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Influence of Leading Edge Slots on a Vertical Axis Wind Turbine performance

تأثير الشقوق الصغيرة عند مقدمة الريشة على أداء تربين رياح رأسى المحور

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الملخـــــــص

هذه الورقة تقدم نتائج معملية داخل نفق هوائى لدراسة تأثير إضافة شق صغير ضيق على أداء نموذج لتربين رياح رأسى المحور. تجارب النفق الهوائى استخدم لها نموذج للتربين ذات قطر ٣٠٠ مم ذو ثلاث ريش، والذى يدور عند نسب سرعات لقمة الريشة مختلفة. اختبر نموذج التربين عند زوايا مختلفة لريش مروحة النموذج وهى ٢٠، ٣٠، ٤٠، ٥٠ درجة. ثم أختبر النموذج بإضافة الشقوق الصغيرة الضيقة عند مقدمة الريش الرئيسية للنموذج وعند زاوية ٤٠ درجة والتى حققت أحسن نتائج مقارنة بالزوايا الأخرى قبل إضافة الشقوق. و أختبر النموذج بأطوال مختلفة للشق الصغير تتراوح ما بين ٣٠ % و ٢٨ % و ٢٦ % و ٢٤ % من طول مقطع الريشة الرئيسية للتربين. إستخدام الشقوق الصغيرة الضيقة حققت زيادة فى معامل القدرة للنموذج عندما قورنت بمعامل القدرة قبل إضافة الشقوق. وجد أن معامل القدرة عند إستخدام الشقوق الصغيرة الضيقة وصل إلى القيمة القصوى وهى 27.9 % عند زاوية ريش ٤٠ درجة وبتحسين قيمته 11.6 % عندما قورنت بالحالة التى بدون شقوق والتى أعطت أقصى معامل قدرة مقداره 25 % . ثم حقق النموذج أقصى معامل قدرة وقيمته ٣١ % للحالة ($C_s/C_b = 26\ \%$, $L/C_s = 0.50$, $\beta = 40^\circ$) بتحسين قدره ٢٤ % ، ووصلت أقصى قيمة لمعامل القدرة إلى 32 % عندما أستخدمت الشقوق الصغيرة الضيقة بزاوية قيمتها ١٠ درجات منحرفة عن زاوية الريش الرئيسية ($C_s/C_b = 26\ \%$, $L/C_s = 0.5$, $\beta = 40^\circ$, $\alpha = 10^\circ$) وكانت نسبة التحسين 28 % عندما قورنت بالحالة التى بدون شقوق.

Abstract: An experimental study has been carried out to investigate the performance of a vertical axis wind turbine model, tested with and without slots at main blades leading edge of turbine model rotor. The turbine rotor model consists of three blades with diameter of 300 mm and height of 200 mm, with a blade profile of Joukowsky 603. The study covers the influence of different blade angles with and without leading edge slots on a vertical axis wind turbine performance. Test data obtained from wind turbine rotor model tested in an open wind tunnel at different tip speed ratios and different blade angles using as reference to make a comparison when rotor tested with leading edge slots, firstly, turbine model tested without any slots at blade angle, β of 20°, 30°, 40°, and 50°, and secondly tested with adding leading edge slots at leading edge of main rotor blades with blade angle, β of 40°, which is the best angle using in this work. The torque and power performances are evaluated by the direct torque, rotational speed, and wind velocity measurements. Wind turbine model gave 25 % maximum power coefficient when tested without slots at blade angle, , $\beta = 40^\circ$, using of leading edge slots achieved a good increase in power coefficient when compared with the power coefficient of model tested without any slots. It was found that using of slots can improves vertical axis wind turbine performance, the maximum power coefficient of the turbine model with slots ($c_s/c_b = 0.26$) was 27.9 % at blade angle, $\beta = 40^\circ$, with an improvement of 11.6 % when compared with maximum power coefficient of reference case which tested without any slots, but when slot moved front main blade leading edge, case ($c_s/c_b = 0.26$, $L/c_s = 0.5$), the maximum power coefficient increased to 31 % with improvement of 24 %. When slot angle , α changes from 0° to 15°, the power coefficient improves again with an improvement of 28 % at slot angle of 10° for case of ($c_s/c_b = 0.26$, $L/c_s = 0.5$), when compared with reference case which tested without slots.

Key words: Wind Energy, Wind Turbines, and Power Augmentation.

1. INTRODUCTION

The power of the wind was first used to generate electricity nearly 100 years ago. Today, wind turbines play an increasingly important (through still small) role in meeting the electricity needs. They currently produce over three billions kilowatt-hours of electricity annually-enough to meet the needs of over one million people. The production of energy is one of the most far-reaching of human activities in terms of its environmental impacts.

