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DESIGN AND AERODYNAMIC PERFORMANCE ANALYSIS OF 10 KW HORIZONTAL AXIS WIND TURBINE ROTOR BLADES

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ABSTRACT

Design and aerodynamic performance analysis of 10 KW horizontal axis wind turbine (HAWT) rotor blades are carried out. The blade geometry is calculated under consideration that the drag is equal to zero to obtain the optimal blade geometry. Drag effect is included in theoretical performance calculation. The theoretical performance results showed that the maximum power coefficient was 0.46 at tip speed ratio of 5.5. This value compared well with available research data. The experimental model had been built and tested using a low speed open circuit wind tunnel. The validation of the theoretical results has been conducted at single low-tip-speed ratio. The study between theoretical result and the experimentally measured performance, in the torque and power coefficient region for one value of tip speed ratio resulted in good agreement.

Keywords: *Wind power, wind turbine, rotor blades, power coefficient, torque coefficient, efficiency.*

1.0 INTRODUCTION

The wind is a free, clean, and inexhaustible energy source. It has served humankind well for many centuries by propelling ships and driving wind turbine to grind grain and to pump water. Interest in wind power lagged, however, when cheap and plentiful petroleum products became available. The high capital costs and uncertainty of wind placed wind power at an economic disadvantage. The days of cheap and plentiful petroleum are drawing to an end, and people began to realize that the world's oil supplies would not last forever and that remaining supplies should be conserved for the petrochemical industry.

The use of oil as a boiler fuel, for example, would have to be eliminated. Other energy sources besides oil and natural gas would have to be developed [1].

Studies showed that we can avoid the emission of 1 kg of CO_2 for every 1 kWh of electricity generated by wind energy and the operation of the wind turbine weighing 50 tonnes prevents the burning of 500 tonnes of coal every year [2]. In spite of higher costs than those for coal or nuclear power, wind power may become a major source of energy because of the basic non-economic problems of coal and nuclear power. The advanced technology and significant reduction in the cost will result an increase in productivity. It has been estimated that energy cost reductions of the order 20-25 % may be expected over the next 10 years [2].

Wind energy could be used to provide part of electricity demands for the areas where the wind speed is more than 5m/s, and for water pumping in the area of low wind speed [1-7]. Wind resources in some regions are not high but there are still excellent sites on the islands and mountains where the average wind speed is reasonable.

This paper aims to outline the analysis methods utilized in this study. The blade rotor designing steps will be presented, which includes configuration details and important designing parameters. Following this, theoretical and experimental performance parameters calculations will be performed. Finally, conclusion regarding the results will be discussed.

2.0 THEORETICAL ANALYSIS

2.1 Blade Geometry

2.1.1 Design input data

To design a 10 kW, three-blades fast turning wind turbine rotor, the rated wind speed (V_R) at the site was assumed to be 9 m/s. Three blades were used due to its better aerodynamics, structural stability and lower noise emission [5]. The maximum power coefficient, C_{Pmax} and design tip speed ratio, λ can be obtained from the fast turning machine C_p vs λ curve [7]. The maximum power coefficient was found to be 0.44 at design tip speed ratio of 5.5. The value of C_P will vary with the change of λ.

2.1.2 Rotor Diameter

The rotor diameter that is required depends upon the power output needed, the wind regime in which it must operate, and the tip speed ratio which is chosen. Allowance must be made for losses in the generating machine, the transmission system, and all other parts of the drive train. The rotor must therefore develop a good deal more power than the output of the generator.

Preliminary rotor sizing can be predicated using the elementary actuator disc momentum theory [5-7, 9] With drive train efficiency, η_d, and a generator efficiency, η_g, the actual power output, P_{out} would be

$$P_{out} = \frac{1}{2}\rho A C_p \eta_d \eta_g V_R^3 \qquad (1)$$

Where this expression solved the rotor swept area, A, as

$$A = \pi R^2 = 2P_{out}/\rho C p \eta_d \eta_g V_R^{\,3} \tag{2}$$

Assuming that the wind turbine used has a height of 10m, where the density, $\rho = 1.224 \frac{kg}{m^3}$ and the generator and train efficiency (η_g, η_d) are assumed to be equal to 0.9. The rotor radius (R) is calculated from Eq. (2) and found to be 4.376 m.

