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AERODYNAMIC LOADS ON A 3-BLADED VERTICAL AXIS WIND TURBINE: Parametric Study and Experimental Validation

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Abstract

Prediction of aerodynamic forces acting on a wind turbine is a crucial step in the design process to avoid wind turbine fatigue failure. The presented work is a parametric study and experimental validation for the aerodynamic loads acting on 3-bladed H-rotor vertical axis wind turbine (VAWT) with a NACA 0021 airfoil. Good agreement has been obtained between predicted load values and the experimental results.

1.1 Introduction

Wind turbines have been used for many years to generate electricity and drive pumps for irrigation purpose. The rapid urbanization and economic growth in developing countries such as Egypt which is suffering from severe power shortages is the major drive to look for alternative energy options such as wind energy **[1-7]**. Vertical axis wind turbines (VAWTs) have proven to be practical and effective devices for extracting wind energy. VAWT is suited for built-up at urban areas and requires low wind start-up speed. The mechanical components of the VAWTs are located near the ground, which make the maintenance convenient and easy. Furthermore, VAWTs can harvest the wind from any direction, thus doesn't require a yaw mechanism to control movement **[8-10]**.

The H-rotor VAWT is a lift-type VAWT; it uses lift forces generated by the wind hitting airfoils to create rotation **[11]**, Predicting the aerodynamic forces acting on a wind turbine is essential in the design process, The major challenges associated with the design of VAWTs are the varying forces on the turbine **[12]**. The measurement of the forces acting on the turbine's blades is very difficult due to uncertainty and large errors obtained from prototype measurements. To perform accurate small scale VAWT experiments, the Reynolds numbers should match and this is not easy to get because of the difficulty of obtaining realistic flow around the prototype. Therefore, it is important to carry out experiments on large scale to reach force coefficients similar to those of full scale VAWTs.

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Experimental data used to calculate the forces acting on straight blade VAWT (H rotor) at high Reynolds numbers are limited. Recently, an experimental work had been done by **Rossander et. al. [12]** on 12 KW VAWT by using of four load cells attached between the support arms and the hub.

To perform similar work but under different conditions and different design parameters is very expensive and time consuming. Therefore, analytical analysis was carried out in the current study to execute a parametric study to facilitate the design process.

The motivation of the current study is to predict the aerodynamic loads acting on the 3-bladed H-rotor VAWT blades with a NACA 0021 airfoil. Turbine parameters effects on the forces and consequently the stresses acting on blades are considered in order to estimate fatigue life.

1.2 Analytical Analysis

1.2.1 H-rotor VAWT blade design parameters

The blade element momentum **(**BEM) model was used for modeling the proposed VAWT. The (BEM) model includes the Double-Multiple Streamtube model (DMST) that is considered to be an accurate streamtube model as it studies the energy losses of the flow for the front and back half of the VAWT individually **[14]**. The DMST model considers different induced velocities once for the upstream and the other for the downstream sections of the. The DMST model was compiled into a Matlab code and calculations were separately made for both the upstream and the downstream blade positions.

The dimensions of the 3-bladed H-rotor VAWT along with an estimation of the turbine's rotational speed are presented in **Table (1)**. **Rasha et al. [13]** presented the detailed figure for the model used in the current study. The far stream wind velocity used in the design is set to be 5 m/s which is almost equal to the average wind speed in Portsaid, Egypt (where the suggested wind turbine will be operated) according to the latest climatic reports **[14].**

Table 1: Current study H-rotor VAWT design parameters.

Design parameter	Values of current study
Rotor radius (m)	1
Blade length (m)	2
Blade chord (m)	0.2
Tip speed ratio (-)	4
Number of blades (-)	3
Free stream velocity (m/s)	5
Air density (kg/m^3)	1.225
Angular speed (rad/s)	20
Power (Watt)	171
Pitch angle	0°
Blade airfoil	NACA 0021

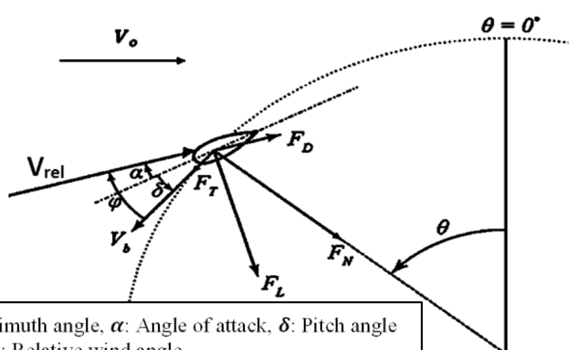
1.2.2 Relation between angle of attack α and pitch angle δ

Figure (1) shows that the angle of attack α is the angle between the blade chord and the relative air velocity vector. This angle changes continuously with the blade position, the relation between the angle of attack α and the blade azimuth angle (rotational angle) θ is determined by solving the velocity triangle given in **Fig. (1)** which ultimately leads to the equations given by **Anderson [15]** as follows:

$$\alpha = \tan^{-1}\frac{\sin\theta}{\lambda+\cos\theta} \quad (1)$$

$$\lambda = \frac{\text{Blade tip tangential speed}}{\text{Actual wind speed}} = \frac{\omega R}{V_o} \quad (2)$$

where; λ : the tip speed ratio, ω: Angular speed (rad/s), R : Rotor radius (m) and V_o : Free stream velocity (m/s).



