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Aerodynamic Drag and Lift Forces Approaches on a Movable Wind Turbine

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Abstract

The utilization of lift and drag forces for power generation is becoming increasingly attractive and gaining a great share in the global renewable energy production. This study proposes to find out the impact of aerodynamic force on a moving wind turbine. The study was evaluated based on the air flow towards (same and opposite direction) to the moving wind turbine. The result shows an increase of rotor speed when wind turbine is moving in the direction of air flow. With expectation for further details research would carry out to validate this approach.

Keywords: Lift; Drag; Force; Aerodynamic; Turbine

1.0 Introduction

Wind energy has attracted more interest for several reasons and has increasingly become the most harvested renewable energy source [1]; [2]. This new approach was motivated by dragging a turbine-like kite in an air medium resulting to the necessary force to rotate blades. This approach could also applicable in driving airplane wings, sailing, wind tunnel, parachuting, the transport of pollens, etc. Due to the consideration of efficient-energy demand, the shrouded wind turbine as being a relatively smaller size, one could suggest installing on movable objects such as train, van, lorry etc. to harness wind energy crossing over the moving wind turbine (as shown in Fig. 2). As the turbine is moving, the kinetic energy of the turbine in an air medium is significant particularly at higher speed. Thereby exhibiting strong lift and drag forces, causing it rotor rotate. Hence, the resulting force turns generator shaft to produce electrical power.

The air flow on wind turbine blades plays an important role in comparison to others factors responsible for renewable energy production. Wind turbines are mostly determined by the characteristics of lift and drag forces. Often considered the most important in this study, aimed to proposed a new approach in harvesting air flow, emphasize to evaluate the impact of lift and drag forces on a moving wind turbine.

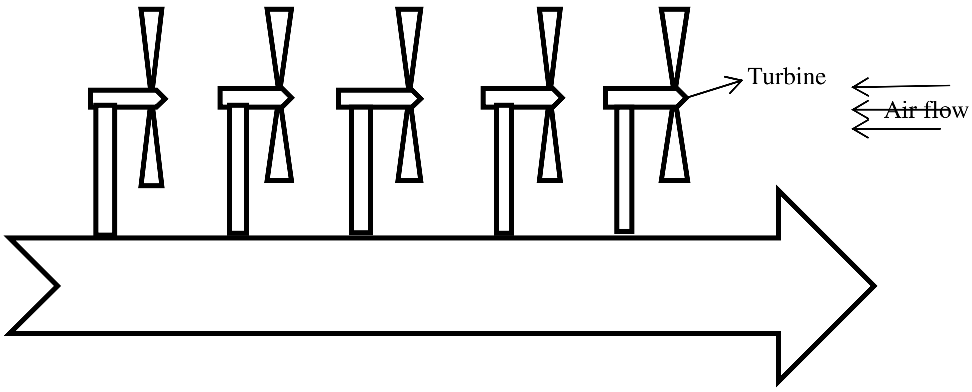

Fig. 1 Movable wind turbines

2.0 Theoretical Background

Theoretical background on wind energy system and energy harvesting concept from the aerodynamic lift and drag force is described as follows.

2.1 Aerodynamic forces on Wind Turbine

Theoretically, the resistance force acting on movable turbine in the air is the result of the speed of the air that being pushed to rotate blades. The principle of lift and drag forces can be considered as a generalization of the wind turbine. Aerodynamic forces are produced when a rotor rotates [3]. The aerodynamic lift and drag produced are resolved into useful thrust (T) in the direction of rotation absorbed by the generator and reaction forces (R) [4]. The aerodynamics behavior of the wind turbines is described by the forces of a rotating turbine parameters. Among them are (i) turbine speed, (ii) rotor blade tilt, (iii) rotor blade pitch angle (iv) size and shape of turbine, (v) area of turbine, (vi) rotor geometry whether it is a HAWT or a VAWT, (vii) and wind speed [5]. Therefore, understanding and application of aerodynamic principles is an essential part of wind turbine development [3].

Airflow over turbine blades creates two types of aerodynamic forces; drag forces (directional to the airflow, and lift forces, (perpendicular to the airflow). Some time called, the net upwards force (the lift) and the net backwards force (the drag). The lift and drag forces can be split into components parallel and perpendicular to the direction of the undisturbed wind [6]. And today researches are stating that horizontal axis wind turbines (lift force design) theoretically have higher power efficiencies than vertical axis wind turbines (drag force design) [7]. The horizontal axis or propeller-type approach currently dominates wind turbine applications [8]; [9].

