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Effect of Incident Wind Angle on Power Generation of Building Integrated Wind Turbines

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Abstract

A new technique has been developed which enables estimation of flow characteristic of a ducted flow in a through-building opening in presence of wind turbine(s). This technique has been implemented to estimate pressure, velocity and turbulence intensity of flow in the through-building openings integrated with the wind turbine when the approach wind is coming from different directions toward the building. It is shown that power generation of the ducted wind turbine(s) in windward condition is significantly higher than the than the free stream wind turbine at the same approach wind velocity. It is also shown that a properly designed layout preserves the velocity in the through-building opening in a reasonable range of incident wind angles so that, power generation of the ducted wind turbine(s) would be higher than the free stream one at the same approach wind velocity.

Introduction

Despite the advantages of application of wind turbines in urban built-environment to provide power generation at the point of use, this idea is undermined by practical hurdles including relatively low power output and unreliable performance due to unfavourable urban wind conditions. However, investigations have proved that the installation of small wind turbines on urban buildings can provide great potential to generate energy efficiently [1, 2]. Wang and co-workers [3, 4] reported the aerodynamic design of a small urban wind turbine with scoop based on wind tunnel tests, which reportedly boosted wind speed and power output by a factor of 1.5 and 2.2 respectively, compared with a bare wind turbine of the same swept area. The practical application of through-building openings for wind energy harvesting has been investigated for Pearl River Tower [2]. This study was extended by accommodating a site-specific local wind climate data. The results indicated that power captured improved particularly at locations where average wind speed was lower and wind was more turbulent [5].

Although studies [3-8] have shown installing wind turbines inside a properly designed through-building openings may provide a strong enhancement in power generation of wind turbines, this approach may reduce the probability of efficient power generation by blocking the approach wind when the building is not faced windward or leeward. Therefore, power generation of the ducted wind turbine in different incident angles needs to be compared with a free stream one which is profited by passive yaw mechanism. This study aims to investigate power generation of a small commercialized Horizontal Axis Wind Turbine (HAWT), Ampair 300[9], installed in a through-building opening in a tall building when a realistic wind is approaching with different magnitudes and incident angles.

The flow characteristics will change inside the through-building opening when the turbine(s) is/are installed inside them. By capturing some momentum from the flow, the ducted turbine increases pressure gradient and reduces the available velocity across the opening. Therefore, for power generation analysis of the turbine(s), this study develops a technique capable of estimating the influence of the turbine(s) on the flow characteristics inside the opening in their presence. Replacing the actual wind turbines with an adequate sink of momentum, this technique estimates velocity, pressure gradient and turbulence intensity of the approach wind in the presence of wind turbine(s) in the through-building opening.

Methodology

The main purpose of this stud is to compare power generation of a small HAWT installed in a through-building opening with the same turbine installed in free stream condition at the same elevation. Ampair 300, has been selected for this purpose. Figure 1 shows the power and rotational speed of this turbine against different approach wind velocities in free stream condition.

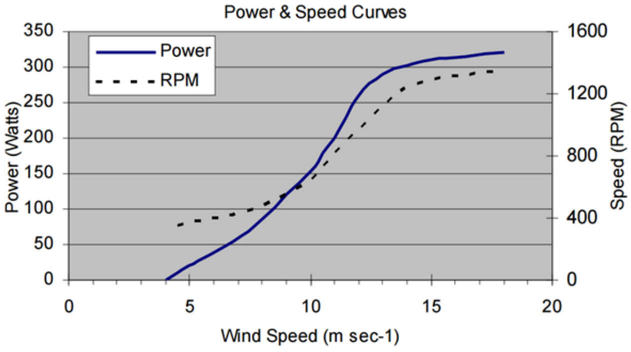


Figure 1 power and rotational speed of Ampair 300 against different approach wind velocities [9].

In this study, a Computational Fluid Dynamics (CFD) model is developed for the HAWT(s) installed in through-building openings inside a simple tall building model with a square plan and the dimensions of 96m× 32m × 32m as shown in Figure 2. Two through-building openings are designated at height of 3/4H at two ends of two opposing building faces. “H” refers to the building height. The windward and leeward side of the corridors are open to the exterior. The cross-section area of the corridors is $4\times4\ m^2$.