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Wind energy and other renewable energy sources, such as solar and geothermal energy, offer the prospect of producing large amounts of electricity with greatly reduced effects on the environment. The development of wind by wind turbines has been increasing steadily; this directly pushes wind technology into a more competitive arena.

The flapping motion of a single wind turbine rotor had been studied by Thresher et al.,[1986] and equations describing the flapping motion had been developed. The analysis was constrained to allow only flapping motions for a cantilevered blade, and the equations of motion are linearized. The flapping motions were small and neither control system effects nor tower motion effects were significant.

Brown, et al., [2000] presented results for the time history of flap-wise force on rotor blades of horizontal axis wind turbines as the blades pass through the tower shadow region. Normal force deviations up to 50 % of the mean loading can occur when the blade passes through the near wake of a typical tower but considerably less when passing the tower upwind.

A detailed experimental study of the flow field over the downstream portion of an NACA 0015 airfoil have been completed over a range of incidence angles up to 10° by Kentfield and Clavelle [1993], the experimental results served to illustrate, particularly with respect to boundary layer velocity profiles, changes in the flow pattern due to the attachment, to the airfoil pressure surface, of a Gurney flap of depth 1.5 %. The experimental findings generally indicated that some prior hypotheses relating to Gurney flap, or divergent trailing edge, operation required modification. It was also shown that an airfoil section with a rounded, truncated, trailing edge, similar to trailing edges found in some wind turbine blades, appears to be capable of generating noise, due to vortex shedding, of considerably higher frequency than alternative forms of blunt trailing edge.

The Gurney flap, or divergent trailing edge, had been shown to be effective in improving the performance of many types of isolated subsonic airfoils, particularly at high lift coefficients (Kentfield, [1994]). Tests at a low Reynolds number carried out on a pitch-optimized wind-tunnel model-wind-turbine, the configuration of which was representative of some commercially available units, showed a very significant performance improvement due to the use of Gurney flaps. On the basis of a theoretical analysis it appeared that greater performance improvements could be expected from the application of Gurney flaps to more modern turbines of lower solidity than the Nordtank unit.

An experiment of lift enhancement of a two-dimensional airfoil with a small trailing edge flap was conducted by Nengsheng [2000] in a low-speed, closed-loop wind tunnel at Shantou University. NACA63-215 is selected as the tested airfoil and Reynolds number was $2.4x10^5$, based on airfoil chord. In experiments the angles of attack varied from 0° to 40° and heights of the flaps are 1 %, 1.5 %, 2 %, and 2.5 % of airfoil chord. The lift and drag coefficients were determined from the surface pressure distributions, which were measured for all tested conditions. All tested types of flaps, attached to the airfoil on the lower surface near the trailing edge, significantly increased the lift coefficient, with little or no change in drag coefficients. The best increment in performance is by the addition of Gurney flaps, for which the trailing edge angle is 90° to the airfoil chord. The addition of the Gurney flap produced a significant lift increase compared with the baseline configuration, and a large flap produced a larger increase as the flap heights were varied from 1 % to 2.5 % of the airfoil chord, the best height of Gurney flap is approximately 2 % of airfoil chord.

El Sibaie. et al. [1990] studied the effect of some design parameters, as blade chord length, blade length, blade setting angle, blade solidity, and blade profile on the performance of a horizontal axis wind turbine, by applying the blade element theory. They found that the maximum power coefficient was in the neighborhood of 0.49, while the corresponding experimental value obtained was about 0.37. Also Khalafallah et al, [1986] studied the effect of blade twist and blade chord variation with the radius. They showed that the non-constant chord-segmented blade rotors have a better performance and maximum power coefficient is only 10 % less than that of the fully twisted blades.

Cetin, et al. [2005] studied the optimum speed ratio of wind turbines, they found that the speed ratio is depending on the profile type used and the number of blades, and therefore this optimum value can take different values of profile type and number of blades.

Abd Elmotalip, et al. [2002] studied the effect of tip vane on power coefficient of four bladed horizontal axis wind turbine model, turbine model with tip vane gave an improvement in maximum power coefficient of 13.33 % when compared with model tested without tip vane. Abd Elmotalip, [2006] showed that use of two stages wind rotor achieved an improvement in power coefficient and rotor rotational speed. It was found from this study that using of two rotors for horizontal axis wind turbine is better than one rotor for all range of wind speed with an improvement of 49 % in maximum power coefficient.

Clifford, et al. [2000] presented the results of computational simulations and wind tunnel experiments on the effect of the disturbance field of the tower on the flow around a horizontal axis wind turbine rotor blade. The wind tunnel experiments used a 2 m diameter model of a three bladed rotor run in varying proximity to a model tower. The results of these computational simulations compared with the experimental measurements of force time histories taken on sections of the blade.

