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A new approach for optimization of Vertical Axis Wind Turbines

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ABSTRACT

A new approach has been developed for the optimization of Vertical Axis Wind Turbines (VAWTs). The approach is derived from double multiple streamtube theory (DMST) and adopts the concept of "Representative streamtube" wherein the entire aerodynamic property of the VAWT is assumed to be represented by a single streamtube occupying a specific azimuthal location. Five input parameters namely; power, wind velocity, aspect ratio, air viscosity and air density and six output parameters that are minimally required for the construction of a straight bladed, constant pitch VAWT are considered in the study. The discrete data of lift and drag coefficients pertaining to specific values of Reynolds number and angle of attack are arranged in the order of decreasing lift to drag ratio and starting with the first set of coefficients, a check is made if it is eligible to become Representative streamtube for the particular problem. The check is done through a tri-directional "Demand Factor" test that seeks the compatibility of Reynolds number and angle of attack values of the aerofoil data under consideration. The first set which gains the eligibility to become "Representative streamtube" marks the solution for the particular problem.

1. Introduction

A good summary of the models developed for analysis of Vertical Axis Wind Turbines (VAWTs) has been presented in (Islam et al., 2008). In general, the computational models have been classified under three categories: Momentum model, vortex model and cascade model. Among these models, momentum model is the most prominent one and the one that is being researched the most. Momentum model was first introduced as single streamtube theory which evolved into multiple streamtube theory which further evolved into double multiple streamtube theory (DMST) with increased accuracy achieved on every revision. Fig. 1 depicts the progression of streamtube theory with each set of parallel lines denoting a streamtube. In this figure: V_u, $V_u(1), V_u(2)$ and $V_u(3)$ are the upstream wind velocities in the streamtubes that are a modification of the external wind velocity effected through the actuator disk effect of the wind hitting the rotating VAWT. Here, $V_d(1), V_d(2)$ and $V_d(3)$ are the downstream wind velocities in the streamtubes.

Double multiple streamtube theory (DMST) is being attributed to Paraschivoiu who devised the theory as early as 1981 (Paraschivoiu, 1981). The theory has thus been widely used (Homicz, 1991; Tang et al., 2011; Beri and Yao, 2011). The DMST has also been validated experimentally (Bogăţeanu et al., 2010) and methods developed (Maheri et al., 2006) to aid faster convergence of DMST iterations has improved it's acceptability among researchers. The versatility of the method has enabled its use as a primary analysis tool to lead in to analyzing secondary effects like the gyroscopic effect (Blusseau and Patel, 2012; Borg et al., 2013).

Streamtube theories are the most convenient method for optimization exercises. Re-running the analysis after changing the parameters are the quickest with regards to computational effort and time. On the other hand, rigorous analysis such as Computational fluid dynamics (CFD) involves, extra effort in re-runs including changing the parameter for the new model, regenerating the mesh around the modified region, further refinement to meet error tolerance, etc. Also, such methods demand significant computational time. Table 1 outlines some of the optimization studies carried out in the past using streamtube theories. In this table, "SST" stands for single streamtube theory and "MST" stands for multiple streamtube theory (the theories depicted in Fig. 1).

Despite being the simplest of methods available for the optimization of VAWTs, the formulation of streamtube theories (as will be discussed in Section 2) is complex enough that a formula based numerical optimization process is difficult through it. This is because, the variables involved in analysis are so inter-connected to each other that the seperation of their effects is difficult. It is for this reason that most of the optimization studies using streamtube theories are based on the traditional approach of incrementing certain analysis controlling parameters and re-running the analysis for each case

