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Energy Procedia 158 (2019) 376–381

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

# Hybrid DMST model for high-solidity straight-bladed VAWTs

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**Abstract**

Straight-bladed vertical-axis wind turbines (SBVAWTs) have unsatisfactory power generation and self-start ability due to continuous variation of attack angle to the blades. This study attempts to propose a proper analytical tool for high-solidity SBVAWTs since high-solidity SBVAWTs could be valuable in application for their comparatively low operational speed and good self-start performance. The applicability of the double-disk multiple stream-tube (DMST) model, which is a mainstream tool for SBVAWTs, is first examined for high-solidity SBVAWTs using the measurement data of aerodynamic forces on the blades obtained from wind tunnel tests. It is found that the complex flow field around the high-solidity SBVAWT introduces difficulties for the current DMST model to make satisfactory predictions. A hybrid DMST model, which uses the attack angle-dynamic aerodynamic force coefficient relationship established based on the measurement data, is then proposed. The aerodynamic forces estimated from the proposed hybrid DMST model manifest that the hybrid DMST model could predict the aerodynamic forces on the blades of the high-solidity SBVAWT with higher accuracy than the existing DMST models.



*Keywords:* Vertical axis wind turbine, straight-bladed, high-solidity, DMST, hybrid DMST, optimal pitch

## 1. Introduction

Since the DMST model is computationally inexpensive, it is widely used in the performance assessment and optimization of SBVAWTs. DMST models with some modifications and supplementary are found to be able to predict the performance of low-solidity or moderate-solidity SBVAWTs [1, 2]. Compared to the low to moderate-solidity SBVAWTs, high-solidity SBVAWTs are believed to have relatively good self-start ability due to larger average static torque coefficients [3, 4]. Moreover, high-solidity SBVAWTs can achieve higher power coefficients at


10.1016/j.egypro.2019.01.118

lower tip-speed ratios, which enable them to work at low rotational speeds [5]. Therefore, high-solidity SBVAWTs are of value in application because with low operational tip-speed ratios, excessive centrifugal forces will not be introduced, which makes wind turbine less demanding on structural strength. However, high-solidity SBVAWTs will make the flow field around the blades more complex, compared with low to moderate-solidity SBVAWTs [6, 7]. Therefore, although the DMST model will be a proper analytical tool for high-solidity SBVAWTs, the applicability of the current DMST model to the high-solidity SBVAWTs is unclear.

This study therefore conducted wind tunnel studies first to directly measure aerodynamic forces on SBVAWTs. The applicability of the current DMST model is then examined through the comparison with the measurement results of aerodynamic forces. A hybrid DMST model, which uses the attack angle-dynamic aerodynamic force coefficient relationship established based on the measurement data, is then proposed.

## 2. Measurements of aerodynamic forces on blades

The main purpose of wind tunnel experiments is to acquire aerodynamic force time-histories of the blades of SBVAWTs under various conditions. Such wind tunnel experiments require recording the azimuth angle and the aerodynamic forces synchronously. The SBVAWTs used in the experiments were designed as a three-blade SBVAWT with a radius of 1 m. The blades are NACA0018 type and with a length of 1m. The high-solidity SBVAWT was designed to have the blades with a chord length of 300mm (denoted as c300).

Fig. 1 Straight-bladed vertical-axis wind turbine in experiments

To measure the aerodynamic forces on blades, special force sensors, which are capable of measuring the aerodynamic forces in two orthogonal directions, were designed by the authors. An azimuth angle sensor, a photoelectric sensor made of a pulse generator and encoder disc, was placed at the main shaft. In this way, the aerodynamic forces on the blades could be directly measured and the azimuth angle could be recorded synchronously. A series of wind tunnel experiments were carried out to investigate the effects of azimuth angle, tip speed ratio, inflow wind speed and blade chord length on the aerodynamic (both tangential and normal) forces of the blades. More detailed information can be found in the thesis of Peng[8].

