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Experimental Investigation on Drag Characteristics of HAWT Tower Due to Tower Shadow

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Keywords：wind tunnel experiments, tower shadow, drag ratio, HAWT, Reynolds number effect, pitch angle

ABSTRACT

In Horizontal Axis Wind Turbines (HAWT), the interference between the wind turbine rotor blade and the tower is a pervasive problem that affects the tower as well as blades, structures, and power performances; hence, the study of the physical mechanism needs engineering attention. This interference phenomenon influences the flow field and excites the complex unsteady wind loads acting on the tower. Towers of the wind turbines have the potential geometry such as lattice, tubular, hybrid but this study focuses on cylindrical towers. The Wind tunnel experiment is carried out on scaled down three bladed wind turbine model with S809 aerofoil section blade to investigate the flow physics for tower alone and tower with rotating rotor for the Reynolds number ranging from 10^2 to 10^4. The aerodynamic drag force acting on the wind turbine tower with the rotating rotor is in increasing trend than the single tower without interference, which is almost constant. The results show that at low Reynolds number the coefficient of drag on the tower alone is more than the tower with rotating rotor whereas this case reverses as the Reynolds number increases. The drag force acting on the tower under the blade rotation effect has been investigated, and an aerodynamic term (Drag ratio) is proposed, which will be helpful for guiding the structural designer of the wind turbines.

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INTRODUCTION

Worldwide energy demand, environmental concerns and limits to fossil fuel consumption are more and more severe in this century. Among several energy sources being explored, wind power is a clean, renewable energy and has attracted investors, researchers, and government. World wind energy (2014) reports that total wind energy capacity of the world reaches 369 GW, out of which 50 MW has added in 2014, and also cumulative market growth by 16%. The horizontal axis wind turbine is now being widely used throughout the world to extract energy from the wind. Although relevant studies were performed in the horizontal axis wind turbine, numerous problems and limitations still exist that have to be resolved. One such problem is the unsteadiness due to the interaction between the rotor blade and supporting tower due to the blade rotation. This interaction influences the blade and tower, especially the presence of a tower creates an aerodynamic disturbance to the blade and hence affects its fatigue life. The distribution of the wind is altered by the presence of the tower. For upwind wind turbines, the wind is redirected when crossing the front of the tower directly and thereby reduces the torque of each blade. Irrespective of the location of the tower whether it is upwind or downwind turbine, the tower shadow exists. Tower shadow is defined as the influence of the tower in the wind turbine rotor performance. The upstream turbulence primarily affects fatigue damage in upwind turbine blades, and hence the study of the stochastic model of the influence of tower shadow was performed by Pedersen et al., (2012). Also, they insist that such load from tower shadow effect must be included in the design load case of Dolan et al., (2006), Hughes et al., (2008). They have discussed that the oscillations of the rotor blade passing through the supporting tower in three bladed wind turbines experience periodic power pulsating as 3p frequency. Also, it is mentioned that, even at constant wind speed, at a particular height a turbine rotor encounter variable wind as it rotates. Any form of disturbances to the blade rotation affects the power performance of the wind turbine directly; hence it needs attention to research. International Electro Technical Commission specification IEC 61400 - 12 - 1 (IEC, 2005) proposes a mathematical model for anemometer boom lengths to minimize upstream and downstream flow distortions based on CFD results.

Studies by Thiringer et al., (2001), Bayne and Bayne et al., (2000), considers the power pulsation experienced in the grid by the blade passing through the supporting tower and they mentioned that this is also a source of 3p oscillations. Roohollah et al., (2009) discussed the impact of tower shadow, yaw error and wind shears on power quality. Also, it is mentioned that fluctuations in wind turbine mechanical torque increase with an increase in tower shadow effect. Even though Roohollah et al., (2009) concluded that the impact of yaw error and horizontal wind shear on power and voltage oscillations is more severe than the effects of tower shadow and vertical shear, it is considered an aerodynamic point of view. In the experimental studies made by Stephen Orlando et al., (2011) to show the tower shadow on anemometer readings for several elevations, it was discussed that the change in velocity ratio concerning the Reynolds number is in the increasing trend. The results from the authors also show that there is a wind speed deficit ranging from 35% to 18%, depending upon the wind speeds from higher to lower in the anemometer measures in the tower wake. Various other researchers Vermeer et al., (2003), Li et al., (2012) and Gebhardt et al., (2010) studied the wake on wind turbine tower both computationally and experimentally. More comprehensive studies by Fadaeinedjad et al., (2011), show that depreciation in power quality is due to the stochastic nature of the wind speed and direction, wind shears, tower shadow and yaw error. Abdallah et al. (2005) discuss a detailed review of the impact of uncertainty in aerofoil characteristics on wind turbine performance and structural loading. In spite of reducing the cost per kWh, the manufacturers always want to increase the energy yield of wind farms as much as possible. The increase in diameter of the rotor to maximize the energy yield is associated with tower blade interference.