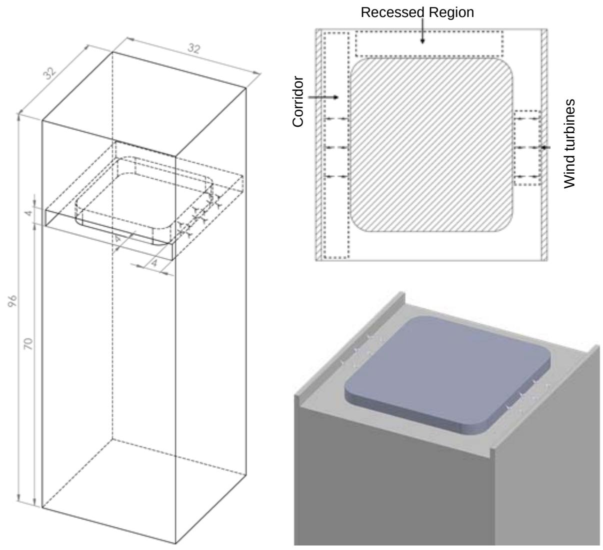


Figure 2 Building model and schematic view of wind turbine locations inside the corridors.

The CFD model of the HAWT has been previously developed and verified [10]. For generating the power curve of the ducted HAWT, at each velocity (of the ducted flow) its rotational speed needs to be set to the corresponding rotational speed in the free stream condition. Therefore, numerous simulations have been undertaken to find different rotational speeds and the resultant torque on the rotor at each approach wind velocity. The operational rotating speeds at each wind velocity are extracted and multiplying those rotating speeds by their relevant resultant torque gives similar power generations reported by the manufacturer company. Then, at each approach wind velocity and corresponding rotating speed the resultant torque exerted on the ducted turbine is also computed and the power generation is calculated. Figure 3 shows power generation of the HAWT against the approach wind velocity provided by the manufacturer's specifications beside the power generation computed by the CFD model of the free stream and ducted turbine. This figure shows power generation of the ducted HAWT at zero wind incident angle is significantly greater than the free stream one [7].

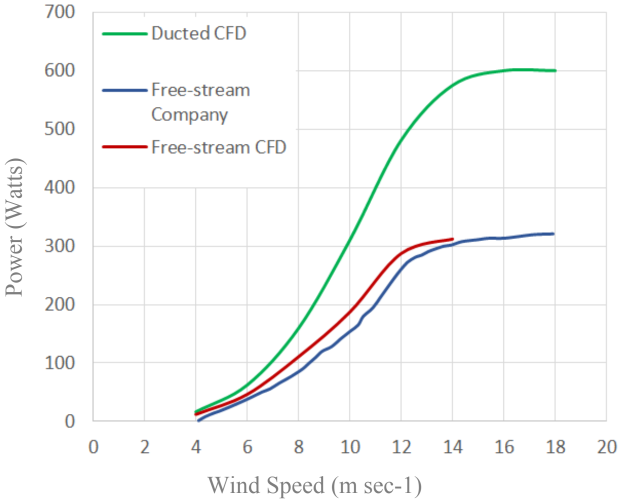


Figure 3 Power generation of the free stream and ducted HAWT against the approach wind velocity.

Each power generation calculated and shown in Figure 3 corresponds to a thrust force that the ducted flow is exerting on the ducted HAWT. The reaction of the ducted HAWT to the thrust force is acting similar to a sink of momentum to the ducted flow which drops the pressure and reduces the velocity there. The corresponded reacting thrust (between the ducted flow and ducted turbine) is monitored and recorded as shown is Figure 4.

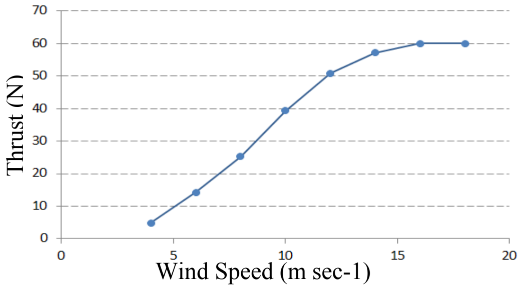


Figure 4 Thrust force exerted on the ducted HAWT against the approach wind velocity.

