Structure Analysis of an Innovative Vertical Axis Wind Turbine with Inclined Pitch Axes using Finite Element Method

Jia Guo, Pan Zeng and Liping Lei*

Key Laboratory for Advanced Materials Processing Technology of MOE, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China

* E-mail address: leilp@tsinghua.edu.cn

Abstract. Pitch regulation is critical to power performance of wind turbines. However, the complexity of the conventional pitch system of vertical axis wind turbines (VAWTs) retards its appliance. In the present study, an innovative pitch system of a VAWT with inclined pitch axes was proposed where a slider in the main shaft actuated upwards or downwards drives blades to be folded by linkage mechanisms. Effect of design parameters of the pitch system on blade folding movement control sensitivity was evaluated. Loads of pitch hinge, deformation of blades and stresses of components were analyzed as well as natural frequencies of the wind turbine with various azimuth and fold angles under rated operational conditions by finite element method and effect of design parameters on structural performance of the wind turbine was investigated. It was found that deformation of blades and stresses of supporting arms deteriorated but natural frequencies of the wind turbine increased when blades were folded in the negative direction. In addition, the increasing arm interval height improved structural performance with the increasing natural frequencies. In the contrary, the decreasing blade linkage length, shaft linkage length and slider height improved structural performance with the decreasing natural frequencies. This study laid the foundation for the further design optimization of the novel pitch system.

1. Introduction

Pitch regulation is important to wind turbines since it can control the power output and mitigate loads, as well as improving self-starting ability specifically for vertical axis wind turbines (VAWTs)[1]. Pitch mechanisms for horizontal axis wind turbines (HAWTs) are technically quite mature and widely applied in wind power industry[2]. Blades are connected to the hub via pitch bearings and pitch motors actuate blades to rotate around blade aerodynamic center lines. However, for VAWTs there are no widely accepted pitch mechanisms. Several pitch system designs were mentioned in the previous literature[3, 4] but these designs are complicated. Guo et al.[5, 6] proposed an innovative VAWT design with inclined pitch axes (not coincident with the aerodynamic center line) for small scale VAWTs which is structurally simple and practical. The present study mainly focuses on structural performance of the novel pitch system design.

Structural analysis is essential for VAWTs since they are typical rotary machine and may encounter structural problems during their whole service life such as resonance and fatigue failure caused by cyclic and random excitation from wind[7]. The structural performance and dynamic responses of VAWTs without pitch regulation have been investigated by numerical and experimental methods[8-
In the present study, the principle design of the novel pitch system was described and design parameters were pointed out first. Then effect of design parameters on blade folding movement control sensitivity was clarified. Loads of the novel pitch system and stresses of components of the wind turbine were assessed as well as natural frequencies of the wind turbine with various azimuth and fold angles. In addition, effect of design parameters on structural performance of the novel VAWT prototype was elucidated compared to a conventional VAWT.

2. Principle design of the novel pitch system

The innovative pitch system of a VAWT with inclined pitch axes is shown below (figure 1). Blades are connected to the main shaft via supporting arms in the lower section. A slider is driven to move upwards and downwards along the main shaft and are connected to blades via shaft linkages, shaft joints (cardan joints), driving arms, blade joints (spherical joints) and blade linkages successively.

![Schematic diagrams of (a) a blade with an inclined pitch axis (b) a VAWT design using the novel pitch mechanism.](image)

**Figure 1.** Schematic diagrams of (a) a blade with an inclined pitch axis (b) a VAWT design using the novel pitch mechanism.

Design parameters of the novel pitch system include the inclined angle ($\gamma$), the arm interval height, the slider height, the blade linkage length and the shaft linkage length as is shown in figure 2.

![Schematic diagram of design parameters of the novel pitch system.](image)

**Figure 2.** Schematic diagram of design parameters of the novel pitch system.
3. Kinematic analysis

Three coordinate systems are established to elaborate the kinematics of the innovative pitch system (figure 3). The first one is the inertial coordinate system (ICS), of which the origin is located at the intersection of the supporting arms and the main shaft, the x axis is in the free stream direction, the y axis is perpendicular to the free stream and the z axis is vertical upwards. The second one is the blade azimuth coordinate system (BCS), of which the origin is located at the intersection of the supporting arm and the blade, the x, y and z axis is tangential, normal and vertical, respectively. The third one is the pitched blade coordinate system (PCS), of which the origin is same as that of BCS, the x, y and z axis is in the direction of chord, thickness and span of a pitched blade, respectively.