Hence, in this paper, we report on experiments undertaken to measure the pressure distortion on the wind turbine tower due to the rotor rotation. The effect of drag characteristics with respect to the Reynolds number based on the tip speed of the turbine blade, influenced by the tower shadow in terms of drag ratio for various pitch angles is discussed.

METHODOLOGY

In this paper the blade rotational effect on the wind turbine tower pressure and forces are discussed in detail. For this purpose, a term Drag ratio is defined. Drag ratio due to tower shadow (D_{TS}) is defined by the ratio between coefficients of drag due to tower only $(C_D)_T$ and with the rotating rotor $(C_D)_{WRT}$.

$$D_{TS} = \frac{(C_D)_T}{(C_D)_{WRT}} \tag{1}$$

The coefficient of drag was calculated based on the surface pressure integration on the tower for various heights from H1 to H8 respectively as shown in Fig. 2(a). The coefficient of pressure (C_p) was calculated for every pressure probe and plotted with respect to the angle (θ) and for various heights of the tower from H1 to H8. The coefficient of pressure (Anderson, 2010) was calculated from the following equation, where P is the total pressure, P_0 is the static pressure, ρ is the density of the air and V_∞ is the free stream velocity.

$$C_{p(mean)} = \frac{P - P_0}{\frac{1}{2}\rho V_\infty^{\ 2}} \tag{2}$$

For ideal condition, the pressure distribution C_p over the circular cylinder (Anderson, 2010) can be written as

$$C_{p(mean)} = 1 - 4\sin^2\theta \tag{3}$$

Hence the maximum and the minimum values of C_p lie between 1 and -3 respectively. However, the deviation from this value practically is because of the local effect of flow and its being disturbed. The idea of introducing the drag ratio (D_{TS}) is to understand the deviation of coefficient of drag value from the standard value for the particular Reynolds number. In this case, the Reynolds number is calculated based on blade tip speed (U_{tip}) and tip chord (C_{tip}) with coefficient of viscosity (μ).

$$Re = \frac{\rho U_{tip} C_{tip}}{\mu} \tag{4}$$

The tip speed can be calculated from the rpm of the rotor blades, which is measured using electronic proximity sensors, which detects the metallic objects without touching them. A proximity sensor consists of an induction loop. Electric current generates a magnetic field, which collapses by generating a current that falls asymptotically towards zero from its initial values when input electricity disconnects. Based on the materials inside, the inductance of the loop changes. Since metals are effective inductors; their presence increases the current flowing through the loop. This change can be converted into a signal and monitored. The sensor is located above the nacelle in such a way that the flow is less disturbed. The upstream effect due to the presence of the proximity sensor is assumed to be negligibly less. The Reynolds number of the tower alone cases are considered by assuming the corresponding free stream velocity when the tip speed corresponds to tower with rotor rotating case. By knowing the tip speed of the blade, tip speed ratio (λ) can be calculated. The tip speed ratio is the ratio between the blade tip speed (U_{tip}) and free stream velocity (V_∞).

$$\lambda = \frac{U_{tip}}{V_\infty} \qquad (5)$$

The coefficient of drag can now be calculated by integrating the pressure at a particular height for various angles (Anderson, 2010)

$$C_D = \int_0^{2\pi} C_p \cos\theta \qquad (6)$$

Where C_p is the mean coefficient of pressure and θ is the angle in which pressure measured in the tower.

EXPERIMENTAL SETUP

The wind tunnel facility used in all experiments is an open circuit wind tunnel with a fan, adjustable to rotate at various rpm; control can be made to increase the least count of 1 rpm. The test section is of rectangular cross section of size 1m × 1.2m and 2m long and a maximum speed in the test section is 50 m/s; the test section is equipped with multi-channel pressure scanner which can measure simultaneous pressure measurement with the sampling frequency of 325 Hz. Wind tunnel layout is shown in Fig. 1(a) and the horizontal axis wind turbine pressure model with pressure probes are shown in the Fig. 1(b).

