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Design of a Straight-Bladed Darrieus Turbine with Overhanged Blade Support

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ABSTRACT

A theoretical investigation of an optimum design method for a vertical axis straight-bladed Darrieus wind turbine with blade section of symmetric profile is presented. The design is performed at variable turbine speed. In the design the blades are considered to be supported like that of overhanged beam. The analysis has been made keeping the blade stress constant. The result shows that for some region of solidity the turbine with overhanged supported blades is economical than that with simple supported blades.

NOMENCLATURE

A	projected frontal area of turbine
AR	aspect ratio
C	blade chord
c_m	blade pitching moment coefficient
C_n	normal force coefficient
C_p	turbine overall power coefficient
C_Q	turbine overall torque coefficient
C_t	tangential force coefficient
D	turbine diameter
F_{cf}	centrifugal force
F_n	normal force in radial direction
F_{net}	net normal force in radial direction
F_t	force in tangential direction
H	height of turbine
I_x	moment of inertia of blade section about chordal axis
L_B	total length of supporting strut and blade
M_b	bending moment
m_b	blade mass per unit length
N	number of blades
P_o	overall power

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Q	overall torque
Q_s	instantaneous starting torque
Q_{sm}	mean value of starting torque
rpm	turbine speed in revolutions per minute
R	turbine radius
S_a	permissible blade stress in Newton/sq.mm
S_{bn}	bending stress due to net normal force in Newton/sq.mm.
S_m	maximum value of blade stress in each revolution in N/sq.mm.
t_c	maximum blade thickness as a fraction of chord
t_s	blade skin thickness
V_{cut}	cutout speed
$V\alpha$	wind speed
W	relative velocity
w	load on blade per unit length (kg/m)
θ	azimuth angle
λ	tip speed ratio = $R\,\omega/V\alpha$
λ_{cut}	tip speed ratio corresponding to cutout speed
ρ	fluid density
σ	solidity
ω	angular velocity of turbine in rad/sec.

Subscript

d	design point
m	maximum value

INTRODUCTION

The design of a vertical-axis straight-bladed Darrieus wind turbine is conducted at variable turbine speed condition. Variable speed turbines are designed with a view to apply usually in agricultural fields for pumping water. The aim of the design approach is to make it optimum. The present design method encounters the blades to be supported as that of overhanged nature while reference [1] considers the blades to be supported as that of simple nature. The study shows that turbine with overhanged blade support becomes economical than that with simple blade support in order to produce the same power under same wind conditions. Ofcourse manufacturing problem especially when pitching is to be incorporated into the blades, would occur for the turbine with overhanged blade support.

In order to perform the design of the turbine, many parameters appear to be variable. Few of them are assumed to be fixed. The fixed parameters are number of blades, blade stress, blade pitching, blade section profile and cutout speed. In this design the number of blades is considered as three. Blade permissible stress is chosen as 100 N/mm^2. Blade pitching is encountered as zero. Blade section profile is considered as NACA 0015 because of its better lift drag characteristics. Cutout speed is chosen as 14 m/sec. This parameter is important in controlling the design configurations. Keeping in mind to apply the turbine in agricultural field for pumping water, the design is conducted at constant tip speed ratio. Since constant tip speed ratio design approximately follow the load characteristic curves of such pumps. In this design the blade supporting strut cross-section is assumed as that of airfoil shape in order to make negligible power losses due to supporting struts. Ofcourse it incurs additional production cost. Finally the results obtained of overhanged supported blades are compared with those of simple supported blades [1]. In the comparative study the blade permissible stress is kept same. Keeping the blade stress same the influence of blade support on the turbine configurations is analysed.

DESIGN MODEL

In the design model, the cascade theory as presented in the reference [2], is applied in the aerodynamic calculation. Cascade model is the simplest one, gives reasonable performance prediction and does not make any convergence problem.

For the primary assumed values of power coefficient (C_p), wind velocity ($V\alpha$) and for the given power, the turbine projected area may be determined from,

$$A = \frac{Po}{1/2\ C_p\ \rho\ V\alpha^3} \quad \ldots\ldots\ldots\ldots\ (1)$$

For the given solidity, number of blades and assumed value of aspect ratio, turbine configurations may be found from the following expressions,

$$\sigma = NC/R,\ AR = H/C \text{ and } A = H.\ D\ \ldots\ \ldots(2)$$

After calculating Reynolds number corresponding to the wind velocity and blade chord, power coefficients for a wide range of tip speed ratios are calculated using the cascade theory. Power coefficient may be determined from the expression,

$$C_P = C_Q\,\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where C_Q is the torque coefficient and 1 is the tip speed ratio. C_Q may be obtained from,

$$C_Q = \frac{Q}{1/2\ \rho\ A\ V\alpha^{2R}} \quad \ldots\ldots\ldots\ldots\ldots(4)$$

