AERODYNAMIC CHARACTERISTICS OF A STATIONARY FIVE BLADED VERTICAL AXIS VANE WIND TURBINE

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Abstract: *Drag and torque coefficients of a stationary five bladed vane type rotor have been investigated in this present research work by measuring the pressure distribution on the blade surfaces at various rotor angles. The experimental investigation has been performed at Reynolds number 1.65 × 10^5 in a uniform flow jet produced by an open circuit wind tunnel. It has been observed that the total static torque coefficient increases from 0^0 to 10^0, and reaches its maximum value and then decreases up to 30^0. From this point, the total static torque increases up to 72˚. Total static torque coefficient at different rotor angles curve repeats from 72^0 to 144^0, 144^0 to 216^0, 216^0 to 288^0, and 288^0 to 360^0 angle of rotation. A quasi-steady approach has been applied for the prediction of dynamic performance of the rotor using the static drag and torque coefficients. This method results in a fair agreement with the measured power coefficient.*

Keywords*: Vertical axis wind turbine, vane type rotor, drag coefficient, torque coefficient.*

INTRODUCTION

Among the various types of wind turbines, the most common type is horizontal axis wind turbine. Another type is vertical axis wind turbine. The primary attraction of vertical axis wind turbine is the simplicity of its manufacture compared to horizontal axis wind turbine. Among the different vertical axis wind turbines, the Savonius rotor is a slow running wind machine and has a relatively lower efficiency. Still it is being used in developing countries because of its simple design, easy and cheap technology for construction and having a good starting torque at low wind speed[1, 2, 3]. Rigorous studies on the performance characteristics of Savonius rotor are found in the literatures and these enable the identification of an optimum geometrical configuration for practical design[4, 5, 6, 7, 8, 9]. Most researchers have worked with two, three and four bladed vertical axis wind turbine. The present research work has been carried out to predict the effect of increasing number of blades by developing a vertical axis equally spaced five bladed vane type rotor.

Nomenclature

C_n	normal drag coefficient
C_p	power coefficient
C_t	tangential drag coefficient
C_q	static torque coefficient for a single blade
C_Q	total static torque coefficient
D	diameter of the vane rotor
S	ratio between distance of two blades and diameter of a blade
U_0	free stream velocity
V_w	component of relative velocity along U_0

Greek Symbols:

α	Rotor angle
Φ	Angle of pressure tappings
λ	Tip speed ratio, $D\omega/2U_0$
ω	Angular speed of the rotor

AIM OF THE PRESENT WORK

The present research work has been carried out to study the aerodynamic characteristics of a vertical axis equally spaced five bladed vane type rotor. The study has the following objectives:

1. To study the effects of the five blades of the vertical axis vane type rotor on aerodynamic characteristics i.e. torque coefficient, drag coefficient etc. and determination of the location of separation point with the increase of rotor angle.
2. To determine the drag coefficient and torque coefficient from the measurement of the pressure difference between the convex and concave surfaces of the blades.
3. To make a comparison between the present dynamic prediction (for five bladed vertical axis vane type rotor) and the previous works of vertical axis wind turbine (2-bladed, 3 bladed and 4 bladed Savonius rotor) in terms of power coefficient at different tip speed ratios.

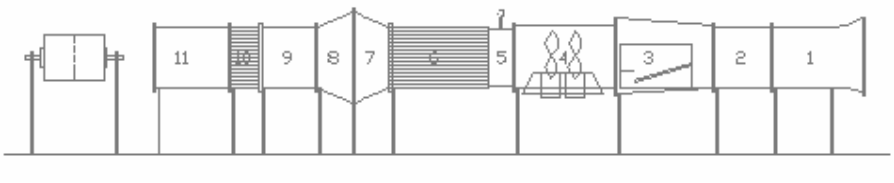
EXPERIMENTAL SETUP AND PROCEDURE

The objectives of the investigation on wind loading and aerodynamic effects on the five semi - cylindrical bladed vertical axis vane type rotor have been conducted with the help of a subsonic wind tunnel together with the experiment set-up of the vane type rotor and an inclined multi-manometer bank.

The Wind Tunnel

The schematic diagram of the experimental setup of the present investigation is shown in Figure 1. An open circuit subsonic type wind tunnel was used to develop the required flow, and the rotor was positioned at the exit section of the wind tunnel. The tunnel was 5.93 meter longwith a test section of 460 mm x 480 mm in cross-section.

