Optimal Design of Vertical Axis Wind Turbines for Mechanical and Aesthetic Performances under Green Lifestyles in Thailand

Pataradanai Onporat¹, Chayapol Nitichakorn¹, Thinnapat Kumpeeyan¹, and Thananchai Leephakpreeda¹,²

¹School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Thailand

Abstract. Although current Vertical Axis Wind Turbines (VAWTs) is highly potential to energy conversion of wind energy under low wind speed conditions, which are abundantly found in Thailand, it is clear that there are no strong attentions of usages from private investors and government. To resolve the problems, the optimal design of VAWTs is proposed to obtain the most efficient power generation and the most physical attractiveness to household users. For each three dimensional VAWT model, the mechanical performance index is determined from the mean power coefficient over tip speed ratios via CFD analysis while the aesthetic performance index is obtained from the mean vote of respondents about their preference to three dimensional VAWT models. The product t-norm of two indices is used to quantify the most efficient power generation and physical attractiveness. The greatest values are chosen as the best designs. It is confirmed that there are significant tradeoffs between engineering achievement and appearance satisfaction for given models in the survey experiment. The mechanical performance index and aesthetic performance index should be taken in account for commercialization design. This work aims at research communities for systematically exploring new wind turbine rotors with innovative shapes, sizes, and orientations for physical attractiveness.

1 Introduction

In Thailand, low wind speed conditions have been widely found in abundant areas from rice farms to terraces of buildings. There are high potentials of current turbine technology in generating mechanical power from wind energy. Additionally, wind energy is clean and free of charge for green lifestyles in Thailand. However, usage of wind turbines is not attractive enough to draw attention of private investors or government to wind power generation. Up to now, Vertical Axis Wind Turbines (VAWTs) are mostly studied for improvement of efficiency under low wind speed conditions. For example, the aspect ratio of blade height to rotor radius was determined for refining mechanical performance [1, 2]. Addition to the sizes of VAWTs, the shapes were entirely selected from aerodynamic performance during rotation [3]. However, the efficient blade shapes are usually enlarged in practical designs to reach structural limitation [4]. Also, the number of blades is the important geometrical parameter of the turbine performance [5]. In literature, there has been no study concerning physical appearance as another performance of VAWTs in practical use [6].

In this work, the novel conceptual design of wind turbines under low wind speed conditions is proposed to obtain efficiency in power generation and attractiveness during standing and rotating states. In other words, this work aims at research communities for exploring new rotors of wind turbines with innovative shapes, sizes, and orientations for physical attractiveness.

2 Experimental setup

The three dimensional models of the prospective VAWTs are developed with a product development software of Solidworks™ where they are shaped, sized, and orientated. For mechanical performance analysis, those three dimensional models are experimentally investigated within a virtual wind tunnel of a standard particle-based Lattice-Boltzmann CFD xFlow™ software, as illustrated in Figure 1. The CFD workflows involves transient simulations with real moving geometries of wind turbine rotors during rotation. The wind speeds at entrance of the wind tunnel are uniformly set at different values of 1 m/s - 6 m/s as low wind speed conditions in Thailand. The VAWTs are placed within a wind tunnel of 1.5 x 1 x 1.5 m². The resolved scale of the wind tunnel is set at 0.1 m while the refined scale surrounding the VAWTs is set at 0.00625 m. The single phase external flow model is developed under isothermal Newtonian conditions of air. The wall-adapting local Eddy is used as the three-dimensional turbulence model in this computation.

At a given wind speed, the testing VAWT is exerted by different torsional loads against turbine torques where it rotates at different angular speeds. The mechanical
The power of VAWT can be determined by multiplication between the torsional load and corresponding constant angular speed of the VAWT while the tip speed ratio are determined according to the angular speed of VAWT and wind speed. The mechanical performance index is obtained from the characteristic curves of VAWTs, that is, the plots of power coefficients against tip speed ratios, as discussed in section 3. To yield the aesthetic performance index, the three-dimensional models during standing and rotating states are visualized via animation with a number of respondents. The mean scaling answers of the respondents’ preferences to VAWTs are collected from a questionnaire survey in terms of linguistic acceptance such as unsound (0), poor (0.25), fair (0.5), very good (0.75), and exceptional (1).

