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Variable pitch to high-solidity straight-bladed VAWTs for power enhancement

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Abstract

Straight-bladed vertical axis wind turbines (SBVAWTs) are a promising type of vertical axis wind turbines but their power efficiency is relatively low due to continuous variation of attack angle. Variable-pitch techniques are thus proposed to enhance their power generation. The current pitch control techniques for SBVAWTs are mainly based on some empirical forms and seldom adopted for practical use. This study first proposes an algorithm to search optimal pitch angles by means of the hybrid double-disk multiple stream-tube (hybrid DMST) model proposed by the authors and by taking the maximization of blades' tangential forces as an objective function. After optimal pitch curves with a wide range of TSRs are computed and obtained, an optimal pitch function is then established and applied to a high-solidity SBVAWT. The results obtained indicate that the power coefficient of the high-solidity SBVAWT could be enhanced prominently with the proposed optimal pitch function.

Keywords: Optimal variable pitch, high-solidity, straight-bladed, vertical axis wind turbine, wind tunnel test, hybrid DMST

1. Introduction

Variable-pitch control technology, widely applied to and well-developed in horizontal axis wind turbines (HAWTs) [1-3], is able to increase the power efficiency of HAWTs. Conceptually, this technology could be applied to SBVAWTs as well to enhance their power efficiency by varying their blade pitches. However, it turns out that it is a very challenging task for SBVAWTs because of their continuous variations of attack angle with respect to incoming wind. Although there are currently several attempts to find out an effective variable pitch scheme for SBVAWTs, most of them are mainly based on some empirical forms and seldom adopted for practical use [4, 5], in which the variable pitch scheme was first decided empirically and its feasibility and effectiveness were then examined by trial and error. Clearly, the pitch control technology for SBVAWTs is still calling for further studies.

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This study aims at obtaining an optimal pitch scheme for high-solidity SBVAWTs by using a proper analytical method rather than by trial and error. High-solidity SBVAWTs are believed to have relatively good self-starting ability and low working tip speed ratio [6, 7]. A hybrid double-disk multiple stream-tube (hybrid DMST) model proposed by the authors [8] is used as an analytical tool, for it is capable of estimating the aerodynamic forces on the blades of a high-solidity SBVAWT. By maximizing the tangential aerodynamic forces on the blades in the rotational direction at each azimuth angle as an objective function, a method of searching for optimal pitch curves is established in terms of the hybrid DMST model, and the optimal pitch curves for a high-solidity SBVAWT with different TSRs are calculated. An optimal pitch function for practical implementation is then proposed according to the characteristics of the calculated optimal pitch curves. Finally, the power coefficients of the high-solidity SBVAWT are computed and compared to those of the fixed-pitch SBVAWTs to assess the feasibility and correctness of the proposed method.

