Performance Prediction of a Straight-Bladed Darrieus Water Turbine using Multiple Stream Tube Model

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Abstract

The use of kinetic energy of flowing water in river or canal is becoming attractive alternative to meet the demand of energy. The aim of the present work is to predict the performance of Darrieus type hydrokinetic turbine. Various computational models have already been developed to predict the performance. In this paper Multiple Stream Tube model is used to predict the performance of a Straight Bladed Darrieus water turbine. It has been observed that performance of a Darrieus turbine mostly depends on parameters like Tip Speed Ratio, Solidity and blade geometry. Effects of these parameters on to the performance of a turbine are carried out here. It is also found that turbine initial blade angular position is also responsible for the self-starting of the turbine. Effect of blade chord length, rotor radius and type of blade is shown in present work.

Keywords — *Darrieus water turbine, water current turbine, VAWT, Multiple Stream Tube Model, Hydro kinetic turbine.*

NOMENCLATURE

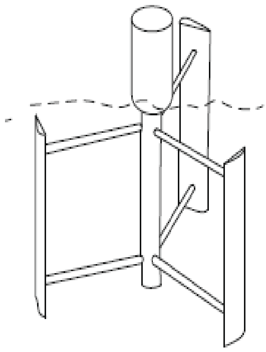
A	Frontal area of turbine
a	Interference factor
C	Chord Length of Blade
C_n	Normal force coefficient
C_p	Coefficient of Power
C_t	Tangential force coefficient
F_s	Average stream wise force
f_s^*	Non-dimensional stream wise force
h	Height of Blade
n	No. of Blades
ns	No. of stream tube
R	Radius of turbine
V_∞	Free stream velocity
V_a	Axial component of velocity
V_c	Chordal component of velocity
V_n	Normal component of velocity
ω	Angular velocity of Blade
α	Angle of attack
θ	Azimuth angle
σ	Solidity of turbine

I. INTRODUCTION

Today, the demand of power is increasing quickly. To meet this obligation, necessarily attention requires on the renewable energy sources. Recently, researches are going on the Darrieus turbine for river application to generate the power from flowing water.

Darrieus turbine was discovered by French inventor G. J. M. Darrieus and patented the concept in 1931 with U.S. patent office [6]. Concept of Darrieus is more popular as wind turbine. However, as water is denser than air, it is possible to extract more power from water compare to wind under certain conditions. In present work focus is made to use Darrieus turbine as hydrodynamic application.

Darrieus turbine mainly consists of two or more hydrofoil blades as shown in Fig. 1 and it is a lift driven turbine. Other companion of this turbine is Savonious turbine as shown in Fig. 2, which is a drag driven turbine. Darrieus produces better power but having poor starting characteristics while Savonious produces less power but having good staring characteristics. From literature it is found that Darrieus shows better performance in water application even at low speed of water as compared to wind application. Thus present work shows an emphasis on Darrieus turbine.



.**Fig 1: Darrieus Turbine**

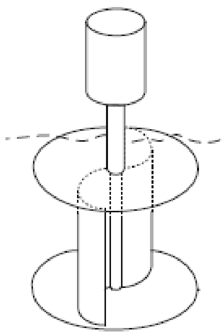


Fig 2: Savonious Turbine

II. BASIC TERMINOLOGY

A. Coefficient of Power (C_p)

Flowing water having the kinetic energy and turbine rotor extracts the part of its energy to produce the power. So the ratio of power developed by the rotor to the kinetic energy of flowing water is called as coefficient of power. Higher value of C_p indicates better performance. According to Betz limit it is found that maximum value of C_p is 0.593 [6]. However it was found that, this value can be increases in the case of water application [1].

$$C_p = \frac{P_{rot}}{P_{hyd}} = \frac{P_{rot}}{\frac{1}{2}\dot{m}V_\infty{}^2} = \frac{P_{rot}}{\frac{1}{2}\rho A V_\infty{}^3} \qquad (1)$$

B. Tip Speed Ratio (TSR)

It is defined as a ratio of blade velocity u to the free stream velocity V_∞. It is one of the most important parameters used to non-dimensionalize the performance of wind or water turbines when comparing different rotor configurations.

