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Wind Turbine Blade Design UsingTheBlade Element Momentum Theory

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ABSTRACT: *Wind tunnel tests and prototyping are the usual methods available for developing engineering components and gadgets but these are usually costly and time consuming. Modelling can save both time and money. The blade design of the wind turbine has been modelled using the blade element momentum approach and a solution algorithm developed. Blade Element Momentum Theory equates two methods of examining how a wind turbine operates. The first method is to use a momentum balance on a rotating annular stream tube passing through a turbine. The second is to examine the forces generated by the aerofoil lift and drag coefficients at various sections along the blade. These two methods then give a series of equations that can be solved iteratively. The model calculates the aerodynamic lift, drag, and pitching moment of aerofoil sections along the wind turbine blades.*

KEYWORD: *stream tube, axial force, pitching moment, upstream, twist angle*

1. INTRODUCTION:

Energy from the wind has been used for centuries. The harnessed energy from the wind as windmills has been used to grind grains, pump water and drive other mechanical devices. For years, the wind power has been exploited to power ships and thus open new frontiers that helped in the expansion of international trade. In the 1920’s through to the 1950’s, many American Pains farmers were reported to have installed wind turbines to generate electricity but the process was slowed by the Rural Electricity Program which was designed to provide electricity to rural America. As grid electricity became available wind-electric generators were mothballed.However the 1970’s saw the resurgence of interest in energy self-sufficiency. This interest was stimulated and associated with the series of oil crisis of this period. The situation has been different with the Danes [1 - 5] who had since the 1890’s channelled their wind energy development efforts towards electricity generation and therefore the technology has evolved and matured over the years. It was only countries that have no coal, oil and gas resources that showed interest in renewable energy development before the seventies. The oil crises of the seventies, the finiteness of fossil fuel and environmental considerations are the main drivers for renewed interest in alternative sources of energy. Every country values its independence but without strong economy this is incomplete but energy availability readily, is an antecedent to strong economy. This can account for fact that the money markets go jittery once there is a hint of possible disruption in oil supply [6 -8].

In the development of the wind turbine there are a number of factors that have to be taken into consideration and these include wind resource and topology of the location as well as the threshold of wind velocities. The wind turbine will not operate if the wind velocity is less than 4 m/s and above 25 m/s, the wind turbine is likely to be turned off from the wind direction to avoid damage to the blades. Notwithstanding the wealth of data from the aviation industry, the design of the wind turbine has it peculiarities. The designer has to consider three distinct issues including the wind turbine blade aerodynamic losses, the mechanical drives and the electrical generator. There is abundant material in the literature on electrical generator and mechanical drives but fewer on blade design. If the blade design is not given adequate attention, the electrical generator and mechanical drives cannot operate optimally. There are software packages on blade design but software packages by their nature are limited to specific applications and extrapolating beyond this range will not guarantee the desired result. Again, anyone who understands the theory behind the production of a software package will make a better analysis of the results from the package. Therefore the purpose of this study is to develop a procedure to design a wind turbine blade using the blade element momentum method

2.0 THE BLADE ELEMENT MOMENTUM MODEL

Aerodynamic lift, drag, and pitching moment along the sections of wind turbine blades can be calculated using the Blade Element Momentum model (BEM). This is achieved by breaking into segments the span of the blade. The information required to carry out the analysis include the turbine geometry, operating condition, blade-element velocity and location, and wind inflow. The data is then used to calculate the various forces for each segment, which are then used to calculate the total distributed forces on the turbine blades. The aerodynamic forces affect the turbine deflections and vice versa, making the interaction fully aeroelastic. The models use relations based on two dimensional localized flow, and the characteristics of the aerofoils along the blade are represented typically by lift, drag, and pitching moment coefficients measured in wind tunnel tests.

The BEM theory is an extension of actuator disk theory, first proposed by the pioneering propeller work of Rankine and Froude in the late 19th century. The BEM theory, generally attributed to Betz [9],actually originates from two different theories: blade element theory and momentum theory [10 and 12]. Blade element theory assumes that blades can be divided into small elements that act independently of surrounding elements and operate aerodynamically as two-dimensional aerofoils whose aerodynamic forces can be calculated based on the local flow conditions. Blade Element Momentum Theory equates two methods of examining how a wind turbine operates. The first method is to use a momentum balance on a rotating annular stream tube passing through a turbine. The second is to examine the forces generated by the aerofoil lift and drag coefficients at various sections along the blade. These two methods are then equated to each other to give a series of equations that can be solved iteratively for each element of the blade.