2. Optimal pitch angles

2.1. *Optimization strategy*

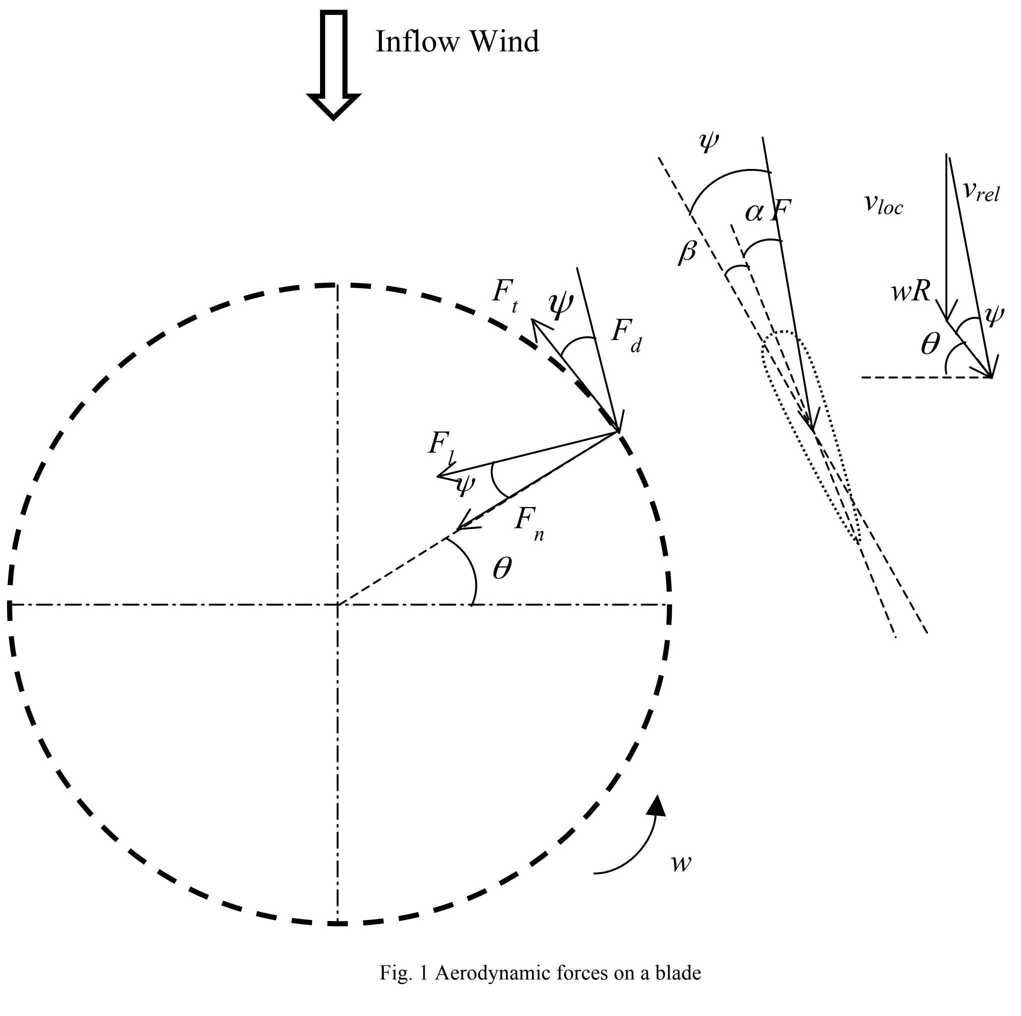

Fig. 1 Aerodynamic forces on a blade

Fig. 1 shows three groups of relationships. The first group of relationship involves the local inflow wind speed(v_{loc}), rotational speed(wR), local relative wind speed(v_{rel}), inflow angle (ψ) and azimuth angle (θ). The second group of relationship refers to the inflow angle (ψ), pitch angle (β) and attack angle (α). The last group of relationship contains the lift force (F_l), drag force (F_d), tangential force (F_t), normal force (F_n) and inflow angle (ψ). These relationships can be expressed as follows:

$$\psi = \frac{v_{loc}(\alpha)\sin\theta}{\omega R - v_{loc}(\alpha)\cos\theta} \tag{1}$$

$$\alpha = \psi - \beta \tag{2}$$

$$F_t = F_l(\alpha)\sin\psi - F_d(\alpha)\cos\psi \tag{3}$$

The instant torque T can then be calculated by

$$T = F_t R \tag{4}$$

in which R is the radius of the rotor.

The power captured from the flow in a circle can be finally calculated by

$$P = N\int_0^{2\pi} T \cdot \omega d\theta \tag{5}$$

in which N is the number of the blades and ω is the angular rotation speed of the rotor.

From Eq.(1) to Eq.(3), it can be seen that the pitch angle can alter the angle of attack and thus influence the inflow angle ψ and the local wind speed v_{loc} and eventually change tangential force. One can easily figure out that for the purpose of improving the SBVAWTs' power efficiency, aerodynamic tangential forces on the blades should be maximized. Therefore, the maximization of tangential forces is taken as an objective function in this study.

