ENABLING FORM TO BE ADJUSTED BASED ON PERFORMANCE

Performance-based parametric design approach for high-rise buildings' integrated wind turbines

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Abstract. Attempts to integrate performance analysis with architectural design process have been commonly restricted to final design stage assessments when it is too late for major modifications in buildings’ form. Similarly, enhancement of wind power production in high-rise architecture via optimization of buildings’ aerodynamic behaviour has been problematically incorporated in the schematic design stage. Therefore, these efforts have not been resulted in creation of a design agenda and aerodynamic guidelines for form generation in early design phases. This paper, accordingly, discusses a parametric design procedure to optimize wind power production in high-rise office buildings via aerodynamic transformations and refinement of form. The paper’s intention also includes the development of fundamental architectural strategies and guidelines for the design process of tall office buildings integrated wind turbines.

Keywords. Parametric design; Optimization; Building integrated wind turbine (BIWT); High-rise office; Performance.

1. Introduction

The building sector is currently the largest contributor to the energy and climate crisis (DOE, 2012). A newly emerging way to promote sustainability in the built environment is through integration of renewable energy generators such as wind power in buildings. Thus, in a distributed generation concept, buildings transform to renewable power units with minimum transmission / distribution losses. However, the effectiveness of the proposed solutions is seriously dependent on early integration with architectural design process.
Recently, “Parametric design” (PD) and “Building performance simulation (BPS)” have been deeply restructuring the design process. Architects are able to predict building performance and adoptively adjust the building characteristics in early design stage, when fundamental changes are still possible. An interactive communication between BPS (Computational Fluid Dynamic (CFD), for this paper) and PD can be developed to inform architects during the evolution of the geometry based on performative criteria.

2. Research statement

Air-flow patterns around buildings are considerably influenced by buildings’ geometrical characteristic. This is apparent in buildings taller than average urban terrain. Hypothetically, aerodynamic modification of buildings form can turn this unstructured phenomenon to a massive concentrator effect, capable of boosting wind power production in taller buildings (Mertens, 2006).

Accordingly, this research seeks to enhance wind power production in high-rise offices via aerodynamic refinements of form (using mathematical models and CFD analysis) within an evolutionary parametric design process. There are particular limits associated with use of PD and CFD (Figure 1). A smart data exchange between PD and CFD in an optimization platform develops a decision mechanism to collect the architectural concepts with improved acceleration / concentration of flow over turbines. The mechanism is reinforced with optimization technique such as Genetic Algorithm (GA).

2.1. RESEARCH OBJECTIVES

- Classify tall buildings’ characteristics influencing wind,
- Study PD to produce parametric transformations of models
- Explore appropriate PD, mathematical models and CFD tools
- Develop a mechanism to enable form to be adjusted by performance

Figure 1. Research statement, limits associated with use of PD and BPS in design process (Abdolhossein pour et al., 2012) adopted from (Yi, 2008) & (Ilgin and Günel, 2007)
2.2. RESEARCH HYPOTHESIS

- Wind velocity escalates as altitude rises. This is beneficial as turbine’s output power is proportional with the cube of velocity, equation (1).
- High-rise buildings provide tall and economical structures for turbines.
- The concentrator effect results in faster flow and larger pressure difference across the bodies. This significantly increases turbine power, equation (3).
- Onsite production minimizes power losses realized in transmission process.

2.3. RESEARCH LIMITATION / FUTURE STUDIES

The research scope is limited to the study of tall office buildings and related criteria. The turbulence effects of surrounding buildings, vibration, structural & façade issues, BIWT economy, lifecycle cost and development of math-models for the study are not parts of this paper and remain for future studies.