$$TSR = R\omega / V_\infty \qquad (2)$$

C. Solidity (σ)

It is defined as the ratio of a Blade area to the Rotor area. In practical terms, rotor solidity gives a sense of how much lifting area is present on a rotor relative to its size.

$$\sigma = nC/D \qquad (3)$$

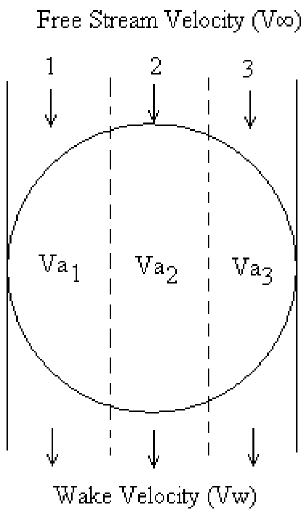
Where, D is the diameter of the rotor. From literature survey, it is found that C_p is related with TSR and Solidity.

III. MULTIPLE STREAM TUBE MODEL

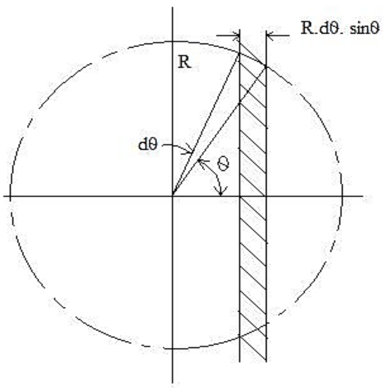
Various Momentum models have been developed by different researchers. In 1974, Wilson &Lissaman developed a MST model for wind power generation. Strickland in 1975 presented an advanced model for Darrieus type wind turbine. Strickland had introduced wind shear effects in calculation. Thus in present work attention is provided on Strickland's model.

As shown in Fig. 3 (a), a series of equally spaced and parallel stream tubes are assumed to flow towards turbine rotor. Width of each stream tube is $R.d\theta.sin\theta$ for any azimuth angle increment $d\theta$ as shown in Fig. 3 (b).

Fig. 4 shows the velocity triangle. Where V_a is the induced or axial velocity component. It is found that ultimate goal of each model is to calculate the V_a by iterative process. In present work Strickland's model is adopted to calculate V_a.



(a)



(b)

Fig3: Multiple Stream Tube Model

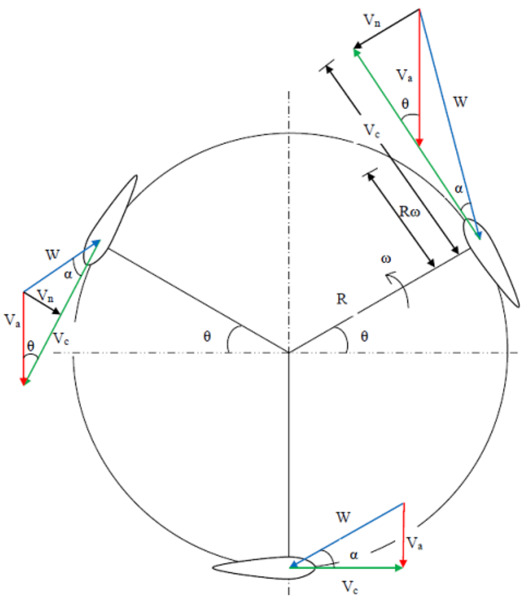


Fig4: Velocity triangle of a turbine blade

Governing equations like continuity, momentum and energy equations are applied to predict the performance. Turbine efficiency for a straight bladed rotor with MST model follows an iterative process. When water flows towards the rotor passage its velocity decreases due to interference. So Strickland had introduced the Interference Factor 'a'.

Where,

$$a = (V_\infty - V_a) / V_\infty \quad (4)$$

A. Design Procedure

Initially induced velocity V_a is estimated by considering 'a' equal to 0.01 and by doing iterative process new value of 'a' can be obtained at a respective azimuth angular position. From above eq. (4) V_a can be initialized by putting the value of V_∞ which can be measured.

Flowchart as shown in Fig. 5 can be followed for the calculation.