Dawod [2007] suggested a new method for increasing the performance of horizontal axis wind turbine by testing a wind turbine model with up-wind rotor and with up-wind and down-wind rotors together, the study achieved an improvement in power coefficient of wind turbine reached to 51 % due to use of down-wind rotor with up-wind rotor on the same shaft.

Mousa, et al. [2010] studied the effect of trailing edge flap on power coefficient of two and four bladed vertical axis wind turbine model. Turbine model with trailing edge flap gave an improvement in maximum power coefficient of 7.14 % for two-blade rotor and 12.7 % for four-blade rotor when compared with model tested without trailing edge flap. Also, Shehata and Abd Elmotalip [2010] presented wind tunnel experiments on the influence of frontal and rear short flaps on a horizontal axis wind turbine. This study showed that use of shorted frontal flaps achieved good improvement in maximum power coefficient when compared with reference case. It gave maximum power coefficient of 49.6 % with an improvement of 3.33 % for three-bladed rotor, and the model achieved an improvement of 2.5 % when tested with shorted rear flaps.

The mechanical power output of a simple rotor, given by $C_p(1/2)\rho\ AV^3$, depends on the wind speed V, the effective area A of the rotor, and the power coefficient C_p. The power coefficient for a simple wind rotor has its theoretical upper limit at 16/27 (0.593), better known as the Betz limit. Some designs of wind rotors have peak power coefficients close to 0.5. However, the peak power coefficient of common wind rotors is in the range of 0.2 to 0.4 [Sivasegaram, 1986].

This paper shows the effect of leading edge slots on torque and power coefficients of a vertical axis wind turbine by testing a small-scale wind turbine model with and without slots adding at suction side of main blade of turbine rotor model.

II. DESCRIPTION OF TEST RIG

In order to study the effect of adding leading edge slots on a vertical axis wind turbine performance, a turbine model with three bladed rotor tested firstly as reference case without any slots, and then the model tested with adding slots to leading edge of the main rotor blades, Fig.(1) shows a photograph of experimental test rig with tested three-bladed rotor model, which has a diameter of 300 mm, the blades are twisted, tapered, and equipped with Joukowski airfoil-sections, Fig.(2)

shows a detail of experimental test rig. The model has airfoils having the maximum thickness of 15 percent of the chord length. The blades were made from wood. Fig.(3-a) shows a detail of tested model with leading edge slots, Fig.(3-b) shows a detail of different configurations of main blade with slot. Turbine rotor blades are made from wood, and they manufactured with a profile obtained according to the following procedure.

$$\eta_1 = 2e.b(\,1+\cos\varphi\,)\sin\varphi + 2\gamma.b.\sin^2\varphi$$

$$\eta_2 = -\,2e.b(\,1+\cos\varphi\,)\sin\varphi + 2\gamma.b.\sin^2\varphi$$

$$\xi = 2b.\cos\varphi$$

where

$e = t_{max.}/1.3\ C$ & $b = 0.25\ C$ & φ = airfoil angle

$t_{max.} = 0.15\ C$ & C = blade cord & γ = camber line angle.

The main objective is to measure the wind velocity, turbine rotational speed, and shaft torque for different values of rotor blade angle, β, and for different values of down-wind rotor blade angle, β. The results presented here will deal with four different blade angles (20°, 30°, 40°, and 50°). Then turbine rotor model tested with frontal and rear short flaps to the effect of flaps on turbine performance.

III. MEASUREMENTS

Thermal anemometer is used in measuring of air flow velocity. This instrument is especially suited for flow measurements of low velocities (0.0 to 20.0 m/s). Air velocity and temperature can be measured simultaneously. With the thermal anemometer the measuring element (NTC-bead) is heated up to a constant temperature of + 100 °C by means of electronic control. Owing to the air flow the measuring element cools off, by this regulation the NTC-bead is energized until it has regained the constant temperature of + 100 °C. So the measurement of air flow is directly proportional to the power used in maintaining bead thermistor at 100 °C.

A simple force or torque gauge is used as a brake to measure the torque applied by each model, and by using weights hanged freely around a pulley which is mounted on the rotating shaft by adding weights gradually until the shaft is fully stopped, then torque could be measured. Also rotational speed was measured by means of light tachometer.

IV. POWER AND TORQUE COEFFICIENTS

The power coefficient C_p is a function of wind turbine rotor characteristics and the working tip speed ratio of the turbine, it can be expected in the following form.

$$C_p = P_R\,/\,(\,0.5\,\rho\,AV^3\,)$$

$$= T_R\,.\,\omega\,/\,(\,0.5\,\rho\,AV^3\,)$$

Improvement in power coefficient is defined as:

$$\square\ C_p = [C_{p(\text{with slot})} - C_{p(\text{without slot})}]\,/\,C_{p(\text{without slot})}$$

where P_R is the realizable power from a wind turbine, T_R is the measured torque, and ω is the angular velocity of the rotor model.