3. Background discussion

3.1. WIND BEHAVIOR CLASSIFICATION AROUND OBSTACLES

As wind approaches a building, the surrounding flow patterns are noticeably dependent on the body’s dimensional ratio. Bodies with similar dimensional sizes bend the flows in a 3D pattern (Figure 2). But, bodies with one length noticeably larger than others mostly deflect the flows around the smaller body’s section (Mertens, 2006, Hoerner and Borst, 1975). Wind deflection often raises the velocity of flow. 2D bodies experience larger induced velocities than 3D bodies as air has to move on only one surface (Batchelor, 2000).

![Figure 2. Flow pattern over 3D, left and 2D bodies, right](image)

3.1.1. Flow separation and Sharpe edges effect

When wind hits a building, the fluid moves up on the body’s upwind side, but has difficulty staying attached to the downhill surface. When flow is fast enough, it separates from the surface and creates a wake behind the body.
This phenomenon is called flow separation. Flow over sharp edges separates considerably easier than over rounded edges (Cengel et al., 2011, p678).

3.2. BUILDINGS AERODYNAMIC CLASSIFICATION

Building forms can be classified as bluff or aerodynamic (streamlined) bodies depending on their geometry and alignment with regard to flow direction (Mertens, 2006). A body can be either bluff or aerodynamic depending on how it faces wind. A flat plate is an aerodynamic body if flow moves parallel to it; and a bluff body if the incident flow angle is about 15°-90° (Figure 3).

- **Bluff buildings** are characterized by an easy and early separation of flow from the building surface. Bigger wakes behind the bluff bodies result in larger pressure difference at the building surfaces. Thus bluff geometries experience higher induced drag force in by wind (ibid).
- **Aerodynamic buildings** are characterized with a very small separation. The thin front boundary layer remains attached to surface (ibid).

![Figure 3. Flow pattern over an aerodynamic body (left) and a bluff body (right) in parallel flow. Flow direction from left to right. (Mertens, 2006, pp. 24)](image)

3.3. BUILDINGS INTEGRATED WIND TURBINE (BIWT) TYPOLOGY

Common integrations of turbines with a building are described in Figure 4 (Stankovic et al., 2009, p.22). Concepts include single tower with turbine on top, side or inside a duct as well as twin tower with turbine in between. This paper narrows down the study on twin towers type only.

![Figure 4. Generic typology BIWT (Babsail, 2011, p.42) adopted from (Stankovic et al., 2009)](image)
3.4. WIND TURBINE PHYSICS (POWER EQUATION)

The power content \( P_{\text{Wind}} \) of an air parcel is found by equation (1) where \( V \) is free-stream velocity, \( A \) is equal to turbine swept area and \( \rho \) is air density. However, when flow passes a turbine, only portion of its kinetic energy is captured. Turbines’ power coefficient \( (C_p) \) is defined by ratio of the captured turbine power \( (P_T) \) to wind power content \( (Sathyajith, 2006) \), equation (2). Turbines slow down wind by extracting its kinetic energy. This negative acceleration originates in resisting forces generated by blades (second law of Newton). If turbine is pushing wind, air reacts equally in opposite way (third law of newton). If velocity on turbine is \( V_T \), then power (energy per second) for a turbine is found from (3) where \( F \) is the reaction force and \( \Delta P \) is the pressure drop across turbine. Betz’s law proves \( C_{P,\text{Max}} \) for a bare horizontal axis turbine cannot exceed 16/27~0.593 (Hau and von Renouard, 2013).

\[
P_{\text{Wind}} = \frac{1}{2} \rho \cdot A \cdot V^3 \quad (1)
\]

\[
C_p = \frac{P_T}{\left(\frac{1}{2} \rho \cdot A \cdot V^3\right)} \quad (2)
\]

\[
P_T = F \cdot V_T = (\Delta P \cdot A) \cdot V_T \quad (3)
\]

3.4.1. Shrouded Wind turbines and Vortex model

Shrouded wind turbine is composed of two air-foil section or a ring airfoil duct and a wind turbine in the centre (Figure 5). Measurements shows power enhancement for shrouded augmented wind turbines.