The flow velocity in the test section was kept constant at 13 m/s. The Reynolds number based on the rotor diameter D = 200 mm was 1.65 x 10^5. The effect of



1	Converging mouth entry	7	Diverging section
2	Perspex section	8	Converging section
3	Rectangular diverging section	9	Rectangular section
4	Fan section	10	Flow straightener section
5	Butterfly section	11	Rectangular exit section
6	Silencer with honeycomb section		

Figure 1: Schematic diagram of wind tunnel.

temperature was also kept under consideration in this experiment and the experiment was carried out at atmospheric temperature i.e. at t = 30°C.

In order to smoothen the flow, a honeycomb was fixed near the outlet of the wind tunnel. The setup had a bell-shaped converging duct at the entry. To generate the wind velocity, two axial flow fans were used, with each of the fans connected to a motor of 2.25 kW capacity and 2900 rpm. A butterfly valve was used to control the wind speed. A silencer was connected just after the butterfly valve for reduction of the noise.

The central longitudinal axis of the wind tunnel was always kept at a constant height of 990 mm from the floor. The axis of the model was also placed coinciding with the axis of the wind tunnel. The converging duct inlet was then merged into the wind tunnel so that air can enter smoothly into the tunnel and maintain uniform flow into the duct, keeping it free from any outside disturbances. The flow through the wind tunnel was induced by a two-stage axial flow fan of 18.16 m^3/s capacity with a head of 152.4 mm of water.

The Five Bladed Vane Type Rotor

The constructional detail of the test section is shown in the Figure 2. Five bladed vane type rotor was made up of five half cylinders (blade) of diameter, d = 65 mm and height, H = 340 mm. Rotor diameter, D was 200 mm. Optimum value of d/D ratio was taken as 3. The cylinders were made of PVC material. The center-to-center distance of the blade was 137.5 mm. The whole rotor was fixed on an iron frame by using two side shafts and two ball bearings.

The pressure measurements were made at 8 pressure tappings on each blade. The tappings were made with copper tubes of 1.5 mm outer diameter and 10 mm length and were press fitted to the tapping holes. The tappings were located at the mid-plane of one side of each blade and connected to an inclined multi-manometer (manometric fluid was water and had an accuracy of ± 0.1 mm of water column) through 2 mm PVC tubes.

Before measuring the pressure distribution, the mean velocity was measured in a vertical plane at 0.5 m downstream from the exit of the wind tunnel without placing the rotor by means of a pitot static tube connected to an inclined manometer with kerosene as the manometric fluid. The measured velocity distribution was found more or less uniform.

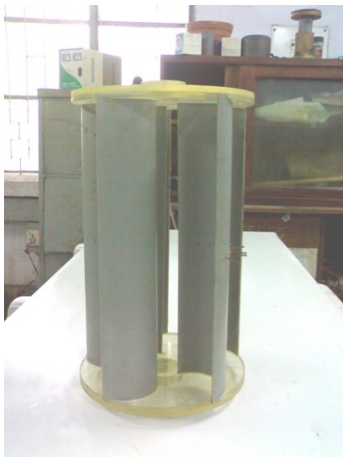


Figure 2: Five bladed vertical axis vane type rotor.

Figure 3: Experimental setup in the laboratory.

The pressure distribution over the blade surfaces was measured step by step by using the multi-manometer bank. The experimental set-up is shown in Figure 3. At first, the vane rotor with the frame was placed 500 mm down stream of the exit section of the wind tunnel. One blade of the rotor was fixed parallel to the free stream velocity i.e. parallel to the horizontal, which was called the reference plane and from this plane angle of rotation was measured. At the beginning, the first blade was at 0° angle of rotation, exposing the convex surface in front of free stream air, so the other four blades were at 72°, 144°, 216°, and 288° angle of rotation respectively. The rotor was then made static by fixing one end of the shaft with the angle-fixing

device. Then power was supplied to the motor of the wind tunnel for starting flow of the free stream air of uniform velocity over the blades of the rotor. Pressure on the convex surface of blades was measured at a particular rotor angle α, fixing the rotor at static condition.

Gradually, pressure on the convex surfaces was measured in this process for every 10° interval of rotor angle up to 350° angle of rotation. The same steps were performed for the measurement of the pressure on the concave surfaces.