Finding the reacting thrust that the turbine(s) is/are exerting on the ducted flow at each approach wind velocity leads to governing the equations of a sink of momentum. By replacing the CFD model of the ducted HAWT in the through-building opening with a simple volume including the momentum sink, the pressure drop and velocity reduction due to the presence of the ducted HAWT can be estimated. The resultant pressure and turbulence intensity created at the upstream of the ducted HAWT and also the velocity across the through-building opening provide the required information to explicitly install an actual CFD model of the turbine in a simple duct with corresponding flow characteristics. Now the power generation of the explicit model gives an accurate estimation of the ducted turbines.

CFD Setup

This HAWT has 1260mm diameter and four of them have been located at the middle of a 4×m4m×32m corridor as shown in Figure 5. Using the symmetry boundary condition, one quarter of the corridor housing one single turbine was generated and extended to the other three quarters after each solution. CFD model of the turbine, and the duct were built in actual size using hybrid mesh including 1,320,000 structured and 950,000 unstructured meshes in each quarter of the corridor that housed one turbine. Structured mesh was built around the rotating disk, and very fine unstructured mesh was built within the rotating disk and on the rotor surface as shown in Figure 5. Inlet and outlet boundary conditions were set as velocity inlet and outflow while the velocity, pressure and turbulence intensity of the inlet flow were estimated by the developed technique. Fluent has been used as the CFD solver using transient $k-\omega$ SST turbulence model.

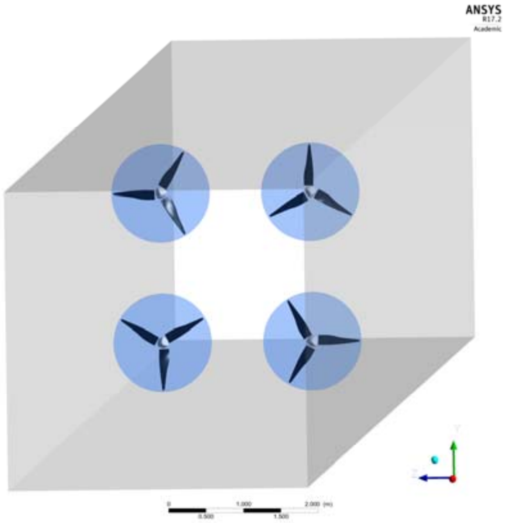
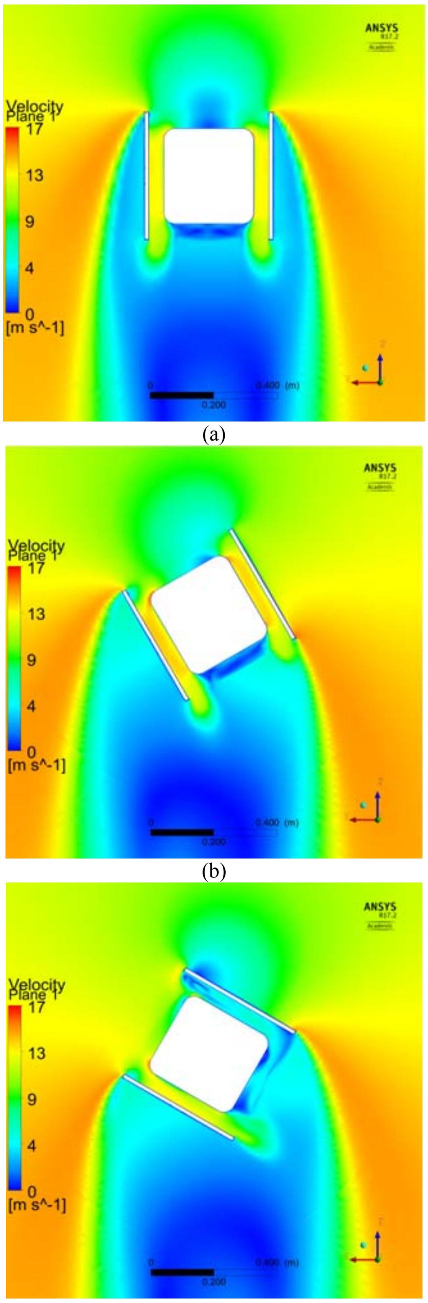


Figure 5. CFD model of the ducted HAWTs in trough-building opening.