θ: Azimuth angle, α: Angle of attack, δ: Pitch angle and φ: Relative wind angle.
F_L: Lift force F_D: Drag force, F_N: Normal force and F_T: Tangential force.
V_O: Freestream velocity, V_b: tangential velocity of the blade and V_{rel}: relative wind velocity.

Fig. 1: Aerodynamic forces and the velocity vectors acting on VAWT blade [12].

The blade pitch refers to turning the wind turbine's blades into or out of the wind to control the production or absorption of wind power. Wind turbines use this to adjust the rotation velocity and the generated power **[16]**. The relationship between the blade pitch angle δ and the angle of attack α is determined as follows:

$$\varphi = \alpha + \delta \quad (3)$$

where; φ : the relative wind angle.

1.2.3 Aerodynamic Forces

Wind Turbines extract energy from the wind force acting on the turbine's blade. When the wind is in motion towards the turbine's blade, which has an airfoil cross section, the turbine's blade experiences lift and drag forces that move the blades thus transferring the wind energy into kinetic energy of the blade (refer to **Fig. (1)**).

Lift force is generated perpendicular to the direction of the relative wind speed while drag force is in the same direction of the relative wind speed **[16, 17]**.

The lift and drag forces are calculated as follows:

$$F_L = \frac{1}{2}\rho A_s V_o^2 C_L \quad (4)$$

$$F_D = \frac{1}{2}\rho A_s V_o^2 C_d \quad (5)$$

where; F_L : Lift force (N), F_D: Drag force (N). ρ : Air density (=1.225 kg/m^3 at 15 °C), A_s : Swept area (m^2), C_L : Lift coefficient and C_d : Drag coefficient.

The swept area for the H-rotor VAWT with a rectangular shape is equal to:

$$A_s = D.H \quad (6)$$

where; A_s : Swept area (m^2), D : Rotor diameter (m), and H: Blade length (m).

The tangential force F_T can be obtained as the resultant of both the lift F_L and drag force F_D in the direction of the blade motion. The resultant of these forces is the normal force F_N which is perpendicular to the chord. The tangential force F_T is used in calculating the turbine power while the normal force F_N imitates the loads on the wind turbine blades.

The normal and tangential forces can be calculated as follows (refer to **Fig. (2)**):

$$F_N = F_L\cos\alpha + F_D\sin\alpha \quad (7)$$

$$F_T = F_L\sin\alpha - F_D\cos\alpha \quad (8)$$

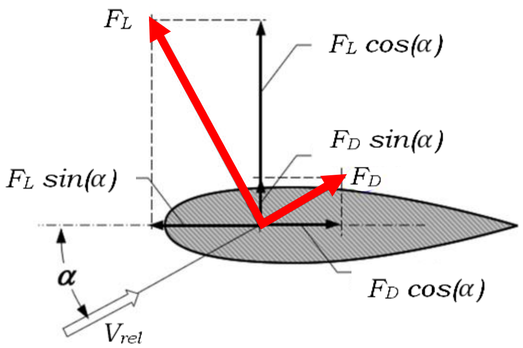


Fig. 2: Lift and drag forces components.

The centrifugal force $\boldsymbol{F_c}$ is another load acting on the blade in the radial direction. The centrifugal force depends on both radius and the square of the angular speed and is equal to:

$$\boldsymbol{F_c = m_b\, R\, \omega^2} \tag{9}$$

where; $\boldsymbol{m_b}$: Blade mass (kg) and $\boldsymbol{R}$: Rotor radius (m)

For the constant value of the rotational speed, the radial force $\boldsymbol{F_r}$ is the sum of centrifugal force $\boldsymbol{F_c}$ and the normal force $\boldsymbol{F_N}$ as follows:

$$\boldsymbol{F_r = F_c + F_N} \tag{10}$$

2. Results and Discussion

2.1 Verification with experimental results

In order to check the validity of the analytical calculations, a comparison with the experimental and simulation data for the normal and tangential forces acting on a 12-KW straight bladed VAWT provided by **Rossander et al. [12]** was made. **Rossander et al. [12]** VAWT's parameters are listed in **Table 2** .

Table 2: H-rotor VAWT design parameters after Rossander et al. [12].

Design parameter	Values after Rossander et al. [12]
Rotor radius (m)	**3**
Blade length (m)	**5**
Blade chord (m)	**0.25**
Tip speed ratio (-)	**3.59**
Number of blades (-)	**3**
Free stream velocity (m/s)	**12**
Air density (kg/m^3)	**1.275**
Angular speed (rad/s)	**5.3**
Power (Watt)	**12000**
Pitch angle	**2°**
Blade airfoil	**NACA 0021**

The comparative results are given in **Figs. (3.a and 3.b)**.