The wind turbine rotor is an energy converter which transforms kinetic energy from the moving air into mechanical energy. There are two types of rotors: fixed speed rotors and variable speed rotors [10]. If the blades can switch between lift and drag modes, then it can selectively harvest energy when a strong displacement take place. Most of investigations carried on rotor tend to improve aerodynamics of the blades in order to increase performance and efficiency of wind turbines [11]; [12]. The rotor consists of the hub and blades of the wind turbine [13]. Having direct impact in the smoothness of rotor operation. The wind speed is maximum in the highest point when the blade in the upward position and minimum in the lowest point when the blade in the downward position [1]. When air flows past a rotor at an angle of attack, both the lift and drag acting on the airfoil are nonzero. Therefore, air that crossed through the blades undergoes lift and drag forces to achieved rotational displacement of turbine. Even though crosswind has been shown to be more effective in drawing more power.

The wind turbine is controlled via the blades pitching and torque to obtain the maximum power output of a wind turbine. The input to the rotor is the wind speed and the angle of attack for the determination of torque. The application of torque is to cause (twist) internal forces or pressures to smooth out the power fluctuations in the wind. When the load resistance decreases, greater torque is required to rotate the generator (the turbine speed becomes slower with decreasing resistance).

2.2 Aerodynamic Lift and Drag Forces

The aerodynamic forces are determined by using the wind velocity, frontal projected area, air density and dynamic pressure. To determine these parameters it is unnecessary to resolve lift and drag coefficients on wind turbine. Each of these forces are detailed in the following subsections.

2.2.1 Aerodynamic Drag force

Drag is a force that opposes motion due to an object's shape, material, and speed [14]. This is called drag force or air resistance. [15] defined drag force in fluid mechanics, as the force which exerted on the solid object in the upstream direction of the relative flow velocity. This drag force (F_D) is a function of the frontal projected area (A_f) of the turbine, drag coefficient (C_D). F_D = fun (C_D, A_f , V, ρ).

Drag force is expressed as

$$F_D = (1/_2\,\rho A_L V^2)C_D \qquad (1)$$

where the 1/2 is included to form the dynamic pressure, $\frac{1}{2}\rho V^2$

Air impacts the object creates pressure. A high pressure on the rear of the blade however will push the object forward, reducing drag. That is to say, the more perpendicular a forward-facing turbine is to the flow, the more likely it will create pressure and thus drag. Likewise, a backward-facing surface experiencing underpressure will pull the object backwards, again creating drag.

Drag coefficient (C_D) is the dimensionless parameter used to quantify the aerodynamic resistance of the moving turbine through its medium. And are minimized as much as possible in high performance wind turbines.

The drag coefficient is the ratio between aerodynamic drag and the product of dynamic pressure of moving air stream and the projected frontal area [16];

$$C_D = \frac{F_D}{1/_2\rho A_D V^2} \qquad (2)$$

Drag coefficient usually interrelated with a particular surface area [17]. However, a lot of researcher estimates the projected frontal area to estimate the air drag [18]-[20]. More streamlined objects will have a low Cd, less streamlines objects will have a high Cd.

The drag coefficient of a turbine increases when the blade is smooth, and it requires more power to overcome aerodynamic drag. Increasing rotor diameter rises the Reynolds number of the blade [21].

The blades area is the frontal projected area of the turbine, parallel to the direction of air flow and normal to the lift force. The swept area of the turbine can be calculated from the length of the turbine blades using the equation for the area of a circle:

$$A = \pi r^2 \qquad (3)$$

2.2.2 Aerodynamic Lift Force

Lift is the force used to overcome gravity [22]. Lift force for all wind speeds is created immediately at wind impact, and occurs just as the rotor starts to rotate. Aerodynamic lift is the force responsible for the power yield generated by the turbine and it is therefore essential to maximise this force using appropriate design [4]. Wind turbines using aerodynamic lift can be divided according to the orientation of the axis of rotation on the horizontal axis and vertical axis turbines [9]. The lift generated at the turning blades creates a reaction force, called thrust, opposing the incoming wind [23]. The forces on the turbine are a function of the turbine angle of attack and the local relative air speed. The blades are assumed to be rigid and are easily excited by air to manipulating its angle of attack. Wind turbine rotors and aerodynamic lift can be generated by varying angles normal to the wind direction. This is called Angle of Attack (AoA) [24], produces maximum lift. The blade pitch is adjusted to control the angle of attack in amplifying the lift [25]. Lift increases when angle of attack increases. For a lift driven rotor the relative velocity at which air strikes the blade (V) is a function of the blade velocity at the radius under consideration and approximately two thirds of the wind velocity (Betz theory) [26]; [4]. Lift force is also a function of dynamic pressure, surface area and lift coefficient as shown in Equation:

