A Theoretical Investigation Of The Design And Performance Of A Horizontal Axis Wind Turbine At Various Wind Conditions Of Bangladesh.

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Abstract : The objective of this study is to design a suitable wind turbine by considering average wind velocity of different zones of Bangladesh. The rotor configuration for twist and chord is determined by applying momentum theory and blade element theory assuming no drag no tilting or no coning.

In present analysis three types of blade shapes have been considered: optimum chord optimum twist, linear chord linear twist, linear chord zero twist. Considering aerodynamic performances, it has been observed that a linear chord linear twist is comparable to the optimum designed blade while offering a considerable reduction in manufacturing time and cost.

The effect of coning angle, tilt angle and several wind conditions e.g. wind gradient, wind shift and tower shadow are also discussed.

Keywords : *Horizontal axis wind turbine, Wind shear, Tower shadow.*

INTRODUCTION

Modified Blade element theory or Strip theory which is used for the present analysis is the most frequently used theory for the design and performance analysis of a horizontal axis wind turbine. This section discusses the design of a horizontal axis wind turbine in which lift forces on airfoils are the driving forces. According to this theory , a rotor can be designed which produces an optimum power coefficient to choose the lift and drag ratio of the profile considered and to keep it constant along the blade span. A second condition is that both a strongly varying blade twist are desired. This leads to a very complicated rotor blade configuration which can be expensive to manufacture and may not have structural integrity . In this paper, it is shown that it is possible to approach very closely the optimum blade configuration by taking a linearly tapered and linearly twist blade. For the lower design tip speed ratios a larger number of blades are chosen. This is because, the influence of B on Cp is larger at lower tip speed ratio. However, for the higher λ_d smaller number of blades are chosen. Because larger number of blades for a high λ_d will lead to very small and thin blades which results in manufacturing problems. Type of load used also limits the choice of λ_d. If it is a piston pump or some other slow running load , in most cases, it will require a high starting torque and λ_d should be chosen low. If the load is running fast like a generator or a centrifugal pump, then a high λ_d should be selected. The guide lines for the choice of λ_d and B [1] is given in Table 1. Throughout this study NACA 4418 airfoil section has been used for the blade section of the windmill.

Table 1:

Design Tip Speed Ratio (λ_d)	Number of Blades (B)
1	6-20
2	4-12
3	3-6
4	2-4
5-8	2-3
8-15	1-2

In Bangladesh , windmill may be extensively used along the coastal areas and as well as the hilly areas of Chittagong, Chitagong Hill Tracts, Sylhet, Mymensingh and Comilla. Winds are available mainly during the monsoons and around one to two month before and after the monsoons. In Bangladesh the peak winds for ,most of the stations are available during the hot and dry months March, April and May. Windmills, during this period , may be used for pumping water for irrigation provided the water is being previously stored in reservoir. The wind energy distribution during the year is such that about 55% is available during the time when the need for water pumping is low and about 25% is available in the seasons when the need for water pumping at its peak. Six stations from all over Bangladesh have been analyzed the availability of wind velocity. The wind velocity is measured two meter above the ground. It is shown in Table 2 [2].

Table 2 :

Sl. No.	Stations	Potentials month for power generation by windmill	Average wind speed (m/s)
1.	Chittagong	March to September	4
2.	Dhaka	March to October	3.2
3.	Khepupara	February to September	3.5
4.	Comilla	March to September	2.8
5.	Teknaf	June to September	2.3
6.	Jessore	April to September	2.1

CALCULATION SCHEME

The calculation scheme for the present study is as follows:

a) The choice of basic parameters such as number of blades, the radius of rotor, the types of airfoil and the design tip speed ratio for the windmill.

b) The calculation of the blade twist and the chord at a number of stations along the length of the blade in order to produce maximum power at a given tip speed ratio by every section of the blade.

Choice of rotor parameters

For the design of a wind rotor ,a design tip speed ratio is to be chosen. The general rule is that for the lower design tip speed ratio a higher number of blades is chosen and for a higher design tip speed ratio a lower number of blades is chosen. Because choice of higher number of blades for high design tip speed ratio will lead to very small and thin blades which results in manufacturing problems.

To obtain the optimum configuration each blade of the rotor is divided into a number of radial stations. Four formulas [3] will be used to determine the blade twist and chord distribution along the length of the blade.

For local tip speed ratio:

$$\lambda = \lambda_d r/R \tag{2.1}$$

Relation for flow angle:

$$\lambda_r = \frac{sin(2cos\phi - 1)}{(1-cos\phi)(2cos\phi+1)} \tag{2.2}$$

Where,

$$\phi = \frac{2}{3} tan^{-1} \frac{1}{\lambda_r}$$

For twist angle:

$$\beta_T = \phi - \alpha \tag{2.3}$$

For chord:

$$C = \frac{8\pi r}{BC_{Ld}} \tag{2.4}$$

The blade starting torque can be calculated by [3]

$$Q_{st} = \frac{1}{2} rV_{\infty}^2 B \int_0^R C(r)C[90 - \beta r(r)]rdr \tag{2.5}$$

The rotor configuration is determined using the assumption of zero drag and without any tip loss. Each radial element is optimized independently by a continuously varying chord and twist angle to obtain maximum energy extraction.

Aerodynamic forces

After a wind turbine rotor is optimally designed, the aerodynamic forces and moments may be calculated. These forces and moments are obtained by applying the blade element and momentum theories. The different velocity components acting on a rotor blade element is shown in Figure 1.

