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Optimum Design of a straight bladed Darrieus turbine at Variable Turbine speed

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Abstract

A simplified design approach is presented for a vertical-axis straight-bladed Darrieus wind turbine. The design is conducted for variable turbine speed condition. A number of parameters such as solidity, design power, design wind speed, cut out speed, blade material, number of blades, airfoil shapes, supporting structure etc. control the design of a turbine. Considering all these variable parameters, the present design method gives guidelines to have optimum turbine configurations.

Nomenclature

A	projected frontal area of turbine
AR	aspect ratio $= H/C$
C	blade chord
C_p	turbine overall power coefficient
C_{pd}	power coefficient at design point
C_Q	turbine overall torque coefficient
D	turbine diameter
F_{cf}	centrifugal force
F_n	normal force (in radial direction)
F_{net}	net normal force (in radial direction)
H	height of turbine
I_x	area moment of inertia about chordal axis
m_b	blade mass per unit length
N_b	number of blades
P_o	overall power
Q	overall torque
Q_s	starting torque
rpm	turbine speed in revolutions per minute
rpm_d	rpm at besign point
rpm_m	maximum rpm
R	turbine radius
S_a	allowable stress in Newton mm^2
S_{bn}	bending stress due to net normal force in Newton/mm^2
S_{bt}	bending stress due to tangential force in Newton/mm^2
S_m	maximum value of blade stress in each revolution N/mm^2
t_e	maximum blade thickness as a fraction of chord
t_s	blade skin thickness
V_{au}	induced velocity in upstream side

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V_{ad}	induced velocity in downstream side
V_{cut}	cut out speed
V_{wu}	wake velocity in upstream side
V_{wd}	wake velocity in downstream side
$V_{\propto}$	wind speed
$V_{\propto_d}$	design wind speed
θ	azimuth angle
λ	tip speed ratio $=R\omega/V_{\propto}$
λ_d	tip speed ratio at design point
ρ	fluid density
σ	solidity $=NC/R$
ω	angular velocity of turbine in rad/sec

Introduction

Variable speed vertical-axis straight-bladed Darrieus wind turbines may be applied to perform water pumping for irrigation. It may also be used in the DC genarator/regulator/storage battery combination for generation of electricity in the remote areas. For this design there appear a number of variable perameters. Few of them are considered to be fixed before conducting the design analysis. These are number of blades, blade material, blade supporting type and cut out speed. In the design cut out speed is considered 14 m/sec and the blade material is chosen as the aluminium alloy. Blade supporting type is considered as that of simple svpported one.

In the present design analysis, the variable speed design is carried out at constant tip speed ratio. In other words, the load characteristic curve is assumed in such a way that the tip speed ratio remains constant. The constant tip speed ratio design may approximately follow the load characteristic curve of either a positive displacement pump or a centrifugal pump. However, to make the accuracy of the design, actual pump characteristic curve is necessary to be encountered. In the present design method, emphasis is given on finding a general design approach of a variable speed turbine rather than to study a particular problem.

Aerodynamic Design

A number of parameters control the design of a vertical axis Darrieus wind turbine. In this design the number of blades is considered as three. It produces relatively lower fluctuation of energy in each revolution of the turbine. In the design the strut profile is chosen as of airfoil shape which offers negligible loss of power. The turbine blade profile is selected as NACA 0015 It gives better lift-drag characteristics. Primarily the design power coefficient and aspect ratio are assumed and the design calculation is performed. Turbine configuration is determined. Cascade theory [1] is applied in order to find performance characteristics. Induced velocity is obtained from [1],

$$\frac{Vau}{V\propto}=\left(\frac{Vwu}{V\propto}\right)^{k_1} \quad \text{and} \quad \frac{Vad}{Vwu}=\left(\frac{Vwd}{Vwu}\right)^{k_1} \qquad (2\ 1)$$

where k_1 is an exponent obtained from a fit of experimental results. Power coefficient is calculated from,

$$C_p = C_Q.\lambda \qquad 2(2.)$$

where C_Q is obtained from,

$$\delta C_Q = \frac{\delta Q}{\frac{1}{2}\rho\lambda\ V\propto^2 R} \qquad (2.3)$$

Finally the blade stress is obtained corresponding to the cut out speed because at cut out speed stress is maximum, Maximum bendinding stress is determined from the following expression,

$$Sb_m = \frac{F_{net}\ H\ C\ t_c}{16\ I_x} \qquad (2.4)$$

If the maximum stress developed in the blade reaches near the allowable stress, the design is considered to be correct otherwise the design is repeated for safe stress limit.