$$F_L = (\tfrac{1}{2}\,\rho A_L V^2)C_L \qquad (4)$$

where the 1/2 is included to form the dynamic pressure, $\frac{1}{2}\rho V^2$ because the blades extract energy from the wind based on Bernoulli's principle due to the pressure difference to obtain lift.

The lift coefficient given as

$$C_L = \frac{F_L}{1/_2\rho A_L V^2} \qquad (5)$$

Lift forces will increase when rotor blade is turned in an increases the angle of incidence of air on it. An increase in the angle of attack beyond 2.2^0

decreases the lift-drag ratio [25]. This indicates no decrease in relative wind velocity at any rotor speed [4]. That is to say, an increase in turbine speed, increases the lift on the turbine. Conversely, decrease in turbine speed, decreases the lift on the turbine.

2.2.3 Translational Aerodynamic Drag Force

The turbine pushes air with a area equal to the multiplication of the drag force and projected radius of the rotor. The translational aerodynamic drag force on the turbine due to the turbine moving in a straight line through the air (some time referred to as linear drag) is given by;

$$F_{\alpha} = {}^{1}/_{2}\, C_T A_T \rho V^2 \quad (6)$$

However, the translational torque is the result of translational drag force multiply by the rotor radius, r, which expressed as

$$F_T = F_{\alpha}.r \quad (7)$$

$$F_T = {}^{1}/_{2}\, C_T A_T \rho r V^2 \quad (8)$$

2.2.4 Translational Aerodynamic Lift Force

The corresponding translational aerodynamic lift force is given as;

$$F_{L\alpha} = {}^{1}/_{2}\, C_L A_L \rho V^2 \quad (9)$$

Whereas, translational torque;

$$F_{LT} = F_{L\alpha}.r \quad (10)$$

$$F_{LT} = {}^{1}/_{2}\, C_L A_L \rho r V^2 (11)$$

2.3 Aerodynamic Lift and Drag Forces Design Considerations

Based on these Equations, both the lift and the drag are proportional to the air density, the area of the airfoil, and the square of the wind speed [4]. In comparison Table 1 show the general behavior of lift and drag forces to consider when designing wind turbine, often helpful to carry out this study.

Table 1 lift and drag aerodynamic comparison

Drag force	Lift force
Perpendicular to the direction of air flow	Parallel to the direction of the air flow.
Move slower than the wind flow	Move quicker than the wind flow
Causes rotor to slow down	Causes rotor to speed up
The air moving over the airfoil yields drag force	This pressure difference across the airfoil yields lift force
Increases with an increase in air flow cross the blades	Increases when rotor blade is turned in an increase of angle of incidence cross the blades
Vertical axis wind turbines recommended for most applications.	Horizontal axis wind turbines recommended for most applications.
Has a higher torque	Has a lower torque
Acted upon by gravity	It's Overcome gravity

For better considerations, the aerodynamics of the moving wind turbines was considered in this study sssknowledge in harvesting wind energy.

3.0 Methodology

The method in this study was designed to discuss new approach application of aerodynamic lift and drag forces on the moving wind turbine.

The approach was similar to the conventional wind turbine, except that the constraint equations derived from the second Newton's Law by applying translational torque was adopted for evaluating drag forces for both the turbine and wind speed at; wind blowing against the direction of motion of the turbine; and wind blowing in the same direction of motion of the Turbine. For example

(a) Wind speed: V = V_T= 5m/s

(b) Wind blowing against the direction of turbine motion: V = V_T + V_W= 5+4 = 9m/s

(c) Wind blowing in the same direction of turbine motion: V = V_T-V_W= 5 - 4 = 1m/s. Where

In order to evaluate the wind turbine output, analysis was carried out under a wide wind and turbine speed range (from 3 to 16m/s) by considering only drag aspect (without considering lift force) of aerodynamic given as the functions of some parameters in Table 2.

Table 2 parameters for lift and drag force evaluation

Parameters	Symbols	Values
Radius of the rotor	r	0.4m
Frontal area of rotor	A	$0.5m^2$
Air density	ρ	$1.225Kg/m^3$
Drag coefficiency	C_D	0.4

The evaluated results should give a clear indications on how lift and drag forces was distributed to allowed us to get closer to the real operating conditions.