2.1 Axial Force

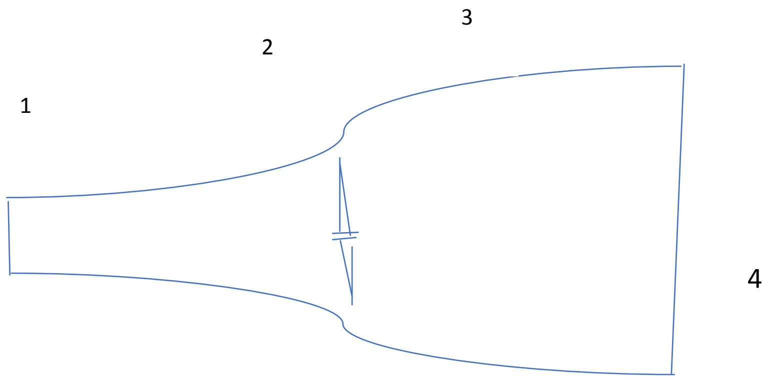

Fig 1. The Axial Stream Tube

Consider the stream tube around a wind turbine shown in Figure 1. Four stations are shown in the diagram 1, some way upstream of the turbine, 2 just before the blades, 3 just after the blades and 4 some way downstream of the blades. Between 2 and 3 energy is extracted from the wind and as a result, there is a change in pressure equivalent to Δp. At station 4 it is assumed that the static pressure has recovered fully to its freestream value to give $p_1 = p_4$. We can also assume that between 1 and 2 and between 3 and 4 the flow is frictionless so we can apply Bernoulli's equation. After some algebra:

$$P_1 + \frac{1}{2}\rho U_1^2 = P_2 + \frac{1}{2}\rho U_2^2 = P + \frac{1}{2}\rho U^2 \quad (1)$$

where

$$P + \frac{1}{2}\rho U^2 \quad (2)$$

is a general Bernoulis equation that holds between stations 1 and 2

But the energy extracted across the rotor blade is accounted by pressure drop, Δp

Therefore

$$P_1 + \frac{1}{2}\rho U_1^2 - \Delta p = P_4 + \frac{1}{2}\rho U_4^2 \quad (3)$$

Similarly,

$$P_3 + \frac{1}{2}\rho U_3^2 = P_4 + \frac{1}{2}\rho U_4^2 \quad (4)$$

But $P_1 = P_4$

Therefore equation (3) becomes

$$P_1 + \frac{1}{2}\rho U_1^2 - \Delta p = P_1 + \frac{1}{2}\rho U_4^2 \quad (5)$$

From which

$$\Delta p = \frac{1}{2}\rho(U_1^2 - U_4^2) \quad (6)$$

Thrust, T due to pressure drop

$$T = \Delta p.\ A = \frac{1}{2}\rho(U_1^2 - U_4^2).A \quad (7)$$

Net thrust (from equations 2 and 7)

$$T = \rho U.A\ (U_1 - U_4) = \frac{1}{2}\rho(U_1^2 - U_4^2).A$$

That is

$$\rho U.A\ (U_1 - U_4) = \frac{1}{2}\rho(U_1^2 - U_4^2).A$$

$$= \frac{1}{2}\rho(U_1 + U_4).\ (U_1 - U_4).A$$

From which

$$U = \frac{1}{2}\rho(U_1 + U_4) \quad (8)$$

Define the axial induction factor,

$$a = (U_1 - U)/U_1$$

From which

$$U = (1 - a)U_1 \quad (9)$$

From equations 8 and 9

$$U_4 = (1 - 2a)U_1 \quad (10)$$

Net power

$$W_{net} = ½ρU.AU_1^2 - ρU.AU_4^2$$

$$= ½ρU.A(U_1^2 – U_4^2) \quad (11)$$

In equation 11, substituting for U from equation 9 and for U_4 from equation 10

$$W_{net} = ½ρ.AU_1(1 – a)\{ U_1^2 - U_1^2(1 – 2a)^2\}$$

$$= ½ρ.AU_1(1 – a)\{ U_1^2 - U_1^2(1 – 2a)^2\}$$

$$= ½ρ.AU_1^3(1 – a)\{1- (1 – 4a + 4a^2)\}$$

$$= ½ρ.AU_1^3(1 – a)4a(1 - a)$$

$$= 2aρ.AU_1^3(1 – a)^2 \quad (12)$$

Similarly by substituting for U_4 from equation 10 in equation 7, net thrust is obtained as