RESULTS AND DISCUSSION

Normal Drag Coefficient:

Normal drag coefficient, C_n of an individual blade effect of five bladed vane rotor is shown in Figure 4 for different rotor angles. For the flow over the five-bladed system, considering a single blade the normal drag coefficient $C_n(\alpha)$ decreases with the increase of the rotor angle from α=0˚ to 10˚, and then increases up to 30˚. Between α=30˚ to α=50˚, drag coefficient $C_n(\alpha)$ remains constant and after that it increases up to α=90˚. The value of C_n decreases from α=90˚ to α=110˚ and increases up to α=130˚. It slightly decreases from α=130˚ to α=180˚ and increases from α=190˚ to α=270˚. At α=280˚ it falls sharply up to α=360˚. Therefore, positive torque is available from α=70˚ to α=180˚ and from α=210˚ to α=300˚. Negative torque is available in the range of α=0˚ to α=60˚, from α=190˚ to α=200˚ and from α=310˚ to α=360˚. So, the drag coefficient $C_n(\alpha)$ for the first blade, which contributes for the torque production, is negative for a rotor angle of 0˚ to 60˚ and reaches its maximum value at α=60˚.

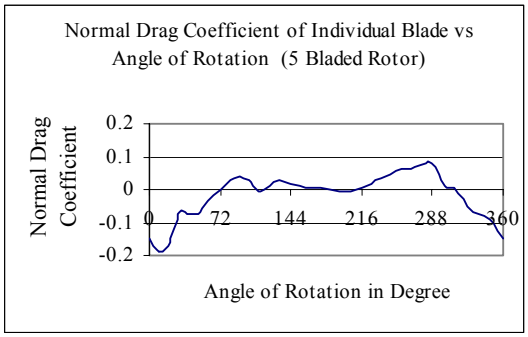


Figure 4: Normal drag coefficient of individual blade effect.

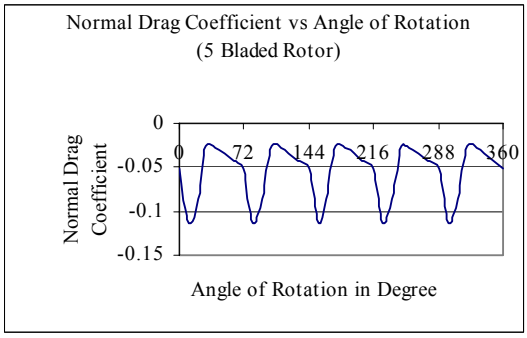


Figure 5: Normal drag coefficient with the combined blade effect.

For normal drag coefficient, C_n with five blades combined effect is shown in Figure 5 for different rotor angles. Drag coefficient, C_n decreases with the increase of the rotor angle from α=0˚ to α=10˚, and increases up to α=30˚. Then it decreases from α=30˚ to α=60˚. The system repeats from α=72˚ to α=144˚, α=144˚ to α=216˚, α=216˚ to α=288˚, and α=288˚ to α=350˚. In case of the five bladed system, the C_n rises and falls sharply.

Tangential Drag Coefficient:

Tangential drag coefficient, C_t of an individual blade effect of five bladed vane rotor is shown in Figure 6 for different rotor angles. For the five-bladed system, on the first blade, the tangential drag coefficient, C_t decreases with the increase of the rotor angle from α=0˚ to 10˚, and then increases up to 90˚. From α=90˚ drag coefficient C_t falls smoothly till α=110˚. Again it rises from α=110˚ to α=130˚ and decreases from α=130˚ to α=210˚. From α=210˚ it increases up to α=280˚. After that position the drag coefficient, C_t decreases sharply till α=360˚. Therefore, positive thrust is available between 70˚ to 180˚ and 220˚ to 300˚ angle of rotation. Negative thrust is available from 0˚ to 60˚ and 220˚ to 300˚ angle of rotation.

For tangential drag coefficient, C_t with five blades the combined effect is shown in Figure 7 for different rotor angles. Drag coefficient, C_t decreases with the increase of the rotor angle from α=0˚ to α=10˚, and then increases up to α=30˚. Then it again decreases up to α=40˚. The drag coefficient increases from α=40˚ to α=60˚ and decreases from α=60˚ to α=72˚. The system repeats from α=72˚ to α=144˚, α=144˚ to α=216˚, α=216˚ to α=288˚, and α=288˚ to α=350˚.