Design power coefficient is calculated from,

$$C_{pd} = 0.9\ C_{pm} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where C_{pm} is the maximum power coefficient in the power coefficient versus tip speed ratio distribution. Design tip speed ratio is chosen corresponding to C_{pd}. Until the value of C_p in equation (1) is not reasonably closer to the value of C_{pd}, calculation is repeated. Maximum angular velocity of the rotor may be obtained from the relation,

$$W_m = \frac{\lambda_d\ Vcut}{R} \quad \ldots\ldots\ (6)$$

Figure 1 shows how the blades of a straight-bladed Darrieus turbine may be supported. Figure 2 presents a horizontal section of a straight-bladed Darrieus turbine showing aerodynamic forces acting on a blade airfoil. The centrifugal and normal forces acting on the blade airfoil may respectively be expressed as,

$$F_{cf} = m_b\ \omega^2 R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

and

$$F_n = 1/2\ C_n\ \rho\ W^2 C\ H \quad \ldots\ldots\ldots\ldots\ldots(8)$$

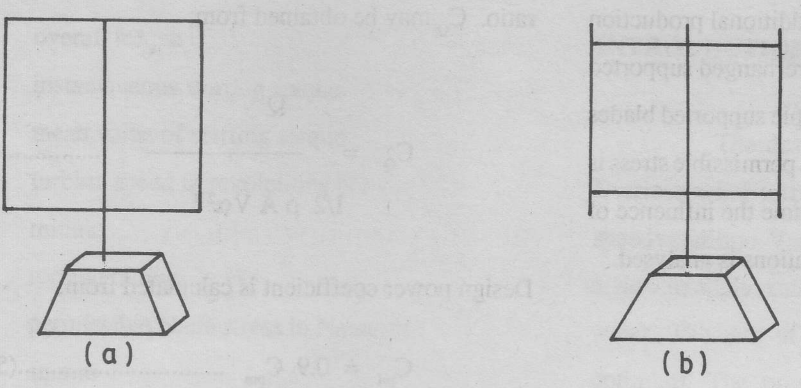

Figure 1 : Turbine blade support types:
(a) Simple supported blades (b) Overhanged supported blades.

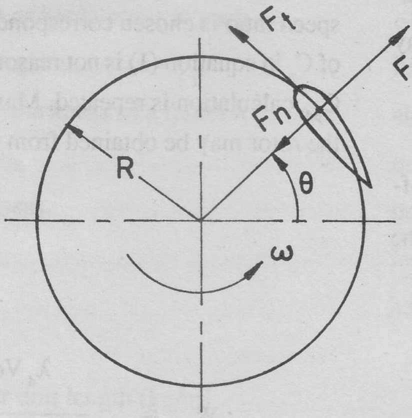

Figure 2 : Horizontal section of a straight-bladed wind turbine showing forces on the turbine blade.

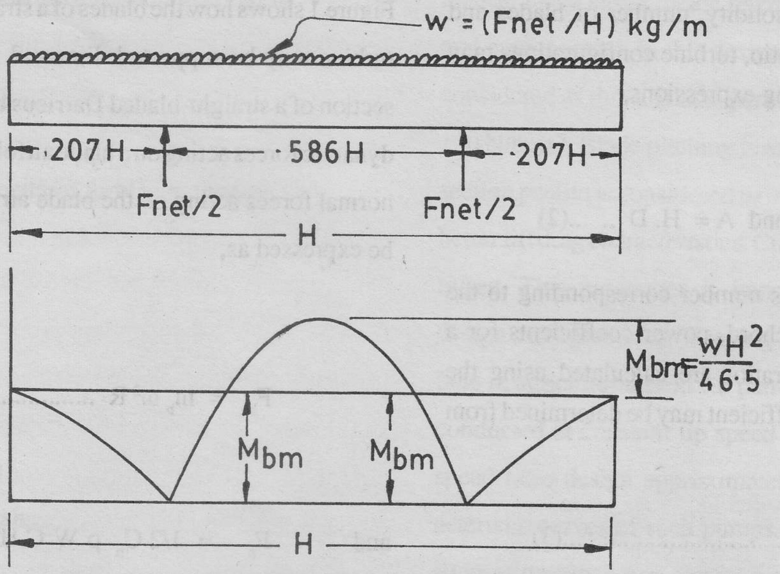

Figure 3 Bending moment diagram of a overhanged supported blade.

The net normal force acting on the blade airfoil in radially outward direction may be obtained from,

$$F_{net} = F_{cf} - F_n \quad \text{......... ....(9)}$$

One may observe from the figure 3, the nature of bending moment developed for an overhanged blade support with distributed load. Blade supports are placed in such a way that, the bending moment on either side becomes equal. Under this condition, the blade bending stress at any azimuthal position may be calculated from the expression,

$$S_{bn} = \frac{F_{net}\, H\, C\, t_c}{93\ I_x} \quad \text{..........(10)}$$

Corresponding to the cutout speed for which the blade stress becomes the highest, local maximum blade stresses are calculated from the equation (10) at various values of blade skin thickness. For the developed stress higher than permissible blade stress, a new value of aspect ratio is assumed and the calculation is repeated. Bending stress in the tangential direction is negligible in compared to the bending stress due to net normal force, hence it is neglected in the analysis.