$$T_{net} = 2aρ.AU_1^2(1 – a) \quad (13)$$

Available Power and thrust are respectively

$$W_{avail}= ½ρ.AU_1^3 \quad (14)$$

$$T_{avai} = ½ρ.AU_1^2 \quad (15)$$

Power and thrust Coefficient are respectively

$$C_W =\{2aρ.AU_1^3(1 – a)^2\}/(½ρ.AU_1^3)$$

$$= 4a(1 - a)^2 \quad (16)$$

$$C_T = \{2aρ.AU_1^2(1 – a)\}/(½ρ.AU_1^2)$$

$$= 4a(1 - a) \quad (17)$$

Differentiate C_W with respect to *a*

$$dC_W/da = d\{4a(1 – a)^2\}$$

$$= 4(1 - 3a)(1 – a) \quad (18)$$

2.2 Treatment of the Annular Element

The following assumptions are made in the treatment of the annular elements: it is assumed that there is no radial dependency, that is that what happens to one element is not felt by the others. The force from the blades on flow is constant in each annular element. This is to say that the rotor has infinite number of blades and to correct this assumption, the Prandtl Tip Loss factor is introduced. Consider the rotating annular stream tube of height *dr*at a radius, *r* and overall radius, *R*. The Area of the radial strip *dr* in figure 2is$2\pi rdr$, therefore

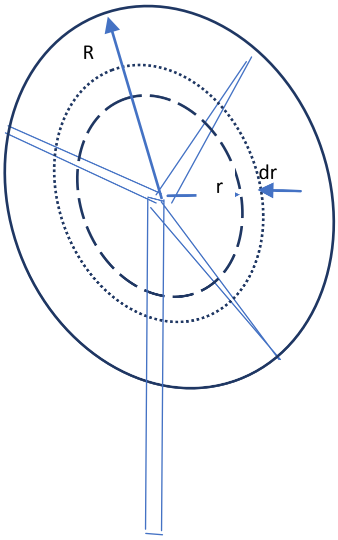

Fig. 2 The Rotating Annular Stream Tube

$$dT = (U_1 - U_4)\ dm/dt = 2\pi r\rho U\ (U_1 - U_4)dr \qquad (19)$$

The torque, *TQ* on the annular element is found by the use of moment of momentum equation and the rotational speed, $u_\theta$in the wake

$$dTQ = 2\pi r^2 \rho U u_\theta dr \qquad (20)$$

From equations (9) and (10), equation (19) can be expressed as shown below

$dT = 4\pi r\rho U_1^2 a(1 - a)dr$ and equation (20) becomes (21)

$$dTQ = 4\pi r^3 \rho U_1 \omega (1 - a)a' dr \qquad (22)$$

where ω is the angular rotation of the stream tube and

$$a' = u_\theta/(2\omega r) \qquad (23)$$

local pitch angle, θ

$$\theta = \theta_p + \beta \qquad (24)$$

where

β = blade twist

θ_p = pitch angle

α = angle of attach

$\varphi = \theta + \alpha$ (24b)

$\tan\varphi = (1 - a)U_1/(1 + a')\omega r$ (25)

U_{rel}= relative velocity can be obtained from

$U_{rel}^2 = [(1 - a)u_\theta]^2 + [(1 + a')\omega r]^2$ (26)

Or

$U_{rel}\sin\varphi = U_1(1 - a)$ (26b)

Or

$U_{rel}\cos\varphi = \omega r\,(1 + a')$ (26c)

Define lift, L and drag, D forces

$L = ½\rho U_{rel}^2 cC_L$ (27)

$D = ½\rho U_{rel}^2 cC_D$ (28)

Projecting per unit length the normal, F_n and tangential, F_t forces onto the rotor plane

$F_n = L\cos\varphi + D\sin\varphi$ (29)

$F_t = L\sin\varphi - D\cos\varphi$ (30)

Normalising with respect to $½\rho U_{rel}^2 c$ to obtain

$C_N = C_L\cos\varphi + C_D\sin\varphi$ (31)

$C_T = C_L\sin\varphi - C_D\cos\varphi$ (31b)

where

$C_N = F_n/(½\rho U_{rel}^2 c)$ (32)

$C_T = F_t/(½\rho U_{rel}^2 c)$ (32)

Define Solidity, σ

$\sigma = c(r)B/2\pi r$ (33)

where

c(r) is the local chord and B = number of blades

The normal and tangential force and torque on the control volume

$dT = BF_N dr$ (34)