Results and Discussion

Design configurations of a variable speed turbine at various solidities are shown in figure 1. The design conditions for wind speed and power are chosen as 8m/sec. and 10kw respectively. It can be seen from this figure that with the in-

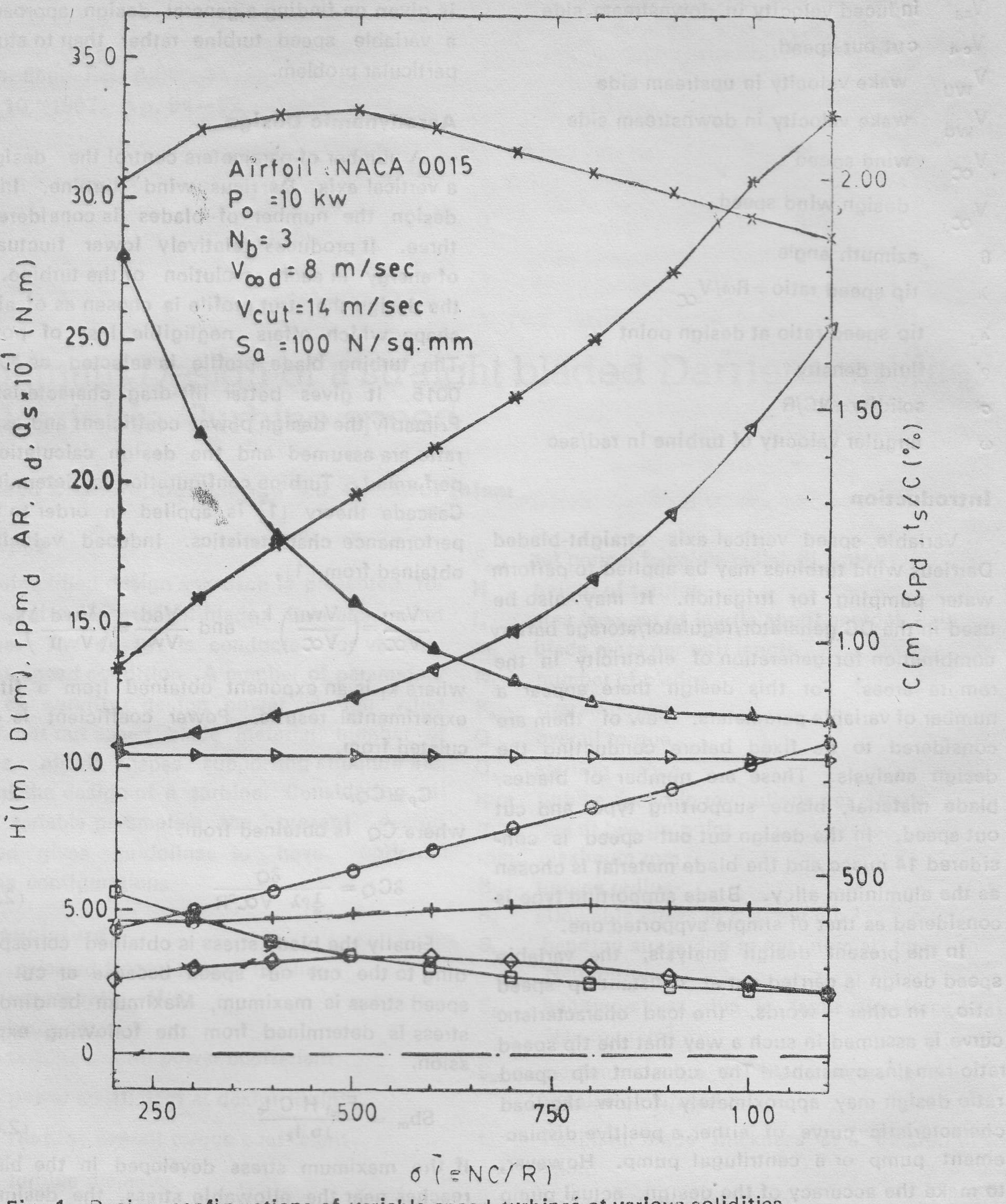

Fig. 1 Design configurations of variable speed turbines at various solidities.

Symbol	O	△	*	+	×	□	□	▷	◁
parameter :	H	D	C	AR	rpm_d	C_{pd}	λ_d	t_s/C	Q_s

crease of solidity the height and chord of the turbine increase nearly linearly while the turbine diameter decreases asymtotically. It is also observed from this figure that with the rise of solidity, starting torque increases adequately. Starting torque is important for the design of a variable speed wind turbine coupled with a