Mertens, (2006) provides below mathematical models for 2D calculation of turbine power enhancement with a diffuser. If \( D_t \) is turbine diameter, \( c \) is the length of air-foil chord, \( C_L \) is the airfoils lift coefficient and \( X_s \) and \( X_a \) are correction factors. Figure 5 defines an augmentation \( \xi \).

\[
X_s = [0.5051 \ln(R/c) + 1.4447] \quad \text{for} \quad 0.2 \leq R/c \leq 5 \quad (4)
\]

\[
X_s = 1/[1 - 0.0511(D_t/2c)^{1.6211}] \quad \text{for} \quad 0.3 \leq D_t/2c \quad (5)
\]

\[
\xi = \frac{X_s \cdot C_L \cdot c}{\pi D_t} \cdot \frac{1}{1 - \frac{X_s \cdot C_L \cdot c}{4\pi D_t \left(1 + \left(\frac{c}{2D_t}\right)^2\right)}}
\]

Figure 5. Augmentation equation and Shrouded turbine (Mertens, 2006, pp. 99 & 108)
\[ \xi = X_a C_L c/(\pi D_t)/(1 - X_a C_L c/(4\pi D_t (1+c/2D_t)^2)) \]  \hspace{1cm} (6)

Equation (6) is the equivalent of the augmentation equation shown in Figure 5. According to (6) shrouded turbine \( C_{P,\text{Max}} \) is calculated by (7).

\[ C_{P,\text{Max}} = 16/27 (1+ \xi) \]  \hspace{1cm} (7)

In equation (7), the fraction 16/27 is the Betz’ constant studied in section 4. So, in ideal situation, \( C_{P,\text{Max}} \) of a shrouded turbine can exceed Betz’ limits.

4. Discussion on research methodology

The integration of airflow analysis with early design stage was discussed in Figure 1. The gap between design process and building aerodynamic has not been studied well enough. Also above studies on aerodynamic, turbines physics and BIWT raise a demand for an "Integrated Design-Research Method". The following steps provide an insight for this process.

4.1. CRITERIA DEFINITION (SURVEY OF THE KEY PARAMETERS)

First step is to collect the criteria driving the BIWT design from variety of related fields including geometrical, functional/architectural, urban and climate fields. The parameters are then classified in three categories (Table 1) depending on their impact on BIWT’s performance.

- **Variable Parameters** affect airflow patterns across buildings’ bodies and are typically associated with overall building geometries, corner modifications or tower arrangements. This research studies only a limited number of variable parameters and their effect on flow across tall building. The rest of variable Parameters are kept unchanged during the study and left for future inquiries.

<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>Constant Parameters</th>
<th>Controlling Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Geometrical</td>
<td>- Architectural</td>
<td>- Architectural, functional</td>
</tr>
<tr>
<td>Footprint geometry</td>
<td>Floor to floor height</td>
<td>Lease span</td>
</tr>
<tr>
<td>Extrusion,</td>
<td>Number of floors, Gross area</td>
<td>Core planning</td>
</tr>
<tr>
<td>Taper, Twist</td>
<td>Building orientation</td>
<td>Max tower aspect ratio</td>
</tr>
<tr>
<td>- Arrangement (Twin towers)</td>
<td>- Climate</td>
<td>Min allowable distance</td>
</tr>
<tr>
<td>Distance between towers</td>
<td>Site location</td>
<td>between buildings</td>
</tr>
<tr>
<td>Turbine placement</td>
<td>wind direction</td>
<td></td>
</tr>
<tr>
<td>- Duct Opening (single tower)</td>
<td>- Urban</td>
<td></td>
</tr>
<tr>
<td>Duct profile geometry</td>
<td>Terrain roughness</td>
<td></td>
</tr>
<tr>
<td>Height &amp; location of turbine</td>
<td>Adjacent tall building</td>
<td></td>
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</tbody>
</table>
Constant Parameters include those influencing the BIWT performance, but not the building form itself. Constant parameters are not in the research scope; hence their values are constant throughout the study (Table 1).