Also the torque coefficient C_t is given as.

$$C_t = T_R\,/\,(\,0.5\,\rho\,AV^2\,r_m\,)$$

where

$$r_m = (D/2)\ (\,1 + \lambda^2\,)^{0.5}\,/\,2$$

V. RESULTS

Figure (4) shows the relation between rotor rotational speed, N, and wind velocity, V, for three-bladed vertical axis wind turbine rotor model tested at blade angle of 20°, 30°, 40°, and 50° for three-bladed rotor. It is observed from this figure that test model rotor with blade angle of 40° achieved higher values of rotor rotational speed than cases of blade angle of 20°, 30°, and 50°. It is occurred 280 r.p.m.

at wind velocity of 8 m/s and increased to 640 r.p.m. at wind velocity of 18 m/s.

Fig. (5) shows the torque coefficient versus tip speed ratio for turbine model tested at blade angle of 20°, 30°, 40°, and 50° for three-bladed rotor. It is observed from this figure that test model rotor with blade angle of 40° achieved good values of torque coefficient when compared with cases of blade angle of 20°, 30°, and 50°. It is occurred a maximum value of torque coefficient equal to 11 % at tip speed ratio of 7.94, which is higher than all cases tested in this part of experiment as shown in the following table.

Table (1) Max. Torque Coff. Comparison

β	Tip Speed Ratio	Max.Torque Coeff.
20	5.1	10.2 %
30	7.6	7.3 %
40	7.94	11 %
50	9	10 %

Fig. (6) shows the relation between the power coefficient C_p and tip-speed ratio λ for three-bladed rotor of vertical axis wind turbine model tested at different blade angle β (20°, 30°, 40°, and 50°). From this figure, it can be seen that the power coefficient increased with increasing of blade angle from 20° to 40° and then decreasing with increasing in blade angle from 40° to 50°. The maximum power coefficient is 12.9 % at tip speed ratio of 5.1 at β =20°, but the model gave maximum power coefficient of 22.6 % at tip speed ratio of 8.5 for β = 30°. When blade angle increases from 30° to 40°, the maximum power coefficient increases to 25 % at tip speed ratio of 8.55 and at blade angle of 50° the maximum power coefficient is 24.3 % at tip speed ratio of 9.5. It is noticed from Figs. (5-6) that case of blade angle β = 40° gave higher values of torque coefficient and power coefficient than other cases of β = 20°, 30°, and 50°. Therefore, turbine model with three blades tested at blade angle equal to 40° achieved good values of power coefficient in the present work.

Wind turbine rotor model tested with addition of leading edge slots to improve the performance of a wind turbine. Turbine model tested with slots to study its effect on performance of a vertical axis wind turbine model tested in this experimental work. Four curves of power coefficient, C_p, against tip speed ratio, λ, are presented in Fig.(7) for rotor model with and without leading edge slots tested at blade angle, β = 40°. Four curves of power coefficient, C_p, against tip speed ratio, λ, are depicted in Fig.(7) for rotor model with different slot lengths (C_s/C_b = 30 %, 28 %, 26 %, and 24 %), tested at blade angle, β = 40°. The first curve is for case of (C_s/C_b = 30 %), (β = 40°), it shows that maximum power coefficient of 26.1 % occurred at tip speed ratio of 8.57, the second curve is for rotor model tested for case of slots (C_s/C_b = 28 %), which gave 27 % maximum power coefficient against tip speed ratio of 8.6. It is clear that case of (C_s/C_b = 28 %), achieved a higher value of power coefficient when compared with case of (C_s/C_b = 30 %), and case of (C_s/C_b = 26 %), achieved an improvement in maximum power when compared with case of (C_s/C_b = 28 %), it occurred maximum power coefficient of 29 % at tip speed ratio of 8.61 ,but case of (C_s/C_b = 24 %), gave little decrease in maximum power coefficient when compared with case of (C_s/C_b = 26 %). Therefore, case of (C_s/C_b = 26 %), achieved a better value of maximum power coefficient than all cases tested in this section of experimental test, with an improvement of 16 % when compared with reference case which tested without slots (β = 40°).

