ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

INFLUENCE OF TRAILING EDGE FLAPS ON HORIZONTAL AXIS WIND TURBINE PERFORMANCE

A. Abd Elmotalip **G. A. Z. Mousa**

Mechanical Power Engineering Department, Faculty of Engineering
Suez Canal University, Port-Fouaad, Port-Said, Egypt.
E-mail: gazmousa@hotmail.com Tel: 0 10 58 317 99

ABSTRACT

An experimental study has been carried out to investigate the performance of a horizontal axis wind turbine model. The test has be done without and with flaps at trailing edge of turbine rotor, one flap placed on pressure side of rotor blade and the other on its suction side. The turbine rotor consists of three blades with tip diameter of 260 mm. The study covers the influence of different blade angles with and without flaps on the wind turbine performance. Test data obtained from horizontal axis wind turbine rotor model tested in an open wind tunnel at different tip speed ratios and different blade angles is used as a reference to make a comparison when rotor tested with trailing edge flaps. The turbine torque and power are evaluated by the direct measurement of rotational speed, and wind velocity. It was found that blade angle β of 45° is the better angle giving maximum power coefficient of 22.6 % without flaps. Then turbine model is tested with flaps on pressure and suction sides of its rotor blade at trailing edge for β of 45°. Also, it is noticed that flaps on pressure and suction sides of turbine rotor blade at trailing edge can improve wind turbine performance. Also using flap of both pressure and suction sides increases power coefficient of turbine model. The maximum improvement achieved was a 13.27 % increase in power coefficient in case of model with pressure side flap for ($L/C_F = 0.75$), and a 10.62 % in case of model with suction side flap for ($L/C_F = 0.5$). Flaps of pressure and suction sides achieved an improvement of 19.47 % in turbine model power coefficient for pressure side flap with ($L/C_F = 0.75$), and suction side flap with ($L/C_F = 0.5$).

ويتناول البحث دراسه عمليه لدراسة الأداء لنموذج تربينة رياح ذات محور دوران أفقى. و قد تمت الدراسة بأجراء تجارب فى حالتى بدون و مع تركيب رفرفات على الحافة الخلفية لروتور التربينة. و قد وضعت رفرفة على جانب الضغط لريشة الروتوروالأخرى على الجانب الماص (السحب). يتألف ال [تتربين روتور] من ثلاثة نصال مع طرف قطر 260 mm . و الدراسة تغطى التأثيرات المختلفة لزوايا الريش على أداء التربينة فى وجود و عدم وجود رفرفات . والنموذج يختبر في تربينة نفق مفتوحة في مختلفة طرف عند نسب سرعة مختلفة و ايضا زوايا ريش(نصال) مختلفة بغرض ان تكون مرجع للمقارنة عندما اختبار الروتور مع رفرفات الحافية الخلفية للتربينة. و قد وجد أنه فى حالة استخدام زاوية الريشة 45° تعطى معامل أداء بقيمة % 22.6 فى حالة عدم وجود الرفرفات. وبوضع الرفرفات على كل من جانبى الضغط و السحب فقد تحسن الاداء عند زاوية 45° كما تحسن بزيادة معامل القدرة للتربينة. و قد حدثت أقصى تحسن بزيادة حوالى % 13.27 فى معامل القدرة فى جانب الضغط بينما كانت الزيادة % 10.62 فى جانب السحب. و قد بينت التجارب أنه فى وجود الرفرفات على كل من جانبى الضغط و السحب فقد تحسن معامل الاداء للقدرة بنسبة % 19.47

Keywords: Wind Energy, Wind Turbines, and Power Augmentation.

1. INTRODUCTION

Turbine power generation has intensified during the past ten years. 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 billion 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. 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.

Thresher et al.,[1986] presented the flapping motion of a single wind turbine rotor and equations describing the flapping motion were 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.

Cetin, et al. [2005] studied the optimum speed ratio of wind turbines. They found that the speed ratio is depends on both the profile type used and the number of blades. Furthermore, showed that the optimum value of the speed ratio depending on profile type and the used number of blades. They analyzed the parameters affecting the power factor of the used model and then the optimum speed ratios were determined for different types of blade profiles with several numbers of blades.