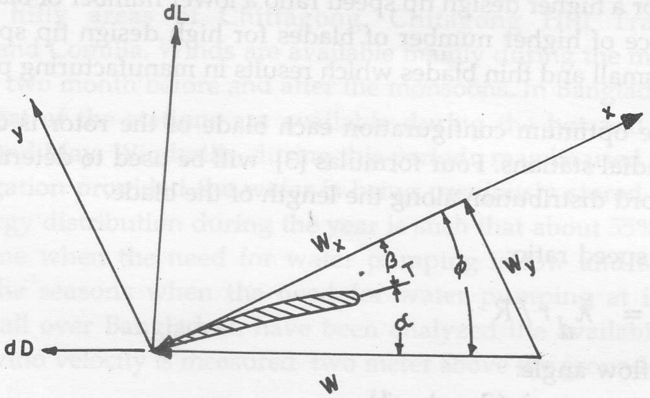

Fig. 1 : Velocity Diagram for a Rotor Blade Element.

The components of relative velocity W can be expressed by [4]

$$W_x = V_{\infty 0} \cos\gamma \cos\theta_k + V_{\infty 0} \sin\gamma \sin\theta_k \sin\alpha_T - \Omega r \cos\beta\,(1+a') \tag{2.6}$$

$$W_y = V_{\infty 0} [\sin\gamma \cos\alpha_T \cos\beta(1-a) + \sin\beta \sin\theta_k \cos\gamma - \sin\gamma \sin\beta \sin\alpha_T + \cos\theta_k] \tag{2.7}$$

The local angle of attack α is defined as

$$\alpha = \phi - \beta_T = \tan^{-1} (W_y / W_x) - \beta_T \tag{2.8}$$

The expressions for thrust, torque and power coefficients are given by [4]

$$C_T = \frac{8}{\pi R^2} \mathrm{Cos}^2\beta \mathrm{Cos}^2\alpha_T \sin^2\gamma \int_0^{2\pi}\int_0^R \left(\frac{V_{\infty 0}}{V_\infty}\right)^2 aF(1-aF)\left(1+\frac{C_D}{C_L}\tan\phi\right) r dr d\theta \tag{2.9}$$

$$C_Q = \frac{8\Omega}{\pi R^2 V_\infty^2} \mathrm{Cos}\alpha_T \sin\gamma \mathrm{Cos}^4\beta \int_0^{2\pi}\int_0^R V_{\infty 0} r^3 a'F(1-aF)\left(1-\frac{C_D}{C_L}\frac{1}{\tan\phi}\right) r dr d\theta \tag{2.10}$$

$$C_P = \frac{8\Omega^2}{\pi R^2 V_\infty^3} \mathrm{Cos}\alpha_T \sin\gamma \mathrm{Cos}^4\beta \int_0^{2\pi}\int_0^R V_{\infty 0} r^3 a'F\left(1-aF\right)\left(1-\frac{C_D}{C_L}\frac{1}{\tan\phi}\right) r dr d\theta \tag{2.11}$$

EFFECTS AT VARIOUS WIND CONDITIONS

In reality, the wind velocity will be neither uniform, nor steady or unidirectional. Vertical wind gradient, gustiness and wind turning with elevation all present various difficulties to the design and operation of wind turbines. The local flow conditions and the techniques to predict the magnitude of the effects of the flow variations must be known beforehand. The different conditions include the effect of blade shapes, number of blades, wind shear, wind shift and tower shadow, rotor tilt and blade coning have been discussed here systematically.

Effect of blade shapes

The normal procedure for determining the blade shape of a horizontal axis wind turbine is to optimize independently each radial element by continuously varying chord and twist angle to obtain maximum energy extraction. This method results in complex blade shapes which can be expensive to manufacture and may not have the structural integrity. In order to reduce these problems it is possible to linearize the chord and twist angles. This results in a small loss of power . However , if linearization is done in sensible way the loss is only a few per cent.

In the present analysis , three types of blade shapes have been considered: optimum chord - optimum twist (SH=1), linear chord- linear twist(SH=2) and linear chord - zero twist(SH=3) . The linearization of the chords and twist angles have been done by taking the values from the optimum blade configuration [4] at r=0.5R and r=0.9R.

Figures 2 and 3 show the distribution of chord and blade setting angles for these three types of blades. From these figures, it is found that the changes in chords and twist angles are very small at the outer half of the blade, large variations with the linear chord and twist distribution are found only at the lower part of the blade. Variation of power, thrust and torque with non dimensional blade radius are shown in Figure in 4. It must be realized that about 75% power, thrust and torque that is extracted by rotor from the wind , is extracted by outer half of the blade[5]. This is because of the fact that the blade swept area varies as the square of the radius. So linerization will not lead any significant power loss but the starting torque will be less and in cases where staring torque is an important factor this effect must be considered. Variation of starting torque with pitching angle for different blade configuration is shown in Figure 5. Starting torque can be increased by increasing the pitching angles . The effect of blade twist is to maintain the aerodynamic angle of attack at maximum lift to drag ratio. Considering both aerodynamic and structural performances, it has been observed that a linear-chord linear blade is comparable to the optimum- blade optimum twist, while offering reduction in manufacturing time and costs.