pump. These starting torques are calculated at a wind speed of 4m/sec. Obviously high solidity turbine is good in consideration of higher starting torque and lower diameter, on the other hand, low solidity turbine is good in consideration of lower height and chord. A turbine with large diameter is not desirable because it incurs higher power losses due to additional drag created by the large supporting struts. Blade skin thickness remains constant with solidiiy. Also the aspect ratio does not very much. The design power coefficients are higher in the middle range of solidity. The lengths of struts and blades is minimum for blade solidity of 0.700.

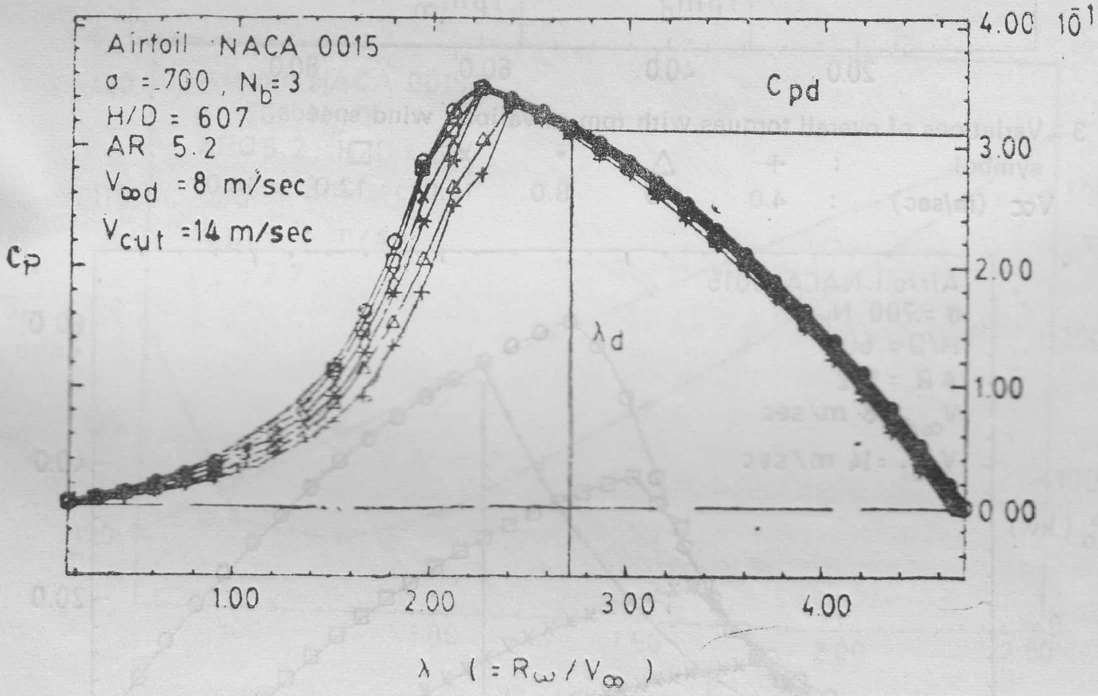

Fig. 2 Variations of overall power coefficients with tip speed ratios at different wind speeds.