The hybrid DMST model proposed by the authors is used, and the optimal pitch angle could be solved one by one independently for each stream-tube. Since the double-disk assumption divides each stream-tube into upwind and downwind zone, each stream-tube has upwind tangential force F_{tu} and downwind tangential force F_{td}. However, aerodynamic forces in the downwind zone are difficult to be predicted due to the complicated flow field influenced by the upwind zone. To this end, the optimization of tangential forces in the upwind area is given priority. The optimal pitch in the downwind zone will be taken to be antisymmetric to that obtained from the upwind zone to facilitate the real implementation.

The proposed optimal pitch algorithm algorithm takes the maximum F_{tu} as the objective function. By using the hybrid DMST model, the tangential force could be calculated, and the maximum F_{tu} could be searched by varying the upwind pitch from $-\pi/2$ to $\pi/2$.

2.2 Optimal pitch angles

A high-solidity SBVAWT is taken as an example to calculate its optimal pitch angles. The basic information of the high-solidity SBVAWT is listed in Table 1. The optimal pitch angles are calculated according to the proposed algorithm. The optimal pitch curves at TSRs ranging from 0.7 to 2.2 are calculated at an interval of 0.1 and showed in Fig.2. The pitch angle β is defined positive in anticlockwise.

Table 1 Parameters of the high-solidity SBVAWT

Blade numbers	3
Airfoil	NACA0018
Rotor radius	1 m
Chord width	300mm

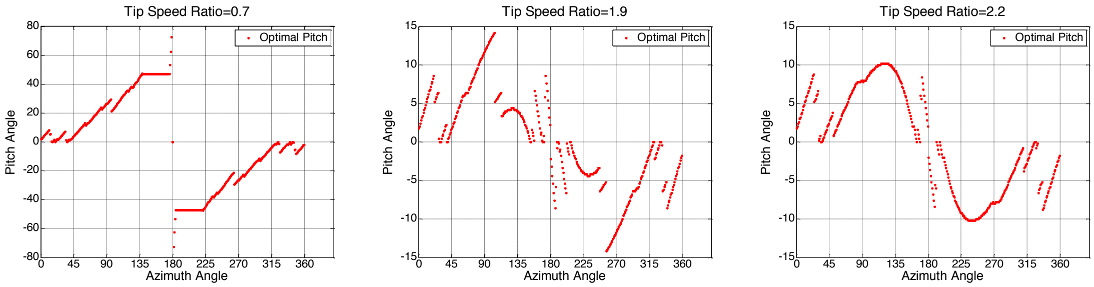

Fig. 2 Optimal pitch curves based on the hybrid DMST model

Fig. 2 manifests that with different TSRs, the optimal pitch curve varies to some extent but with some common features. It is noticed that the calculated optimal pitch angle curves are not smooth. However, it will be better and practical if they are smooth curves when they are applied for practical use.

Fig. 3 shows the comparison between the tangential force coefficients with and without the optimal pitch angles. The comparative results indicate that with the variable optimal pitch angle, the tangential force coefficients are increased, and accordingly the torques in the rotational direction are increased.

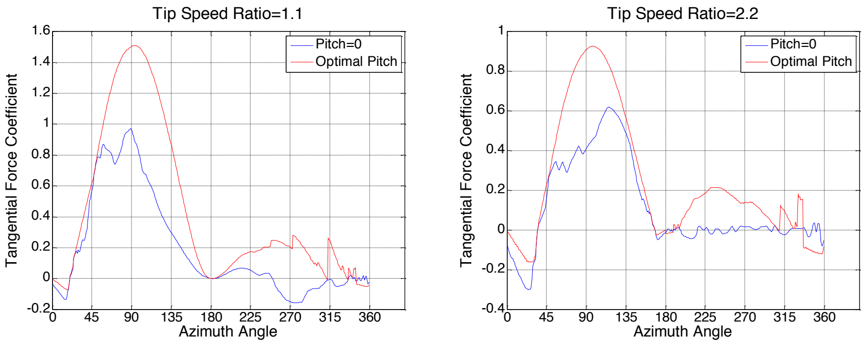

Fig. 3 Tangential force coefficients with optimal pitch and zero pitch

3. Optimal pitch function for practical implementation

The optimal pitch angle curves obtained from the last section cannot be directly used for the practical implementation because they are not smooth and continuous. It is necessary and inevitable to find an optimal pitch function capable of representing the characteristics of the optimal pitch curves and making power efficiency enhancement possible in practice.