Fig. 1(a) Low Speed, Wind tunnel at MIT.

Fig. 1(b) Experimental pressure model in Wind tunnel

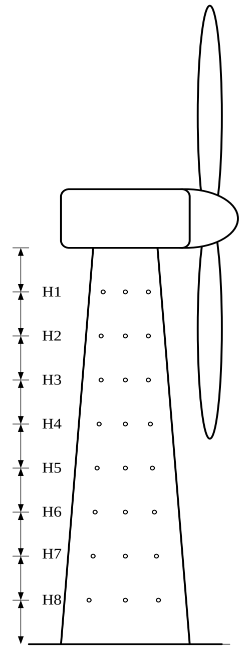

Fig. 2 (a) Schematic of wind turbine model with pressure probes on various heights, Not to scale

Pressure probes made at eight levels with an equidistance of 37mm in the wind turbine tower and the schematic of geometric details are shown in Figs. 2(a) – (b). Series of velocity measurements were obtained independently in the free stream with hot wire anemometer with wind speed ranging from 4 ~ 14 m/s. The turbulence intensity is less than 3% in the test section of the wind tunnel. Three components of velocity Ux, Uy, Uz were collected at 60 Hz with 3000 data points for each wind tunnel fan setting. A linear relation is obtained between the fan RPM setting and the velocity obtained in the wind tunnel test section. Electronic pressure scanning is used to measure the pressure distribution on the surface of the tower and more than 9000 data per pressure point per set is obtained. Measured pressures at every height are integrated and coefficient of drag calculated for eight levels for various setups of free stream velocity. Seven nominal wind speeds were tested for the wind turbine configuration which corresponds to the Reynolds number ranging from $10^2 – 10^4$; explicit Re values for all cases are given in Table.1. However, this Reynolds number change with various pitch angle φ, as pitch angle increases the rpm of the rotor increases, in turn, the tip speed U_{tip} increases. The experiments performed to analyze the interference between the tower and the blade only in uniform flow and hence the boundary layer profiles are not simulated.

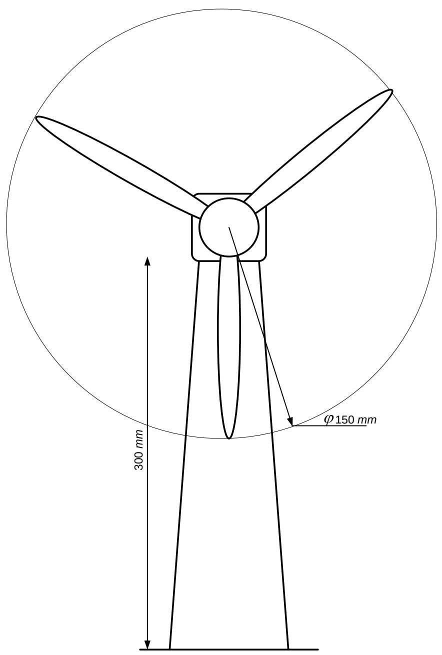

Fig. 2 (b) Schematic and geometric coordinate system of wind turbine model, Not to scale.

Table 1. Experimental test cases made in wind tunnel at pitch angle φ = 0°.

Cases	Free stream velocity (m/s)	Rotor rotation (rpm)	Tip Speed (m/s) U_{tip}	Reynolds number (Re)	Pressure measurement levels
(i)	5.7	242	3.8	1.17×10^3	H1 ~ H8
(ii)	6.2	350	5.48	1.69×10^3	H1 ~ H8
(iii)	8.0	445	6.99	2.16×10^3	H1 ~ H8
(iv)	9.3	550	8.62	2.66×10^3	H1 ~ H8
(v)	10.6	650	10.2	3.15×10^3	H1 ~ H8
(vi)	11.9	753	11.78	3.64×10^3	H1 ~ H8
(vii)	13.1	872	13.36	4.13×10^3	H1 ~ H8

RESULTS AND DISCUSSIONS

Pressure Characteristics

The mean pressure distribution (Cp) for the wind turbine without the rotor blade is shown in Fig.3. The distribution shows at various height levels H1 to H8 from top to bottom of the wind turbine tower, where H1 is close to the hub and nacelle. Mean pressure distribution varies from 0.78 to 1.2 for various heights due to the change in diameter as the different sections as shown in Fig.3. Also, the effect of the nacelle interference is inferred at the height H1, where the distribution is one sided. The mode of the distribution from 0° to 360° does not show much difference with respect to the height of the tower. Fig. 4 shows the mean pressure distribution (Cp) for the tower with rotor blade, and it is rotating at 350 rpm at the free stream velocity V∞=6.25m/s with the tip speed ratio (λ) of 0.66. The pressure distribution is one sided due to the effect of the rotor rotation, and this may lead to the side force component, however, at H8, the effect is not significant since it is far from the rotor blade.