4.0 Results and Discussion

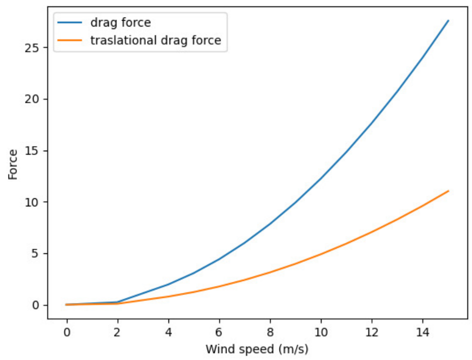

Fig. 2 Variation of drag and translational drag force across air flow

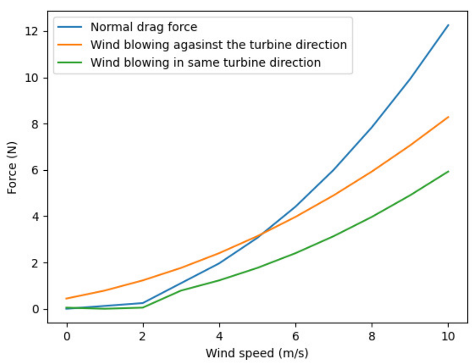

Fig. 3 Distribution of forces across air flow

From Fig. 2 It appears that the drag and translational drag forces acting on the turbine are highly dependent on the velocity. It also found that the when turbine is moving in an air stream, the translational drag required less force (high speed) than that of non-movable wind turbine. Revealing that the high pressure from air stream is expected by the moving turbine, yielding an increase in rotor[1] speed.

Fig. 3 shows the result of air flow and turbine speed; added when they are in opposite directions; subtracted when they are in the same direction; and[2] normal when turbine is not moving, which was observed that the force profiles are velocity dependent. It was also observed that the non-moving turbine experience larger force to rotate rotor compared to when air is blowing from either same or opposite direction to the turbine. But, it[3] experience distortion at low turbine speed by air flow fluctuations from different directions as shown. This shows that the turbine moving in the direction of air flow required less energy to attain a maximum speed requirement for wind energy production.

The effect of the drag force is clearly seen in the result, an increase in force on the turbine in the same direction of air flow, increases rotor speed and decreases when in opposite direction. Therefore, greater is the drag force, greater the power output of the wind turbine.

4.0 Conclusion

It was concluded that the aerodynamic lift and drag force depends on the direction of air flow. As the turbine is moving in same direction of air flow, the rotor speed increases, while decreases in an opposite air flow.

Therefore, It is possible to generate and optimize net power by utilizing lift and drag forces from this approach to improve energy harvest from wind turbine.

6.0 Recommendations

This approach focused on harvesting energy from the air flow without considering the mechanical aspect. The aerodynamic design principles for a modern wind turbine blade are detailed to include blade plan shape and optimal attack angles. Such measures and some missing aspect (not even mention in this study) are expected to carry out further research to validate this approach.

If this approach were designed, installed and operated, then an increase in rotor speed at the point of maximum power production were expected.

Reference

Gan, L.K.; Shek, J.K.H.; Mueller, M.A. (2018): Modeling and characterization of downwind tower shadow effects using a wind turbine emulator. *IEEE Trans. Ind. Electron*. Vol. 64, 7087–7097.

Ahmed G. A., Alyami, S., Sayed, K. and Alhejji, A. (2019): Dynamic Modeling of Wind Turbines Based on Estimated Wind Speed under Turbulent Conditions.*Energies*. Vol. 12, 1907; doi:10.3390/en12101907. www.mdpi.com/journal/energies.

Korobenko, A. (2011): Computational analysis of the dynamic forces in drive train components of an offshore wind turbine. *All Theses*. 1176. Available at: https://tigerprints.clemson.edu/all_theses/1176.

[4] Peter, J. S. and Richard J. C. (2012): Wind Turbine Blade Design. *Energies*. Vol. 5: 3425-3449 doi:10.3390/en5093425

[5] Manyonge, A. W. ,Ochieng, R. M., Onyango, F. N. and Shichikha, J. M. (2012): Mathematical Modelling of Wind Turbine in a Wind Energy Conversion System: Power Coefficient Analysis. *Applied Mathematical Sciences,* Vol. 6(91):4527 - 453

[6] Ali, H. A. (2012): Effect of drag on the performance for an efficient wind turbine blade design. *Energy Procedia*. Vol. 18: 404 – 415. doi: 10.1016/j.egypro.2012.05.052

[7] Qasim, A. Y., Usubamatov, R. and Zain, Z. M.(2011): Design of Vertical Axis Wind Turbine with Movable Vanes. *Australian Journal of Basic and Applied Sciences.* Vol. 5(11): 896-902.ISSN 1991-8178.