![Figure 3. Schematic diagrams of three coordinate systems (a) ICS and BCS (b) PCS.](image)

Then the blade folding movement control sensitivity is calculated, namely variations of the fold angle ($\eta$) corresponding to stroke of the slider ($s$). The coordinate of the blade joint in PCS is

$$q_{bj,p} = [0 \ -l_{bj} \ h_{bj}]^T$$  \hspace{1cm} (1)

The transformation matrix from PCS to BCS is

$$T_{p2b} = \begin{bmatrix} \sin^2 \gamma \cos \eta + \cos^2 \gamma & \sin \gamma \sin \eta & \sin \gamma \cos \gamma (1 - \cos \eta) \\ -\sin \gamma \sin \eta & \cos \eta & \cos \gamma \sin \eta \\ \sin \gamma \cos \gamma (1 - \cos \eta) & -\cos \gamma \sin \eta & \sin^2 \gamma + \cos^2 \gamma \cos \eta \end{bmatrix}$$  \hspace{1cm} (2)

So the coordinate of the blade joint in BCS is

$$q_{bj,b} = T_{p2b} q_{bj,p}$$  \hspace{1cm} (3)

The coordinate of the shaft joint in BCS is

$$q_{sj,b} = [0 \ l_{sj} - R \ h_{bj} + h_{sj} + s]^T$$  \hspace{1cm} (4)

The length of the driving arm is constant during the blade folding movement, so

$$|q_{bj,b} - q_{sj,b}| = |q_{bj,b} - q_{sj,b}|_{s=0,j=0}$$  \hspace{1cm} (5)

Variations of the fold angle to nominal stroke of the slider under conditions of different design parameters are shown in figure 4. As can be seen in figure 4(a) the blade folding movement control sensitivity varies during the whole folding process and increases when the inclined angle gets closer to 90°. As for arm interval height, the blade folding sensitivity increases when arm interval height decreases but chances are that the blade folding sensitivity becomes too high so that blade folding movement may lose control. In addition, the blade folding sensitivity increases with slider height,
blade linkage length and shaft linkage length. However, the range of the fold angle can be limited because of small slider height.

![Figure 4](image)

**Figure 4.** Effect of design parameters on blade folding sensitivity (a) inclined angle (b) arm interval height (c) slider height (d) blade linkage length (e) shaft linkage length.

4. **Structural analysis**

An innovative VAWT with inclined pitch axes is simulated in ANSYS as well as a conventional one as a counterpart. The model is a 10 kW prototype whose parameters and materials are shown in table 1 and table 2[12]. The MPC184 element are applied for blade joints (spherical joints), shaft joints (cardan joints) and pitch hinges of the pitch system and other components of the wind turbine are modeled by BEAM188 element. Specifically, the cross sections of blades are airfoils achieved by user-defined mesh. Appropriate mesh size is determined and mesh independence is examined. The computational models of the wind turbine are shown in figure 5.

| Parameters | Value |
|------------|-------|
| Power / kW | 10    |
| Wind speed / (m/s) | 12 |
| Rotational speed / (r/min) | 143 |
| Diameter / m | 4    |
| Blade number | 3    |
| Airfoil | NACA 0018 |
| Blade span / m | 6    |
| Blade chord / m | 0.6  |

Table 1. Summary of operational parameters of the VAWT[12]

| Components | Material |
|------------|----------|
| Tower      | Q235     |
| Main shaft | 40Cr     |
| Arm        | Q235     |
| blade      | GFRP     |

Table 2. Materials of components of VAWT[12]

The loads of the wind turbine include inertial ones (C), gravity (G) and aerodynamic ones (F_T, F_N). Inertial loads are directly proportional to rotational speed and are around 5 × 10^4 N under rated condition. Gravity and aerodynamic loads are roughly one order of magnitude smaller than inertial loads. In addition, the displacements of the bottom foundation of the tower are all constrained. The loads of pitch hinges (Fsum and Msum refer to the magnitude of resultant forces and moments, respectively), displacement of blades (U_r and U_z refer to radial and vertical displacement,
respectively), stresses of blades and arms and natural frequencies are assessed under conditions of various azimuth, fold angles and design parameters.

In terms of the conventional VAWT, as is shown in figure 5, loads of pitch hinges, displacement of blades and stresses of blades and arms varies in accordance with aerodynamic loads. But natural frequencies of the wind turbine remain constant.

![Figure 5](image5.png)

**Figure 5.** Variations of results versus azimuth (a) loads of pitch hinges (b) displacement of blades (c) natural frequencies.

In terms of the innovative VAWT, results with various fold angles are shown in figure 6. When blades are folded in the positive direction, that is to say, leading edges of blades are folded outside, the sum of forces decreases and the sum of moments increases, and vice versa. As for the displacement of blades, it stays the same when blades are folded in the positive direction, but increases rapidly when blades are folded in the negative direction. Similarly, stresses of arms increase when blades are folded in the negative direction. So does the first natural frequency of the wind turbine.