2.1.3 Selection of the Airfoil

A new airfoil MEL 002 was selected for the blade rotor. This airfoil was designed by Hikaru Matsumiya [8] for wind power application, since it has the following characteristics:

1) relatively smooth stall phenomena
2) higher performance in low R_{ec} region
3) has the suitable characteristics in the wide R_e range from 10^5 to 10^6.

2.1.4 Design steps

Only the equations for the rotor in optimal case $(C_d = 0)$ with the C_l vs α curves of the chosen airfoil [8] are required for the calculation of the blade geometry. Glauert presented a blade element analysis to find the ideal blade geometry based on neglecting the airfoil drag but includes wake rotation or swirl [5-7]. The equations used in the Glauert idea are the same as those of modified blade element theory but with the above assumptions. Therefore the geometry relations can be written as

$$\cot^2 \phi = \frac{(1-k)(1+h)}{(1+k)(h-1)} \tag{3}$$

$$c = \frac{8\pi r}{bc_l}\left(\frac{\sin^2 \phi}{\cos \phi}\right)\left(\frac{1-k}{1+k}\right) \tag{4}$$

$$\lambda = \lambda_d\left(\frac{r}{R}\right) \tag{5}$$

where c is the local chord, ϕ is the local setting angle, and the values of constants k and h can be obtained from equations in Section 2.2 except that drag coefficient (C_d) is assumed zero. For the calculation of the blade geometry, a certain number of stations must be taken along the blade and for each station, the chord, c and setting angle, ϕ have to be calculated. It is assumed that the blade starts at about 0.2R and a good first choice is to take nine stations. The blade design steps are as follows:

1. Start with r/R = 0.2
2. Calculate λ from Eq. (5)
3. Calculate k and h from Eqs. (13) and (12)
4. Calculate ϕ from Eq. (3)
5. Obtain α and c_l from MEL002 airfoil graph at $\left(\frac{C_l}{C_d}\right)_{\max}$
6. Calculate local β from the velocity diagram [5-7], where $\beta = \phi - \alpha$
7. Calculate local chord (c) from Eq. (4)
8. Select another value of r/R and work again from step 2 to 8 (r/R = 0.2 to 1.0).

All the calculated results are presented in Table 1. The first column is for the calculated theoretical value. The second column is for the values obtained after linearization of the chord. If the chord changes, there will be a change in lift coefficient and therefore in α and β. Using linearized chords, these parameters have been calculated again and placed in the right part of the column. The new lift coefficient C_l is calculated from Eq. (4). The third column is for the values obtained after linearization of the twist angle (β). Linearization of the twist is specially required for the blades made out of curved sheets, because great stresses are introduced if a curved sheet is non-linearly twisted [9].

2.2 Theoretical Performance

A frequently used and accurate method for performance calculation for wind turbine rotors is to assume that the flow through the rotor occurs in non-interacting circular streamtubes. This method, when used with the induced velocities, has been called by a variety of names, including modified blade element theory, blade element theory, vortex theory and strip theory. In this method, it is assumed that the locally flow at radial station is 2-D [5-7]. The equations that were used are:

$$C_F = 2\int_0^1 \left(1 + k^2\right)\left(\frac{r}{R}\right) d\left(\frac{r}{R}\right) \tag{6}$$

$$C_Q = 2\int_0^1 E \cdot \left(\frac{r}{R}\right)^2 \left(1 + k^2\right) Cot\phi \cdot d\left(\frac{r}{R}\right) \tag{7}$$