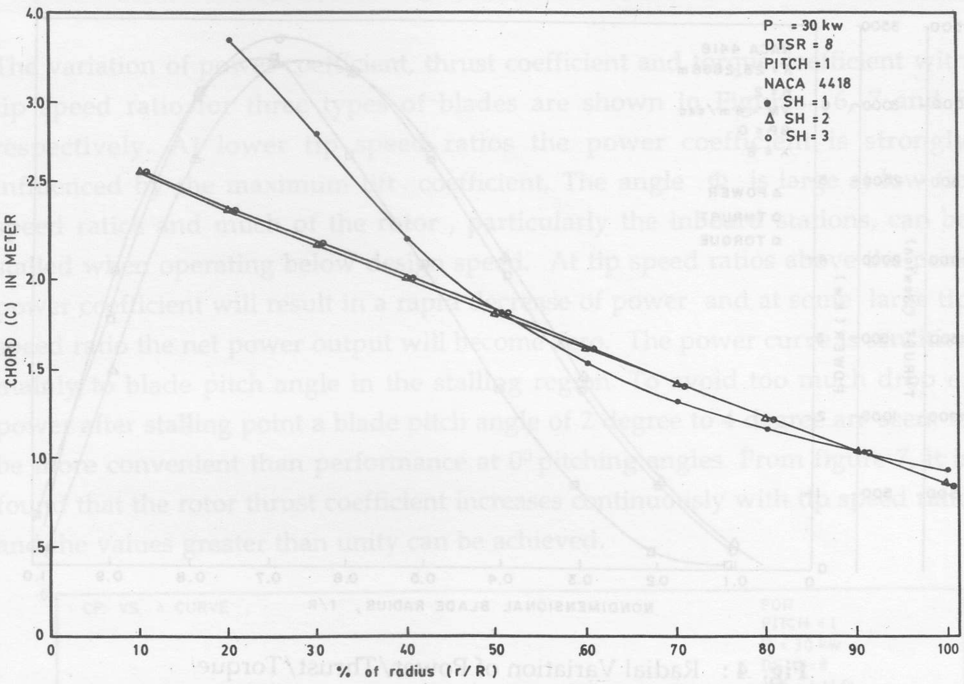

Fig. 2 : Optimum and Linearized Blade Chord Distribution

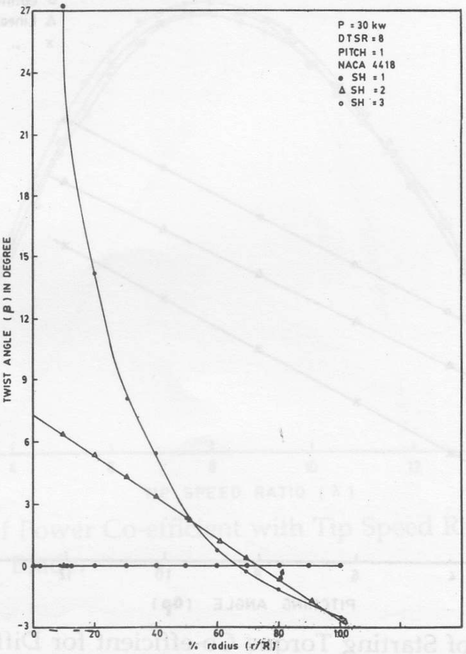

Fig. 3 : Optimum and Linearized Blade Twist Distribution

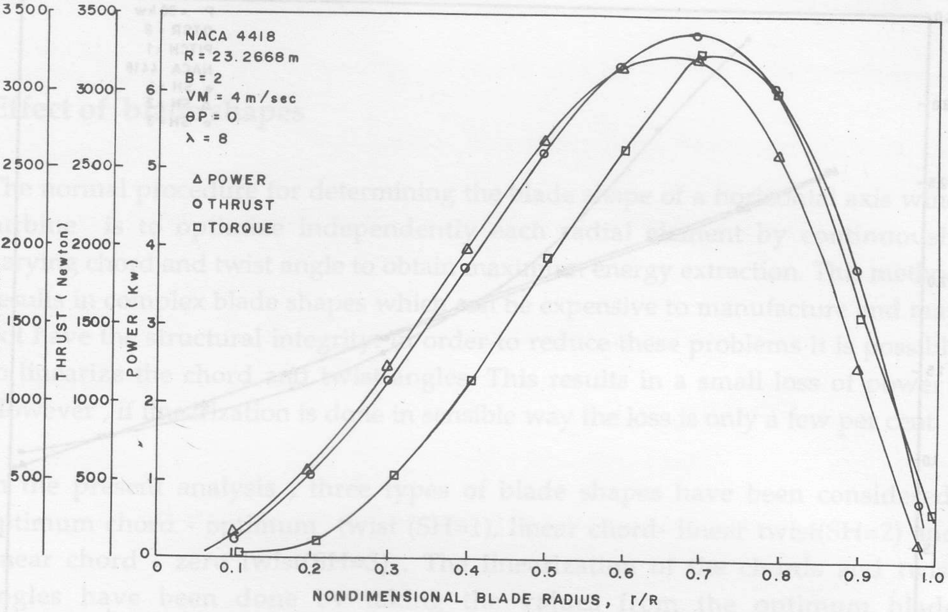

Fig. 4 : Radial Variation of Power/Thrust/Torque

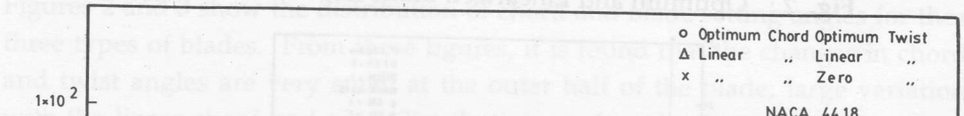

Fig. 5 : Comparison of Starting Torque Co-efficient for Different Blade Shapes Wind Turbines.