A detailed experimental study of the flow field over the downstream portion of an NACA 0015 airfoil has been completed over a range of incidence angles up to 10° by Kentfield and Clavelle [1993]. Their 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. This tendency is 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 by Kentfield (1994) to be effective in improving the performance of many types of isolated subsonic airfoils, particularly at high lift coefficients. Tests at a low Reynolds number carried out on a pitch-optimized wind-tunnel model-wind-turbine. The Model configuration was representative of some commercially available units. The model 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 , et.al.(2000) in a low-speed, closed-loop wind tunnel at Shantou University. NACA63-215 profile is selected as the tested airfoil and Reynolds number based on airfoil chord was 2.4×10^5. In their 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. These distributions 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 obtained by the addition of Gurney flaps. For these flaps, the trailing edge angle is 90° to the airfoil chord. The addition of the Gurney flap produced a significant lift increment compared with the baseline configuration. The large flap produced a larger increment 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 with the aid of blade element theory 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. 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 and El-Dandoush (1986) studied the effect of blade twist and blade chord variations 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. The results of multi-bladed rotor tests carried out by Abed (1985) achieved a maximum power coefficient around 22.7 % and a maximum torque coefficient around 31.5 %. The characteristics of the tested rotors are affected by the type of blade section and many parameters such as; solidity, geometric pitch angle and blade twist. This study showed that the cambered bladed rotors are better than flat bladed rotors and an increase in power and torque coefficients were achieved by twisting the blades.

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 (or 0.593). This limits is 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].

Yonezawa, et al. (2004) demonstrated that turbulent characteristics of wind flowing into horizontal axis wind turbine rotors bring complicated fluctuations of aerodynamic loads on the rotor blades. This fluctuation of load causes a variation of power output. They used a wind field simulation model constructed on the basis of a Fourier method for predicting of turbulence effects on the aerodynamic loads.

This paper shows the effect of trailing edge flaps on power and torque coefficient of horizontal axis wind turbine by testing a small-scale turbine rotor model with and without flaps on pressure and suction sides of rotor blades. The results of this experiment show good improvements in power and torque coefficients due to the exist of trailing edge flaps.

2. DESCRIPTION OF TEST RIG

In order to study the effect of trailing edge flaps on the horizontal axis wind turbine performance, turbine rotor tested firstly without any flaps. Secondary, turbine rotor with a flap blade suction side trailing edge flap has been tested. In the third step, the rotor with blade pressure side trailing edge flap has been tested. Finally in the fourth step, both suction side and pressure side trailing edge flaps are tested. The model has airfoils having the maximum thickness of 20 percent of the chord length. Figure (1) shows a photograph of tested rotor model with three blades, and trailing edge flaps. The model has a diameter of 260 mm and the blades are twisted, tapered and equipped with Joukowski airfoil-sections. The blades and flaps were made from wood.

In the present test program, a small model of HAWT is used to achieve improvements in power coefficient using flaps on suction side and pressure side of trailing edge of rotor blades. In this study, a set of experiments is carried out to establish the effect of trailing edge flaps on wind turbine performance. The test program involves a systematic variation of variables affecting the performance curve C_p versus λ, thus leading to an optimum combination of parameters. Present tests were carried out in subsonic wind tunnel. Figure (2) shows a photograph for the construction of tested model with wind tunnel. The tunnel has a cross section 300 mm x 300 mm. The tunnel can provide a wind speed in the range 1 m/s to 26 m/s.

The main objective is to measure the following wind velocity, turbine rotational speed, and shaft torque for different values of blade angle, β. The results presented here deal with five different blade angles. Figure (3) shows the details of main rotor blade and flaps.

3. MEASUREMENTS

Thermal anemometer is used here to measure the air flow velocity. This instrument is especially suited for flow measurements of low velocities (0.0 to 20.0 m/s). Air velocity and its 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 gauge is used as a brake to measure the torque applied by each model. This gauge utilizes 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.

4. 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.

$$C_p = P_R / (0.5 \rho A V^3)$$

$$C_p = T_R \, \omega / (0.5 \rho A V^3)$$

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

Also the torque coefficient C_t is given as.

$$C_t = T_R / (0.5 \rho A V^2 r_m)$$

where

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

5. EXPERIMENTAL RESULTS

Basically on model of wind turbine which was used in the test program. A smaller three bladed rotor model was primarily designed to study the effect of trailing edge flap on suction side of turbine rotor blade, the effect of trailing edge flap on pressure side of blade, and the effect of both together. A straight shaft supported the blades assembly in a pair of self-aligning bearings. In this study, the model was tested in a low speed, low turbulence wind tunnel with a working test section of dimensions 300 mm and 450 mm.