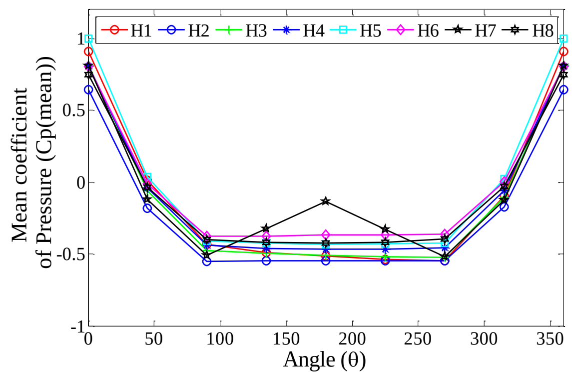

Fig. 3 Mean Pressure coefficient (C_p mean) on wind turbine tower without the rotor blades at Free-stream velocity V∞ = 6.25 m/s.

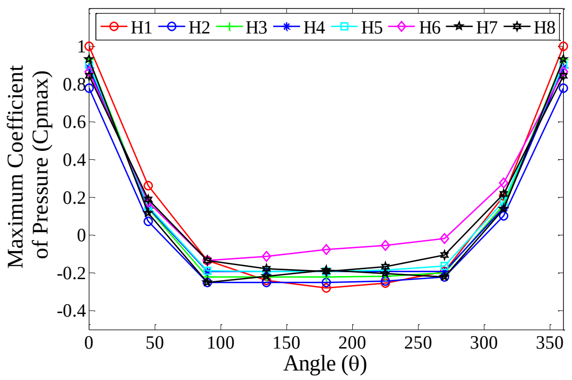

Fig. 4 Mean Pressure coefficient (C_p mean) on wind turbine tower with rotor blades at free-stream velocity V_∞ = 6.25 m/s and pitch angle φ=0°.

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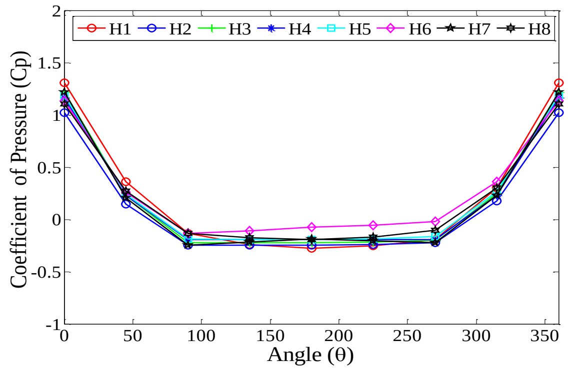

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Fig. 5 Maximum Pressure coefficient (C_p max) on wind turbine tower without the rotor blades at free stream velocity V_∞ = 6.25 m/s.

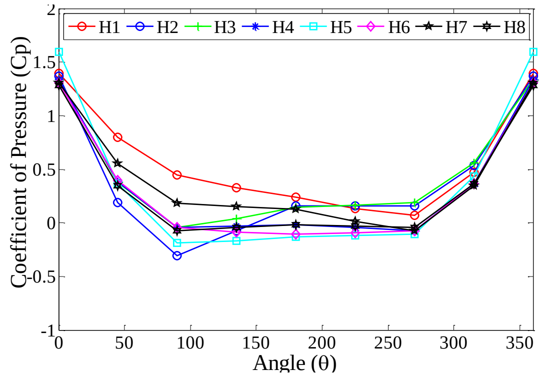

Fig. 6 Maximum Pressure coefficient (Cp max) on wind turbine tower with rotor blades at Free-stream velocity V_∞ = 6.25 m/s and pitch angle φ = 0º.