Since the optimal pitch curves vary with azimuth angle and tip-speed ratio, the optimal pitch function is determined to be a function of azimuth angle θ and tip-speed ratio λ. According to the calculated optimal pitch curves, the optimal pitch function is taken as

$$\beta = \sum_{j}^{3}\left(\sum_{k}^{3} a_{jk}\lambda^{k-1}\sin\left(j\theta\right)\right) \tag{6}$$

in which a_{jk} (j=1,2,3; k=1,2,3) are the fitted parameters; the unit of β is in degree; and the unit of θ is in radian. It can be seen from Eq. (6) that the third-order superposition of the product of sinusoidal function and quadratic function is chosen.

The data used for finding the fitted parameters are the optimal pitch angle curves at the azimuth angles from 0 to 2π at an interval of $\pi/180$ and at TSRs ranging from 0.7 to 2.2 at an interval of 0.1. The Trust-Region in MATLAB Optimization Toolbox is used to solve the optimization equation to get better robustness. The R-square value is 0.8292, which is quite close to 1 and indicates that the fitted function represents the calculated optimal pitch curves well. The fitted parameters are listed in Table 2.

Table 2 Fitted parameter a_j

j \ k	1	2	3
1	69.60	-66.04	17.38
2	-52.66	52.90	-13.92
3	-34.44	-37.51	9.87

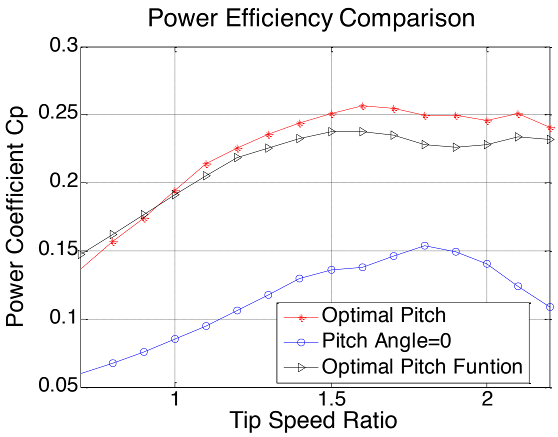

Fig. 4 Power coefficients

Fig. 4 shows the power coefficients evaluated by the hybrid DMST model with the optimal pitch angle, the optimal pitch function, and the fixed pitch angle. The results demonstrate that with the calculated optimal pitch angles or the proposed optimal pitch function, the power efficiency can be considerably increased compared with one with fixed-pitch angle. Furthermore, the power efficiency of the high-solidity SBVAWT with the optimal pitch function is quiet close to the one with the calculated optimal pitch angles, which indicates that the proposed optimal pitch function is effective and capable of representing the calculated optimal pitch angles.

4. Concluding remarks

The major conclusions and remarks from this study can be summarized as follows:

(1) A method of obtaining optimal pitch curves has been developed in terms of the hybrid DMST model proposed by the authors and by taking the maximum upwind tangential force F_{tru} at each stream-tube as an objective function.

(2) To verify the proposed algorithm, the optimal pitch curves at tip-speed ratios ranging from 0.7 to 2.2 have been calculated for a high-solidity SBVAWT and their characteristics have been discussed. The results indicate that the proposed algorithm can provide a feasible and applicable way to obtain optimal pitch curves that are able to enhance the power efficiency of the high-solidity SBVAWT.

(3) By considering the features of the calculated optimal pitch curves, an optimal pitch function has been proposed. The proposed function is a function of azimuth angle and tip-speed ratio. The parameters in the function are provided based on the tested high-solidity SBVAWT but can be changed accordingly to given high-solidity SBVAWTs.

(4) The power coefficient curves with and without optimal pitch have been computed and compared to each other. The power coefficients could be substantially increased with the proposed optimal pitch function.

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