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Nomenclature

List of symbols

α	angle of attack
λ	tip speed ratio
λ_L	lower bound of tip speed ratio
λ_{opt}	the optimum value of tip speed ratio at which computation are performed
λ_U	upper bound of tip speed ratio
μ	viscosity of wind
ω	angular velocity
ρ	density of air
θ	azimuthal location
a	induction factor
AR	aspect ratio
C	chord length
C_D	drag coefficient
C_L	lift coefficient
C_n	force coefficient along the normal direction
C_P	coefficient of power
C_{PL}	lower bound of optimum coefficient of power
C_{Pmax}	optimum coefficient of power at which calculation is being performed
C_{PU}	upper bound of optimum coefficient of power
C_Q	torque coefficient
C_t	force coefficient along the tangential direction
C_T	coefficient of thrust
DF_A	aero-Induction demand factor
DF_C	compatibility demand factor
$DF_C\text{-}L$	lower limit of compatibility demand factor
$DF_C\text{-}U$	upper limit of compatibility demand factor
DF_H	hybrid demand factor
L	length of the blade
LD	the lift to drag ratio at which computation is being carried out
LD_L	lower bound of optimum lift to drag ratio
LD_U	upper bound of optimum lift to drag ratio
N	number of blades
N_s	number of streamtubes (including upstream and downstream streamtubes)
P	power requirement (rated power)
R	radius of the rotor
Re	Reynolds number
Sol	solidity
V_a	axial flow velocity
$V_d(1)$, $V_d(2)$, $V_d(3)$	downstream wind velocities in the double multiple streamtube model
V_e	wind velocity for the downstream half
V_∞	external wind velocity
V_R	relative velocity
V_u	upstream wind velocity in the single streamtube model
$V_u(1)$, $V_u(2)$, $V_u(3)$	upstream wind velocities in the multiple and double multiple streamtube model

seperately and determining the optimum combination based on the results of all permutations and combinations.

The input and output parameters in the optimization of VAWT that are considered in this study are listed in Table 2. The input parameters listed in the table covers most of the factors that are typically considered in VAWT design and the output parameters include all the parameters that are minimally required to completely manufacture a simple and straight bladed VAWT. Extra parameters may be required to define VAWTs with pitched blade and curved shapes, which are not considered in this study. The aerofoil shapes are classified into various families like NACA, Selig, Eppler, Selig/Donovan, Miley, Wortmann, Clark and Gottingen. There are also stand-alone types like Jacobs USNPS4, Bergey BW-3, etc. The output parameters listed in the table are depicted in Fig. 2.

The optimization process developed through this paper adopts a simplistic model of maximization of lift to drag ratio which is a direct measure of increase in the efficiency of VAWT. The methodology uses the concept of effective lift to drag ratio discussed in (Soraghan et al., 2013). Through the effective lift to drag ratio, the entire aerodynamic performance of the VAWT is represented by the azimuthal location of the streamtube that provide the value of torque equal to average instantaneous torque for the VAWT. The ratio of lift and drag coefficient corresponding to that particular streamtube is called "effective lift to drag ratio". For convenience, the azimuthal location that provides the effective lift to drag ratio is referred to as "Representative streamtube" in this paper. The optimization of the VAWT on the basis of Representative streamtube provides a great advantage over the regular approach that it obviates the need of carrying out iterations for all azimuthal locations.

2. Basic formulations

Consider the plan view of a 3-bladed VAWT as shown in Fig. 3. Only parameters that are relevant to the discussion in this section are depicted. Additional features such as connecting struts, substructure and machine components are not shown for clarity.

During operation, the VAWT is subjected to two types of forces simultaneously. They are:

1) Wind force from an arbitrary direction.
2) The angular rotation of VAWT about its central pole.

Due to the omni-directionality of VAWT rotor, regardless of the wind direction, a symmetric face is always presented to receive the wind without the need for a yawing mechanism which is a feature in Horizontal axis wind turbines (HAWTs). Consider a close-up view of the VAWT geometry shown in Fig. 4. The net effect of two forces acting together can be obtained by considering the resultant of the forces. The angle at which the resultant force hits the blade will also be modified due to the combined action of the forces. Fig. 5 shows a scaled up image of the wind hitting the rotating VAWT wherein, the actual wind velocity, V_∞ gets modified to V_a due to the actuator disk effect which further gets modified to V_R due to the rotating effect of the VAWT.

From basic trigonometry using Fig. 5, the angle at which the wind hits the rotating VAWT denoted as angle of attack (α) is given by,

$$\sin\alpha = V_a \sin\theta / V_R \tag{1}$$

Here, V_a is the modified wind velocity due to the 'actuator disk' effect of the wind hitting the rotating VAWT. Hence, out of the actual wind velocity, V_∞ only a portion of the same would be effective in generating wind energy. The relationship between these velocities is denoted by a dimensionless factor termed, "induction factor" (a) given by,

$$a = 1 - V_a / V_\infty \tag{2}$$