Turbine model tested with case of (C_s/C_b = 26 %), but with different positions of slot by moving it distance, L, frontal main blade leading edge with different cases of L/C_s = (0, 0.25, 0.5, and 0.75) as shown in Fig. (3) to study its effect on performance of a vertical axis wind turbine model tested in this experimental work. Fig.(8) shows the relation between rotor rotational speed, N, and wind velocity, V, for three-bladed vertical axis wind turbine rotor model tested at blade angle of 40°, with different positions of leading edge slots, for cases of (L/C_s = 0, 0.25, 0.5, and 0.75). It is observed from this figure that test model rotor with case of leading edge slot of (C_s/C_b = 26 %, and

L/Cs = 0.5), achieved higher values of rotor rotational speed than another cases of leading edge slot positions tested in this work. It is occurred 323 r.p.m. at wind velocity of 8 m/s and increased to 768 r.p.m. at wind velocity of 18 m/s.

When model tested with moving slots a distance, L, frontal main blades leading edge as shown in Fig.(3), four cases of ratio (L/C_s) are tested in this part of test to show the effect of slot position to the main blade of turbine rotor on a vertical axis wind turbine model. Four curves of torque coefficient, C_T, against tip speed ratio, λ, are presented in Fig.(9) for rotor model with ratio (L/C_s) of 0, 0.25, 0.50, and 0.75 tested at blade angle, $\beta = 40^\circ$. It is noticed that case of (C_s/C_b = 26 %, $L/C_s = 0.5$, $\beta = 40^\circ$), achieved higher value of maximum torque coefficient when compared with another cases, it gave 12.1 % maximum torque coefficient at tip speed ratio of 8.74 with an improvement of 12.04 % when compared with reference case. Four curves of power coefficient, C_p, against tip speed ratio, λ, are presented in Fig.(10) for rotor model with ratio (L/C_s) of 0, 0.25, 0.50, and 0.75 tested at blade angle, $\beta = 40^\circ$. The first curve is for case of (C_s/C_b = 26 %, $L/C_s = 0$, $\beta = 40^\circ$), which shows a maximum power coefficient of 29 %, the second curve is for case of (C_s/C_b = 26 %, $L/C_s = 0.25$, $\beta = 40^\circ$), it gave 29.3 % maximum power coefficient occurred at tip speed ratio of 8.64, but the third curve is for case of (C_s/C_b = 26 %, $L/C_s = 0.50$, $\beta = 40^\circ$), which achieved 31 % maximum power coefficient occurred at tip speed ratio of 8.74, and the fourth curve is for case of (C_s/C_b = 26 %, $L/C_s = 0.75$, $\beta = 40^\circ$), it gave 30 % maximum power coefficient occurred at tip speed ratio of 8.68. Therefore, case of (C_s/C_b = 26 %, $L/C_s = 0.5$), achieved a better value of maximum power coefficient than all cases tested in this section of experimental test, with an improvement of 24 % when compared with reference case which tested without slots ($\beta = 40^\circ$).

In this part of test, the experimental work deals with study of effect of changing in leading edge slot angle (α) from 0° to 15° for case of (C_s/C_b = 26 %), which achieved better improvement in maximum power coefficient. Four curves of power coefficient, C_p, against tip speed ratio, λ, are presented in Fig.(11) for different angles of leading edge slots ($\alpha = 0^\circ, 5^\circ, 10^\circ$, and 15°) cases, with blade angle of ($\beta = 40^\circ$). The first curve is for reference case in this part of test (C_s/C_b = 26 %, $\beta = 40^\circ$, $\alpha = 0^\circ$), which shows that maximum power coefficient of 31% occurred at tip speed ratio of 8.74, the second curve is for rotor with case of (C_s/C_b = 26 %, $\beta = 40^\circ$, $\alpha = 5^\circ$), which gave 31.2 % maximum power coefficient against tip speed ratio of 8.75. The third curve is for case of (C_s/C_b = 26 %, $\beta = 40^\circ$, $\alpha = 10^\circ$), this curve shows that maximum power coefficient of 32 % occurred at tip speed ratio of 8.9. Finally, forth curve shows that maximum power coefficient decreases to 31.5 % at tip speed of 8.8 for case of (C_s/C_b = 26 %, $\beta = 40^\circ$, $\alpha = 15^\circ$), It is clear that case of rotor with case of (C_s/C_b = 26 %. $\beta = 40^\circ$, $\alpha = 10^\circ$), achieved higher values of power coefficient when compared with another cases. Therefore, this case is the better configuration tested in this experimental work.

In final comparison, two curves of power coefficient, C_p, against tip speed ratio, λ, are presented in Fig.(12). The first curve is for reference case, without any slots tested at blade angle, $\beta = 40^\circ$, it shows that maximum power coefficient of 25 % occurred at tip speed ratio of 8.55, the second curve is for rotor with leading edge slots, case of (C_s/C_b = 26 %, $\beta = 40^\circ$, $\alpha = 10^\circ$), which gave 32 % maximum power coefficient against tip speed ratio of 8.9. The improvement in maximum power coefficient, □C_{pmax} in case of (C_s/C_b = 26 %, $\beta = 40^\circ$, $\alpha = 10^\circ$) is 28 % when compared with reference case tested without slots at blade angle of, $\beta = 40^\circ$. It is clear that slots at leading edge of main blades improves the performance of a vertical axis wind turbine model tested in this experimental work.