![Figure 6](image6.png)

**Figure 6.** Variations of results versus fold angles (a) loads of inclined pitch hinges (b) displacement of blades (c) natural frequencies.

Then effect of design parameters is revealed and performance of the innovative VAWT is compared with that of the conventional VAWT as is shown in figure 7-10. First of all, when arm interval height increases, the sum of forces of inclined pitch hinges and the radial displacement of blades diminish. Stresses of blades and driving arms reduce while stresses of supporting arms grow. Natural frequencies increase at the same time.

![Figure 7](image7.png)

**Figure 7.** Variations of results versus arm interval height (a) loads of inclined pitch hinges (b) displacement of blades (c) natural frequencies.
As for slider height, the sum of forces of hinges, the vertical displacement of blades and stresses of arms decrease with the reducing slider height, but the first natural frequency declines as well.

![Figure 8](a) Variations of results versus slider height (a) loads of inclined pitch hinges (b) displacement of blades (c) natural frequencies.

Effect of blade linkage length is similar to that of shaft linkage length. The sum of forces of hinges, stresses of driving arms and the first natural frequency all decrease when blade linkage length and shaft linkage length decrease.

![Figure 9](a) Variations of results versus blade linkage length (a) loads of inclined pitch hinges (b) displacement of blades (c) natural frequencies.

![Figure 10](a) Variations of results versus shaft linkage length (a) loads of inclined pitch hinges (b) displacement of blades (c) natural frequencies.

5. Conclusion
An innovative pitch system of a straight bladed VAWT was depicted and kinematic and structural analyses were conducted. Main findings of the present study are summarized as follows. The blade folding movement control sensitivity is negatively correlated with the arm interval height while positively correlated with the slider height, the blade linkage length and the shaft linkage length. Loads of pitch hinges, displacement of blades and stresses of blades and arms varies in accordance with aerodynamic loads. Furthermore, deformation of blades and stresses of supporting arms
deteriorated but natural frequencies of the wind turbine increased when blades were folded in the negative direction. In addition, the increasing arm interval height improved structural performance with the increasing natural frequencies. Nonetheless, the decrease of the other three parameters improved structural performance with the decreasing natural frequencies.

Acknowledgments
This study is supported by the National Natural Science Foundation of China (No. 51875305).

References
[1] Jain P, Abhishek A. 2016, Performance prediction and fundamental understanding of small scale vertical axis wind turbine with variable amplitude blade pitching [J]. Renewable Energy, 97(97-113).
[2] Tiwari R, Babu N R. 2016, Recent developments of control strategies for wind energy conversion system [J]. Renewable and Sustainable Energy Reviews, 66(268-85).
[3] Benedict M, Lakshminarayan V, Pino J, et al. 2016, Aerodynamics of a small-scale vertical-axis wind turbine with dynamic blade pitching [J]. AIAA Journal, 54(3): 924-35.
[4] Elkhouri M, Kiwata T, Aoun E. 2015, Experimental and numerical investigation of a three-dimensional vertical-axis wind turbine with variable-pitch [J]. Journal of Wind Engineering and Industrial Aerodynamics, 139(111-23).
[5] Guo J, Zeng P, Lei L. 2019, Performance of a straight-bladed vertical axis wind turbine with inclined pitch axes by wind tunnel experiments [J]. Energy, 174(553-61).
[6] Guo J, Zeng P, Lei L. Vertical axis wind turbines with inclined pitch axes based on inclined hinged blades: China, 0669046.0 [P/OL]. 2019.10.29-
[7] Rehman S, Rafique M M, Alam M M, et al. 2019, Vertical axis wind turbine types, efficiencies, and structural stability: A review [J]. Wind and Structures, 29(1): 15-32.
[8] Lin J, Leung L K K, Xu Y-L, et al. 2018, Field measurement, model updating, and response prediction of a large-scale straight-bladed vertical axis wind turbine structure [J]. Measurement, 130(57-70).
[9] Carne T G, Lobitz D W, Nerd A R, et al., SAND82-0345 [R]. Albuquerque: Sandia National Laboratories, 1982.
[10] Malcolm D J. 2019, On the structural response of two- and three-bladed vertical axis wind turbines [J]. Wind Energy.
[11] Bianchini A, Cangioli F, Papini S, et al. 2014, Structural analysis of a small H-Darrieus wind turbine using beam models: Development and assessment [J]. Journal of Turbomachinery, 137(1):
[12] Li J. The statics analysis and dynamics analysis of 10kW H-type vertical axis wind turbine [D]. Beijing: North China Electric Power University, 2014.