$$C_P = \lambda^2\left(1 + k^2\right)\left(1 - h\right) \tag{8}$$

$$\eta = \frac{C_P}{C_F} \tag{9}$$

where

$$E = \frac{cc_l b \cos(\phi - \varepsilon)}{4\pi r \cos\varepsilon - \sin 2\varepsilon} \tag{10}$$

$$\varepsilon = \frac{C_d}{C_l} \tag{11}$$

$$h = \frac{1+E}{1-E} \tag{12}$$

$$k = \frac{1-G}{1+G} \tag{13}$$

$$G = \frac{cc_l b \cos(\phi - \varepsilon)}{8\pi r \cos\varepsilon - \sin^2 \varepsilon} \tag{14}$$

$$\lambda = \left(\frac{R}{r}\right)\left(\frac{1+k}{1+h}\right)\cot\phi \tag{15}$$

The coefficients of performance (power, torque, force coefficients and efficiency, η), are not a constant. They varies with the wind speed, the rotation speed of the turbine, turbine blade parameters such as angle of attack, rotor diameter and pitch angle. The rotor geometry has already been determined earlier in Table 1. One often wants to know what kind of C_Q vs. λ, C_P vs. λ and η vs. λ curves that can be expected from this rotor. The calculation steps using the above equations are as follow:

1. Start with $\frac{r}{R} = 0.2$
2. Assume that the value of ϕ is positive value, starting with a small value.
3. Obtain the value of β from Table 1.
4. Calculate the value of α ($\alpha = \phi - \beta$)
5. At know α, the values of C_l and C_d to be obtained from the airfoil curves [8].
6. Calculate h, k and E using Eqs. (10), (12) and (13).
7. Calculate λ from Eq. (15).
8. Repeat steps 2 to 7 for different ϕ value.

9. Take other value of $\frac{r}{R}$, and repeat steps 2 to 8.

A Fortran program based on the above steps had been written and used along with graphical integration method to obtain the performance parameters, which are presented in Figure 1 to Figure 4.

Figure 1 showed that the maximum power coefficient (C_p) is found to be 0.46 at design tip speed ratio, $\lambda_d = 5.5$. Figure 2 showed that the maximum torque coefficient, C_Q to be equal 0.09 at λ of 4.8.

2.3 Rotor in Yaw

The rotor performance parameters as obtained in the above section are only valid for the rotor perpendicular to the wind. If the rotor yaws due to the fluctuation of wind direction or due to the safety system turning the rotor out of the wind, the rotor performances change. To predict how they change as a function of the yaw angle, the effective component of the wind must be determined. Using the formula from the Section 2.2, the performance parameters can be calculated using the following equations

$$\begin{aligned} \lambda(\delta) &= \lambda \cos \delta \\ C_Q(\delta) &= C_Q \cos^2 \delta \\ C_P(\delta) &= C_P \cos^3 \delta \\ C_F(\delta) &= C_F \cos^2 \delta \\ \eta(\delta) &= C_P(\delta) / C_F(\delta) \end{aligned}$$

The results in Figure 1 showed the relationship between yaw angle and maximum power coefficient, C_P. At yaw angle of 15°, the value of C_P dropped from 0.46 to 0.41 and at 30° angle, C_P dropped from 0.46 to 0.295.

3.0 EXPERIMENTAL WORK

3.1 The Rotor Model

The rotor model scale ratio (S.R) depends on the wind tunnel test section, which was used for the test. Scale of 1:12 was chosen to suit the Mechanical laboratory wind tunnel at Universiti Putra Malaysia (UPM). The model rotor radius is calculated and found to be 37.5 cm, and all the calculated results which are needed to build the model were obtained.

The design of a model rotor presents some difficulties not encountered with the usual wind-tunnel model of an airplane. To begin with, the hub and hinge design and construction can usually be worked out in a satisfactory manner, but some difficulties arise with the rotor blade representation. For most model sizes the built-up blade is not practical, because both of the small size of the skin and twist angle, and also because of the exaggerated effect of the skin wrinkles due to the scale of the model [10].