symbol	:	+	△	*	x	□	O
V∞ (m/sec)	:	4 0	6.0	8.0	10.0	12.0	14.4

Figure 2 shows the power coefficient distribution with tip speed ratio while the figures 3 and 4 show respectively the distribution of overall torque and power with rpm of turbine at various wind speeds. The solidity is kept fixed at .700 for 10 kw. output. One may observe from the

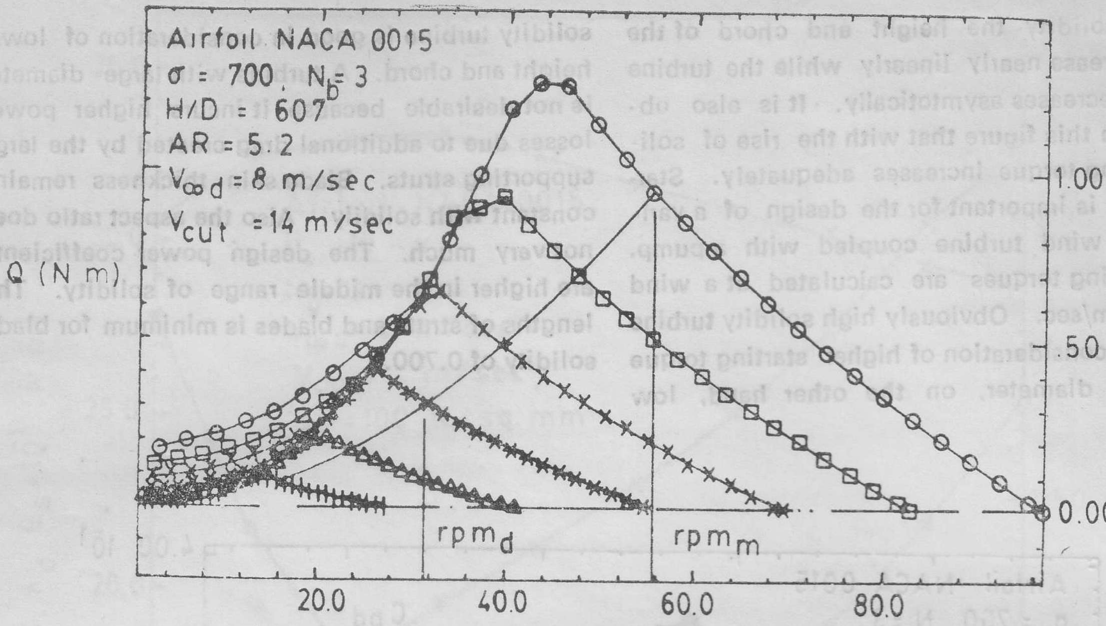

Fig. 3 Variations of overall torques with rpm at various wind speeds.