Relative flow velocity is given by:

$$W = \sqrt{V_c^2 + V_n^2} \quad (5)$$

Where,

$$V_c = R\omega + V_a cos\theta \quad (6)$$

$$V_n = V_a sin\theta \quad (7)$$

Angle of attack can be obtained by:

$$\alpha = tan^{-1} (V_n/V_c) \quad (8)$$

Blade Reynold no. is obtained by:

$$R_{eb} = \rho WC/\mu \quad (9)$$

For a given Reynold no. and angle of attack the coefficient of Lift (C_l) and Drag (C_d) can be obtained from already available data of Sandia Laboratory (Robert E. Sheldahi et. al., 1981).
Lift and Drag force is given by:

$$L = 0.5\, C_l\, \rho\, C\, h\, W^2 \quad (10)$$

$$D = 0.5\, C_d\, \rho\, C\, h\, W^2 \quad (11)$$

Average stream wise force is given by:

$$F_s = 2\, \rho\, A\, V_a\, (V_\infty - V_a) \quad (12)$$

Since each blade passes through a stream tube twice in one revolution than average thrust force is:

$$F_s = n.f_s\, (d\theta/\pi) \quad (13)$$

Where, $f_s$is the stream wise force for individual blade element.

Eliminating F_s from eq. (12) and eq. (13) and by putting the expression for 'A' yields:

$$\frac{n\, f_s}{2\pi\rho R\, h\, sin\theta\, V_\infty^2} = \frac{V_a}{V_\infty}\left(1 - \frac{V_a}{V_\infty}\right) \quad (14)$$

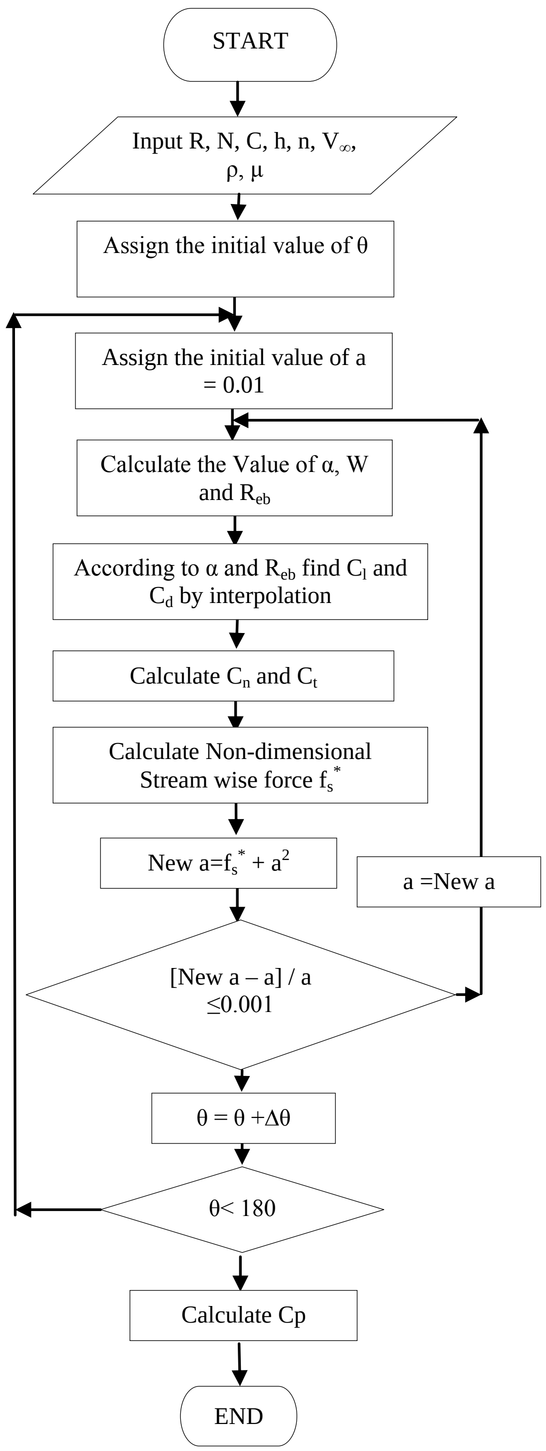


Fig 5: Design Procedure

Left side of eq. (14) is termed as non-dimensional stream wise force (f_s^*). Thus,