Mean starting torque value may be determined from,

$$Q_{sm} = \frac{1}{2\pi} \int_{o}^{2\pi} Q_s\, d\, q \quad \text{...............(11)}$$

where,

$$Q_s = 1/2\, \rho\, C\, H\, V_a^2\, (C_t\ R + C_m\, C) \quad \text{...........(12)}$$

RESULTS AND DISCUSSIONS

Design configurations for a variable speed turbine at various solidities are shown in the figure 4. The design wind speed is chosen as 8m/sec while the design power is 10 kw. From this figure it is seen that with the increase of solidity, the height and chord of the turbine increase appreciably while the turbine diameter decreases which is remarkable in the low solidity range only. It is also observed from this figure that with the rise of solidity, starting torque increases adequately. The design power coefficients are higher in the middle range of solidity. The total length of blade supporting struts and blades is minimum around solidity of 0.5. This idea is important when supporting struts are of airfoil shape. At the variable turbine speed condition, the design rpm should be as high as possible in order to reduce transmission losses. The figure 4 reveals that the higher values of rpm occur within solidities from 0.300 to 0.600, but the variation of rpm with solidity is not much.

Figures 5, 6 and 7 show the comparisons of design configurations at various solidities for two types of blade support : simple and overhanged. One may observe from the figure 5 that applying overhanged blade support in place of simple blade support, the diameter of the turbine and chord of the blade profile decrease remarkably while only the height of the turbine increases with a view to produce same amount of power and in the same wind speed. It may be observed from the figure 5 that the aspect ratio for the turbine with overhanged blade support is more than double to that with the simple blade support. For