Controlling parameters are design functional criteria, limiting the range of incremental changes found in variable parameters, to assure that the result of 3D alternatives fall within allowable ranges for high-rise architecture.

4.2. GEOMETRIES AND ARRANGEMENT CLASSIFICATION

According to section 3.2, footprint shapes of tall buildings fall under three classes including basic bluff, complex bluff and aerodynamic buildings. Similarly, section 3.3 discusses concepts for towers arrangement regarding to the turbine (Figure 4) including single tower, twin towers, and clusters.

By overlaying the categories presented in sections (3.2) and (3.3), the study provides an advanced BIWT classification based on buildings’ footprint as well as towers arrangement (Figure 6). This paper only investigates twin towers with airfoil shape geometry. The same research method, though, is applicable for other case studies defined in Figure 6 and 8.

Streamlining or corner modifications reduce turbulence noticeably and prevent early separation across buildings, Figure 7 (Ilgin and Günel, 2007).
4.3. PROTOTYPE DEFINITION (RESEARCH CASE STUDY)

Variable parameters manipulating the selected case-study (twin towers & aerodynamic footprint) are described in detail in Figure 8. However, the numbers of nominated Variable parameters are limited to those bounded in orange which includes tower distance and angles. Unselected case studies and parameters will remain part of a broader study, being done by the author.

4.4. OPTIMIZATION PROCESSES

The algorithmic platform of BPS based form generation is shown in Figure 9. The major procedure sequences include raw data input, parametric model setup, optimization loop, accuracy control and optimal output. For the initial runs first-order mathematical models can be used to speed up the process.
Afterward, CFD simulation (e.g. ANSYS Workbench) will precisely predict the results. Workbench is capable of running parametric CFD simulation while parametrically updating the geometry and mesh.

5. Discoveries and Conclusion

5.1. VERIFICATION OF THE CONCEPT

Equation (6) predicts augmentation factor if tower shape is an aerodynamic body (section 3.2). So, the towers should be placed almost parallel to the flow. Each tower footprint is 50m by 20m (c = 50m) as well as well-rounded corners. Hence, flow separation is assumed to be negligible. Turbine diameter ($D_t$) varies from 30m to 40m (*comparing Bahrain Word Trade Centre $D_t$ is 29m*). Also, towers attack angle ($\alpha$) modified with 1° increments from 0° to 12°. So the total towers swirl is $2\alpha$ and varies from 0° to 24°. (Figure 10).

\[
C_l = 2\pi \alpha \quad \text{or} \quad 2\pi \sin(\alpha) \quad \text{for } \alpha \leq 0.23 \text{ Radian (} -12^\circ \text{ to } 13^\circ \text{)} \quad (8)
\]

According to Kutta theorem, the lift coefficient ($C_l$) of a 2D flat plate or symmetrical airfoil is almost equal by $2\pi$ times angle of attack ($\alpha$) in radian when $\alpha$ is small (Currie, 1974; Abbott and Von Doenhoff, 1959). With substitution of (8) in (6) and parametrically changing $\alpha$ and $D_t$ blow results are obtained. For more accurate prediction, CFD modelling is needed.
5.2. RESULTS AND CONCLUSIONS

Maximum enhancement for all $D_t$ occurs at $\alpha=13^\circ$, but larger $\alpha$ simply lead to flow separation which substantially reduces $C_l$ and $\xi$. Therefore, $\alpha$ approaching to the stall angle elevates the BIWT sensitivity to wind angular fluctuations. Opposite flows slightly reduce the concentrator effect due to separation but it is expected to have better performance than bare turbine of same size. As $D_t$ reduces, $\xi$ raises, however, the total power drops as turbine swept area becomes too small ($A=\pi D_t^2$). Using high-lift airfoils instead of symmetrical ones for towers enhance $\xi$ but can limit towers architecture.

The study proves regional wind data is a vital part for design decisions making as a typical alternative might not work for different locations.

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References