This study includes the effect of flap at trailing edge of turbine rotor blade when extended by distance (L) behind blade trailing edge with (L/C_f) equal to 0%, 25% , 50%, 75%, where C_f is the chord of flap, which placed on suction side of blade.

Figure (4) shows the torque coefficient, C_T, versus tip speed ratio, λ, for turbine model tested at blade angles of 30°, 35°, 40°, 45°, and 50°. It is observed from this figure that test model rotor with blade angle of 45° and 50° achieved good values of torque coefficient when compared with cases of blade angles of 30°, 35 and 40°. Case of blade angle of

β=45° showed maximum value of torque coefficient (12.6%) at tip speed ratio of 1.51. While changing the blade angle to 50° give maximum torque coefficient (12.7%) higher than that obtained for case of blade angle of 45°. It is a great importance to note that this angle i.e. β=50°, releases torque coefficient lower than that of case of (β =45°). Therefore, case of (β=45°) is better than that case of (β=50°).

Figure (5) shows the relation between the power coefficient, C_p, and tip-speed ratio, λ, for wind turbine model tested at different values of blade angle β of 30°, 35°, 40°, 45°, and 50°. From this figure, it can be seen that the power coefficient increases with increasing the blade angle from 30° to 45° and then decreases with increasing the blade angle to 50°. The maximum power coefficient is 13.2% at tip speed ratio of 0.96 at β=30°. But the model gave maximum power coefficient of 14.6% at tip speed ratio of 1.25 for β= 35°. When blade angle was increased to 40°, the maximum power coefficient of 16.3% occurred at tip speed ratio of 1.4. Also the torque coefficient increased by increasing in blade angle β. It can be concluded that from 30° to 45° and then decreases with increasing blade angle to 50°. The model gives 22.6% maximum power coefficient at tip speed ratio of 1.51 for blade angle of 45°, and maximum power coefficient of 18.1% at tip speed ratio of 0.784 for blade angle of 50°.

5.1 Trailing Edge's Suction Side Flap Results

Curves for power coefficient versus tip speed ratio are presented in Figure (6). These curves are for turbine model tested with and without trailing edge flap. The effect of trailing edge flap was investigated by testing model at different values of wind turbine speed. The figure shows that with installing trailing edge flap on suction side of rotor blade a significant power coefficient increment occurs comparing to the reference case (i.e. a blade without flap).

This study includes the effect of flap at trailing edge of turbine rotor blade when extended by distance (L) behind blade trailing edge with (L/C_f) equal to 0 %, 25% , 50%, and 75%, where C_f is the chord of flap, which placed on suction side of blade.

Figure (6) shows the relation between power coefficient, C_p, and tip speed ratio, λ , for rotor model with blade angle β=45° with and without trailing edge flap. The turbine model tested firstly without flap, and secondly with flap at turbine rotor blade trailing edge placed on its suction side with L/C_f= 0, 0.25, 0.50, 0.75. All curves are plotted for blade angle of 45°, which is the better angle used in the present study. When the model tested without flap with blade angle β=45°, the curve of power coefficient shows that the power coefficient increases to maximum value. The maximum value of C_p of 22.6% was noticed corresponds to a tip speed ratio of 1.51 and then decreases with increasing the tip speed ratio to value of 21% versus tip speed ratio of 1.62. When model tested with flap at its blade trailing edge with L/C_f=0, the maximum power coefficient increases to 23 % at tip speed ratio of 1.54 with an improvement of 1.77% when compared with reference case which is tested without flap at blade angle of β = 45°. When the extended part of flap appeared with L/C_f=0.25, the maximum value of power coefficient is increased to 23.5% corresponding to tip speed ratio of 1.55. This means an improvement in maximum power coefficient of 3.98 %. For case of L/C_f=0.5, the power coefficient is increased to its maximum value of 25% at tip speed ratio of 1.6. This corresponds to an improvement in C_f of 10.62% when compared with reference case (without flap). Finally, the model is tested with extended part of flap equal to 0.75. It is noticed from Figure (6) that maximum power coefficient decreases comparing to the case of L/C_f=0.5. The model gave 24.4% maximum power coefficient with an improvement of 7.96%. Then when flap extended by L/C_f=0.5 behind blade trailing edge on suction side, the turbine model achieved a higher power coefficient with blade angle of β=45° when compared with cases of L/C_f=0, 0.25, and 0.75 for suction side flap. It is noticed from this figure that using trailing edge flap on suction side of blade results in an increase of power coefficient.