Wood blade works well and the metal leading edge is convenient to use as a tie-in to the metal hub [10]. However, to avoid breaking the model during the experiment, a metal material aluminium was used. Figure 5.a shows the experimental model.

3.2 Similarity Parameters

According to the similitude theory normally introduced in fluid mechanics [11], all model tests must be conducted under geometric, kinematic, and dynamic similarities [10]. Geometrical similarity requires that the shape of the model must be the same as that of the prototype. Accordingly during the building of the model, great attempts were made to ensure that the model would be similar to the prototype (Figure 5).

Kinematic similarity means that the streamline pattern must be similar. According to this condition the Reynolds number for the model must be similar to the prototype. To achieve this condition during the experiment, the range of 10^5 – 10^6 for $R_{e,}$ natural R_e range, was used. Dynamic similarity means the pressure distribution and the forces generated by the wind must be similar. Reference [12] showed that the pressure coefficient can be defined by the following relation, $C_p^* = \psi(R_e, M_a)$, where ψ is an arbitrary function.

The above relation shows that the pressure coefficient at any location on a stationary structure is a function of R_e and M_a. However, for a Mach number less than approximately one-third (i.e. for incompressible flow), the effect of Mach number is negligible, and equation reduces to $C_p^* = Const.$

3.3 Experimental Equipment

Experiments were carried out in an open wind tunnel at the Mechanical Laboratory, UPM. The wind turbine model, which was used for the experiment has a diameter of 75 cm and a maximum chord of 6.5 cm as shown in Figure 5.b.

Digital phase shifting stroboscope was used to measure rotor rotation in revolution per minute (rpm) and weight was placed at the end of the rotor shaft to measure torque.

The measurements on the blades were performed for the following parameter values :

1) Wind tunnel speed of 20 m/s
2) Wind tunnel Reynolds number of 10^5
3) Three yaw angles are used (0°, 15° and 30°)

4.0 RESULTS AND DISCUSSION

The Horizontal Axis Wind Turbine (HAWT) was investigated theoretically and experimentally. The rotor has a radius, R of 4.376 m and was linearly twisted. The airfoil MEL002 type was used.

Blade Geometry: The result presented in Table 1 showed that the rotor have a maximum chord of 0.87 m at *r/R* of 0.2 and minimum chord of 0.26 m at the tip with a maximum twist of 19.38°.

Torque Coefficient (C_Q): The theoretical performance curve in Figure 2 showed that the maximum C_Q of 0.09 was obtained at λ of 4.8. The experimental data showed that the torque coefficient of 0.0484 at λ of 2.3142 for the rotor.

Power Coefficient (C_P): The theoretical performance curve in Figure 1 showed that the maximum C_P of 0.46 was obtained at λ of 5.5. The experimental data showed that the power coefficient of 0.1121 at λ of 2.3142 for the rotor.

Efficiency: Figure 4 showed that the maximum theoretical efficiency for the rotor was 0.84 at λ of 1. It is clear from this result, that as the wind speed increases the efficiency decreases. This is because the energy from wind is proportional with the wind speed. Therefore, the ratio of energy extracted from the wind to the available energy will decrease, which leads to decreasing of the efficiency.

Effect of Yawing Angle (δ): The theoretical and experimental results showed that the power and torque coefficients are affected by the yawing of the rotor (Figure 1 and Figure 2). The theory showed C_p dropped from 0.46 to 0.41 at yaw angle of 15° and to 0.295 at yaw angle of 30°. The maximum C_Q also dropped from 0.09 to 0.084 at yaw angle of 15° and to 0.068 at yaw angle of 30°. A good agreement was achieved between the theory and experiment at yaw angle of 0°, 15° and 30° for single low tip speed ratio (λ) value.