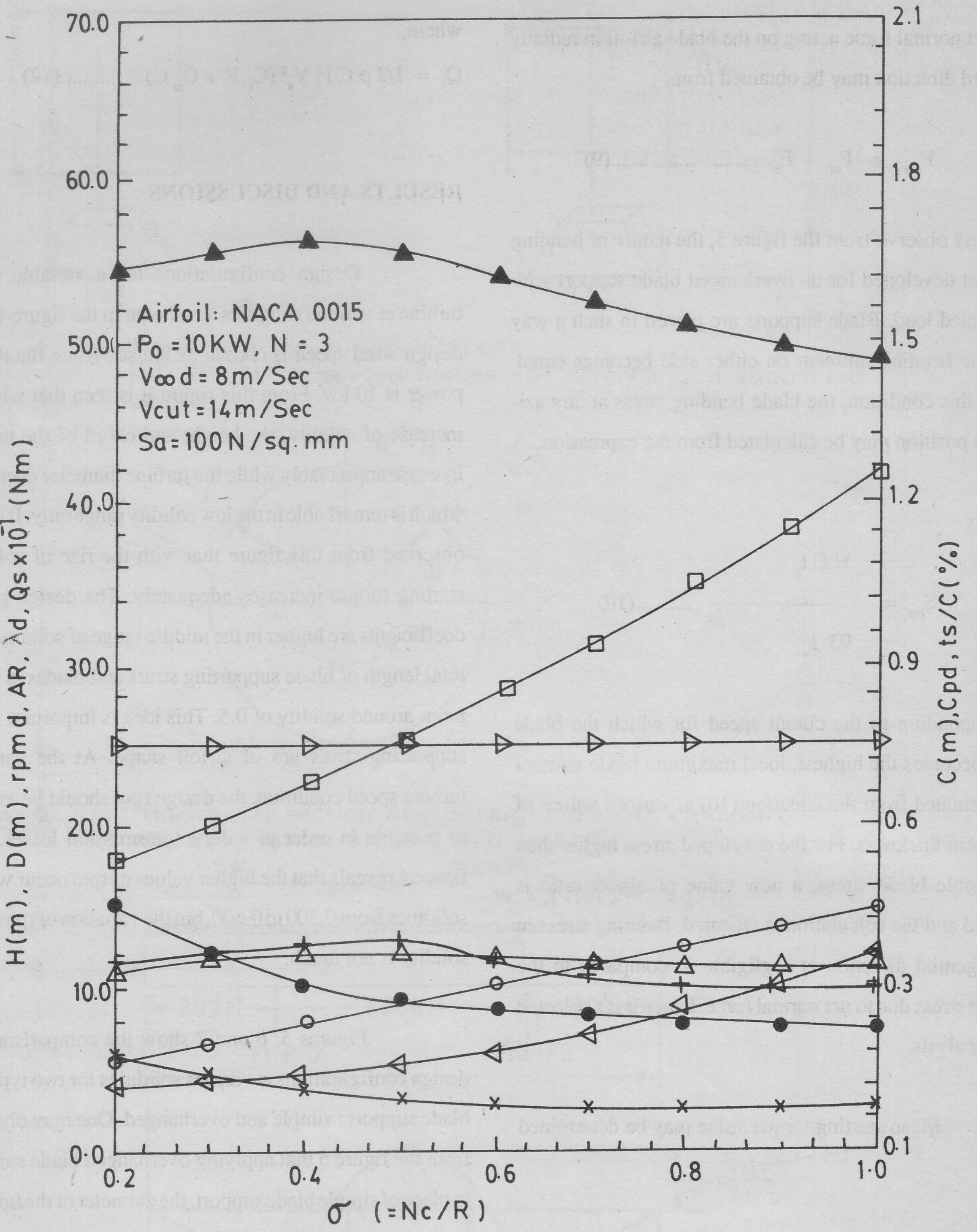

Figure 4 : Design configurations of variable speed turbines at various solidities (overhanged-supported blades).

Symbol :	○	●	□	△	▲	+	×	▷	◁
Parameter :	H	D	C	AR	rpm_d	C_{pd}	λ_d	ts/c%	Q_s

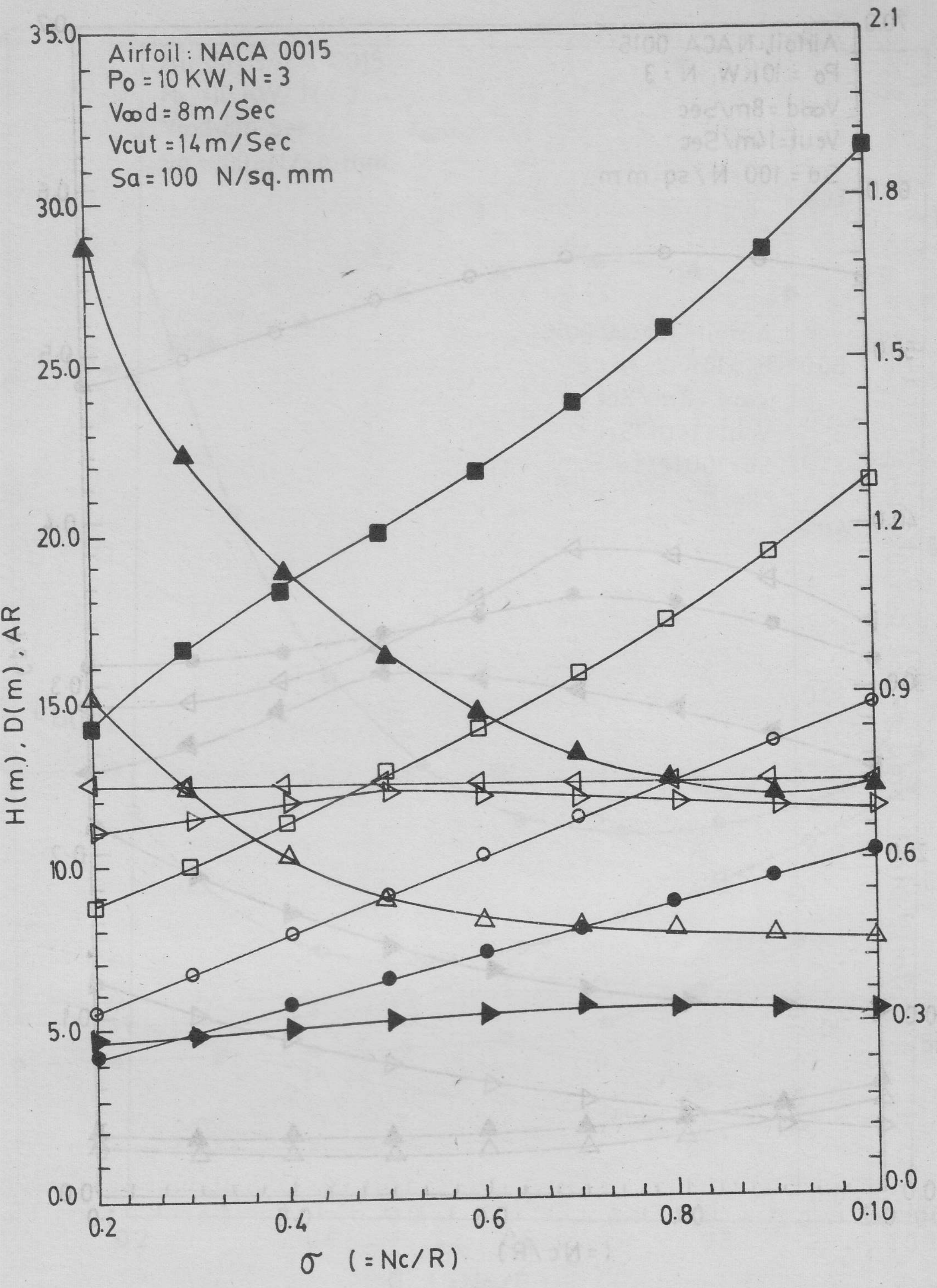

Figure 5 : Comparison of design configurations of variable speed turbines at various solidities.