The variation of power coefficient, thrust coefficient and torque coefficient with tip speed ratio for three types of blades are shown in Figures 6, 7 and 8 respectively. At lower tip speed ratios the power coefficient is strongly influenced by the maximum lift coefficient. The angle Φ is large at low tip speed ratios and much of the rotor , particularly the inboard stations, can be stalled when operating below design speed. At tip speed ratios above the peak power coefficient will result in a rapid decrease of power and at some large tip speed ratio the net power output will become zero. The power curve is sensitive mainly to blade pitch angle in the stalling region. To avoid too much drop of power after stalling point a blade pitch angle of 2 degree to 4 degree are seem to be more convenient than performance at 0^0 pitching angles. From figure 7, it is found that the rotor thrust coefficient increases continuously with tip speed ratio and the values greater than unity can be achieved.

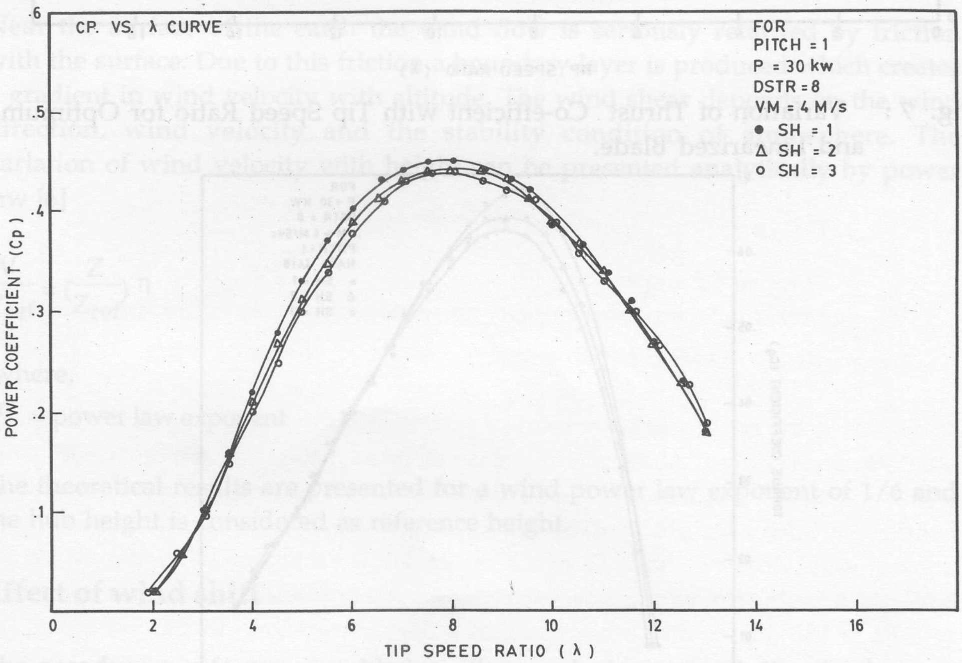

Fig. 6 : Variation of Power Co-efficient with Tip Speed Ratio for Optimum and Linearized Blade.

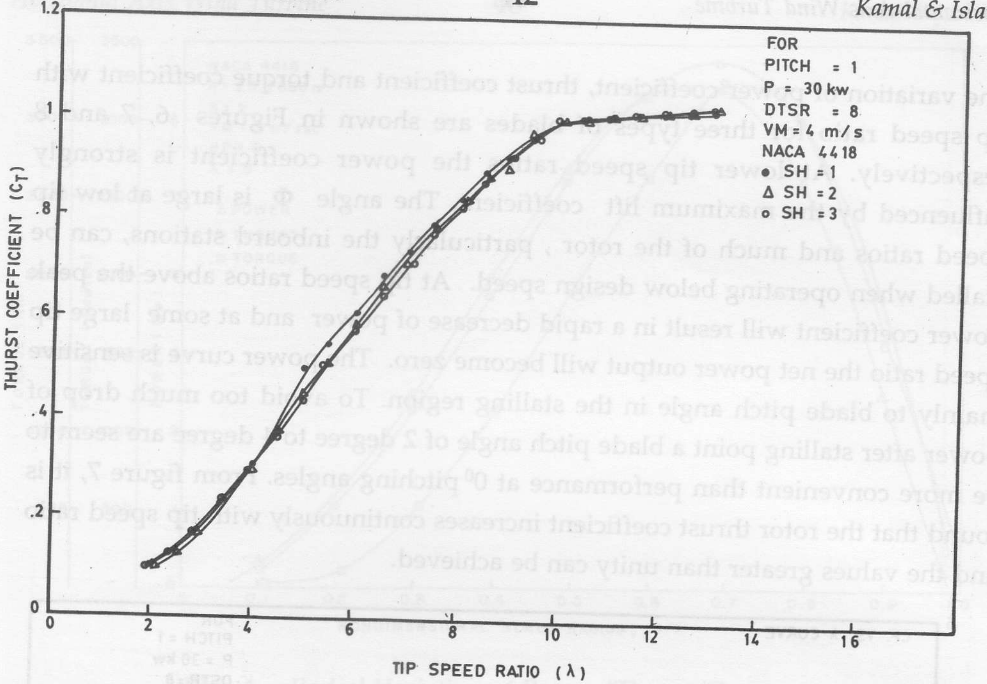

Fig. 7 : Variation of Thrust Co-efficient with Tip Speed Ratio for Optimum and Linearized Blade.