symbol	:	+	△	*	x	□	O
V∞ (m/sec)	:	4.0	6.0	8.0	10.0	12.0	14.0

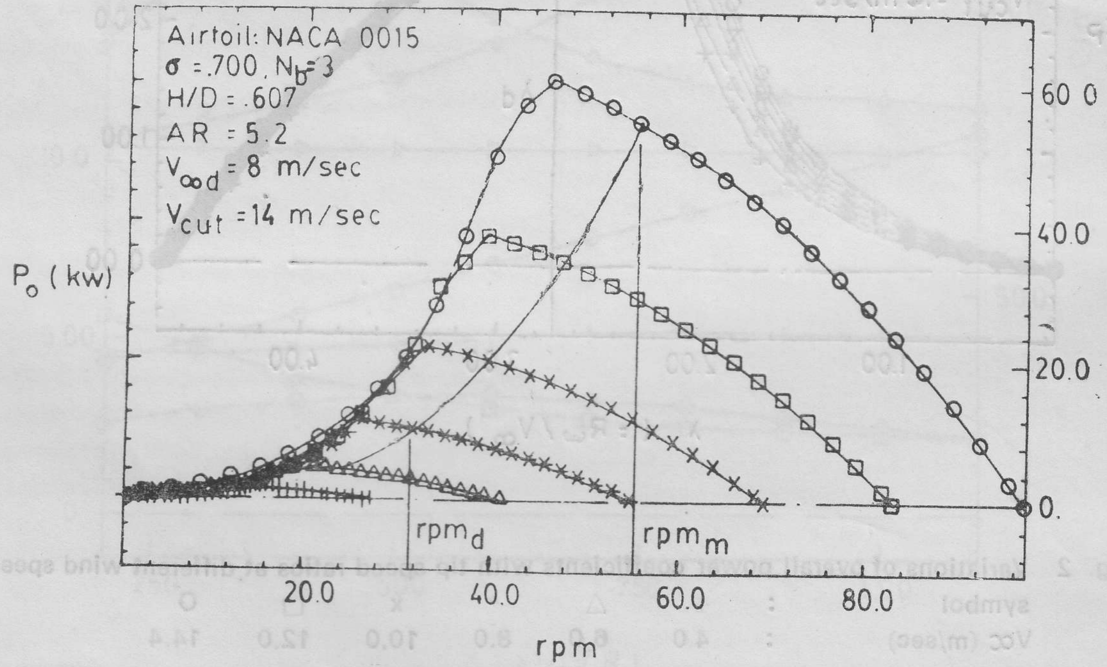

Fig. 4 Variations of overall power with rpm at various wind speeds.

symbol	:	+	△	*	x	□	O
V∞ (m/sec)	:	4.0	6.0	8.0	10.0	12.0	14.0

figure 2 that the design power coefficient has been chosen in the higher side of tip speed ratio. With a view to make the operation stable and smooth, design point is selected after the peak point, system load characteristic curves are shown in the figures 3 and 4. These figures also show that with the change of wind speed, both the torque and turbine speed change adequately. One may observe from these figures that the maximum rpm corresponding to the cut out speed is remarkably higher than the design rpm.

The variations of blade mass and the maximum blade stress with blade skin thickness are shown