Symbol	(Overhanged) :	o	△	□	▷	◁
	(Simple) [Ref.1] :	●	▲	■	▶	◁
Parameter	:	H	D	C	AR	ts /C%

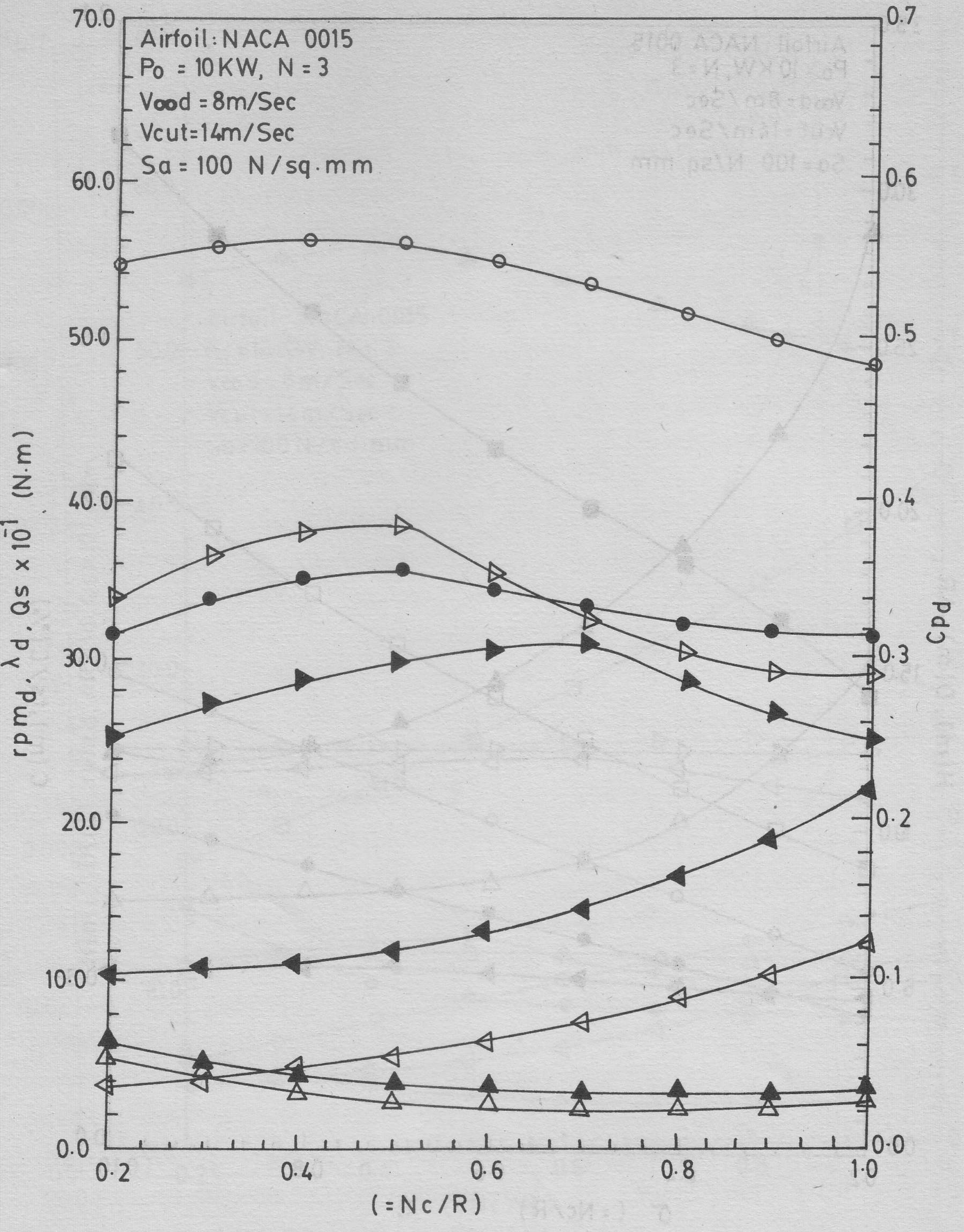

Figure 6 : Comparisons of design configurations of variable speed turbines at various solidities.