Result and Discussion

Using the developed momentum sink in the through-building openings and rotating the building by 30° and 60°, velocity, pressure and turbulence intensity of the ducted flow are measured and recorded. Figure 6 (a-c) shows the resultant velocity contour in the openings at incident wind angle of 0°, 30°, and 60° when the free stream velocity is 12m/s at the 3/4H of the building. According to the velocity contours, the ducted flow has higher velocity than the free stream at the same elevation far from the building in the openings at 0° when the turbines are installed in the through-building opening [11]. Comparing Figures 12(a) and (b) shows that velocity of the ducted flow has even slightly increased by turning the building by 30° which should be due to the negative pressure created at the outlet of the openings. Comparing Figures 6(a) and (c) shows by turning the building by 60° the ducted flow velocity has dropped below 6m/s in the right opening while it is still around 12m/s in the left one.



(a)

(b)

(c)

Figure 6 Velocity contour of the ducted flow at wind incident angles: (a) 0°, (b) 30° and (c) 60° when the free stream velocity is 12m/s at the same elevation.

Using the momentum sink technique, velocity, pressure and turbulence intensity of the ducted flow are estimated and recorded in the presence of the ducted HAWT. Then, the resultant flow characteristics are applied to the inlet of a simple duct which explicitly houses the HAWTs. Power generation of the ducted HAWT installed in the left and right through-building openings at 0°, 30° and 60° incident wind angles are computed and compared with power generation of the HAWT installed at the same elevation in the free stream condition and presented in Figures 7 (a-d). The free stream velocity at the same elevation (3/4H of the building) is 6m/s, 9m/s, 12m/s and 15m/s in Figures 7(a), (b),(c) and (d) respectively.

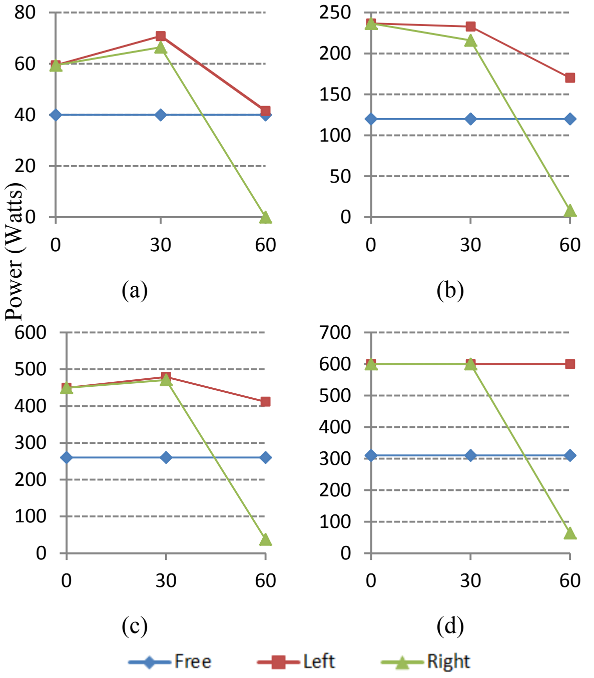
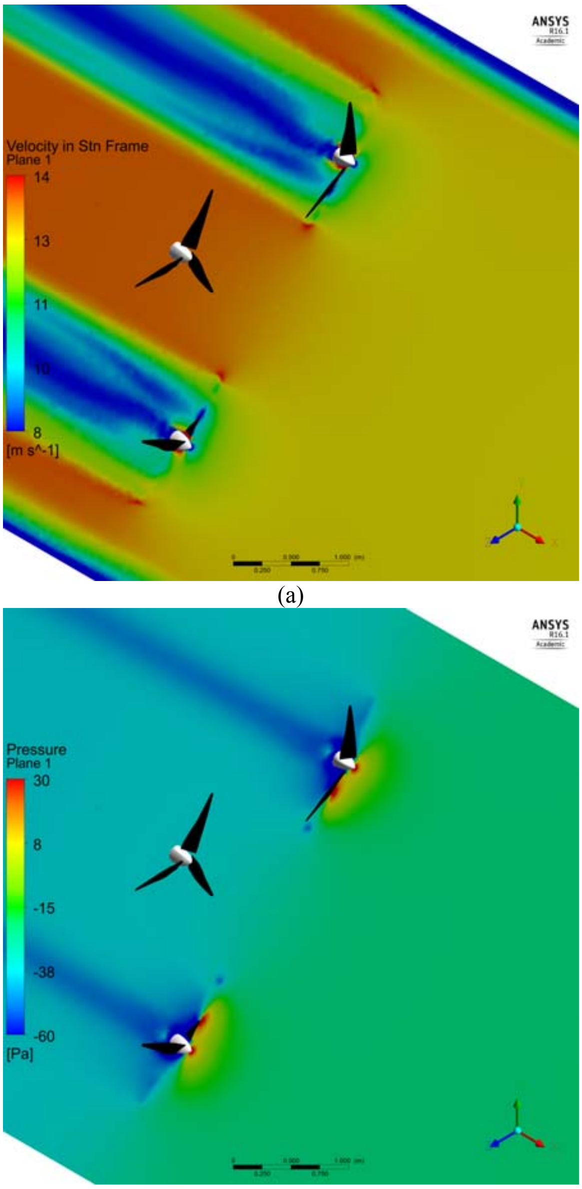