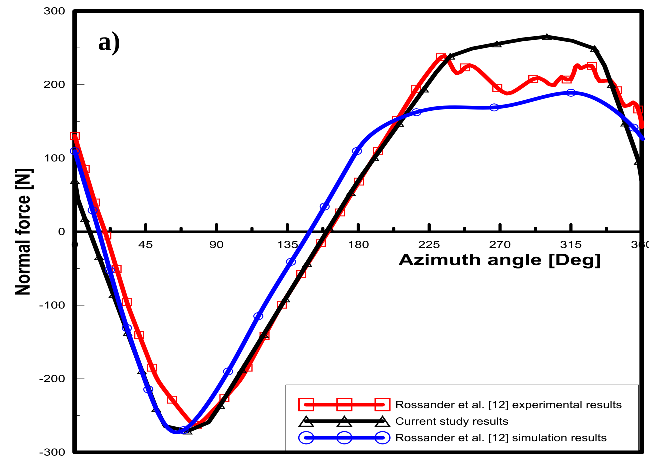


Fig. 3.a: Relationship between normal force and azimuth angle compared with Rossander et al. [12] experimental and simulation results.

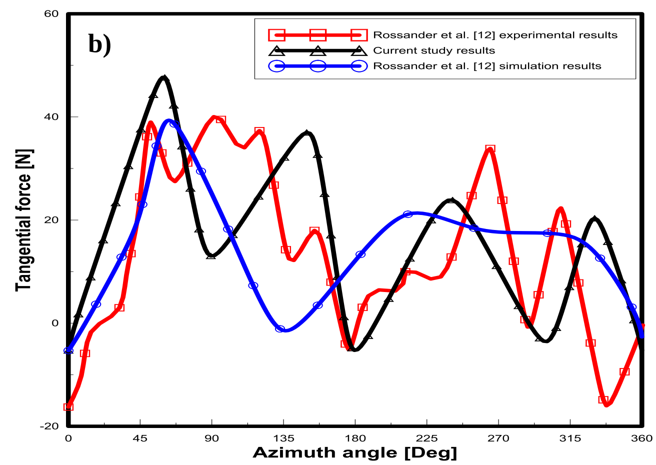


Fig. 3.b: Relationship between tangential force and azimuth angle compared with Rossander et al. [12] experimental and simulation results.

As seen in **Fig. (3.a)**, the current study analytical calculations results and the experimental results provided by **Rossander et al. [12]** almost converged with a percentage of error of only 1.9% at the 90° azimuth angle and 1.26 % at the 225°. Moreover, the tangential force curve created by the analytical model gave a good approximation with the experimental results presented by **Rossander et al. [12]** which can be observed in **Fig. (3.b)**. Therefore, the analytical model can be used for the parametric study which includes the effect of the pitch angle, tip speed ratio and blade thickness.

2.2 Effect of pitch angle on the angle of attack

According to **Eq. 3**, the pitch angle has a direct effect on the angle of attack, which has major effect on the value of lift and drag forces. The relationship between the angle of attack $\boldsymbol{\alpha}$ and the blade azimuth angle $\boldsymbol{\theta}$ for different values of tip speed ratios is plotted in **Figs. (4.a, 4.b and 4.c)** for pitch angle values of -8°, 0° and 8°.