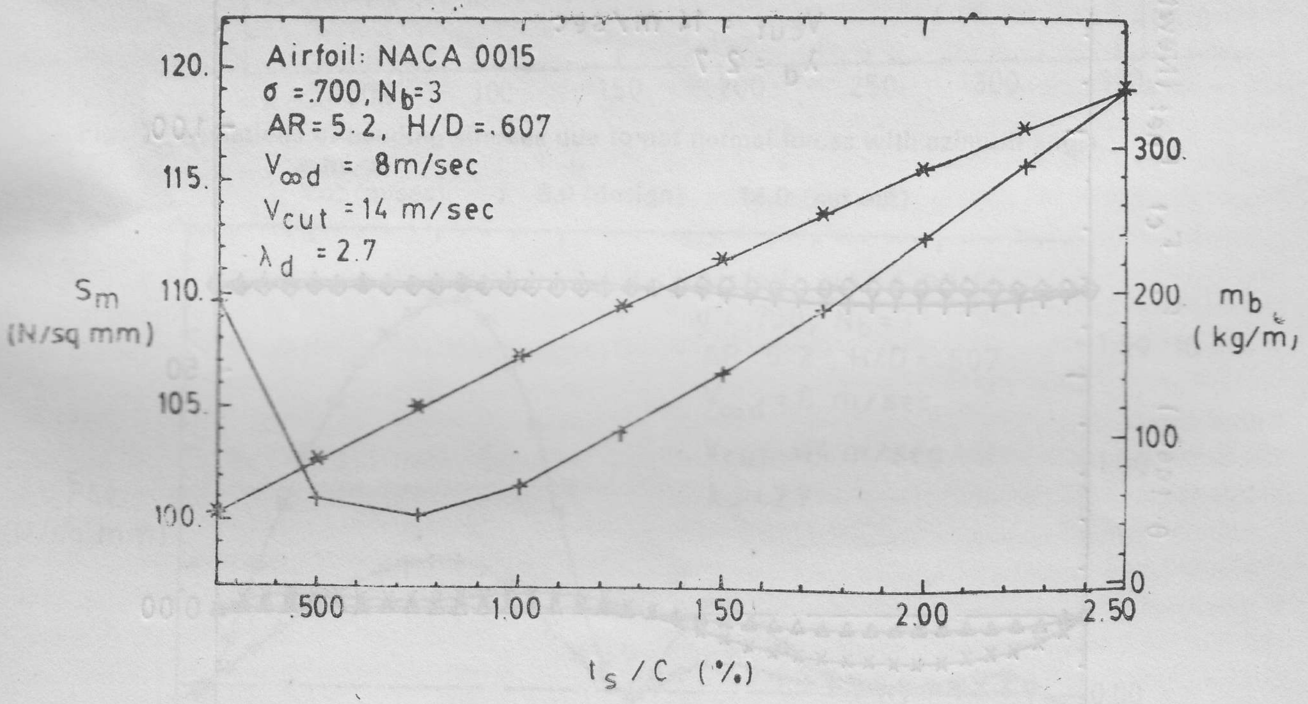

Fig. 5 Variations of blade mass and maximum blade stress with blade thickness.

symbol	:	+	*
parameter	:	S_m	m_b

in the figure 5. The skin thickness which corresponds to the lowest value of the maximum blade stress, is chosen as the design skin thickness.

Figure 6 presents the distributions of normal centrifugal and net normal forces with azimuth angle. The force corresponding to the design