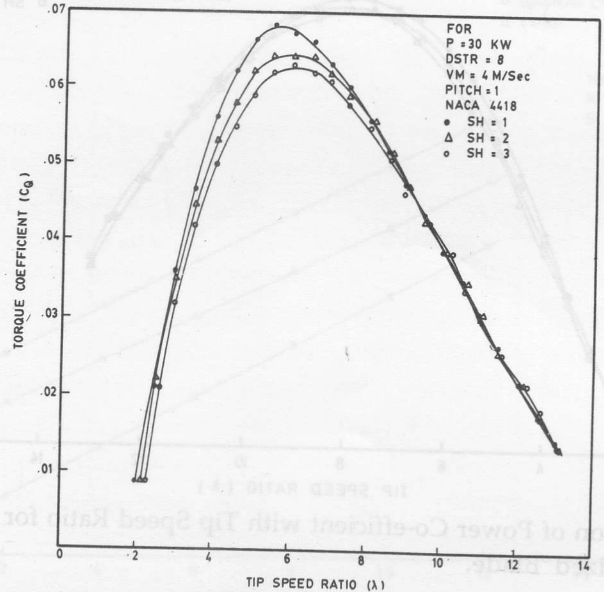

Fig. 8 : Variation of Torque Co-efficient with Tip Speed Ratio for Optimum and Linearized Blade.

Effect of number of blades

As the number of blades increases so does the cost. The advantages of increasing the number of blades are improved performance and lower torque variations due to wind shear. The maximum power coefficient is also affected by number of blades. This is caused by the tip losses that occur at the tips of the blades. These losses depend on the number of blades and tip speed ratios. For the lower design tip speed ratios, in general, a higher number of blades is chosen. This is because the influence of number of blades on power coefficient is larger at lower tip speed ratios. For a high design tip speed ratio, a higher number of blades will lead to very small and thin blades which results in manufacturing problems and negative influence in the lift and drag properties of the blades.

Effect of wind shear

Near the surface of the earth the wind flow is seriously retarded by friction with the surface. Due to this friction a boundary layer is produced which creates a gradient in wind velocity with altitude. The wind shear depends on the wind direction, wind velocity and the stability condition of atmosphere. The variation of wind velocity with height can be presented analytically by power law [6]

$$\frac{V}{V_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^{\eta}$$

where,

η = power law exponent

The theoretical results are presented for a wind power law exponent of 1/6 and the hub height is considered as reference height.

Effect of wind shift

The aerodynamic forces on a blade will vary during a revolution in the case where the rotor axis is not parallel to the wind direction ,even though wind speed is constant. This results from changes in both magnitude and direction of the resulting local wind speed for the profiles which alters with varying moment of the blade with and against the wind direction. In non axial flow, the cyclic variations in the aerodynamic forces at the blade root could lead to resonance in either the blade or the supporting structures and possibly reduce the life time of the turbine. The effects of non axial flow, therefore, need to be considered in the design of the horizontal axis wind turbine.

Effect of tower shadow

The aerodynamic interference created by the tower is an important source of periodic wind load. An evaluation has been conducted for the effect of tower shadow on the forces, power, thrust, moment and stress for a downwind mounted wind turbine blade. The large and abrupt changes that occurs as the blade passes through the tower shadow will obviously cause significant changes in blade. The magnitude of these changes will depend on the amount of the flow blockage occurring and duration of the blade remains in the tower shadow. For present analysis, the blades are assumed to be in the tower wake at azimuths from 165 degree to 195 degree. When blade is initially located vertically up behind the tower $\theta = 0^0$,and rotates to be vertically down at $\theta = 180^o$,the tower blockage is modeled by [7]

$$V(\theta,\lambda) = V_{\theta k}\,[1 - B_f(1+\cos n\theta)]$$

Where B_f = tower blockage factor

≤ 0.5 for $\pi(1-\frac{\pi}{12}) \leq \theta \leq \pi\,(1+\frac{\pi}{12})$

= 0 for other angles

$V_{\theta k}$ = instantaneous wind velocity corresponding to an azimuthal point.

$n\theta$ = angle of tower shadow area

In Figure 9, the percentage decrease of power due to wind shear and the tower shadow is presented. About 7% decrease of power may take place due to wind shear and tower shadow. Figure 10 show the effect of tower shadow on power coefficient with azimuth at different coning angles. Although the variation of coning angle does not have so much effect, large variation will occur when the blade will be in tower shadow. Maximum variation will occur when one blade will be at 180 degree and other blade at 0 degree position. In this condition the upper blade receive maximum wind velocity and lower blade will receive minimum wind velocity.

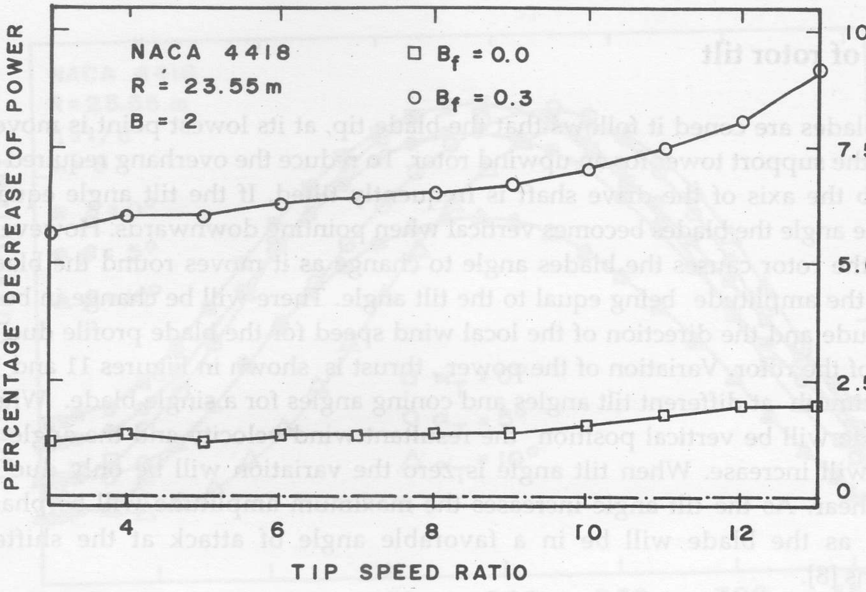

Fig. 9 : Percentage Decrease of Power Due to Tower Shadow.