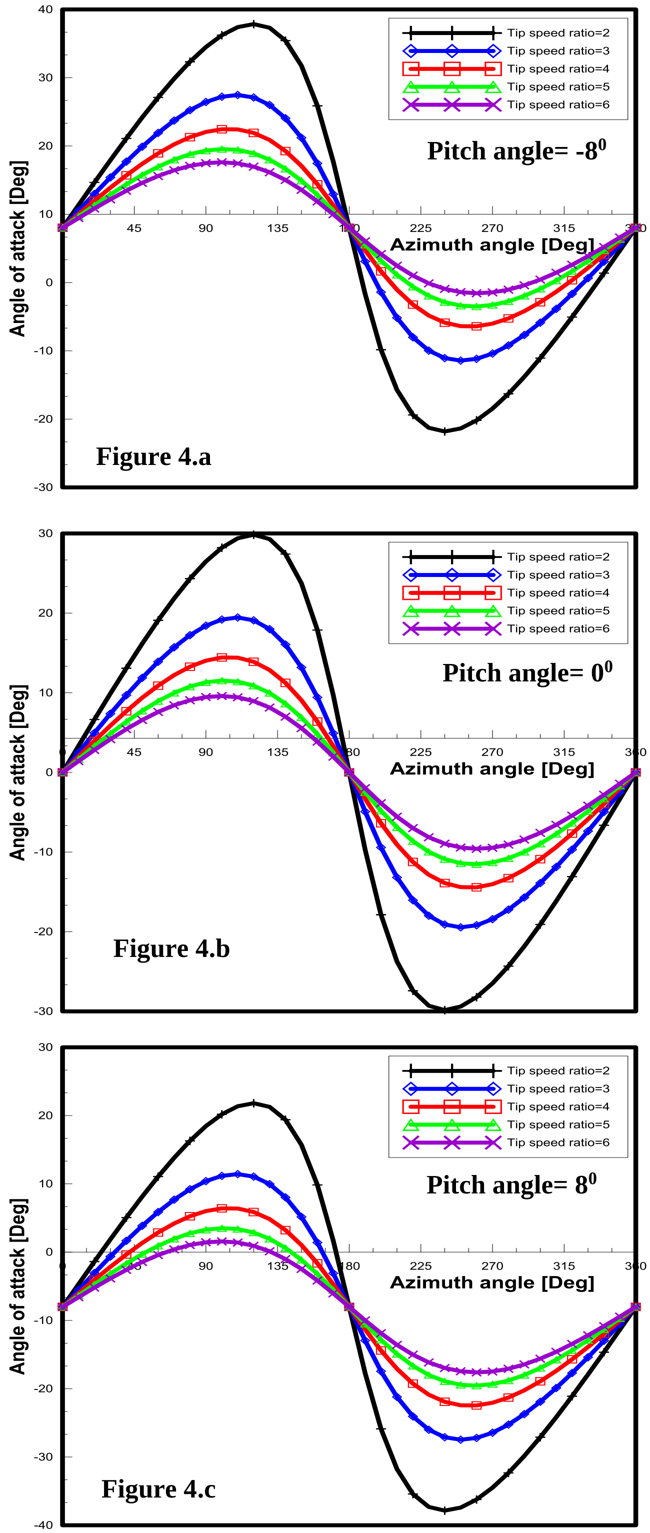


Fig. 4: Relationship between angle of attack and azimuth angle for different tip speed ratios at; a) pitch angle = -8°; b) pitch angle = 0° and c) pitch angle = 8°

The variation of the angle of attack is similar to a sine wave. Moreover, as the tip speed ratio increases, the skewness of the variation becomes less and lower values for the angle of attack are obtained. It is concluded from **Figs. (4.a, 4.b and 4.c)** that the blade pitch angle has a direct influence on the aerodynamic loads acting on the wind turbine blade; as the pitch angle increases the angle of attack decreases significantly which will affect the values of the lift and drag coefficients that will ultimately changes the magnitude of the aerodynamic loads accordingly.

Reynolds number Re_b and the angle of attack are used to find the corresponding lift and drag coefficients. Tables are extracted from **Sheldahl and Klimas [18]**. The relationship between the lift coefficient C_l and the angle of attack α at various values of Reynolds number is represented in **Fig. (5)**.

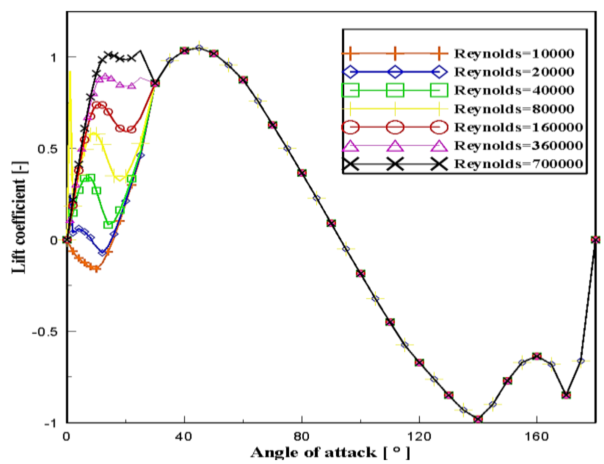


Fig. 5: The relationship between the lift coefficient C_l and the angle of attack α at various values of Reynolds number Re_b.

Figure (5) shows that the increase of the angle of attack is associated with an increase in the lift coefficient, Eventually a reduction in the rate of increase of the lift coefficient occurs, up until reaching the maximum lift coefficient, after which the lift coefficient decreases. The variation of lift coefficient depending on Reynolds number is only patent while $\alpha < 30°$ as given in **Fig. (5)**, then all the curves converge.

2.3 Effect of pitch angle variation on the blade lift force

The pitch angle variation has a direct effect on the aerodynamic loads. **Figs. (6.a, 6.b and 6.c)** show the relationship between Lift force and Azimuth angle for different Tip speed ratios for pitch angle values of -8°, 0° and 8°.