$$f_s^* = \frac{n\, f_s}{2\pi\rho R\, h\, sin\theta\, V_\infty^2} \quad (15)$$

The thrust in the direction of stream can also be defined as:

$$f_s = 0.5\, \rho\, W^2\, C\, h\, (C_n sin\theta - C_t cos\theta) \quad (16)$$

Where, as shown in Fig. 6

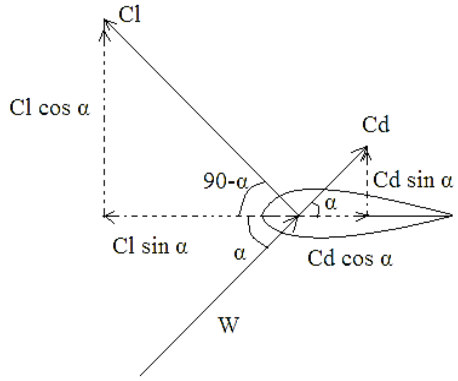


Fig 6: Coefficient of Lift and Drag

$$C_t = C_l \sin\alpha - C_d \cos\alpha \quad (17)$$

$$C_n = C_l \cos\alpha + C_d \sin\alpha \quad (18)$$

From eq. (15) and (16), Non dimensional stream wise force is turned out as:

$$f_s^* = \frac{nc}{4\pi R}\left(\frac{W}{V\infty}\right)^2 (C_n - C_t \cot\theta) \quad (19)$$

New value of interference factor can be written as (Strickland et. al., 1975):

$$a = f_s^* + a^2 \quad (20)$$

Power coefficient relative to stream power turned out as (D. J. Hilton et. al., 1983):

$$C_p = \frac{nC\,(TSR)}{2R*ns}\sum_1^{ns}\left(\frac{W}{V\infty}\right)^2 C_t \quad (21)$$

And relative to Betz limit is [1]:

$$C_{pb} = \frac{27*nc\,(TSR)}{32*R*ns}\sum_1^{ns}\left(\frac{W}{V\infty}\right)^2 C_t \quad (22)$$

Above design procedure can be adopted for calculating the performance of a turbine.

IV. PERFORMANCE PREDICTED CURVES

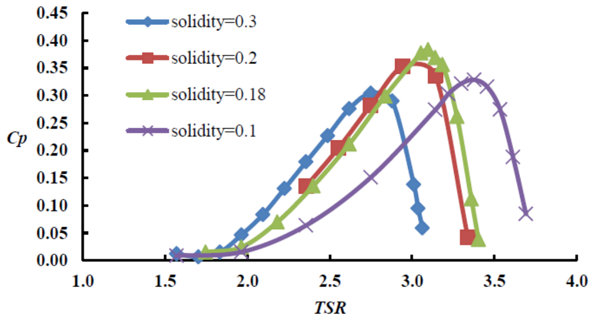
Fig. 7 shows the performance prediction curves for the NACA-0015 profile. Though unsymmetrical NACA profiles produces greater lift than symmetrical one but usually symmetrical profiles are tested for analyzing the performance and conformal transformation techniques are applied for predicting the performance of different profiles.

Prediction is carried out by coding in MATLAB for three NACA 0015 blades having chord length of 0.3 m and height of 2.4 m. free stream velocity is taken as 0.6 m/sec which is usually available in river or canal. No. of stream tube is taken as 36.

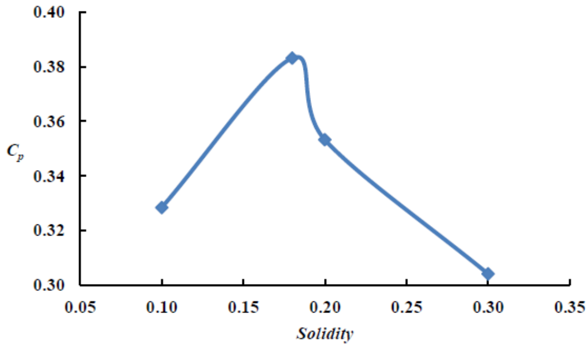
To identify and analyze the effect of solidities rotor radius is considered as a variable parameter. Thus to obtain the solidity of 0.3, 0.2, 0.18 and 0.1 from eq. (3) rotor radius becomes 1.5, 2.25, 2.5 and 4.5 respectively.