5.2 Trailing Edge's Pressure Side Flap Results

Tests were repeated with flap on pressure side of model rotor blade to show the effect of extended flap on power coefficient of horizontal axis wind turbine. The flap extended by L/C_f=0, 0.25, 0.50, 0.75, and 1.0 on pressure side of blade trailing edge.

Power coefficient curves versus tip speed ratio are presented in Figure (7) for turbine model tested with and without trailing edge flap. The effect of trailing edge flap was investigated by testing model at different values of wind turbine speed. The figures show that with utilizing trailing edge flap on pressure side of rotor blade, a significant power coefficient increment occurs comparing to the reference case (i.e. a blade without flap).

Figure (7) shows the variation of power coefficient, C_p, against tip speed ratio, λ , for turbine model tested at blade angle of β=45° with different values of L/C_f, one curve for reference case (without flap), and the other curves with trailing edge flap on pressure side of blade. The turbine model tested firstly without flap, and secondly with flap at turbine rotor blade trailing edge placed on its pressure side with L/C_f= 0, 0.25, 0.50, 0.75, and 1. All curves are plotted for blade angle of 45°, which is the best angle used in the present study. When the model tested without flap with blade angle β=45°, the curve of power coefficient shows that the power coefficient increases with increasing the tip speed ratio until value of maximum power coefficient of 22.6% against tip speed ratio of 1.51, and then decreases with increasing in tip speed ratio to value of 21% versus tip speed ratio of 1.62. When model tested with flap at its blade trailing edge with L/C_f=0, the maximum power coefficient increases to 23.1% at tip speed ratio of 1.6 with an improvement of 2.2% comparing to the reference case (which is tested without flap at blade angle of β=45°). When the extended part of flap appeared with L/C_f=0.25, the maximum value of power coefficient increased to 24 % corresponding to tip speed ratio of 1.6, and occurred an improvement in maximum power coefficient of 6.2%. For case of L/C_f=0.5, the power coefficient increased to its maximum value of 25.2% at tip speed ratio of 1.63, achieving an improvement of 11.5% when compared with reference case (without flap). When extended part of flap increased to L/C_f=0.75, the maximum power coefficient of 25.7% occurred at tip speed ratio of 1.67 with an improvement of 13.27%. Finally, the model tested with extended part of flap equal to 1.0. It is noticed that from Figure (7), that maximum power coefficient decreases when compared with case of L/C_f=0.75, the model gave 23.5% maximum power coefficient for this case with an improvement of 3.97% comparing to the reference case. Then when flap extended by L/C_f=0.75 behind blade trailing edge on pressure side, the turbine model achieved the higher power coefficient with blade angle of β = 45° when compared with cases of L/C_f = 0, 0.25, 0.50, and 1.0 for pressure side flap.

It is clear that the turbine rotor with trailing edge flap gave good results comparing with the performance of turbine rotor tested without flap for all ranges of tip speed ratio used in this study.

5.3 Trailing Edge Flaps at Pressure and Suction Sides Results

Finally, an experimental test carried out on turbine rotor model with two flaps, one on blade pressure side and the other on blade suction side chosen with L/C_f=0.75 for pressure side flap and L/C_f=0.50 for suction side flap whose given higher improvements when each one tested individual. Figure (8) shows the variation of the power coefficient, C_p, versus tip speed ratio, λ, with and without trailing edge flap for blade angle of 45° for four cases of turbine rotor model. The first curve without flap used as a reference case. The second curve with flap on blade suction side with L/C_f=0.50. The third with flap on blade pressure side with L/C_f=0.75. The fourth with two flaps, one on blade suction side with L/C_f=0.50, and the other on blade pressure side with L/C_f=0.75.

It is noticed from this figure that using two flaps, one on suction side, and the other on pressure side increases the power coefficient for all values of tip speed ratio used in this study. This results in higher values of power coefficient comparing to the case of flap on both suction side and pressure side. Curve of two flaps achieved maximum power coefficient of 27% versus tip speed ratio of 1.7 with an improvement of 19.47% comparing to the reference case (i.e. blade without flap).

6. CONCLUSION

The aim of this study is to show how the performance of horizontal axis wind turbine can be improved. To achieve this study, an experimental method was suggested in the present work. A small-scale model of wind turbine is tested with and without trailing edge flaps on both suction side and pressure side of rotor blade.