Fig.(13) shows a comparison between experimental results of recent research and experimental results of [Mousa, et al, 2010] irrespective of different tip speed ratio, λ, and power coefficient, C_p, values of both vertical axis wind turbine rotors. However, these two curves which represent vertical axis wind turbine rotors of

[Mousa, et al, 2010] and recent research show a different trend and intersect only at $\lambda = 8.5$ against a value of power coefficient equal to 28 %. The results obtained by [Mousa, et al, 2010] occurred a maximum power coefficient of 29 % when 4-bladed rotor tested with trailing edge flaps, but recent research results achieved a maximum power coefficient of 32 % when 3-bladed turbine rotor tested with leading edge slots. This comparison shows that using of leading edge slot is more effective than using of trailing edge flap, but both researches achieved improvements when compared with reference results obtained without flaps, and slots.

VI. CONCLUSION

In order to improve the performance of a vertical axis wind turbine, an experimental method was suggested in the present work. A small-scale model of wind turbine is tested without leading edge slots at the first and with slots connected at leading edge of main rotor blades. When turbine model tested without any slots, it achieved a maximum power coefficient of 25% at blade angle of 40° for three-bladed rotor model, blade angle of 40° is the best angle tested in this work. Therefore case of blade angle 40° is chosen for testing turbine model with leading edge slots connecting with main blades of test turbine model.

This study showed that use of leading edge slots achieved good improvement in maximum power coefficient when compared with reference case, it gave maximum power coefficient of 31% for case of (C_s/C_b = 26 %, L/C_s = 0.5), with an improvement of 24 % in power coefficient when compared with reference case for three-bladed rotor model, and the model achieved an improvement of 28 % when tested with leading edge slots for case of (C_s/C_b = 26 %, L/C_s = 0.5, $\beta = 40^\circ$, $\alpha = 10^\circ$). It was found from this experimental study that using of leading edge slots with the rotor main blades of a vertical axis wind turbine model can improve its performance.

NOMENCLATURE

A : Area swept by turbine.
C : Airfoil blade chord.
C_p : Power coefficient.
C_t : Torque coefficient.
D : Rotor tip diameter.
P_R : Measured power = $T_R \times \omega$.
r_m : Rotor mean radius.
T_R : Measured torque.
U_T: Rotor tip speed ($\omega . D/2$).
V : Upstream wind velocity.
α : Slot angle.
β : Turbine rotor blade angle.
γ : Blade camber line angle.
ρ : Air density.
ω : Angular velocity.
λ : Tip speed ratio (U_T/V).
φ : Aerofoil angle.
ξ,η: Coordinates in the Z-plane.

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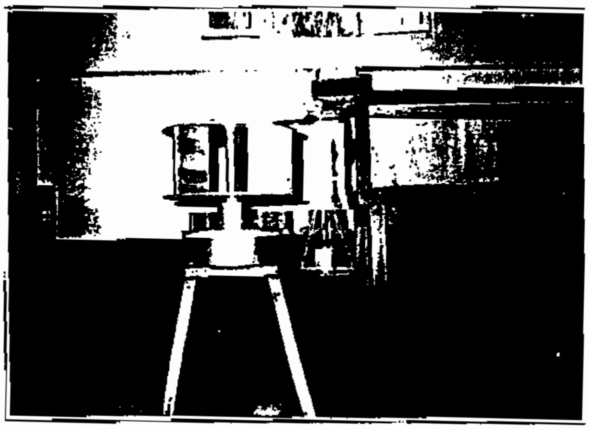

Fig. 1 A photograph of experimental test rig with tested three-bladed rotor model.