[8] Ackermann, T. (2005). Wind Power in Power Systems. *John Wiley & Sons,* New York, NY, USA.

[9] Soriano, L. A., Wen, Y. and Rubio, J. (2013): Modeling and Control of Wind Turbine. *Mathematical Problems in Engineering*. Vol. 2013. Article ID 982597, 13 pages. http://dx.doi.org/10.1155/2013/982597.

[10] Cole J. D. (2012): Computational Modeling of Wind Turbine Wake Interactions. Master of Science. Thesis. *Department of Civil and Environmental Engineering. Colorado State University Fort Collins,* Colorado.

[11] Vermeer, L., Sørensen, J. N. and Crespo, A. (2003): *Progress in aerospace sciences* 39: 467-510.

[12] Siddiqui, M. S., Rasheed, A., Tabib, M. and Kvamsdal, T. (2016): Numerical analysis of nrel 5mw wind turbine: A study towards a better understanding of wake characteristic and torque generation mechanism, *(IOP Publishing),* p. 032- 059.

[13] Biadgo, A. M. and Aynekulu, G. SS(2017): Aerodynamic Design of Horizontal Axis Wind Turbine Blades. *FME Transactions*. Vol. 45(4):647-640.

[14] Maxemow, S. (2009):That's a Drag: The Effects of Drag Forces. *Undergraduate Journal of Mathematical Modeling: One + Two:* Vol. 2: Iss. 1, Article 4. DOI: http://dx.doi.org/10.5038/2326-3652.2.1.4Available at: https://scholarcommons.usf.edu/ujmm/vol2/iss1/4.

[15] French, A. P. (1970). Newtonian Mechanics (The M.I.T. Introductory Physics Series) (1st ed*.). W W. Norton & Company Inc.,* New York. ISBN 393-09958-X.

[16] Pugh, L. G. C. E. (1971). The influence of wind resistance in running and walking and the mechanical efficiency of work against horizontal or vertical forces. *Journal of Physiology*, 213, 255–276. Retrieved from http://jp.physoc.org/content/213/2/255.

[17] McCormick, B. W. (1979): Aerodynamics, Aeronautics, and Flight Mechanics. *John Wiley & Sons,* Inc., New York, ISBN 0-471-03032-5

[18] Heil, D. (2001): Body mass scaling of projected frontal area in competitive cyclists. *Eur. J. Appl. Physiol.* Vol. 85(3–4): 358–366.

[19] Olds, T. and S. Olive, S. (1999): Methodological considerations in the determination of projected frontal area in cyclists. *J. Sports Sci*. Vol. 17(4): 335–345.

[20] Satria, E., Djamal, M., Takita, A and SFujii, Y. (2017): Precision Measurement of Drag Force Acting on a Spherical Body Dropping in the Air. *J. Tech. Soc. Sci.* Vol. 1(1): 7-15.

[21] Brusca, S., Lanzafame, R. and Messina, M. (2014): Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance. *Int J Energy Environ Eng.* 5:333–340. DOI 10.1007/s40095-014-0129-x.

[22] Martin O.L. and Hansen, A. (2008): Aerodynamics of wind turbine Second Edition, *Earthscan,* UK and USA.

[23] Meyer Forsting, A. R. (2017). Modelling Wind Turbi*ne Inflow: The Induction Zone.* DTU Wind Energy. https://doi.org/10.11581/DTU:00000022

[24] Rom, J. (2011): High Angle of Attack Aerodynamics: *Subsonic, Transonic, and Supersonic Flows. Springer* London, Limited.

[25] Daniyan, I. A., Daniyan, O. L., Adeodu, A. O., Azeez, T. M. and Ibekwe, K. S. (2018): Design and Simulation of a Wind Turbine for Electricity Generation. *International Journal of Applied Engineering Research*. Vol. 13(23):16409-164717. ISSN 0973-4562. http://www.ripublication.com.

[26] Gasch, R. and Twele, J. (2002): Wind Power Plants; *Solarpraxis:* Berlin, Germany.