This study showed that the use of trailing edge flap on both suction side and pressure side of turbine blade achieved an improvement in power coefficient. The case of blade angle β=45° gave maximum power coefficient around 22.6% when tested without flap. So, it has been taken as a reference case for the comparison between all cases tested in this work. When the turbine model tested with suction side flap in cases of L/C_f= 0, 0.25, 0.50, and 0.75, case of flap with L/C_f=0.50 gave higher value of power coefficient than others. This corresponds to an improvement of 10.62% comparing to the reference case (i.e. blade without flap).

Also, the present study showed that when turbine model tested with pressure side flap for cases of L/C_f=0, 0.25, 0.50, 0.75, and 1.0, a case of flap with L/C_f=0.75 gave higher value of power coefficient than others. This corresponds to an improvement of 13.27% comparing to the with reference case (i.e. blade without flap).

It can be concluded that the turbine model tested with both suction side flap (L/C_f=0.50) and pressure side flap (L/C_f=0.75) achieved a maximum power coefficient of 27% with an improvement of 19.47% comparing to the reference case (i.e. blade without flap) and the cases of flap on both suction side and pressure side. It means that the turbine model tested with both suction side flap (L/C_f=0.50) and pressure side flap (L/C_f=0.75) together is the best case concerning with the maximum power coefficient.

7. REFERENCES

[1] Abed, K., A., "Investigation of the Performance of Wind Turbines with Simple Blade Shapes," Thesis for the Degree of Master Science in Mechanical Power Engineering, Cairo University, 1985

[2] Brown, C. J., Graham, J. M. R., and Giannakidis, G., " Aerodynamic Interaction between a Wind Turbine Blade and the Tower: Computation and Experiment," European Congress on Computational Methods in Applied science and Engineering, ECCMNS 2000, Barcelona, 11-14 September, 2000.

[3] Cetin, N. S., Yurdusev, M. A., and Ata, R., " Assessment of Optimum Tip Speed Ratio of Wind Turbines," Mechanical Engineering Department, Izmir, Turkey, Mechanical and Computational Applications, Vol. 10, No. 1, 2005, pp. 147-154.

[4] El Sibaie, M., Gohar, M. I., Abd Elmessih, R., N., and Ghorap, A. A. E., "Investigation of the Effect of Some Design Parameters on the Performance of a Horizontal Axis Wind Turbine Model," The Second International Symposium on Renewable Energy Sources, Cairo-Egypt. Oct., 1990, pp 467-477.

[5] Kentfield, J. A. C., and Clavelle, E. J., " The Flow Physics of Gurney Flaps, Devices for Improving Turbine Blade Performance," Presented at the 16th annual Energy-Sources Technology Conference of the ASME. Houston, Texas, February. Wind Engineering, Vol. 17 No. 1, 1993, pp. 24-34.

[6] Kentfield, J. A. C., "Theoretical and Experimentally Obtained Performances of Gurney-Flap Equipped Wind Turbines." ASME Conference Wind Energy 1994', New Orleans January. Wind Engineering Vol. 18 No. 2., 1994, pp. 63-74.

[7] Khalafallah, M. G., and El-Dandoush, S. K., "Effect of Blade Twist on The Performance of a Propeller Wind Turbine." The First International Symposium on Renewable Energy Sources, Cairo-Egypt, March 1986.

[8] Nengsheng Bao, Haoming Ma, and Zhiquan Te, "Experimental Study of Wind Turbine Blade Power Augmentation Using Airfoil Flaps, including the Gurney Flap", Wind Engineering. Volume 24, No. 1,2000, pp. 25-34.

[9] Sivasegaram, S., "Power Augmentation in Wind Rotors," A Review. Wind Engineering, Vol. 10, No.3, 1986, pp 163-179.

[10] Yonezawa, N., Hasegawa,Y.,Imamura, H., and Murata, J.," Aerodynamic Loads on Horizontal Axis Wind Turbine Rotors Exerted by Turbulent Flow," 2nd International Energy Conversion Engineering Conference, August, Nagoya University, Nagoya, Japan., 2004

8. NOMENCLATURE

A	Area swept by turbine.
T_R	Measured torque.
C_f	Flap Chord.
r_m	Rotor mean radius.
C_p	Power coefficient.
V	Upstream wind velocity
C_t	Torque coefficient.
β	Blade angle.
D	Rotor tip diameter.
ρ	Air density.
L	Flap Extenion.
ω	Angular velocity.
P_R	Measured power = $T_R \times \omega$.
λ	Tip speed ratio