Fig. 7(a) shows the effect of *TSR* on coefficient of power at various solidities. It is found that for any solidity of turbine there may be an optimum *TSR* at which optimum value of C_p can be obtained.

From Fig. 7(b), it is found that there must be an optimum solidity at which maximum power can be extracted from the water.



(a)



(b)

Fig7: Effect of solidities on C_p

For continues rotation of turbine, tangential force is responsible but its magnitude depends on its angular position. Fig. 8 shows the variation in tangential force coefficient at different angular position of the blade. It was found that when turbine blade is nearly at 0^0, 90^0& 180^0; the tangential force coefficient is negative which indicates rotation of blade in opposite direction. This can be proved from the experiments. Thus initial angular position of the blade is important for self-starting of a turbine rotor.

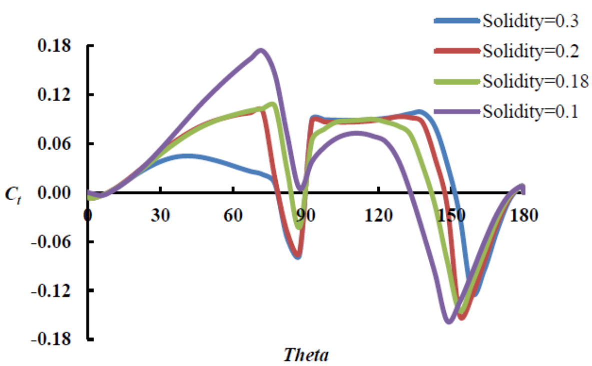


Fig 8: C_t vs. θ at different angular position

To get more insight, further study is made on narrow channel. Performance prediction of a turbine with different chord length is carried out below Fig. 9 for NACA 0021; radius 0.15 m, free stream velocity is taken as 0.5 m/sec.

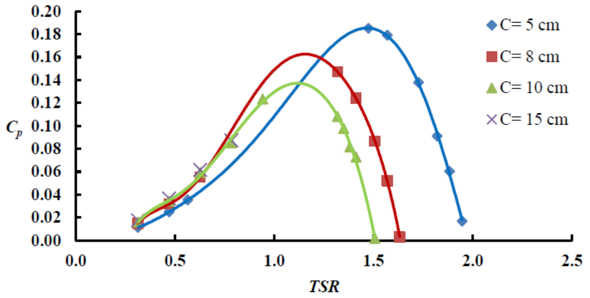


Fig 9: Effect of chord length on C_p

Effect of different NACA blades on the performance of a turbine by varying the length of chord is shown in below Fig. 10 for radius 0.15 m, free stream velocity is taken as 0.5 m/sec, no. of stream tubes as 18.

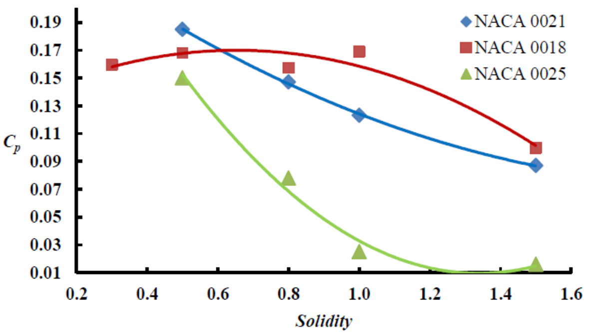


Fig10: Effect of NACA blades on C_p

V. CONCLUSIONS

From various performance predicted curves firstly it is found that optimum value of coefficient of power can be obtained at solidities of 0.16 to 0.19 where TSR is nearly 3. However choice of solidity depends on the size and application of turbine, velocity of fluid, blade profiles and its dimensions as well as nature of flow of a fluid which also plays a crucial role for getting optimum parameters. From the various graph of Cp vs. TSR, it is concluded that turbine must be operate below optimum TSR because after this point, further increases in speed drastically decreases the performance.

Secondly, initial angular positions of the blades are important for good starting. It is also found that MST model is not valid for high TSR and high solidity turbine because of the convergence problem.