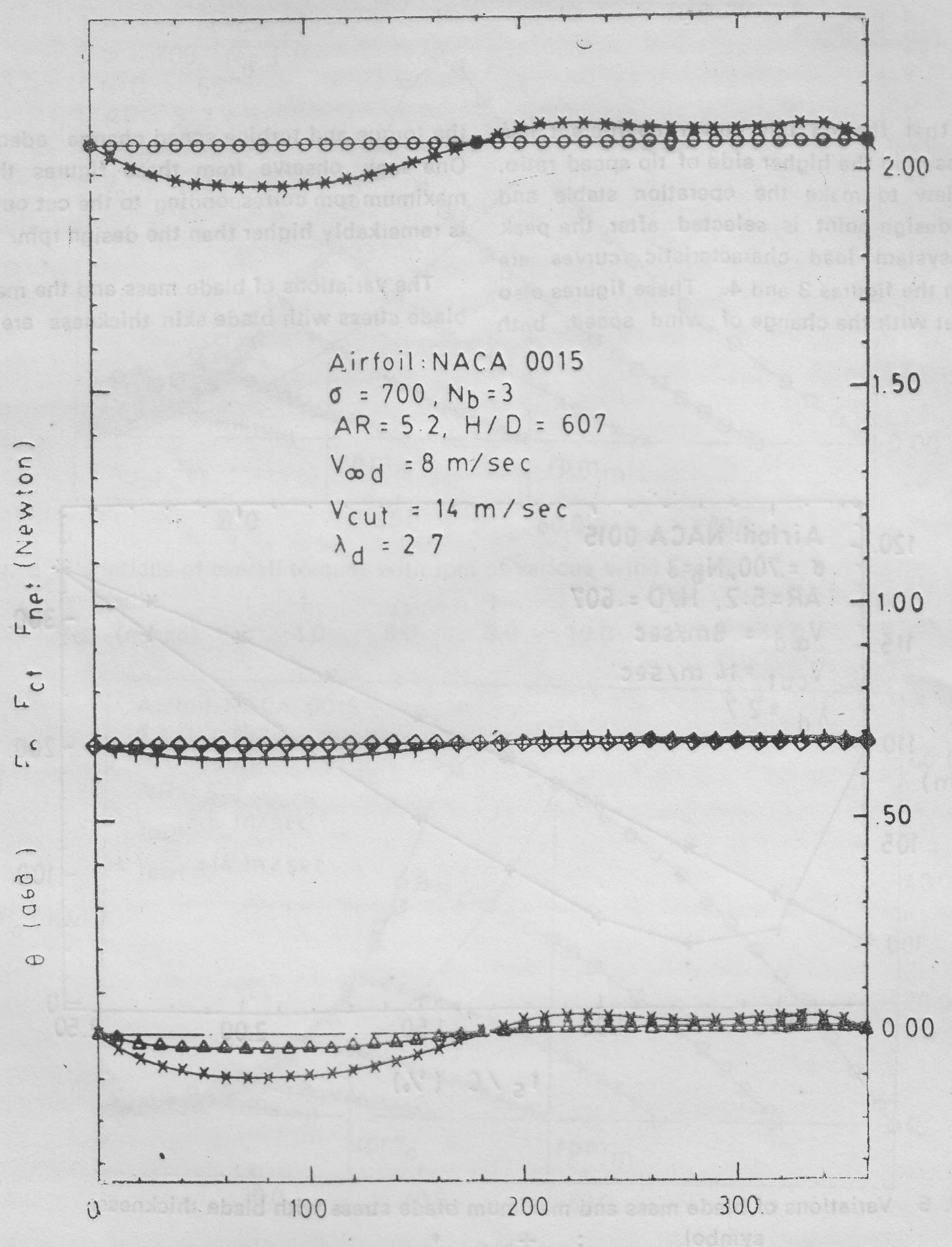

Fig. 6 Variations of normal, centrifugal and net normal forces with azimuth angle.

symbol : △ ◇ + x O *

parameter : F_n F_{cf} F_{net} F_n F_{cf} F_{net}

V∝ (m/sec) : 8.0 (design) 14,0 (cut out)

and cut out speed have been shown in this figure. The net normal forces corresponding to the cut out speed are much higher in comparison to those at the design wind speed. This happens mainly for the high rpm corresponing to the cut out speed and it creates high centrifugal force. This figure also shows that normal forces (aerodynamic) are almost negligible in comparison to the centrifugal forces.

At the design and the cut out speeds, the variations of the bendind stresses with azimuth angle are given in the figures 7 and 8. The

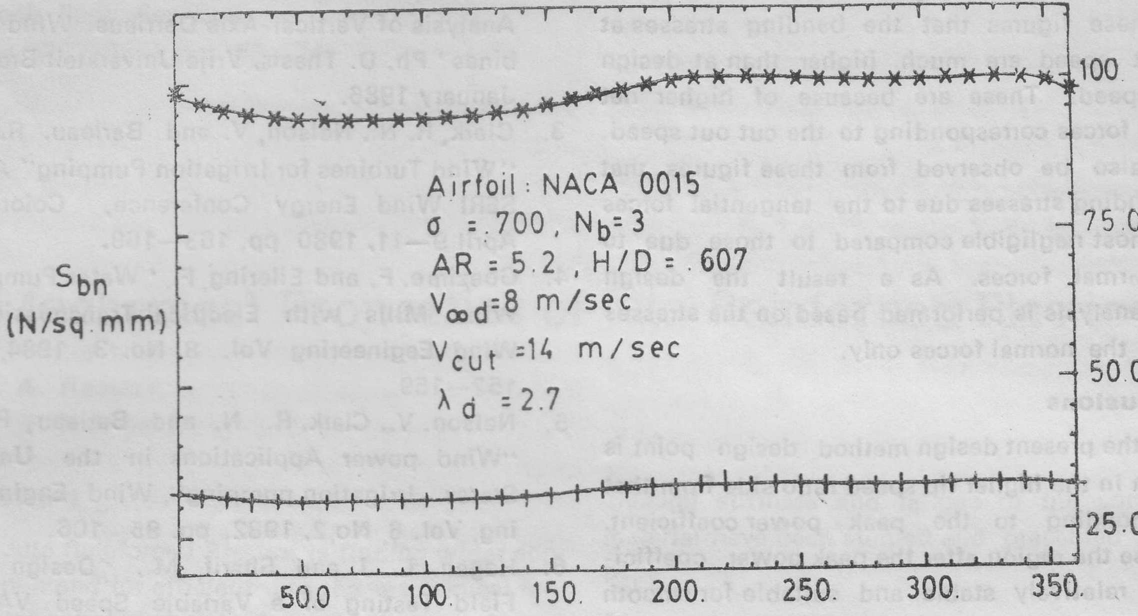

Fig. 7 Variations of bending stresses due to net normal forces with azimuth angle.