Symbol	(Overhanged)	:	○	▷	△	◁
	(Simple [Ref.1])	:	●	▶	▲	◀
Parameter		:	rpm_d	C_{pd}	λ_d	Q_s

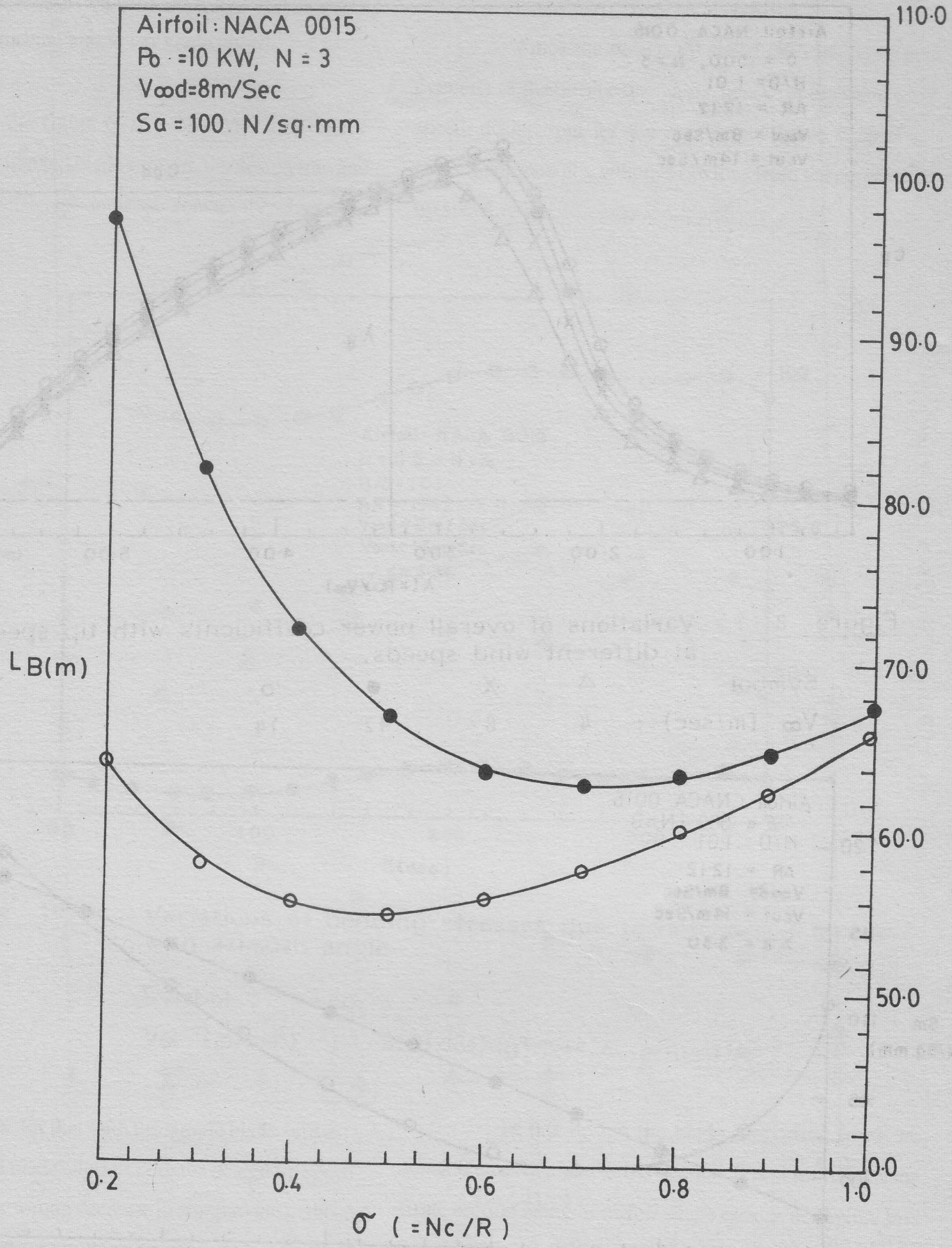

Figure 7 : - Comparisons of total blade length at various solidities.

Symbol : ○ ●

Blade support : Overhanged Simple(Ref. [1]