Fig. 5 and 6 shows the maximum pressure coefficient on the wind turbine tower without and with rotor respectively. In maximum C_p distributions, there is clear evidence of the rotating effect is seen as one-sided distribution where after 180º angle there is a further decrease in pressure. This could be due to the blade moving with a particular rpm and creates high velocity, and that leads to the low-pressure region. Such difference in pressure distribution induces side forces on the tower. Such side forces may induce fluctuating and the vibratory motion of the tower from the structural point of view. In most of the cases, H4 shows deviated value due to the interference between the tip of the rotating rotor and the tower.

Drag Characteristics

Drag characteristics of the turbine model is shown in Fig. 7 for both tower only and tower with rotating rotor for one particular pitch angle and its comparison. The coefficient of drag for the tower only configuration in Fig. 7 (a) shows that there is not much change due to the increase in Reynolds number. However, it has a direct effect on the tower with the rotating rotor. The coefficient of drag initially starts from lower value C_D = 0.6, when compared to the tower alone case of C_D=1.12, where the disturbance created is more or frequency of the disturbance is less, due to low rpm. At such low rpm, the disturbances are created in front of the tower where the velocity increases and pressure decreases. Hence the low pressure region created on the front of the tower when compared to tower alone case, the drag decreases. This phenomenon continues as rpm increases the flow starts disturbed by the rotor rotation and the pressure in front of the tower starts increasing. This is because of the resultant of blade rotation and the free stream velocity, and the drag starts increasing. At higher Reynolds number, the coefficient of drag value is more than the tower alone case. Even though at particular Reynolds number the coefficient of drag for tower alone and tower with rotating rotor is same, but the phenomenon is not same. Drag ratio (D_{TS}) is calculated for the rotor with pitch angle 5º is shown in Fig. 7 (b) to represent the ratio decrease with increase in Reynolds number. This is because of the phenomena that, at the blade, low rpm the tower is disturbed more, even though the frequency is less. For change in pitch angle, the coefficient of drag C_D rises and follows almost similar pattern as shown in Fig.8 (a). At low Reynolds numbers, various pitch angles show the similar value of coefficient of drag. As the pitch angle increases and Reynolds number increases the difference in coefficient of drag value is because of the effect of wake created by individual turbine blade while crossing the tower. This confirms the above phenomenon, however at 15º pitch angle; the coefficient of drag C_D becomes almost similar to tower only case.

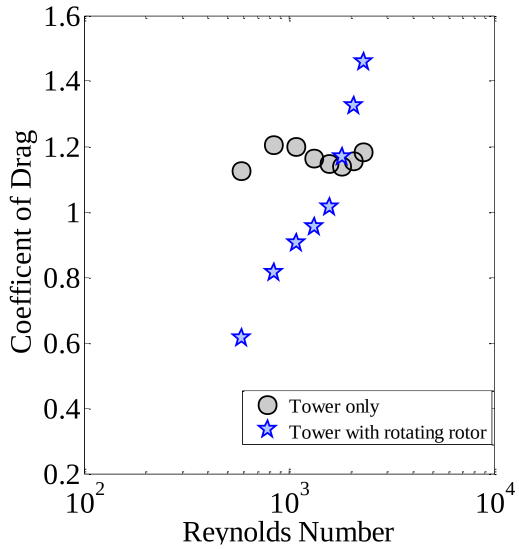

Fig. 7 (a) Coefficient of Drag (C_D) calculated for the Tower only and Tower with rotating rotor.