symbol : + *

V_∞ (m/sec) : 8.0 (design) 14.0 (cut out)

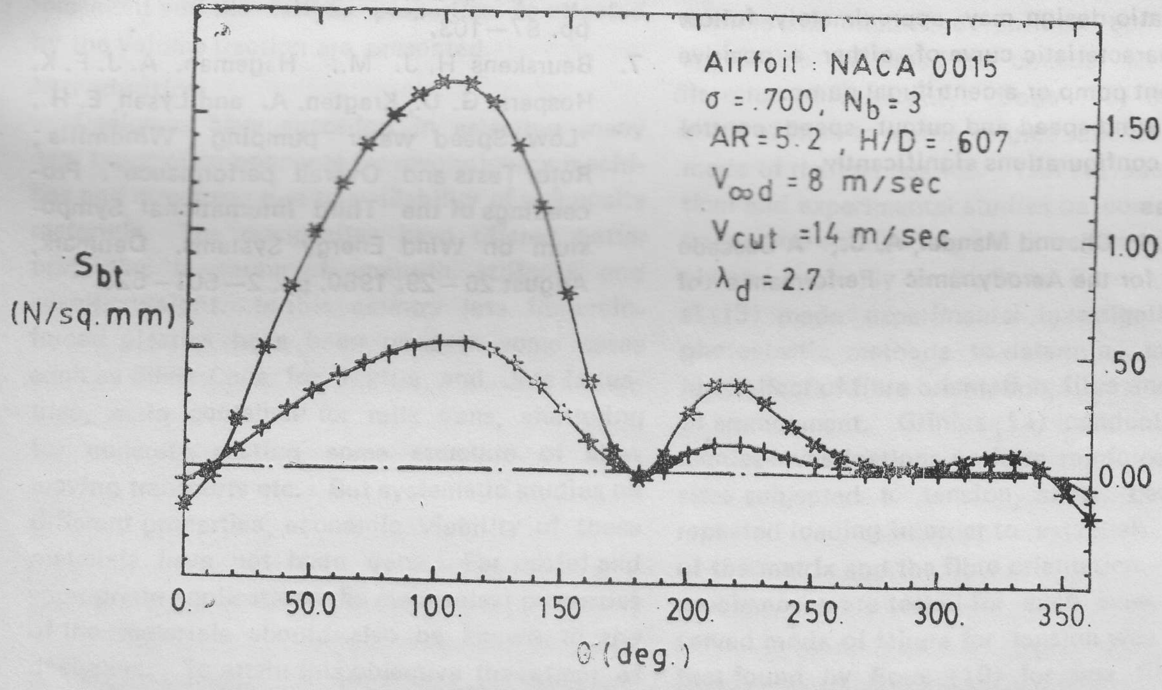

Fig. 8 Variations of bending stresses due to tangetial forces with azimath angle.

symbol : + •

V_∞ (m/sec) : 8.0 (design) 14.0 (cut out) figure 7 shows that the bending stresses due to net normal forces while the figure 8 shows bending stresses due to tangential forces. It is seen from these figures that the bending stresses at cut out speed are much higher than at design wind speed. These are because of higher net normal forces corresponding to the cut out speed. It can also be observed from these figures that the bending stresses due to the tangential forces are almost negligible compared to those due to net normal forces. As a result the design stress analysis is performed based on the stresses due to the normal forces only.

Conclusions

In the present design method, design point is chosen in the higher tip speed ratio side from that corresponding to the peak power coefficient. Because the region after the peak power coefficient is relatively stable and suitable for smooth operation.

The variable speed turbine design is carried out at constant tip speed ratio. The constant tip speed ratio design may approximately follow the load characteristic curve of either a positive displacement pump or a centrifugal pump.

Design wind speed and cutout speed control the design configurations significantly.

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