Figure 7 Power generation of the ducted HAWT installed in the left and right through-building openings at 0°, 30° and 60° when the free stream velocity is: (a) 6m/s, (b) 9m/s, (c) 12m/s and (d) 15m/s.

The resultant power generations indicate that installing the turbine in a through-building opening with a properly designed inlet and outlet can strongly enhance its performance, not only at 0° incident wind angle but also at other angles. For example, at below 30°, power generation of the ducted turbine is 60-100% higher than the free stream wind turbine and at 60°, power generation of the left ducted wind turbines is still higher the free stream one.

A previous study showed that power generation of this HAWT is about 40% higher than the free stream one exposed to the similar approach wind velocity [8] while this study has shown a greater enhancement. The reason is laid behind the actual velocity amplification of the ducted flow. Due to the inlet and outlet design of the through building openings, velocity of the ducted flow has increased above the free stream velocity in these incident wind angles which consequently has increased both the rotational speed and the toque exerted on the rotor. More extensive simulations need to investigate power generation of the ducted HAWT in every incident wind angles to conduct a more complete assessment.

Looking at Figure 7 (d), power generation of the ducted HAWT in the left opening at 0°, 30° and 60° incident wind angles is a constant 600W. The reason is that at this velocity the turbine has reached its maximum capacity and its power generation cannot exceed above this point. Therefore, using more wind turbines at different sections of the through-building opening may result in greater power generation. Installing one or more series of wind turbines behind the first ones in high velocities may decrease the ducted flow velocity to a reasonable value where all the turbines can operate near their maximum power generation capacity. However, as Figures 8(a) and (b) show, the explicit simulation of the ducted HAWTs indicates a dramatic drop in the velocity and pressure at their downstream. As a result, no turbine can efficiently operate right behind the front ones. Therefore, the minimum acceptable distance between the front and rear turbine needs also to be investigated for this purpose.



(a)

(b)

Figure 8 Contours of (a) velocity and (b) pressure at the upstream and downstream of the ducted HAWTs.

Conclusion

By replacing the actual model of a turbine with an equivalent momentum sink this study has developed a new technique capable of estimating the flow characteristic of a ducted flow in a through-building opening in the presence of wind turbine(s). This technique was implemented to estimate pressure, velocity and turbulence intensity of the flow within a through-building openings embedded in a tall building housing four Ampair 300 wind turbines when the building is subjected to a range of incident wind angles. The results show that power generation of the ducted wind turbine(s) at zero incident wind angle is 60-100% higher than the than the free stream wind turbine at the same approach wind velocity and a properly designed layout can preserve the velocity in the through-building opening for incident wind angles below 60°. As a result, power generation of the ducted wind turbine(s) remain(s) higher than the free stream one installed at the same approach wind velocity in those incident wind angles. This study also shows the possibility of integration of more wind turbines in a through-building opening at high wind velocities. However, it is shown that the front turbines can adversely affect the performance of the back turbines if they are located right behind them and thus the minimum separation between the turbines in that condition needs to be investigated.

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