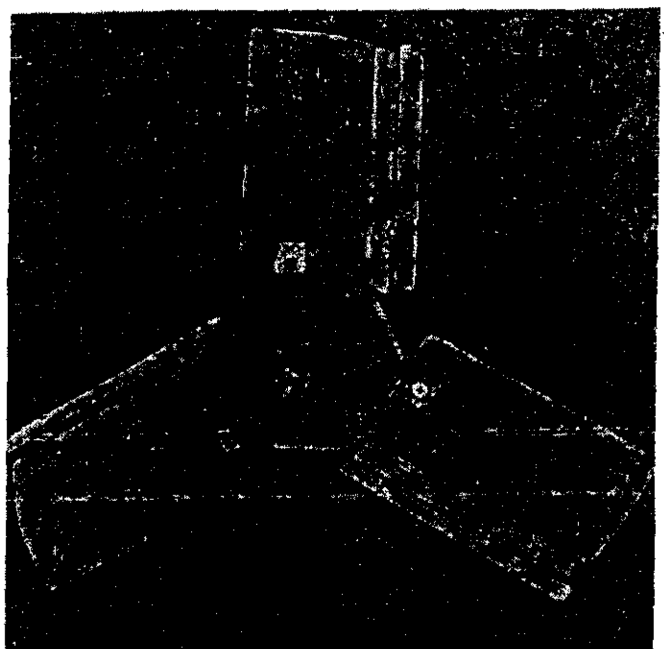


Fig. 1 Photograph of Turbine Rotor Model with Flaps

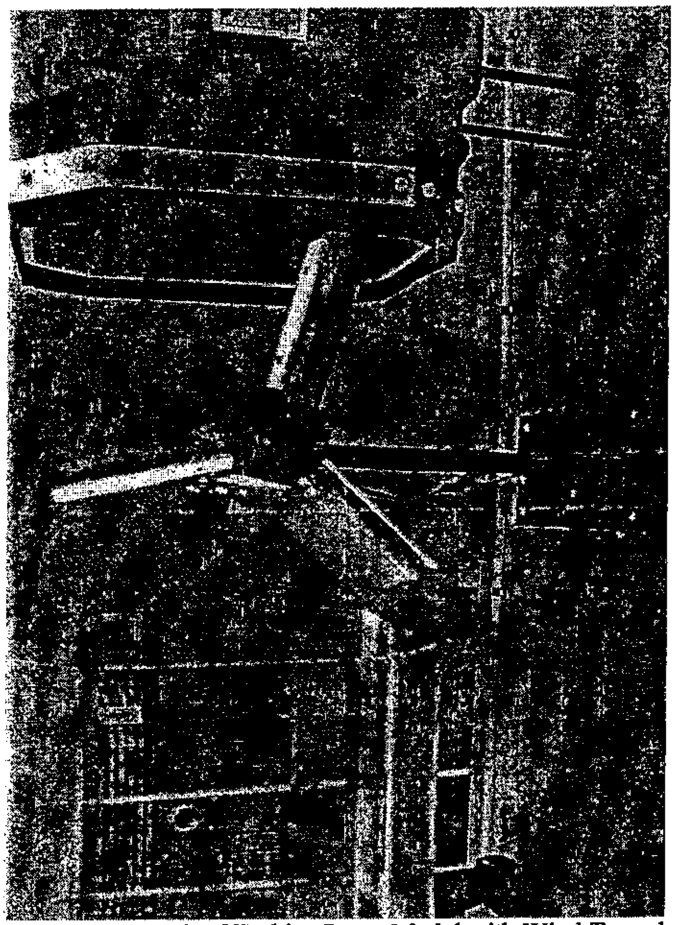
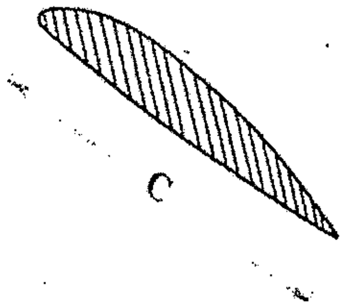
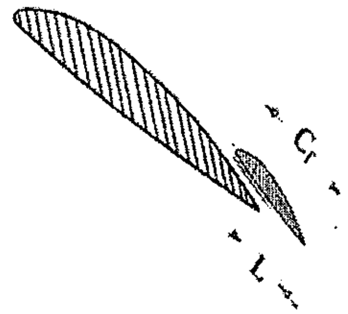