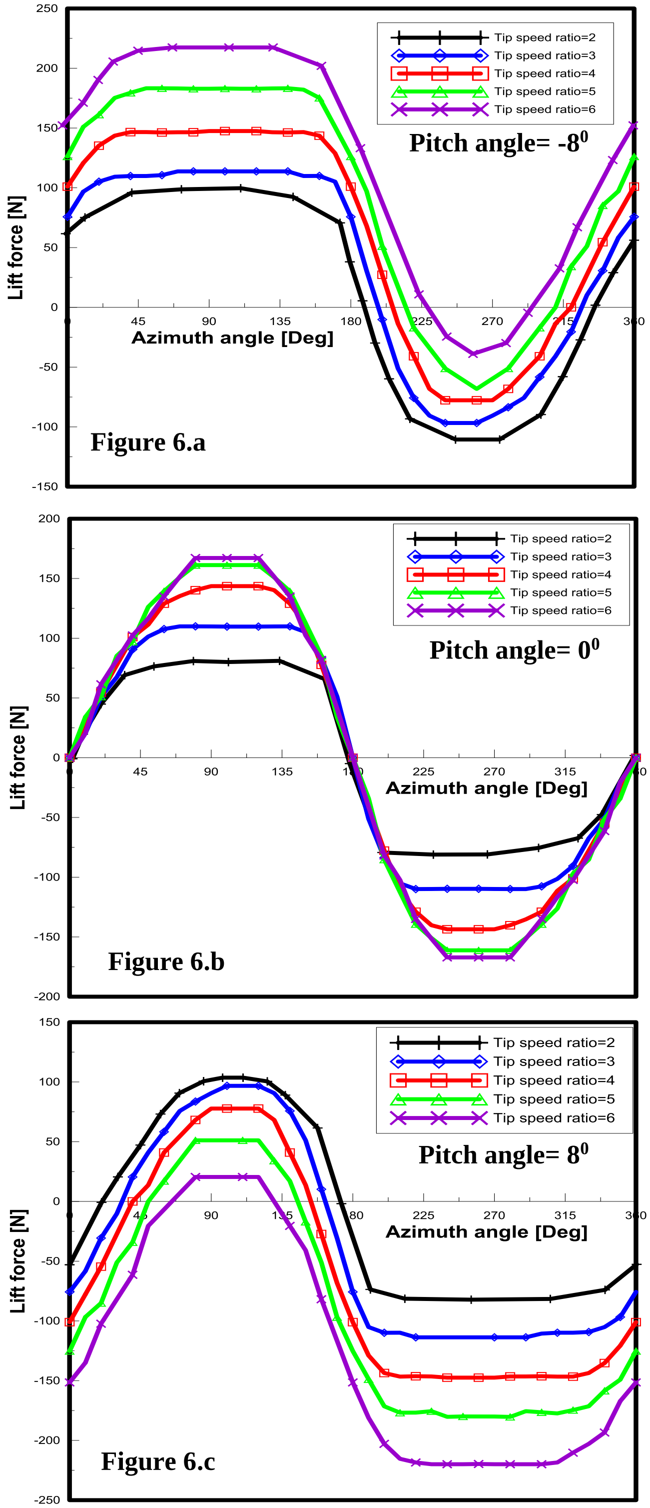


Fig. 6: Relationship between lift force and azimuth angle for different tip speed ratios at; a) pitch angle = -8 º; b) pitch angle = 0º and c) pitch angle = 8 º

It is deduced from the above figures that at lower values of pitch angle the magnitude of the lift force increases by the increase of the tip speed ratio up until the zeroº pitch angle where lift force decreases by the decrease of the tip speed ratio during the 360º rotation cycle.

2.4 Effect of pitch angle variation on the drag force

Figures (7.a, 7.b and 7.c) show that drag force decreases significantly as the tip speed ratio increases for all the pitch angle values. A non-symmetrical variation for the drag force was noted along the blade complete 360º rotation cycle for pitch angle ≠ zeroº.

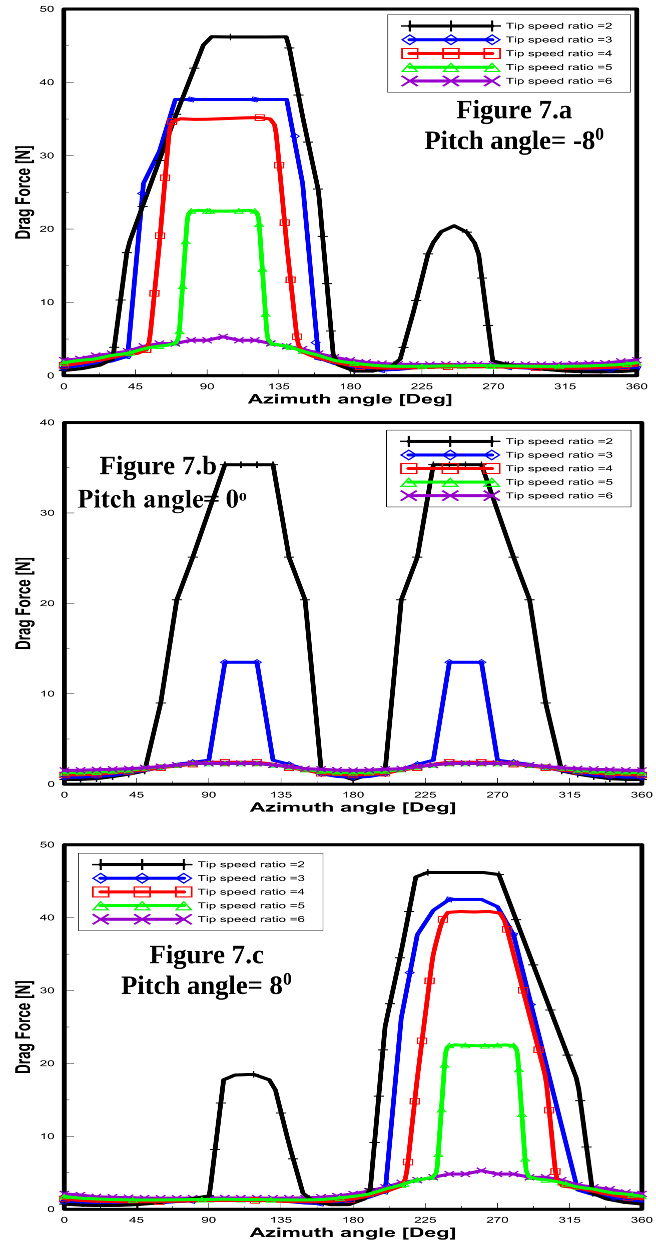


Fig. 7: Relationship between drag force and azimuth angle for different tip speed ratios at; a) pitch angle =-8 º; b) pitch angle = 0º and c) pitch angle = 8º.

2.5 Effect of the pitch angle variation on the normal force

The normal force distribution along the blade's rotational angle is presented in **Figs. (8.a, 8.b and 8.c)** for pitch angle values of -8°, 0° and 8° and different tip speed ratios.