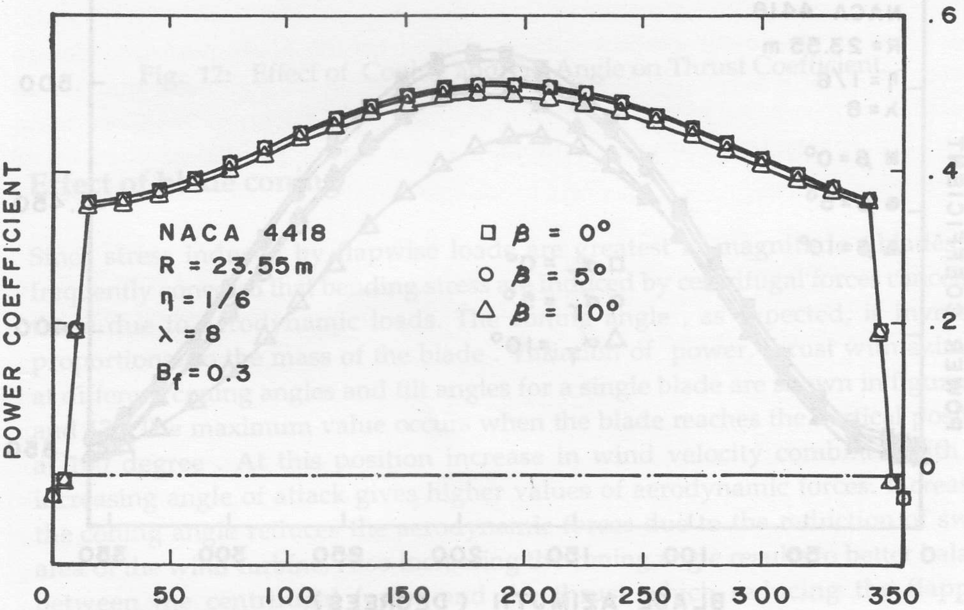

Fig. 10 : Effect of Tower Shadow and Coning Angles on Power Coefficient.

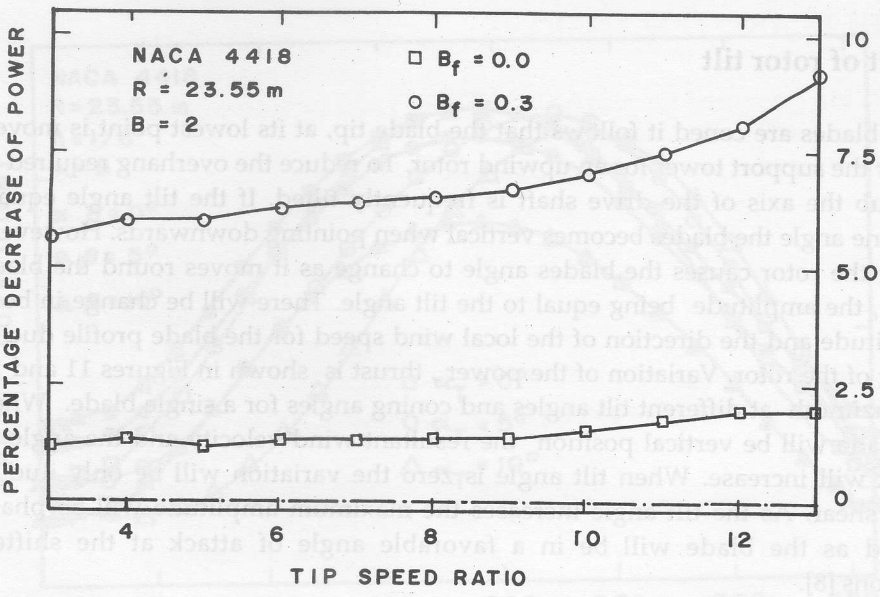

Fig. 9 : Percentage Decrease of Power Due to Tower Shadow.