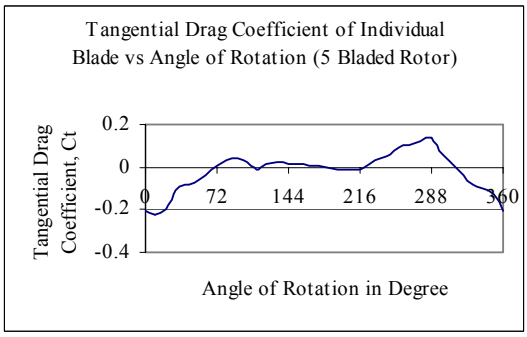


Figure 6: Tangential drag coefficient of individual blade effect.

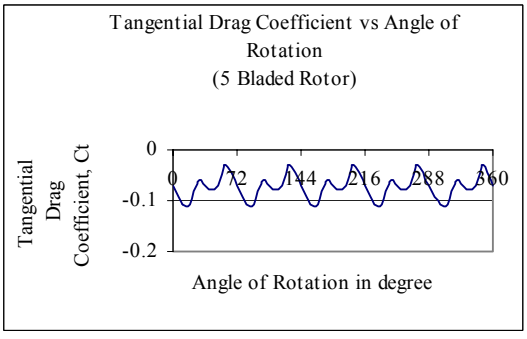


Figure 7: Tangential drag coefficient with combined blade effect.

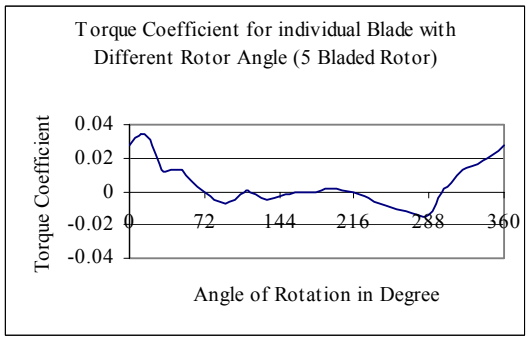


Figure 8: Torque coefficient of individual blade effect.

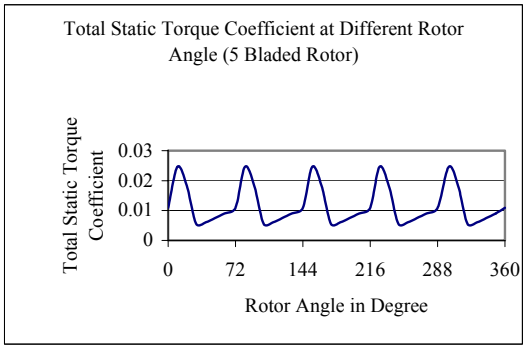


Figure 9: Total static torque coefficient at different rotor angle.

Torque Coefficient

Torque coefficient, C_q with individual blade effect of five bladed vane rotor is shown in Figure 8 for different rotor angles. Considering the flow over the five-bladed system, on the first blade, the torque coefficient increases with the increase of the rotor angle from α=0˚ to 10˚, and then decreases slightly to 30˚ and remains constant till 50˚.

The coefficient, C_q decreases with the increase of rotor angle α, up to 90˚. Between α=0˚ to α=90˚, the torque coefficient is positive for a rotor angle of 0˚ to 70˚ and reaches its maximum value at α=10˚. The coefficient rises from α=90˚ to α=110˚. After that it decreases from α=110˚ to α=130˚, and increases up to α=190˚ smoothly. Then C_q falls from α=190˚ to α=280˚ smoothly. From then onwards, it increases till α=360˚. Therefore, the positive torque is produced for a rotor angle of 0˚ to 70˚, at 110˚, 170˚ to 200˚ and 300˚ to 360˚. Negative torque is available for a rotor angle of 80˚ to 100˚, 120˚ to 160˚ and 210˚ to 290˚. For the five-bladed system, the nature of this curve is opposite to that of the normal drag coefficient, C_n with individual blade effect. The difference is that the value of torque coefficient is smaller than normal drag coefficient with individual blade effect.

Total static torque coefficient, C_q with five blades vane rotor is shown in Figure 9 at different rotor angles. Here the total static torque increases with the increase of the rotor angle up to α=10˚ and reaches its maximum value and then decreases up to α=30˚. From this point, the coefficient C_q increases up to 72˚. The curve repeats from 72˚ to 144˚, from 144˚ to 216˚, from 216˚ to 288˚ and from 288˚ to 350˚. For the five-bladed system, the nature of the curve is opposite to the normal drag coefficient, C_n with combined effect. The difference is that the value of torque coefficient is smaller than that of the normal drag coefficient with combined blade effect. And total static torque coefficient is positive where normal drag coefficient for combined blade effect is negative.