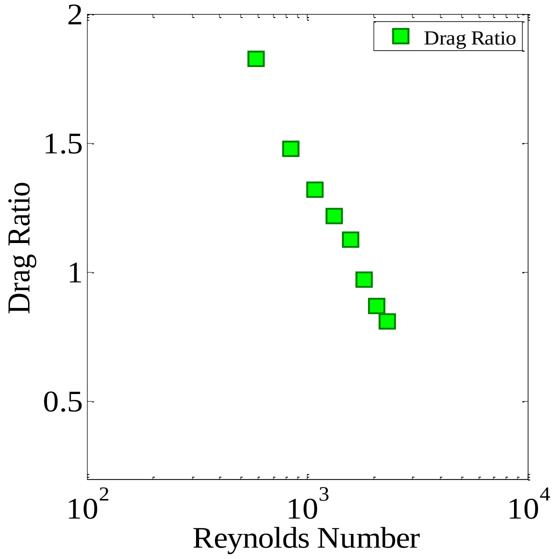

Fig. 7 (b) Drag Ratio (D_{TS}) for pitch angle = 5°

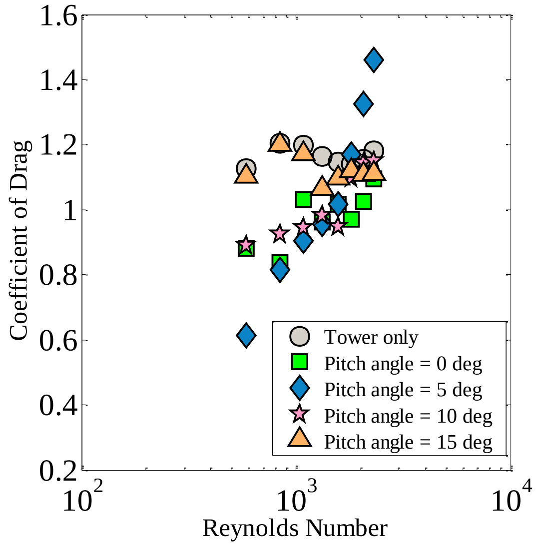

Fig. 8 (a) Coefficient of Drag (C_D) with Reynolds number for various pitch angles

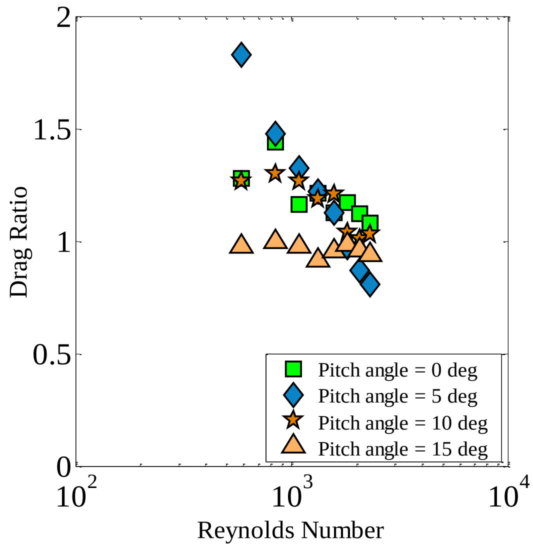

Fig. 8 (b) Drag Ratio (D_{TS}) for various pitch angle

CONCLUSIONS

The current experiment investigated the wind turbine rotor blade and tower interference and its influence on the tower in low speed wind tunnel. A three bladed rotor is designed to perform the wind tunnel experiments at the Reynolds number ranging from 10^2 to 10^4 based on the rotor tip speed. Rotor rpm is measured using the proximity sensors, based on the rpm and rotor diameter, the tip speed of the blade is calculated. The following conclusions were made.

(1) The mean pressure coefficients are symmetrical for the tower alone case whereas for the rotor rotating cases it is one sided due to the interference between the rotor and the blades. The similar results reflected in the maximum pressure coefficient values for the tower only and tower with rotating rotor configurations.

(2) The coefficient of drag (C_D) for the tower alone case is almost constant with the increase in Reynolds number, however for the tower with rotating rotor the drag increases. At low Reynolds number, the Coefficient of drag is lower than the tower alone case but with the increase in Reynolds number, the coefficient of drag increases.

(3) At particular Reynolds number the coefficient of drag is same for tower alone case and tower with the rotating rotor. However, the phenomenon is not same even though the coefficient of drag is same. At tower alone case the coefficient of drag is simply due to the pressure difference between front and the rear of the cylindrical tower. In the tower with rotor rotating, lower the Reynolds number, lesser the frequency of blade crossing the tower and low rpm, the velocity is increased at the front of the tower and pressure decreases, hence the coefficient of drag is smaller than the tower alone case. As the Reynolds number increases, the front tower experiences reduced velocity and increased pressure, since the pressure difference increases, the coefficient of drag increases.

(4) The Drag ratio (D_{TS}) is the ratio between the coefficient of drag due to tower alone and tower with rotor rotating is proposed. The decrease in drag ratio with the increase in Reynolds number is observed.

(5) The coefficient of drag (C_D) increases with increase in Reynolds number for the tower with rotor rotating case.

(6) At low Reynolds number (Re) the effect of pitch angle has not much influence; however, as the Reynolds number increases the coefficient of drag (C_D) increases.

The drag force acting on the tower under the blade rotation effect is investigated and the proposed aerodynamic term (Drag ratio) will be helpful for guiding the structural designer of the wind turbines.

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