From performance prediction on three NACA blades, it was found that NACA-0021 extracts more power than the other profiles for low solidities. At last, issue regarding to the optimum solidity is still challenging part however present work can be consider as a good starting point for predicting the performance.

REFERENCES

[1] D. J. Hilton, 1983, “Performance of a Darrieus water turbine at various solidities”, Eighth Australian fluid mechanics conference, university of Newcastle, N.S.W.

[2] Robert E. Sheldahi, Paul C. Klimas, March-1981, “Aerodynamic characteristics of seven symmetrical airfoil section through 180-Degree angle of attack for use in aerodynamic analysis of Vertical Axis Wind Turbine”, Sandia National Laboratories Report.

[3] Paraschivoiu I., 2002, “Wind turbine design: with emphasis on Darrieus concept”, Montréal: Polytechnic international Press.

[4] M. J. Khan, 2006, “Design consideration of a straight bladed Darrieus rotor for river current turbines”, IEEE ISIE, Montreal, Quebec, Canada.

[5] R. Dominy, 2007, “Self-starting capability of Darrieus turbine”, Proc. IMechE Vol. 221 Part A: J. Power and Energy.

[6] M. Islam, 2008, “Aerodynamic models for Darrieus type straight bladed vertical axis wind turbines”, Renewable and sustainable energy reviews-12, pp. 1087-1109.

[7] Gareth I Gretton, 2009, “The hydrodynamic analysis of a vertical axis tidal current turbine”, Ph.D. thesis, university of Edinburgh.

[8] Brian Kirke, 2003, “Developments in ducted water current turbines”, School of Engineering, Griffith University, PMB 50, Gold Coast Mail Centre, Qld 9726, Australia.

[9] Wlson&Lisaman, 1976, “Aerodynamic performance of wind turbine”, National renewable energy laboratory.

[10] Strickland, 1975, “The Darrieus turbine: performance prediction model using multiple stream tubes”, Sandia Laboratories energy report.

[11] M. M. AslamBhutta, 2012, “Vertical axis wind turbine: A review of various configuration and design techniques”, Renewable and Sustainable Energy Reviews -16, pp. 1926–1939.

[12] Vimal Patel, AshwinAhir, T.I.Eldho, S.V. Prabhu, 2012, “Experimental Investigations on the Performance of Darrieus Straight Blade Turbine for Hydrodynamic Applications”, Thirty Ninth National Conference on Fluid Mechanics and Fluid Power (FMFP-2012), SVNIT Surat.

[13] Prabhu S.V., Vimal Patel, HimanshuChaudhari, 2013, “Performance Prediction of H-Type Darrieus Turbine by Single Stream Tube Model for Hydro Dynamic Application”, International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 2 Issue 3.

[14] M. SaqibHameed and S.KamranAfaq, 2013, “Design and analysis of a straight bladed vertical axis wind turbine blade using analytical and numerical techniques”, Ocean Engineering 57, pp. 248–255.

[15] Feng-Zhu Tai, Ki-Weon Kang, Mi-Hye Jang, Young-Jin Woo, Jang-Ho Lee, 2012, “Study on the analysis method for the vertical-axis wind turbines having Darrieus blades”, Renewable Energy xxx, pp. 1-6.

[16] PayamSabaeifard, 2012, “Determination of Vertical Axis Wind Turbines optimal configuration through CFD Simulations”, International Conference on Future Environment and Energy, Singapore. Vol-28.

[17] Y M Dai, N Gardiner, R Sutton, and P K Dyson, 2011, “Hydrodynamic analysis models for the design of Darrieus-type vertical-axis marine current turbines”, Proc. IMechE Vol. 225 Part M: J. Engineering for the Maritime Environment.

[18] Ibrahim M. Rashed and Hashem.I. Abusannuga, 2011, “On the Aerodynamic Performance of Darrieus Wind Rotor”, Journal of Engineering Research (University of Tripoli) Issue-15.

[19] Radu BOGĂŢEANU, Bogdan DOBRESCU, Ion NILĂ, 2010, “Aerodynamic performance prediction of Darrieus-type wind turbines”, INCAS BULLETIN, Volume 2, pp. 26 – 32.