Comparison Study: The comparison between the maximum power coefficient of the present rotor with other rotors designed by other researcher in this field is showed in Table 2. Those compared data showed that the maximum power coefficient of the present rotor is high. The experimental results for single low value of tip speed ratio as shown in Figure 1 to Figure 4 showed an agreement with the theory for power and torque coefficients.

R.P.M: The experiment showed that the rotor rotated at rpm of 101 at wind speed of 20 m/s.

5.0 CONCLUSION

The blade element theory results showed that MEL002 airfoil had good aerodynamic performance. Therefore, a good performance can be achieved by selecting suitable airfoil for wind turbine application to design the rotor. The maximum theoretical power coefficient of 0.46 was achieved.

The experimental results of the power and torque coefficients for single low tip speed ratio value exhibited discrepancies with predicted figures. These, however, fall sufficiently close to those obtained from the blade element theory.

NOMENCLATURE

A	Rotor area
b	Number of blades
C_F	Thrust coefficient
C_P	Power coefficient
C_Q	Torque coefficient
C	Chord
C_l	Lift coefficient
C_d	Drag coefficient
h	Rotational interference factor
M_a	Mach number
k	Axial interference factor
P	Power
R	Rotor radius
r	Local blade radius
Re_c	Reynolds number based on chord
rpm	Revolution per minute
V_R	Rated wind speed ($V_R \approx 1.4 - 1.6$ average wind speed)

Greeks

α	Angle of attack
β	Twist angle
ϕ	Pitch angle
ε	Drag to lift ratio
δ	Yaw angle
λ	Tip speed ratio
λ_d	Design tip speed ratio
ρ	Density
η	Efficiency

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Table 1 Blade Geometry Calculation Results

r/R	R (m)	λ	φ (deg.)	α (deg.)		C_l		C (m)		β (deg.)			C_d	
				T	L	T	L	T	L	L	T	LL	T	L
0.2	0.8752	1.10	28.182	4	5.8	1.0	1.1003	0.8692	0.79	24.182	22.412	19.30	0.017	0.032
0.3	1.3128	1.65	20.812	4	5.2	1.0	1.0252	0.7176	0.70	16.812	15.622	16.60	0.017	0.032
0.4	1.7504	2.20	16.296	4	4.0	1.0	0.9351	0.5891	0.63	12.296	12.258	13.90	0.017	0.032
0.5	2.1880	2.75	13.322	4	3.5	1.0	0.8808	0.4933	0.56	9.3221	9.862	11.00	0.017	0.032
0.6	2.6256	3.30	11.239	4	3.6	1.0	0.8788	0.4218	0.48	7.2389	7.639	8.60	0.017	0.032
0.7	3.0632	3.85	9.7069	4	4.6	1.0	0.8961	0.3674	0.41	5.7069	5.087	5.90	0.017	0.032
0.8	3.5008	4.40	8.5362	4	4.8	1.0	0.9556	0.3249	0.34	4.5362	3.736	3.00	0.017	0.032
0.9	3.9384	4.95	7.6141	4	5.8	1.0	1.1189	0.2909	0.26	3.6141	1.844	0.50	0.017	0.032
1.0	4.3760	5.50	6.8699	4	7.2	1.0	1.3853	0.2632	0.19	2.8699	-0.360	-1.40	0.017	0.032

T	Theoretical Value
L	1st Linearized Value
LL	2nd Linearized Value

Table 2 Comparison between rotors Cp for a number of wind turbines with the present rotor

Rotor Types	**Diameter (m)**	**No. of Blades**	**Maximum Cp**	**T.S.R (λ)**	**Reference**
Ideal Rotor	---------	-----	0.593	15	5-7
Typical Rotor	NA	2	0.510	6.5	5-7
Cavendish	5.0	2	0.395	10.5	11
ECN Petten	25.0	2	0.405	8.0	11
NASA Model-OA	38.0	2	0.405	11.0	11
A/F GO- 623	10.36	3	0.420	6.0	12
Present Rotor	8.75	3	0.46	5.5	----