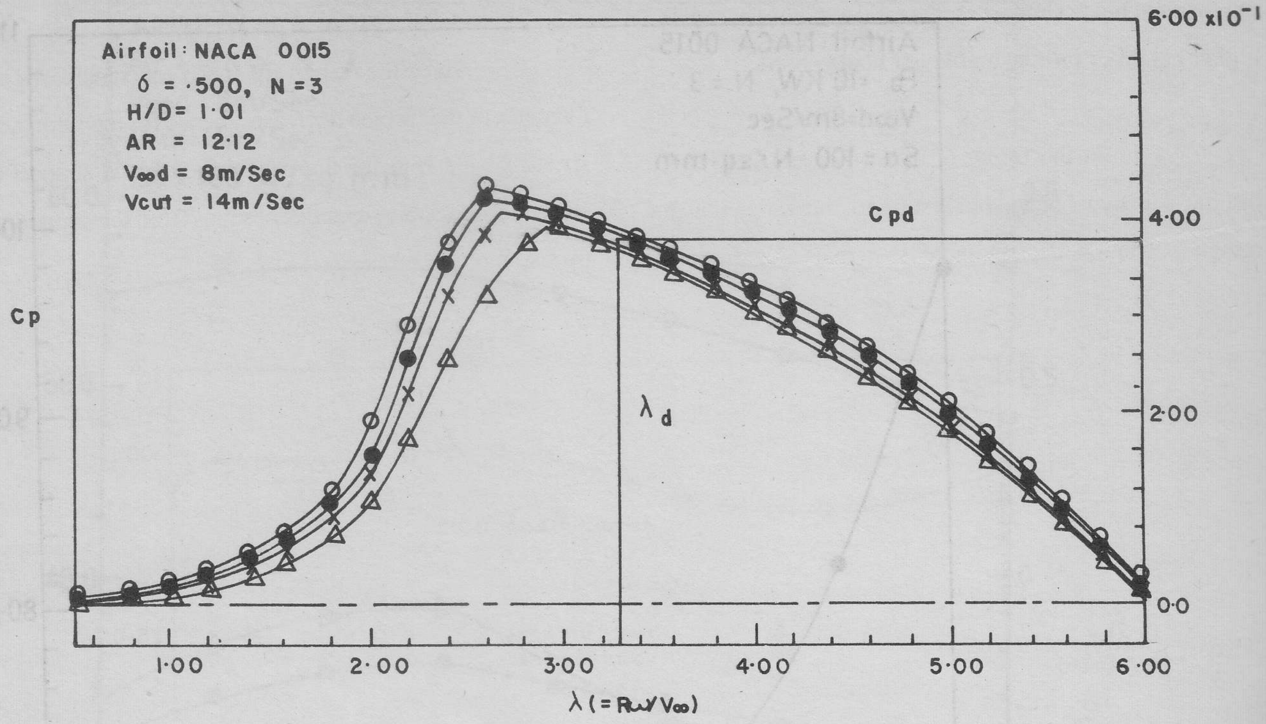

Figure 8 : Variations of overall power coefficients with tip speed ratios at different wind speeds.

Symbol	:	Δ	X	●	o
V∞ (m/sec)	:	4	8	12	14

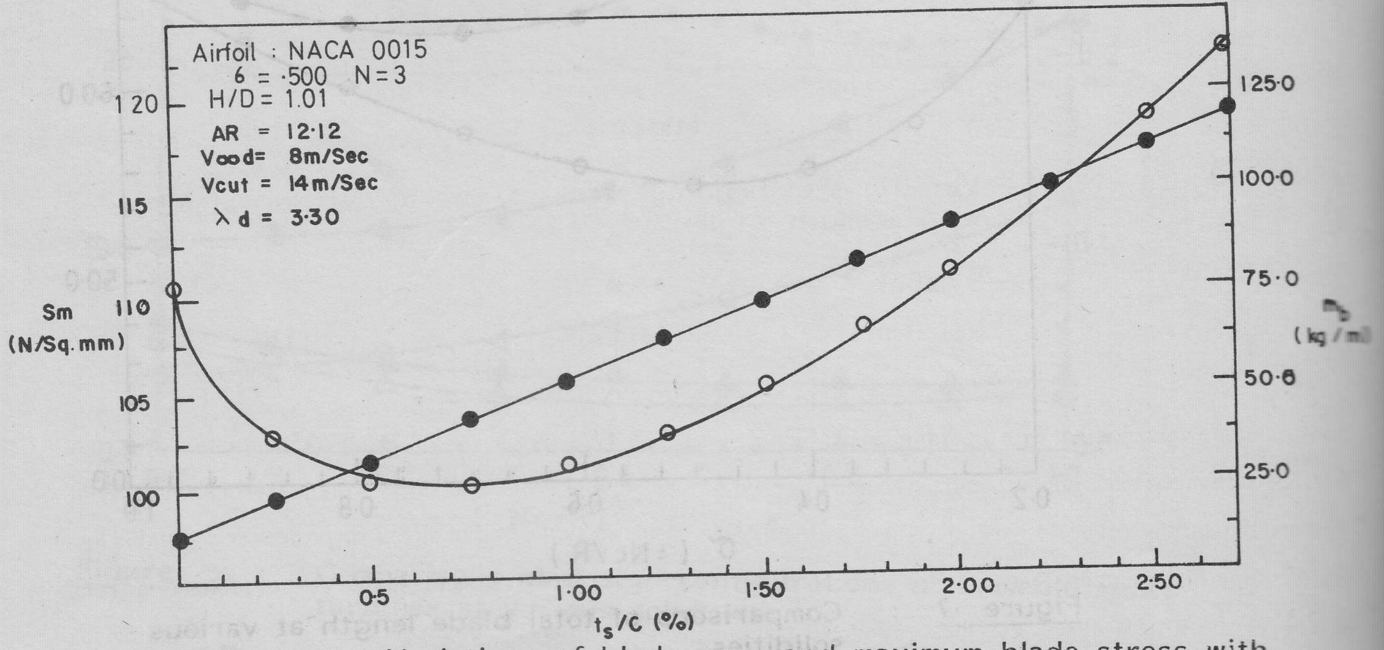

Figure 9 : Variations of blade mass and maximum blade stress with blade skin thickness.

Symbol	:	o	●
Parameter	:	S_m	m_b

overhanged blade support aspect ratio is higher because of higher height of turbine and lower blade chord.