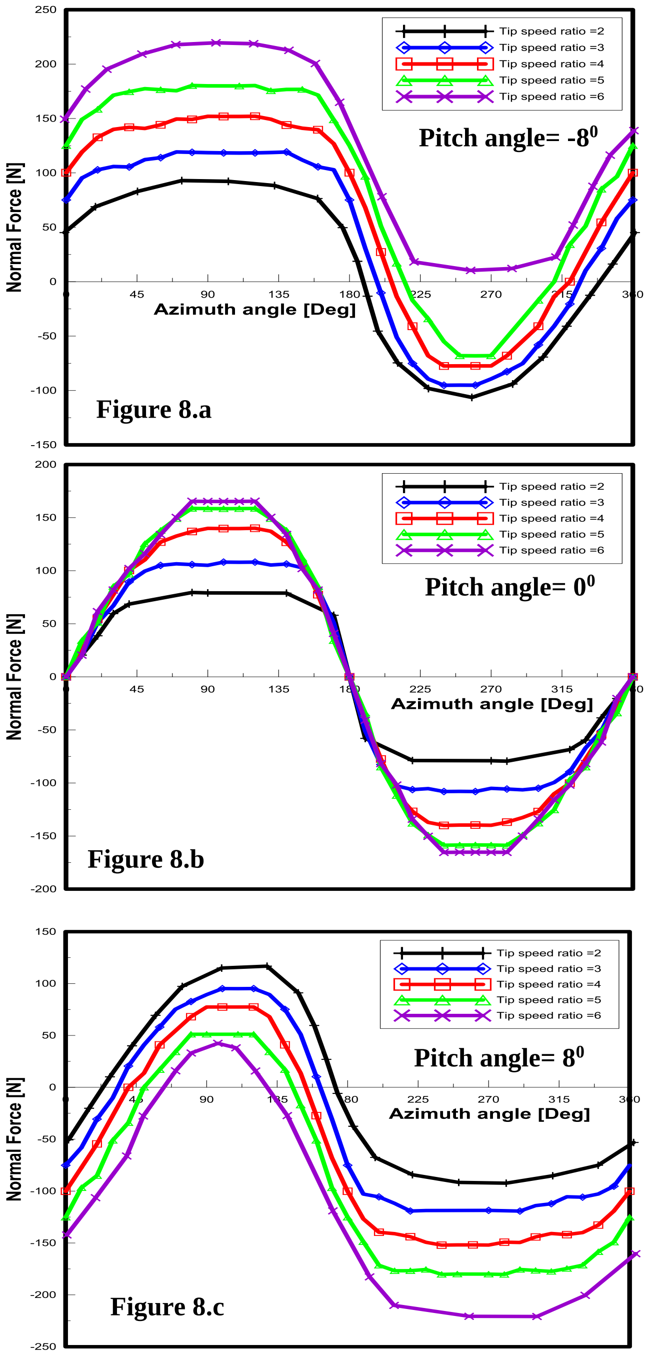


Fig. 8: Relationship between normal force and azimuth angle for different tip speed ratios, a) at pitch angle=-8°, b) at pitch angle = 0° and c) at pitch angle = 8°.

The normal force distribution along the blade complete 360° rotation cycle resembles a symmetrical sign wave for pitch angle = zero°. The normal force magnitude increased by the increase of the tip speed ratio up until the zero° pitch angle then the relation between the normal force and the tip speed ratio is inversed for positive values of the blade pitch angle where the normal force acting on the blade is reduced by the increase of the tip speed ratio. The pitch angle increase caused the decrease of the normal force for tip speed ratios more than 2.

2.6 Effect of pitch angle variation on the tangential force

The tangential component of the aerodynamic forces acting on each blade is responsible for the motion of the rotor. The relationship between the tangential force and the blade position angle is given in **Fig. 9** for different tip speed ratios and pitch angle values of -8°, 0° and 8°.