![Figure 1. CFD performance investigation of VAWTs within a wind tunnel.](https://doi.org/10.1051/matecconf/201929102002)

### 3 Optimal design of wind turbines based on mechanical and aesthetic performance indices

There are two performance indices, such as mechanical performance index and aesthetic performance index, to be defined for best practice. For fair comparison among wind turbines, the mean power coefficient is used to indicate average efficiency of energy conversion over tip speed ratios. The scaled votes of physical attractiveness is used to indicate preference of presentation of wind turbines during standing or rotating states. The mechanical performance index and aesthetic performance index are traded off with maximum t-norm values for selecting the best wind turbines.

#### 3.1 Mechanical performance index

Technically, characteristic curves of VAWTs are obtained from CFD analysis and they are considered with dimensionless variables between power coefficients and tip speed ratios of VAWTs. The power coefficient indicates percentage of mechanical power to wind power while the tip speed ratio is defined as a ratio of speed at blade tip to wind speed. In fact, the characteristic curve shows mechanical power of a VAWT at a given rotational speed, which extracting wind power at a given wind speed. In Eq. (1), the power coefficient can be written as:

\[
C_p = \frac{P_t}{P_w}
\]  

where \( C_p \) is the power coefficient, \( P_t \) is the mechanical power of VAWT, and \( P_w \) is the wind power.

In Eq. (2), the tip speed ratio can be expressed as

\[
\lambda = \frac{\omega r}{v}
\]  

where \( \lambda \) is the tip speed ratio, \( \omega \) is the angular speed of VAWT, \( r \) is the radius of VAWT blade tip, and \( v \) is the wind speed.

In Figure 2, the mean power coefficient over tip speed ratio is used as an overall mechanical performance index in this work, as given in Eq. (3).

\[
\text{MPI} = \frac{\int_0^{\lambda_{\text{max}}} C_p(\lambda) d\lambda}{\lambda_{\text{max}}}
\]

where MPI is the mechanical performance index, and \( \lambda_{\text{max}} \) is the maximum tip speed ratio.

The higher the mean value, the better the mechanical performance. To be compared among VAWTs, the values are normalized between null and unity in order to indicate analogous scales of mechanical performances.

![Figure 2. Determination of mechanical performances from characteristic curve.](https://doi.org/10.1051/matecconf/201929102002)

#### 3.2 Aesthetic performance index

In this study, a questionnaire, as a research instrument, is to quantify physical attractiveness of VAWTs as an overall aesthetic performance index during standing and rotating states. The aesthetic performance index can be used to include various designers’ theme and users’ preference. The models of VAWTs are presented to respondents with questionnaires of preferences. The questions about aesthetic acceptance are surveyed in terms of linguistic answers such as unsound (0), poor (0.25), fair (0.5), very good (0.75), and exceptional (1). Figure 3 illustrates an example of the questionnaire. Each aesthetic performance index is determined by an arithmetic mean.

\[
\text{API} = \frac{\sum_{i=1}^{N} w_i}{N}
\]  

where \( w_i \) is the weight of the \( i \)-th respondent.
where $A$ is the aesthetic performance index, $w$ is the scale of each respondent’s preference to VAWT, and $N$ is the total number of respondents.

**Questionnaire**

Name:________ Date of Survey:________

Your Gender? □ Male □ Female How old are you? □ Under 18 years □ 18-30 years □ Over 30 years

Model: How attractive is the turbine?

- [ ] Uns useful
- [ ] Poor
- [ ] Fair
- [ ] Very Good
- [ ] Exceptional

**Figure 3.** Questionnaire survey on attractiveness of VAWTs.

### 3.3 Selection of the best mechanical and aesthetic performances

The models of VAWTs are ranked as candidate VAWTs according to mechanical and aesthetic performances. The quantitative method for justification of selection for the best mechanical and aesthetic performance is determined from product $t$-norm of normalized values of performance indices in Eq. (5).

$$MOPI = \max_{\forall i} [MPI_i \land API_i]$$  \hspace{1cm} (5)

where $MOPI$ is the maximum overall performance index, $MPI_i$ is the normalized mechanical performance index of the VAWT $i$, and $API_i$ is the normalized aesthetic performance index of the VAWT $i$.