From the figure 6, it is observed that for the turbine with over hanged blade support, the design rpm and design power coefficient increase remarkably from the corresponding value for that with the simple blade support. For the overhanged blade support both the design tip speed ratio and the starting torque decrease in comparison to those for the simple blade support. Starting torques are calculated at a wind speed of 4 m/sec. For the overhanged blade support, starting torque values decrease because of lower diameter of turbine and the design power coefficient increases due to the higher aspect ratio.

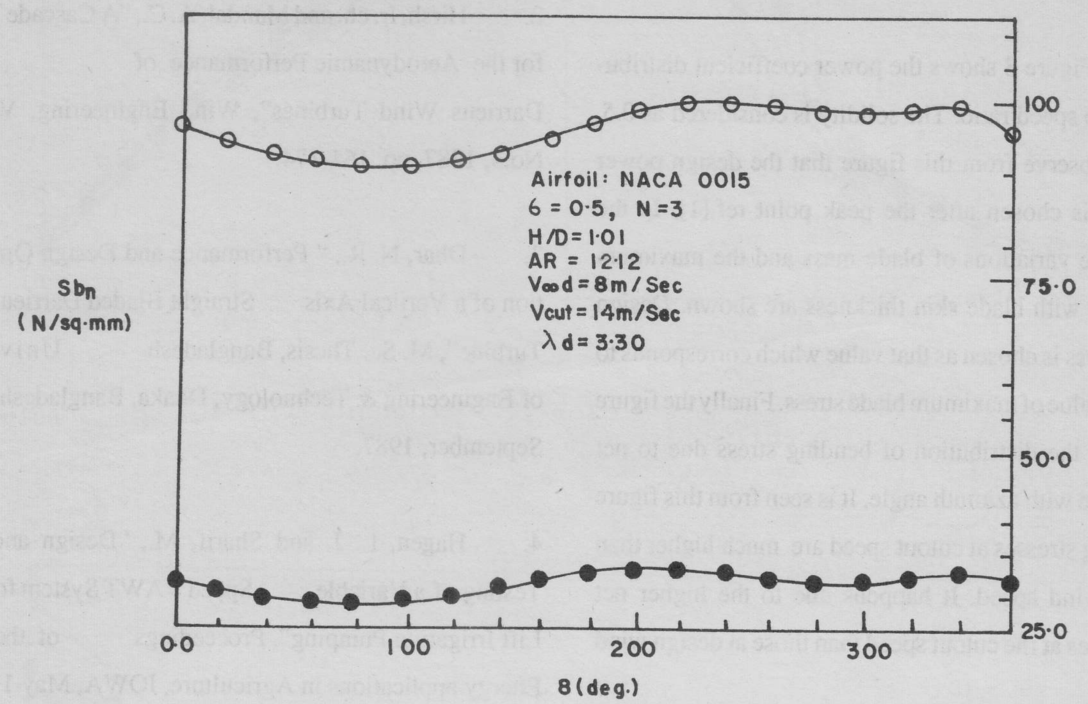

Figure 10 : Variations of bending stresses due to net normal forces with azimuth angle.

Symbol : ● o

V∞ (m/sec) ; 8.0(desing) 14.0 (cutout)

Since the design tip speed ratio increases and diameter of the turbine decreases, hence for the same wind speed, design rpm for the overhanged blade support increases appreciably, which is obvious from the equation of tip speed ratio.

In this design the blade supporting struts are considered as of airfoil cross-section. It is observed that the struts section being of airfoil shape creates negligible loss of power though it incurs higher cost of production. Total blade length is the length of blade supporting struts and the turbine blades. From the figure 7, it may be seen that the total blade length for the turbine with overhanged supported blade is lower in comparison to that with simple supported blade. However, in the lower range of solidity appreciable variation is observed.

Hence it is obvious that concerning cost of production of blade supporting struts and turbine blades, the turbine with overhanged blade support is better in comparison to that with simple blade support.

Figure 8 shows the power coefficient distribution with tip speed ratio. The solidity is considered as 0.5. One may observe from this figure that the design power coefficient is chosen after the peak point ref.[1]. In the figure 9, the variations of blade mass and the maximum blade stress with blade skin thickness are shown. Design skin thickness is chosen as that value which corresponds to the lowest value of maximum blade stress. Finally the figure 10 presents the distribution of bending stress due to net normal force with azimuth angle. It is seen from this figure that bending stresses at cutout speed are much higher than at design wind speed. It happens due to the higher net normal forces at the cutout speed than those at design wind speed.

CONCLUSIONS

For the same blade stress and at the same wind velocity in order to produce indentical amount of power, a turbine with overhanged blade support is economical from that with simple blade support for some region of solidity in the lower range upto about .6 while beyond that the advantage gradually diminishes.

For the design with overhanged supported blades the rpm increases while the starting torque decreases which is a disadvantage for such turbine if compared to that with simple supported blades.

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