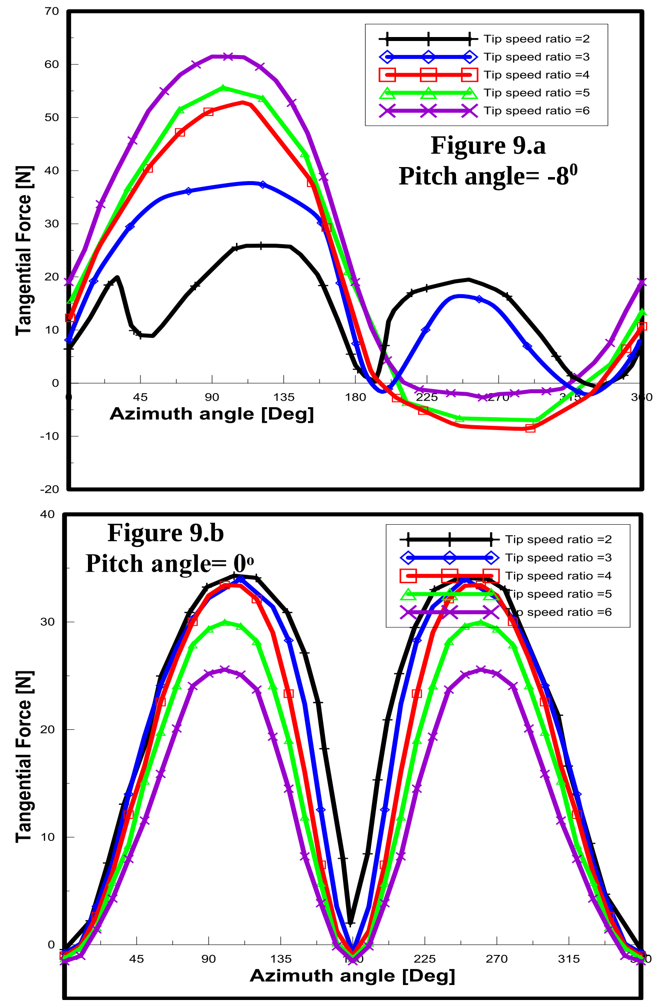


Fig. 9: Relationship between tangential force and azimuth angle for different tip speed ratios; a) at pitch angle = -8°; b) at pitch angle = 0°.

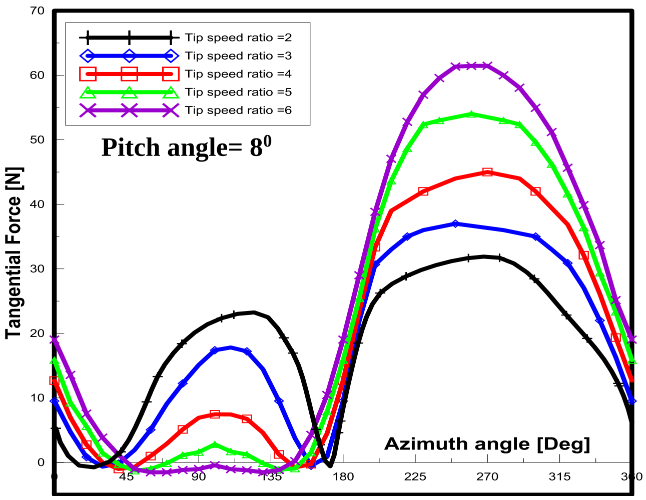


Fig. 9.c: Relationship between tangential force and azimuth angle for different tip speed ratios at pitch angle = 8º

As shown in **Figs. (9.a, 9.b and 9.c)** the distribution of the tangential force along the blade azimuth angle is symmetrical and can be predicted for all the values of the tip speed ratio for pitch angle = zeroº. Tangential force magnitude is reduced by the increase of the tip speed ratio. On the other side, for any other values of the pitch angle, the tangential force distribution along the blade azimuth angle is non-uniform and difficult to be predicted.

2.7 Effect of the blade thickness and pitch angle variation on the Radial force

Radial force calculation is essential when designing the H-rotor VAWT blade, the radial force is the primary load source acting on the blade. Radial force is the sum of normal force and centrifugal force. As the normal force was calculated, it is essential in this step to calculate the centrifugal force of the VAWT blade. Centrifugal force mainly depends on both the rotational speed of the wind turbine rotor and the mass of the blade, therefore, the blade material and thickness will have a direct effect on the total radial force acting on the wind turbine blade.

For the current design, the blade is made of S-2 fiberglass with epoxy resin composite. As compared to conventional glass fiber, S-2 glass fiber offers better fiber toughness, more tensile strength and enhanced stiffness. In addition, S-2 fiberglass/epoxy composite has high level of fatigue resistance. Furthermore, compared to aramid and carbon fibers, S-2 Glass fiber price is almost the half without risking the performance **[18]**.The S-2 fiberglass/epoxy composite density is 2490 kg/m^3. As the blade's thickness plays an important role in altering the blade's mass and consequently the radial force acting on the blade, a hollow blade with thickness of 8 mm ,7 mm , 6 mm and 5 mm were compared together along with a solid blade.

The relationship between the radial force and the blade azimuth angle for different blade thicknesses are given in **Figs. (10.a, 10.b and 10.c)** for pitch angle values of -8º, 0º and 8º and tip speed ratio of 4.