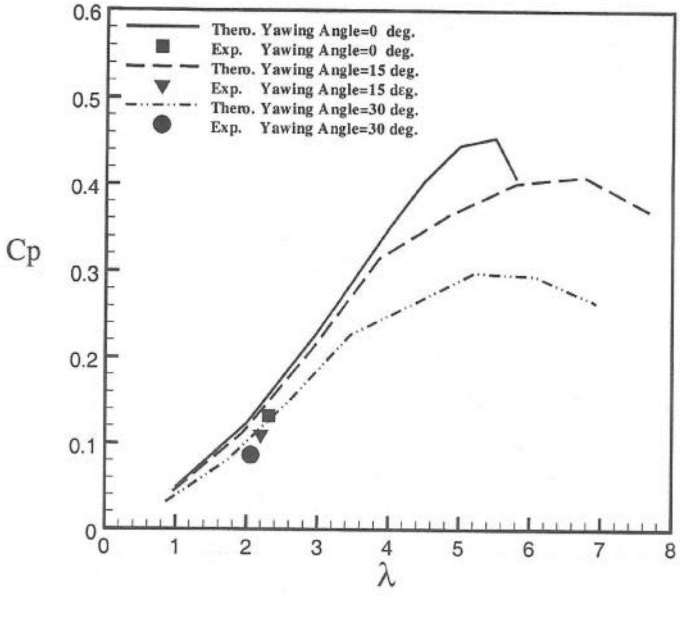

Figure 1 Power Coefficient (Cp) versus Tip Speed Ratio (λ)

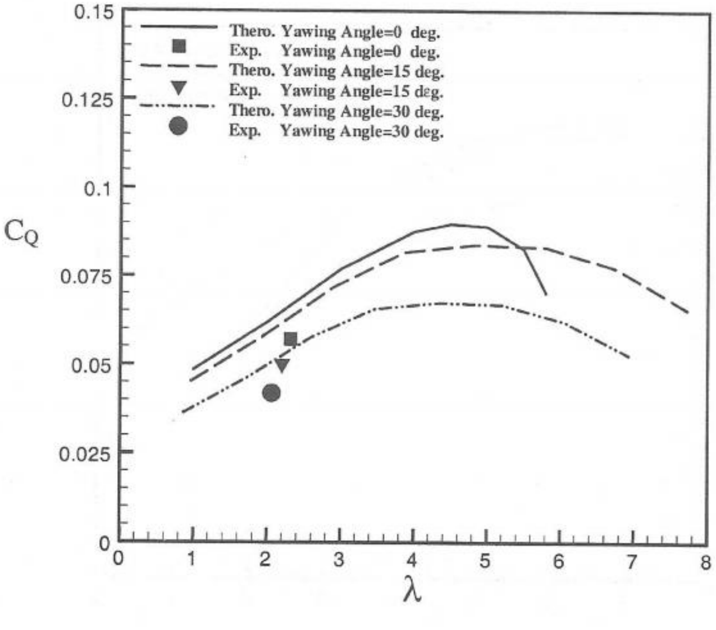

Figure 2 Torque Coefficient (C_Q) versus Tip Speed Ratio (λ)

