of the National Research Council of Canada (NRC). Since then, theoretical aspects of Darrieus turbine operation have been studied in detail by NRC and Sandia.

Laboratories across the United States have been conducting research on wind machines. Their research has shown that one particular machine, the Darrieus machine, has aerodynamic characteristics which differ in some ways from other wind machines. It produces a greater energy output. The Darrieus machine is unique in several aspects compared to conventional windmills which rotate about a horizontal axis. The turbine, usually composed of two or three blades, is omnidirectional and can accept wind from any direction without yawning. Held vertically by guy cables, the turbine does not require placement on a tower to keep the blades above the ground. Additionally, the generator and gear trains are mounted on the ground, simplifying maintenance and repair of the machine components. However, the Darrieus wind machine is not self-starting. Its fixed-pitch blades stall at low speeds and cannot reliably drive the turbine from a standstill. To operate the Darrieus machine as self-starting, one or two Savonius rotors are mounted on the center shaft to propel the turbine at low wind speeds, or an auxiliary motor provides starting torque. The Darrieus machines typically operate at a constant revolution per minute by being connected to a utility grid through a synchronous generator. The Darrieus turbine uses lift as a driving force and is considerably more efficient than drag turbines such as the Savonius. It is, however, generally less efficient than propeller-driven wind machines. Darrieus wind machines ranging from a few kilowatts to 250 kW are used to pump water and generate electric power in remote locations of Canada, the United States, Australia, New Zealand, Argentina, and other countries. Research is being conducted to improve the aerodynamic performance of the turbine and to develop machines in the megawatt range. A new variable geometry Darrieus wind turbine is being developed. In a standard Darrieus turbine, the tip-to-speed ratio varies along the rotor blade from a peak near the blade mid-point to near zero where the blade meets the hub.

Fig. 1. New variable geometry Darrieus wind turbine with structural spring.

Two concepts were considered. In the first concept, the blades themselves act as springs as shown in Fig. 1; in the second concept, an external spring is added as shown in Fig. 2.

Fig. 2. New variable geometry Darrieus wind turbine with external spring.

THEORETICAL

ANALYSIS: Several theories using a single streamtube, multiple streamtubes, or vortex models have been developed to evaluate the performance of a vertical axis wind turbine (Strickland, 1975, 1976; Wilson, 1976; Blackwell, 1975, 1977; Klimas, 1978, 1980; Aya, 1983; Paraschivoiu and Belciug, 1983). The majority of these theories are based on momentum and blade element techniques and assume the turbine is enclosed in a single streamtube with uniform cross-sectional conditions or contained in a number of streamtubes, each with different conditions. Airfoil theory is usually used to determine the effective wind velocity on the blades. The theory generally used to more accurately predict changes in the power coefficients produced by different wind speeds is the multiple streamtube theory. This theory is less complex than the vortex theory and allows for variations in blade geometry and wind shear effects. Consequently, the multiple streamtube theory (Strickland, 1975) was selected for developing a computer simulation program to study the parameters that affect the performance of a variable geometry Darrieus wind turbine. Variable Geometry Model: The basic streamtube theory (Strickland, 1975) was adopted to analyze the performance of the new variable geometry Darrieus machines shown in Figs. 1 and 2. The variable geometry model uses parabolic blades (Blackwell and Reis, 1975), as an approximation for the troposkein blades (Blackwell and Reis, 1979). Using the coordinate system in Fig. 3 and the general equation for a parabola, an expression for the radius in terms of the vertical coordinate was derived. From equation (2) the blade radius for a given height can be determined. Because the angle varies with the changing geometry of the blades, this variation can be determined as well by finding the angle made by the slope of the blade curvature at the radius x.

With the horizontal line, since tan(s) = #2, the derivative $2 of equation (2) leads to the expression for 6. Parameters of the parabola, such as the swept area, arc length, moment of inertia about the axis of rotation, and radius of gyration have also been determined (Blackwell and Reis, 1395). These parameters are listed as follows:

1. Swept area:
2. Arc length:
3. Moment of inertia about the axis of rotation:
4. Radius of gyration:

Each blade is treated as a parabolic beam which has one fixed end, is loaded uniformly, and its deflection is governed by centrifugal forces according to the following expression (Tuma, 1365). E = Young's modulus of elasticity for blade material, while I = cross-section moment of inertia of the blade along the chord line.

The load on each segment along the blade chord line results from the centrifugal acceleration a, acting on the blade, and is defined by the following expression: P = specific density of blade material, V = volume of blade segment. The load can then be expressed in terms of F with the uniformly distributed mass as follows: S = arc length of parabola.

The uniformly distributed load was approximated in the computer simulation work by using the load acting at the radius of gyration. Both the structural spring and the external spring experience the same deflection when subjected to the load. The total spring constant is K = Ksp + Ksp, because K = Ksp, Ksp and Ksp are the structural spring constant and external spring constant, respectively.