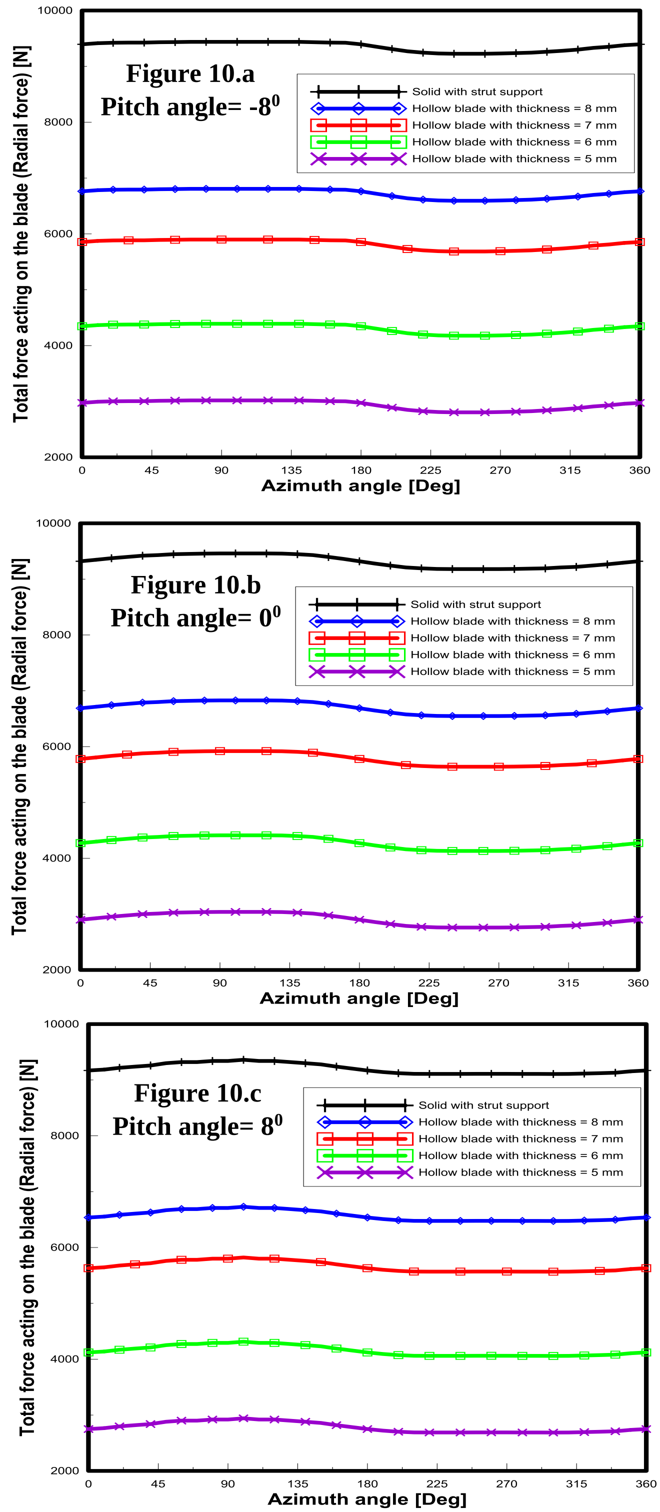


Fig. 10: Relationship between radial force and azimuth angle for different blade thicknesses; a) at pitch angle = -8º; b) at pitch angle = 0º and c) pitch angle = 8º

Figs. (10.a, 10.b and 10.c) show that the blade thickness has a direct and significant effect on the total radial force acting on the wind turbine blade, for all the pitch angle values, radial force is notably reduced by the reduction of the blade thickness that reduced the blade's mass. Increasing the pitch angle resulted in a noteworthy reduction in the radial force.

3. CONCLUSIONS

The analytical calculations gave a good agreement for the forces acting on turbine blade with the experimental results presented by **Rossander et al. [12]**.Therefore; validity of the analytical model used has been accepted in order to carry out parametric study on VAWT having different geometrical dimensions. Normal force variation with the azimuth angle takes the form of sine wave. The centrifugal force does not change with the blade position. Therefore, it can be considered as a mean value when added to the sign wave of the normal force gives the dynamic load that creates a dynamic stress on blades. This normal stresses with positive mean value will be used for fatigue life prediction in further study.

4. REFERENCES

1. NREA, Annual Report 2010/ 2011: Ministry of Electricity & Energy New & Renewable Energy Authority, 2011.
2. NUMOV, Renewable Energy. The Near and Middle East Association, 2016.
3. General Authority For Investment And Free Zones, Renewable Energy Value, Available from: Http://Www.Gafi.Gov.Eg/, 2016.
4. Anon., Egypt's Key Energy Statistics, 2015.
5. Anon. Wind Turbines. Available from: https://en.wikipedia.org/wiki/Wind_turbine#Vertical_axis_design, 2017.
6. Castellano, R., Alternative Energy Technologies: Opportunities and Markets, 2012.
7. Brown, K. and R. Brooks, Design and analysis of vertical axis thermoplastic composite wind turbine blade, in Plastics, Rubber and Composites, 2010.
8. Lee, Y. and H. Lim, Numerical Study of the Aerodynamic Performance of A 500 W Darrieus-Type Vertical-Axis Wind Turbine. Renewable Energy, 2015.
9. Eriksson, S., H. Bernhoff, and M. Leijon, Evaluation of Different Turbine Concepts For Wind Power, 2006.
10. Brusca, S. and M. Messina, Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance. International Journal of Energy and Environmental Engineering, 2014.
11. Anon. Darrieus Wind Turbine. Available from: http://www.reuk.co.uk/Darrieus-Wind Turbines.htm, 2017.
12. Rossander, E., A. Goude, and H. Bernhoff, Measurements of the Aerodynamic Normal Forces on a 12-kW Straight-Bladed Vertical Axis Wind Turbine. Energies, 2015.
13. Soliman, R., Lotfy, M., Abdou, S. ,and Eldomiaty,A., Stress Analysis For Small Vertical Axis Wind Turbine Blades Using Analyitical And Numerical Methods. Portsaid Engineering Research Journal, 2017.
14. Lashin, A., An Analysis of Wind Power Potential In Portsaid, Egypt. Renewable and Sustainable Energy Reviews, 2012.
15. Anderson, J., Fundamental of Aerodynamics. McGraw Hill Series in Aeronautical and Aerospace Engineering, 2010.
16. Anon. Available from: https://en.wikipedia.org/wiki/Blade_pitch, 2017.
17. Anon. Available from: http://www.mpoweruk.com/flight_theory.htm, 2016.
18. Sheldahl, R. and P. Klimas, Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines, Sandia National Laboratories, 1981.