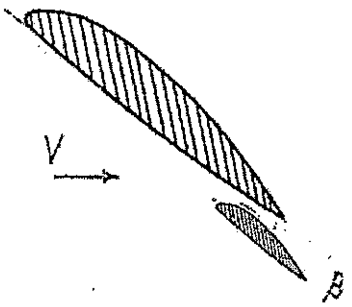
Fig. 2 Photograph of Turbine Rotor Model with Wind Tunnel



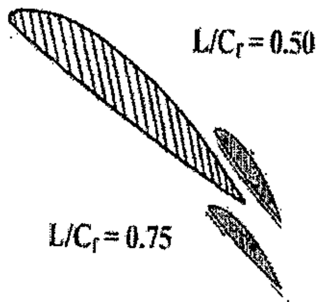
Airfoil Section of Rotor Blade



Airfoil Section of Rotor Blade with Suction Side Flap



Airfoil Section of Rotor Blade with Pressure Side Flap.



Airfoil Section of Rotor Blade with Suction Side Flap and Pressure Side Flap.

Fig.3 Main Blade with Flaps for tested Turbine Rotor Model.

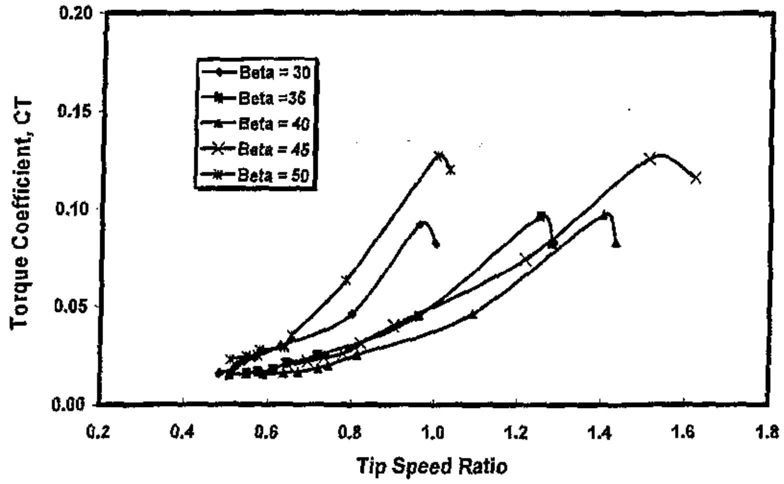


Fig. 4 Torque Coefficient, C_T, versus Tip Speed Ratio, λ, for Horizontal Axis Wind Turbine Model Tested at Blade Angle, β of 30°, 35°, 40°, 45°, 50°.

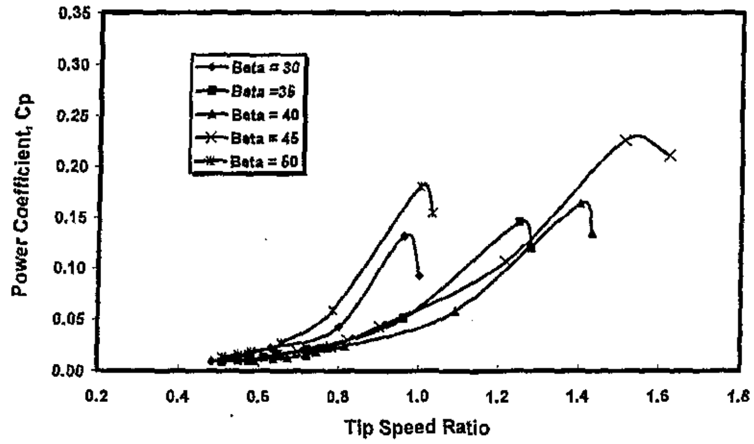


Fig. 5 Power Coefficient, C_p, versus Tip Speed Ratio, λ, for Horizontal Axis Wind Turbine Model Tested at Blade Angle, β of 30°, 35°, 40°, 45°, 50°.