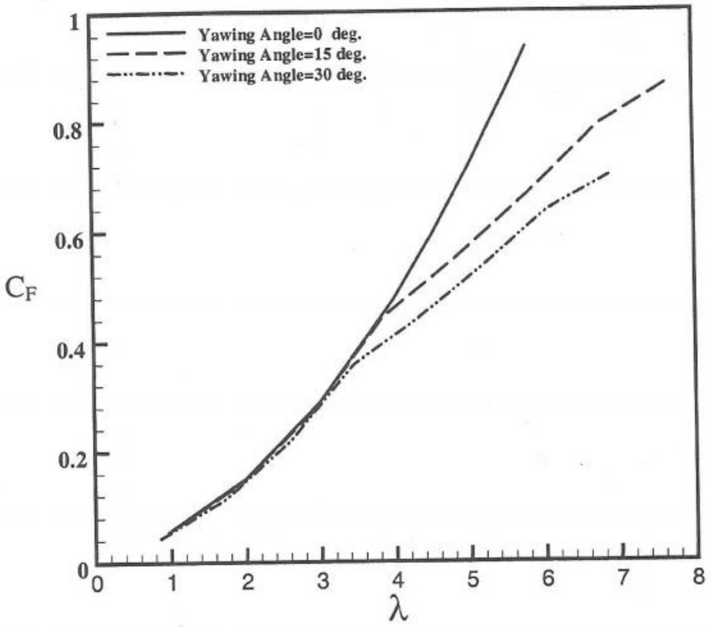

Figure 3 Force Coefficient (C_F) versus Tip Speed Ratio (λ)

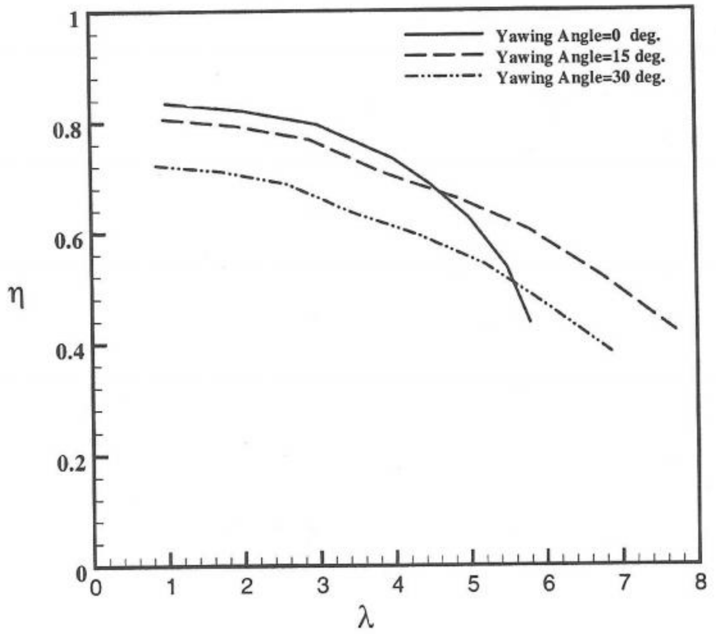

Figure 4 Efficiency (η) versus Tip Speed Ratio (λ)

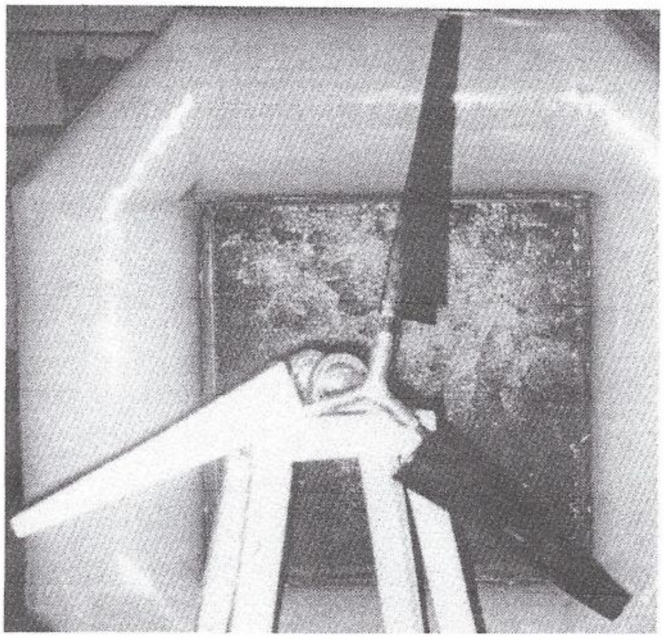

Figure 5.a Experimental model front of the wind tunnel nozzle

Figure 5.b Experimental model and digital stroboscope