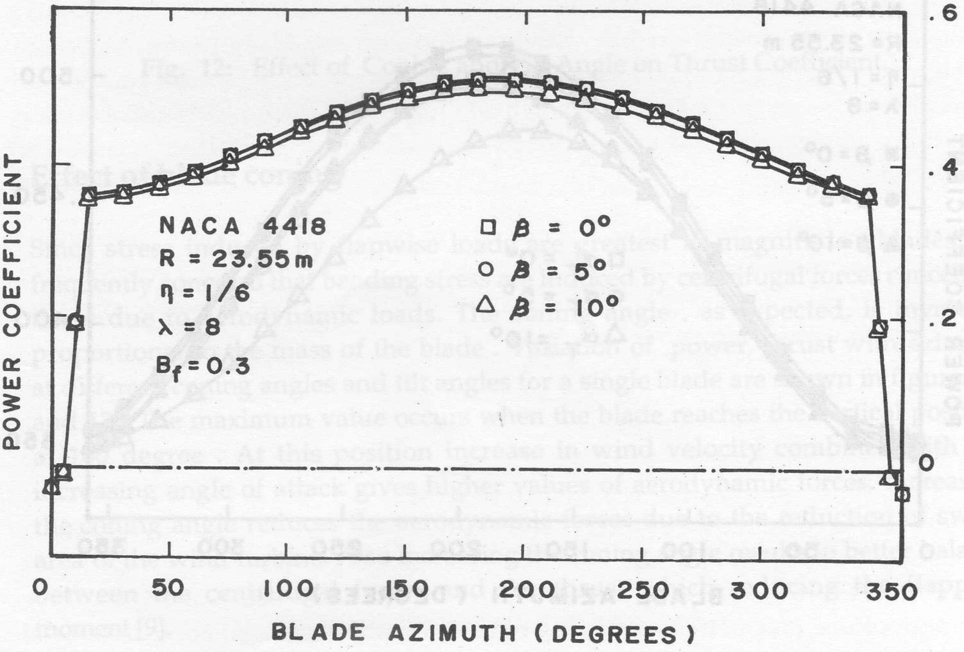

Fig. 10 : Effect of Tower Shadow and Coning Angles on Power Coefficient.

Effect of rotor tilt

If the blades are coned it follows that the blade tip, at its lowest point is moved nearer the support tower for an upwind rotor. To reduce the overhang required at the hub the axis of the drive shaft is frequently tilted. If the tilt angle equals the cone angle the blades becomes vertical when pointing downwards. However , tilting the rotor causes the blades angle to change as it moves round the blade circle , the amplitude being equal to the tilt angle. There will be change in both magnitude and the direction of the local wind speed for the blade profile due to tilting of the rotor. Variation of the power , thrust is shown in Figures 11 and 12 with azimuth at different tilt angles and coning angles for a single blade. When the blade will be vertical position the resultant wind velocity and the angle of attack will increase. When tilt angle is zero the variation will be only due to wind shear. As the tilt angle increases the maximum amplitude will be phase shifted as the blade will be in a favorable angle of attack at the shifted positions [8].

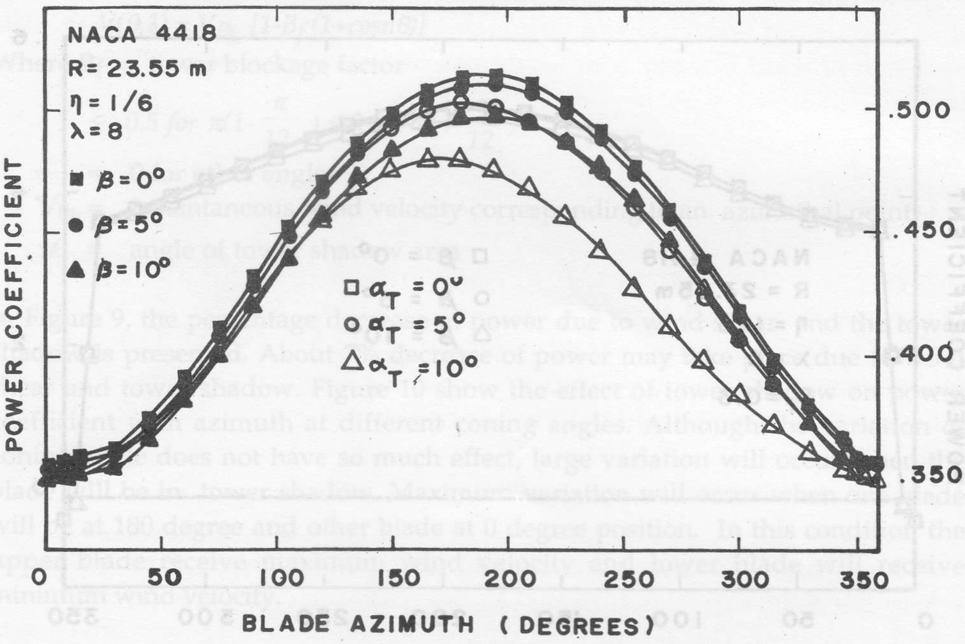

Fig. 11 : Effect of Coning and Tilt Angle on Power Coefficient.

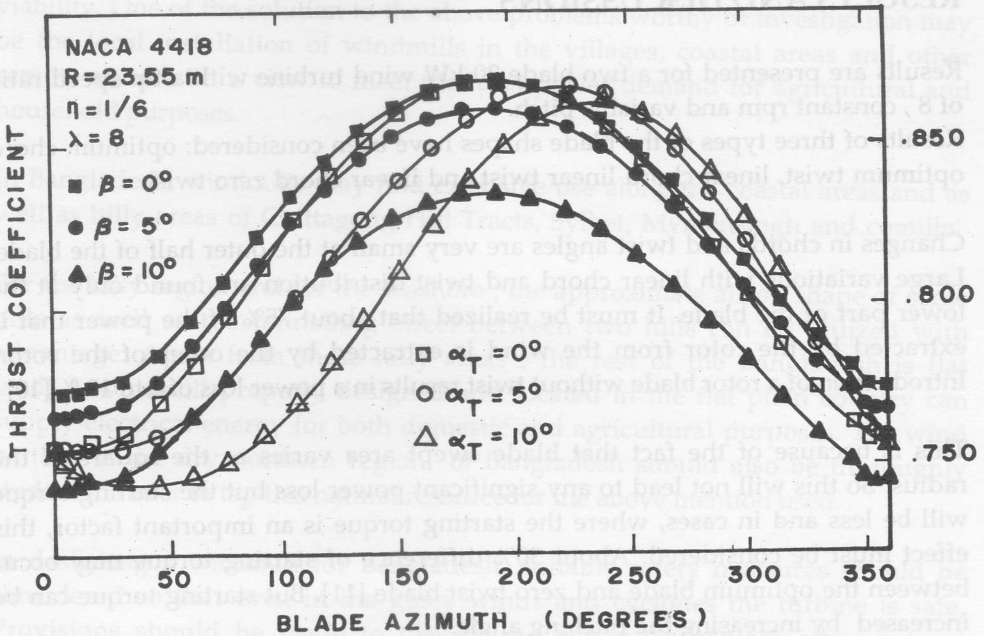

Fig. 12: Effect of Coning and Tilt Angle on Thrust Coefficient.