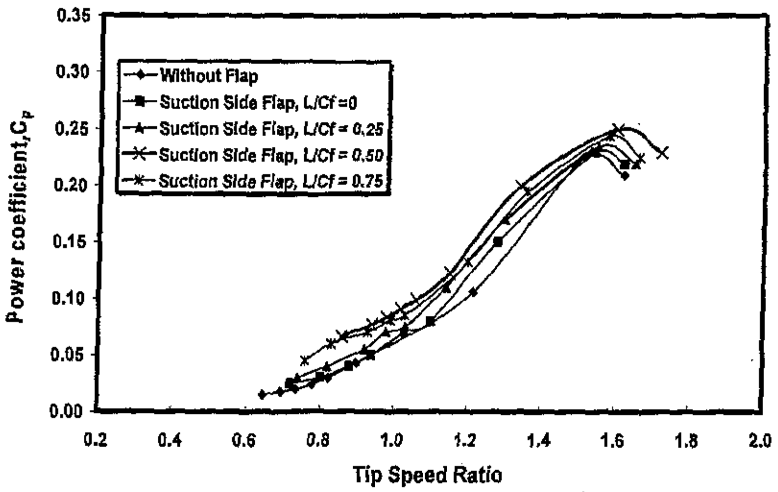


Fig. 6 Power Coefficient, C_p, versus Tip Speed Ratio, λ, for Horizontal Axis Wind Turbine Model Tested at Blade Angle, β of 45° with Suction Side Flap.

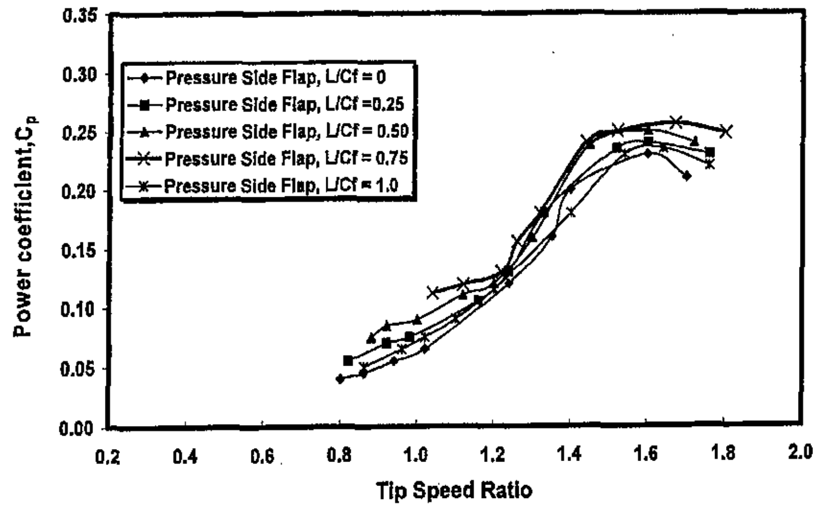


Fig. 7 Power Coefficient, C_p, versus Tip Speed Ratio, λ, for Horizontal Axis Wind Turbine Model Tested at Blade Angle, β of 45° with Pressure Side Flap .

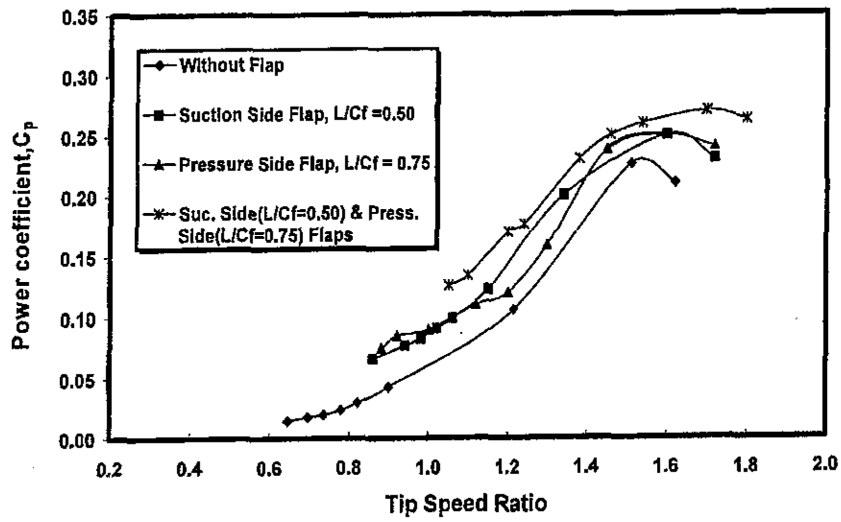


Fig. 8 Power Coefficient, C_p, versus Tip Speed Ratio, λ, for Horizontal Axis Wind Turbine Model Tested at Blade Angle, β of 45° with Pressure & Suction Sides Flaps .