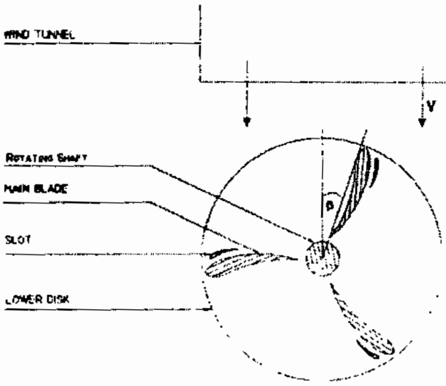

Fig. (3-a) A detail of cross section in tested model with leading edge slots

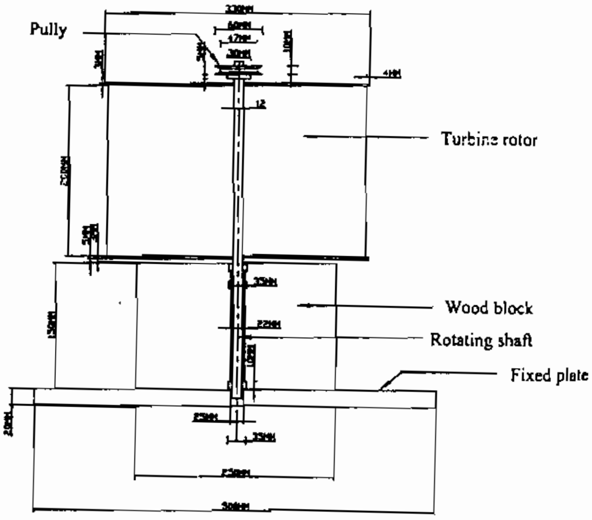

Fig. 2 A detail of experimental test rig.

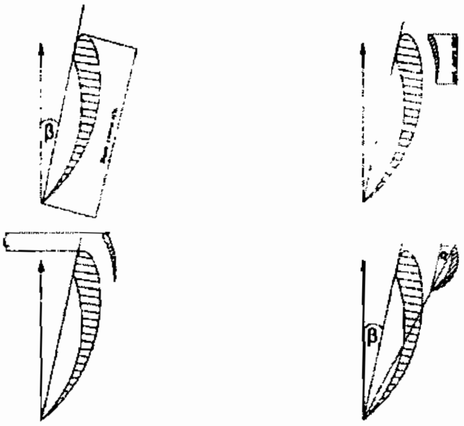

Fig. (3-b) A detail of different configurations of main blade with slot

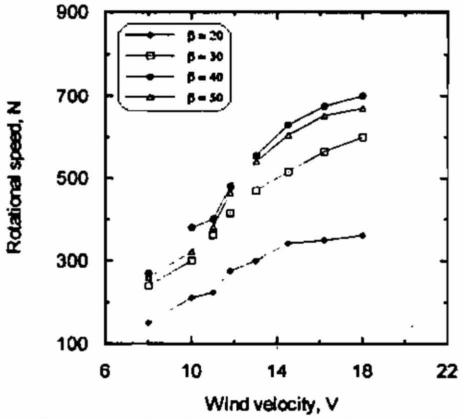

Fig. 4 Rotor rotational speed versus wind velocity for small VAWT model tested at different blade angles with 3-bladed rotor.

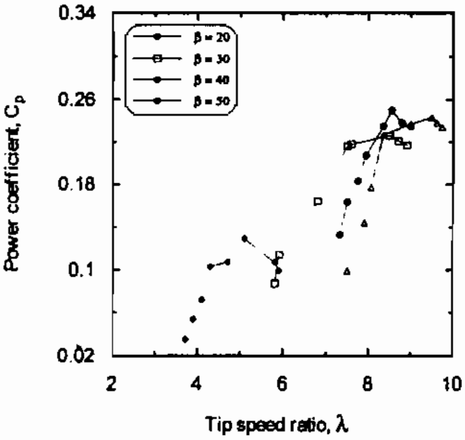

Fig. 6 Power coefficient versus tip speed ratio for small VAWT model tested at different blade angles with 3-bladed rotor.

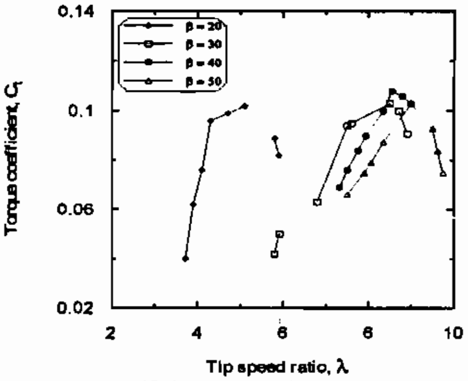

Fig. 5 Torque coefficient versus tip speed ratio for small VAWT model tested at different blade angles with 3-bladed rotor.

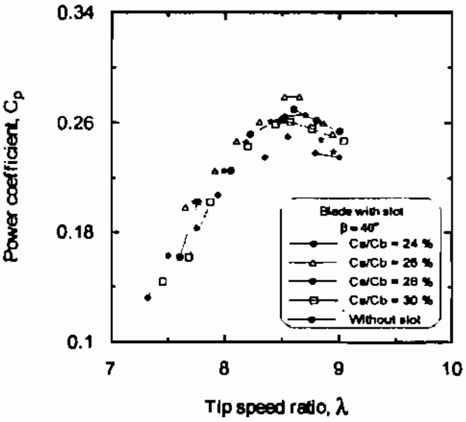

Fig. 7 Power coefficient versus tip speed ratio for small VAWT model tested at blade angle 40° for 3-bladed rotor with different lengths of leading edge slot.