Effect of blade coning

Since stress induced by flapwise loads are greatest in magnitude , blades are frequently coned so that bending stress are induced by centrifugal forces cancelling those due to aerodynamic loads. The coning angle , as expected, is inversely proportional to the mass of the blade . Variation of power, thrust with azimuth at different coning angles and tilt angles for a single blade are shown in figures 11 and 12 . The maximum value occurs when the blade reaches the vertical position at 180 degree . At this position increase in wind velocity combines with the increasing angle of attack gives higher values of aerodynamic forces. Increasing the coning angle reduces the aerodynamic forces due to the reduction of swept area of the wind turbine. Also increasing the coning angle results in better balance between the centrifugal forces and the thrust which reducing the flapping moment [9].

RESULTS AND DISCUSSIONS

Results are presented for a two blade 30 kW wind turbine with a tip speed ratio of 8 , constant rpm and variable pitch.
Results of three types of the blade shapes have been considered: optimum chord optimum twist, linear chord linear twist and linear chord zero twist.

Changes in chords and twist angles are very small at the outer half of the blade. Large variations with linear chord and twist distribution are found only at the lower part of the blade. It must be realized that about 75% of the power that is extracted by the rotor from the wind is extracted by the outer of the rotor. Introduction of a rotor blade without twist results in a power loss of 6 to 10 % [10]

This is because of the fact that blade swept area varies as the square of the radius. So this will not lead to any significant power loss but the starting torque will be less and in cases, where the starting torque is an important factor, this effect must be considered. About 30% difference of starting torque may occur between the optimum blade and zero twist blade [11]. But starting torque can be increased by increasing the pitching angle.

The effect of the tower shadow, tilting, coning on the blade performance are presented in Figure 9 to 12. Tower shadow will lead to an important and drastic variation of forces and moments when blade passes the tower. Increase of coning or tilting angles will reduce the moments and thrust as well as the power produced.

Considering both aerodynamic and structural performances linear chord-twist blade is comparable to the optimum designed blade while offering a considerable reduction in manufacturing time and costs. About 7% decrease of power may take place due to wind shear and tower shadow .

CONCLUSIONS

Bangladesh is an agriculture based country whose economic structure is dependent on agro-product commodities. Due to population explosion Bangladesh needs more food. Having poor economic structure she seeks new technique to improve the agriculture productivity with her efforts. Wind energy can contribute a lot both for irrigation its land and producing electricity for sustaining its economic viability. One of the solution to the above problems worthy of investigation may be the local installation of windmills in the villages, coastal areas and other remote areas with a view to meet the local power demand for agricultural and household purposes.

In Bangladesh, windmills may find extensive use along the coastal areas and as well as hilly areas of Chittagong Hill Tracts, Sylhet, Mymensingh and comilla.

For the hilly region and for the seashore , the approximate airfoil shape of some hills as well as the tunnelling effect between two hills can be utilized with advantage. Apart from these hilly areas , the rest of the Bangladesh is flat land. A windmill properly designed and located in the flat plain country can supply electrical energy for both domestic and agricultural purposes. The wind pattern in the dry northern region of Bangladesh should also be thoroughly studied in order to tap this natural resource for the above mention used.

In designing a windmill for Bangladesh, suitable safety measures should be considered so that even in the gusty winds and cyclones the turbine is safe. Provisions should be made to protect the windmills against other natural calamities.

For three blade shapes considered, it has been shown that the aerodynamic performance of the three blade shapes are almost similar. Some variations are found for the blade with zero twist. In case where the starting torque is not an important factor the blade with linear chord and zero twist may be preferred.

In designing windmills thrust, power, torque and moment variations are considered as the blade passes through the tower shadow. The magnitude of these variations is a function of the amount of flow blockage occurring and how the turbine blade remains in tower shadow. A careful evaluation of the tower shadow to insure that the rotor blades and support can withstand the stress set up as the blades transit as varying wind environment of tower shadow.

For the design of a horizontal axis wind turbine the influence of wind gradient, tower shadow, wind shift, coning , tilting and azimuth should be considered.

LIST OF SYMBOLS

a	axial interference factor
a'	tangential interference factor
B	number of blades
B_f	tower blockage factor
C_D	drag coefficient
C_L	lift Coefficient
C_{Ld}	design lift coefficient
C_P	power coefficient
C_T	thrust coefficient
C_Q	torque coefficient
C_{Qst}	starting torque coefficient
F	Prandtl's loss factor
r	local blade radius
V_d	design wind velocity
$V\infty$	undisturbed wind velocity
V	wind velocity at height Z
$V\infty o$	local wind velocity considering wind shear
$W\infty$	relative wind velocity
α	angle of attack
α_T	tilt angle
λ	tip speed ratio
λ_d	design tip speed ratio
λr	local tip speed ratio
θ_k	blade azimuth angle
ϕ	angle of relative velocity
γ	yawing angle
β	coning angle
β_T	blade twist angle
Ω	angular velocity of rotor
R	rotor radius
ρ	air density
Z	height above ground
Z_{ref}	reference height

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