$dTQ = rBF_T dr$ (35)

Substituting for U_{rel} from equation (32) into equation (26b) and using the result to eliminate F_N from equation (34) to obtain

$$dT = ½\rho BU_1[(1 - a)^2 cC_n dr]/ \sin^2 \varphi \quad (36)$$

$$dTQ = ½\rho BU_1[(1 - a)\ \omega r\ (1 + a')\ cC_T dr]/(\sin \varphi \cos \varphi) \quad (37)$$

By equating equation (21) to equation (36) and eliminating the number of blades, B using equation (33). The following results

$$a = \sigma C_n/(4 \sin^2 \varphi + \sigma C_n) \quad (38)$$

Similarly, by equating equation (22) to equation (37) and eliminating the number of blades, B using equation (33). The following results

$$a' = \sigma C_t/(4 \sin \varphi \cos \varphi - \sigma C_t) \quad (39)$$

When the Prandtl tip loss factor due to wake vortices is taken into consideration, equations (38) and (39) become

$$a = \sigma C_n/(4F \sin^2 \varphi + \sigma C_n) \quad (40)$$

$$a' = \sigma C_t/(4F\sin \varphi \cos \varphi - \sigma C_t) \quad (41)$$

where

$$F = 2\cos^{-1} e^{-f} \quad (42)$$

$$f = (B/2)(R - r)/(r\sin \varphi) \quad (43)$$

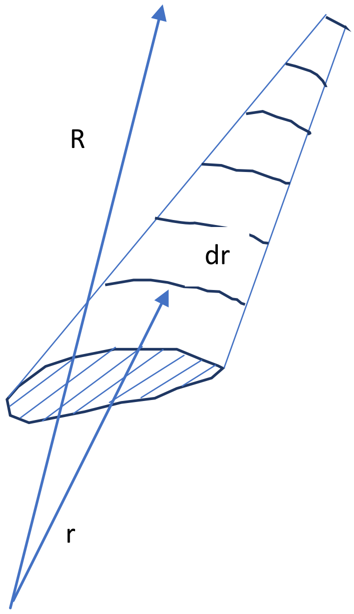

Fig. 3 Elements of the Blade Element Momentum Theory

2.3 The Algorithm

Consider the schematic diagram in figure 3. Blade element theory involves dividing up the blade into a sufficient number of elements and calculating the flow at each one. Overall performance characteristics are determined by numerical integration along the blade span.

The schematic of the elements considered in the solution are shown in figure 3. The algorithm for the solution of equation (40) and (41) may be summarised thus:

Assume initial values for *a* and *a'* for example zero for each. Calculate the flow angle φ using equation (25). Calculate the local angle of attack using equation (24b). Obtain from the table values for $C_l(\alpha)$and $C_d(\alpha)$. Calculate C_N and C_T from equations (31) and (31b). Next calculate f from equation (43) then estimate F. Compute *a* and *a'* from equations (40) and (41) respectively. If a and a' are still outside the tolerance then recalculate the flow angle φ and repeat the iteration process from that point until the tolerance is met. Calculate the load on the element. This is repeated to all the elements and finally summed up to get the load on the individual blade.

3.0 DISCUSSION:

Because of its simplicity, BEM theory does have its limitations. One primary assumption is that the calculations are static; it is assumed that the airflow field around the aerofoil is always in equilibrium and that the passing flow accelerates instantaneously to adjust to the changes in vorticity in the wake. However in practice, the aerofoil response takes time to adjust to a changing wake resulting from new inflow or turbine operating conditions [13]. When large deflections occur , the blades experience large bending movementsoutside the rotor plane and the BEM theory breaks down. Because the theory assumes that momentum is balanced in a plane parallel to the rotor, any deflections of the rotor will lead to errors in the aerodynamic modelling. Another limitation of BEM theory comes from blade element theory. In the theory two dimensional flow is assumed and this involves the neglect of spanwise flow. The theory is therefore less accurate for heavily loaded rotors with large pressure gradients across the span. Some other limitations of the original theory include no modeling of tip or hub vortex influence on the induced velocities and an inability to account for skewed inflow. However, corrections to the original theory have provided some methods to model these aerodynamic effects [14 - 18]. Inspite of the limitations, BEM theory has been used widely as a reliable model for calculating the design parameters for the wind turbine blades.

4. CONCLUSION

The blade element momentum theory has been used to develop an iterative method for the design of the wind for a given input process. Solution algorithm has also been added for the benefit of users.

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