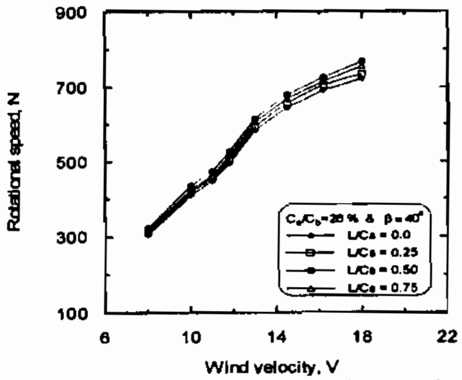

Fig. 8 Rotor rotational speed versus wind velocity for small VAWT model tested at blade angle 40° for 3-bladed rotor with different lengths of slot front leading edge of turbine blade.

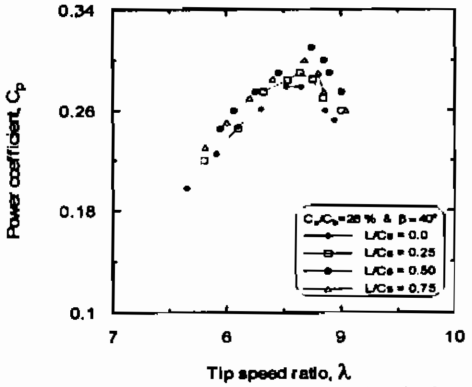

Fig. 10 Power coefficient versus tip speed ratio for small VAWT model tested at blade angle 40° for 3-bladed rotor with different lengths of slot front leading edge of turbine blade.

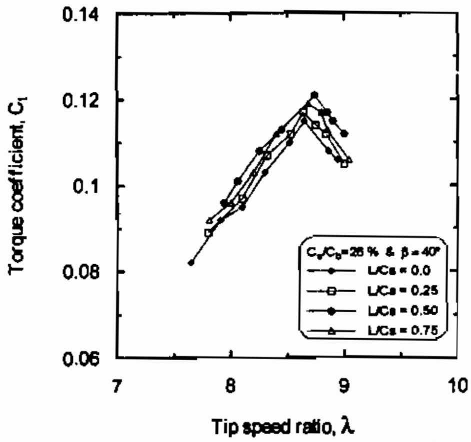

Fig. 9 Torque coefficient versus tip speed ratio for small VAWT model tested at blade angle 40° for 3-bladed rotor with different lengths of slot front leading edge of turbine blade.

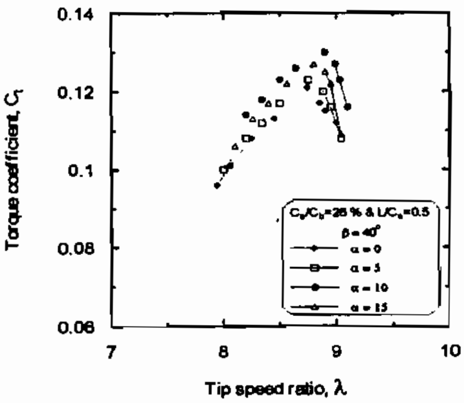

Fig. 11 Torque coefficient versus tip speed ratio for small VAWT model tested at blade angle 40° for 3-bladed rotor at different slot angles.

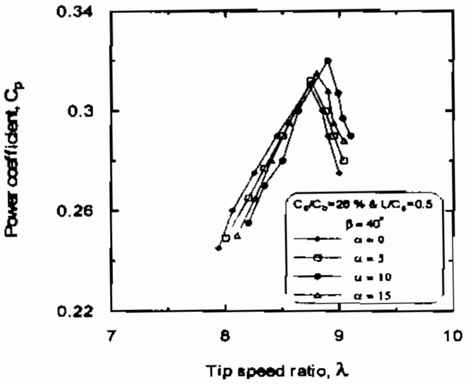

Fig. 12 Power coefficient versus tip speed ratio for small VAWT model tested at blade angle 40° for 3-bladed rotor at different slot angles.

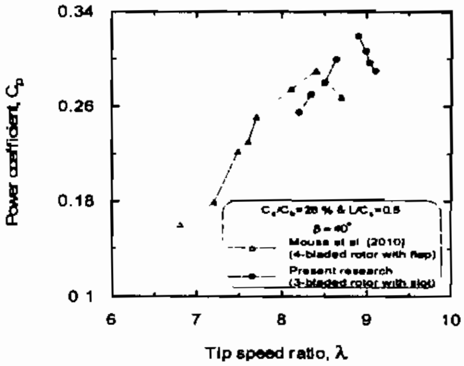

Fig. 13 Comparison between power coefficients of VAWT model tested with leading edge slots at blade angle of 40° and reference case for 3-bladed rotor at blade angle 40°.