**Figure 4.** Schematic diagram of optimal design methods of VAWTs.

Figure 4 shows a schematic diagram of optimal design methods of VAWTs for mechanical and aesthetic performances. A three dimensional model of each VAWT is developed to obtain mechanical and aesthetic performance indices from CFD experiments and survey, respectively. Accordingly, the overall performance index is determined by the product $t$-norm operation for justification to rank all models of VAWT design. The maximum value is used to select the best design.

### 4 Results and discussions

Figure 5(a), Figure 6(a), Figure 7(a), Figure 8(a) and Figure 9(a) show examples of three dimensional models in this study. The theme of VAWT design is to be fitted to green lifestyle in Thailand to promote usage of wind energy in power generation. It should be remarked that Figure 5(a) presents a conventional VAWT for engineering design. The other models are designed for further concerns on physical attractiveness. The corresponding power coefficients of VAWTs are determined via CFD analysis, as illustrated in Figure 5(b), Figure 6(b), Figure 7(b), Figure 8(b), and Figure 9(b). As expected, the VAWT#1 in Figure 5(b) has the highest mean power coefficient. The animations of those VAWT models are presented to vote for physical attractiveness, as shown in Figure 10. Table 1 lists the normalized mean votes as the aesthetic performance indices. It can be seen that the VAWT model#3 of $MOPI = 0.53$ is selected as the best design in the highlight. It is confirmed that there are significant tradeoffs between engineering achievement and appearance satisfaction for given models in the survey experiment.

**Figure 5.** Illustration of (a) VAWT model#1 and (b) characteristic curve.
**Figure 6.** Illustration of (a) VAWT model#2 and (b) characteristic curve.

**Figure 7.** Illustration of (a) VAWT model#3 and (b) characteristic curve.

**Figure 8.** Illustration of (a) VAWT model#4 and (b) characteristic curve.

**Figure 9.** Illustration of (a) VAWT model#5 and (b) characteristic curve.
Figure 10. Voting survey of physical attractiveness of VAWT.

Table 1. Experimental results of \( \overline{\text{MPI}}_l \), \( \overline{\text{API}}_l \), and MOPI

| Model | \( \overline{\text{MPI}}_l \) | \( \overline{\text{API}}_l \) | \( \overline{\text{MPI}}_t \) | \( \overline{\text{API}}_t \) | MOPI |
|-------|-----------------|-----------------|-----------------|-----------------|-------|
| 1     | 6.2             | 0.22            | 1               | 0               | 0     |
| 2     | 1.25            | 0.67            | 0               | 1               | 0     |
| 3     | 3               | 0.65            | 0.55            | 0.98            | 0.53  |
| 4     | 1.95            | 0.63            | 0.16            | 0.94            | 0.15  |
| 5     | 1.6             | 0.44            | 0.076           | 0.51            | 0.039 |

5 Conclusion

From the results, the proposed methodology is effectively to identify the optimal designs for the most efficient power generation and the most attractive usage. The mechanical performance index and aesthetic performance index should be taken in account for commercialization design. This work aims at research communities for systematically exploring new wind turbine rotors with innovative shapes, sizes, and orientations for physical attractiveness.

References

1. S. Unsakul, C. Sranpat, P. Chaisiriroj, and T. Leephakpreeda, CFD-based performance analysis and experimental investigation of design factors of vertical axis wind turbines under low wind speed conditions in Thailand”, J. Flow Control Meas. Visual., 5(4), 86-98, (2017).
2. S. Bruscam, R. Lanzafame, M. Messina, Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine’s performance, Int. J. Energ. Environ. Eng., 5(4), 333-340, (2014).
3. M. Marini, A. Massardo, A. Satta, Performance of vertical axis wind turbines with different shapes, J. Wind Eng. Ind. Aerod., 39(1–3), 83-93, (1992).
4. P.J. Schubel, R.J. Crossley, Wind turbine blade design, Energies, 5, 3425-3449, (2012).
5. A. Rezaeiha, H. Montazeri, B. Blocken, Towards optimal aerodynamic design of vertical axis wind turbines: impact of solidity and number of blades, Energy, 165, 1129-1148, (2018).
6. M.M.A. Bhutta, N. Hayat, A.U. Farooq, Z. Ali, Sh.R. Jamil, Z. Hussain, (2012), Vertical axis wind turbine – A review of various configurations and design