Results of computer simulation: Variable parameters such as structural and dynamic aspects of the Darrieus wind machine described above have been incorporated into the computer program to simulate the work of an optimal machine in a wide range of aerodynamic conditions.

To determine the dynamic aspects of the machine's behavior under simulated conditions, several assumptions were made.

* The blade is treated as a beam of parabolic shape, working within the elastic limit of its material.
* The total load, Wy, contributes towards the blade's deflection.
* Mechanical friction at the axle due to turbine rotation and the varying geometry of the blades is negligible.
* The head resulting from the gravitational forces is negligible.

The calculation process consists of the following steps:

1. The load on the blade is determined by using an assumed value of the angular velocity of the turbine.
2. Deflection of blades is computed from equation (12) by assuming different values for Key.
3. A new value for the turbine height is computed from equation (8).
4. A new equatorial radius, R, which corresponds to R, is computed by using the Newton-Raphson method.
5. The new moment of inertia, I, is computed from equation (6).
6. Power coefficient, C, variation with tip-to-speed ratio, TSR, is determined by using the multiple streamtube theory.

Parameters and variations of w vs H, and u vs TSR were also computed. Computations were done for the Darrieus wind machine that has the following characteristics (Worstell, 1981); turbine height = 16.7 m (54.8 ft), turbine diameter = 18.7 m (61.4 ft), arc length = 24.1 m (79 ft), blade mass = 323 kg (713 lbs), chord length = 0.533 m (1.95 ft), the number of blades = 2 or 3, aerofoil section = NACA 0015.

A computer simulation program was run for the values of = 108 A = 20.645 in, R = 0.3 x 10, cy and Cp, taken for the values of the angle of attack a which was calculated according to the multiple streamtube theory. The computer program was checked out by computing the variation of the coefficient of performance, C, versus tip-to-speed ratio, TSR, for the Darrieus wind machine having the parameters above. It was found that the results agreed well with those obtained elsewhere (Worstell, 1961).

(36:33 ft). Such deflection is structurally unacceptable. During the change in the machine's geometry, the solidity value decreased from about 0.13 to below 6.10, which led to a noticeable decrease in the peak value of the machine's power coefficient.

Within the rotational velocity values used (up to 69.57 rev/min), the change in turbine geometry, although large, was not sufficient to make the turbine regulate its speed by acting like a governor. To control the Darrieus turbine geometry within acceptable blade structural limits and to dampen possible oscillations, an external spring was added as shown in Fig. 2. The complete simulation was done for different external spring constants ranging from K = 3000 to K = 30000. As shown in Fig. 4, the turbine geometry is almost fixed for K = 30000 and varies very little for higher values of K.

The results indicate that by selecting a proper spring constant (see Figs.5 and 6), the blade deflection can be reduced to reasonable limits. The solidity variation is almost the same as for the former concept with a structural spring constant. Although the turbine responds to the variation in rev/min like a governor, as shown in Fig. 9, even when replacing K = 30000 by K = 3000 in the computer simulation program, the machine operation parameters are even farther away from reaching governor conditions because the change in geometry is smaller than for the concept shown in Fig. 1 for the limits of w used in computations.

As can be seen, the curve on the figure changes its shape for different % values and ultimately may bend and reach a plateau at higher values of w and TSR when governor operation conditions are reached. This first generation variable geometry Darrieus wind machine led to a second generation turbine which...

The text is being investigated now. The concept allows the turbine to increase its radius by almost two-thirds of its initial value by using telescopic blades. It is expected that the machine will respond more like a governor. The use of a variable spring constant may be warranted to control the turbine geometry within a broader range of operation parameters. The solidity will vary from 0-13 to about 0.08 which for R= will result in a stronger Cy variation.

Fig. 5. depicts the variation of Darrieus turbine radius R(ft) with angular velocity w (ft/s) for K = 3000

and K = 3000. Ng = 2, C= 0.533 m (1.75 in). Fig. 6. shows the variation of Darrieus turbine height, (ft), with angular velocity w (ft/s) for K = 3000 and K = 300005. More spread out optimum values are expected for C, versus TSR as shown in Fig. 8 (Strickland, 1975).

During normal operation, the variation of turbine geometry does not change the turbine moment of inertia enough to make it act like a governor. Therefore, the turbine can self-regulate its rotational velocity. The decrease of the solidity due to the increase of the turbine radius causes a slight decrease in the coefficient of performance and some flattening of the curve C versus TSR. This creates a possibility for the variable centrifugal and external springs, together with other structural aspects of the blades. As a result of this study, a new generation of variable geometry turbines is proposed. This effect should be investigated as the centrifugal force can cause oscillations in structural dynamics.

A Darrieus wind machine with telescopic blades is proposed as an alternative to the fixed geometry machine.

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