Prediction of Power Coefficient

The quasi-steady approach applied for the analysis of a Darrieus rotor has been considered for predicting the performance of the present vane rotor. The static drag coefficient obtained experimentally at a blade angle of α, has been used in conjunction with the relative velocity, V_r corresponding to a particular tip speed ratio, λ to evaluate the force acting on the blade. The power coefficient has been estimated by averaging the work done over a cycle. The following equations have been used to estimate the power coefficient at a blade angle α[10].

$$C_n'(\alpha) = C_n(\alpha) \times (V_{w1}/U_0)^2 \quad (1)$$

$$C_n'(72° + \alpha) = C_n(72° + \alpha) \times (V_{w2}/U_0)^2 \quad (2)$$

$$C_n'(144° + \alpha) = C_n(144° + \alpha) \times (V_{w3}/U_0)^2 \quad (3)$$

$$C_n'(216° + \alpha) = C_n(216° + \alpha) \times (V_{w4}/U_0)^2 \quad (4)$$

$$C_n'(288° + \alpha) = C_n(288° + \alpha) \times (V_{w5}/U_0)^2 \quad (5)$$

Torque coefficient at α,

$$C_Q'(\alpha) = [C_n'(\alpha) + C_n'(72° + \alpha) + C_n'(144° + \alpha) + C_n'(216° + \alpha) + C_n'(288° + \alpha)] \frac{1-s}{(2-s)^2} \quad (6)$$

Power coefficient at α,

$$C_p(\alpha) = C_Q'(\alpha).\lambda \quad (7)$$

The predicted power coefficients, C_p for different tip speed ratios, λ are shown in Figure 10 for five bladed vane rotor along with the measured data of Islam et al.[1], Ogawa and Yoshida[8], Rahman[11] and Islam et al.[12]. The measured power coefficients matches with the result of Rahman[11] but it deviates with the result of polynomial prediction by Islam et al.[1] and Ogawa and Yoshida[8] only in magnitude.

The measured power coefficients (C_p) for different tip speed ratio (λ) of the present research work agrees with the nature of the C_p vs. λ curve of Islam et al.[12]. The present

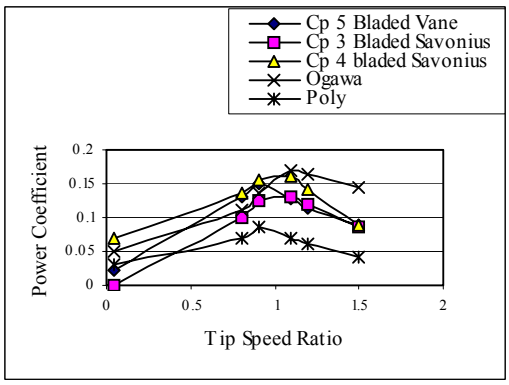


Figure 10: Power Coefficient versus tip speed ratio.

method assumes a potential vortex. However, in reality the flow field around a rotating rotor is also dependent and governed by shear layers, flow separation, high turbulence level, etc. Furthermore, the effect of wake formation has not been considered in the present study.

CONCLUSION

In case of five bladed vane rotor, flow separation takes place over the convex and concave surfaces of the blade and location of such separation point depends on the rotor angle.

The nature of the torque coefficient is opposite to that of the normal drag coefficient on the individual blade of the five bladed vane type rotor. This contributes significantly for producing torque.

Total static torque coefficients for five bladed vane rotor at different rotor angle were also analyzed in the present research work. For five bladed rotor, it is observed that the total static torque varies with different rotor angle. The nature of the curve is opposite to that of the normal drag coefficient due to combined effect. For five bladed vane type rotor, the net torque is always positive.

For the study of dynamic characteristics, the measured power coefficients (C_p) for different tip speed ratio (λ) of the present research work agrees with the nature of the C_p vs. λ curve of other researchers. The present predicted curve is steeper than the predicted curves of other researchers. So it can be concluded that the increases in the number of blades make the nature of the C_p vs. λ curve steeper that provides more power. Comparing with the existing measured data, the present study agrees well with the curves of other research works.

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