## 3. Assessment of the current DMST model for SBVAWT

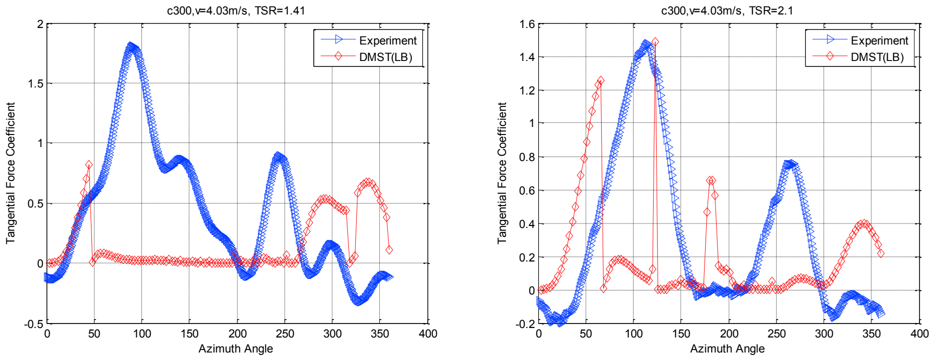


Fig. 2 Comparison of tangential force coefficient of c300 cases

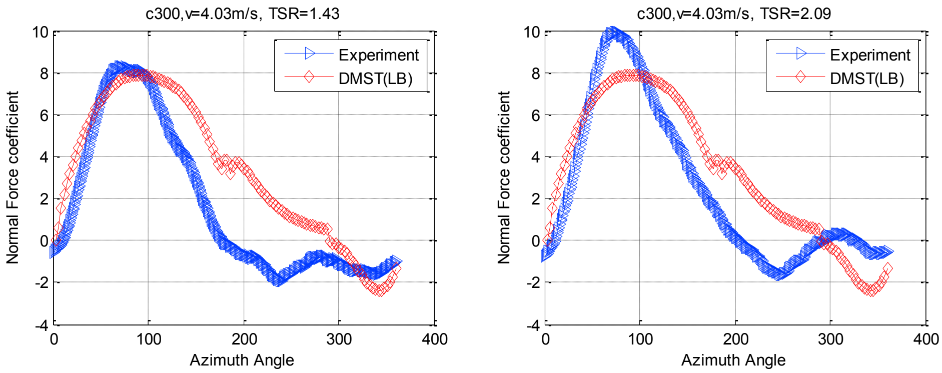


Fig. 3 Comparison of normal force coefficient of c300 cases

The DMST model with the Glauert's correction[1] and the Leishman-Beddoes dynamic stall model[9] (denoted as DMST(LB)) is adopted as the representative of the current DMST models for discussion of its applicability and limitation for high-solidity SBVAWTs through the comparison with the experimental results.

For the high-solidity SBVAWT, the comparison result shows the DMST could not give reasonable results to tangential force coefficient (Fig. 2). Fig. 3 shows that as to normal force coefficients, the current DMST results are in good agreement with the experimental results in trend, but the DMST generally underestimates the magnitude of normal force coefficients of the blades of c300.

## 4. Hybrid DMST model for high-solidity SBVAWT

From the discussion above, we can deduce that the current refined DMST model is still incapable to provide prediction with adequate accuracy for aerodynamic forces of high-solidity SBVAWT. Therefore, further modification to the DMST model should be made.

The difference between the experimental and DMST results probably lies in that the simple quasi-static assumption used in the DMST model could not reflect the complex flow field characteristics, especially for the high-solidity SBVAWTs at low tip-speed ratios. This leads to the attempt to find specific dynamic aerodynamic force coefficients for high-solidity SBVAWTs, which can then be introduced to the DMST model. Based on the collected experimental data, it is possible to establish a specific dynamic relationship between the attack angle and the aerodynamic force in one rotational circle for the high-solidity SBVAWT.

### *4.1. Dynamic aerodynamic force coefficient*

In the DMST model, the aerodynamic forces are expressed by

$$F_t = \frac{1}{2}\rho v_{rel}^2 cl\left(C_l\left(\alpha\right)\sin\alpha - C_d\left(\alpha\right)\cos\alpha\right) \tag{1}$$

$$F_t = \frac{1}{2}\rho v_{rel}^2 cl\left(C_l\left(\alpha\right)\sin\alpha - C_d\left(\alpha\right)\cos\alpha\right) \tag{2}$$

in which $F_t$ and $F_n$ are the tangential force and normal force respectively; $\rho$ is the air density; $v_{rel}$ is the relative local wind speed; $c$ is the chord length of the blade; l is the length of the blade; $\alpha$ is the attack angle; $C_l$ and $C_d$ are the lift force coefficient and drag force coefficient respectively.

When the aerodynamic forces are known, the aerodynamic force coefficient can be calculated by the following equation.

$$C_l\left(\alpha\right) = \frac{2}{\rho v_{rel}^2 cl}\left(F_n\cos\alpha + F_t\sin\alpha\right) \tag{3}$$

$$C_d(\alpha) = \frac{2}{\rho v_{rel}^2 cl}\left(F_n \sin\alpha - F_t \sin\alpha\right) \tag{4}$$

Ten groups of the experimental data are selected to calculate the dynamic aerodynamic force coefficients, and the rest of data sets are used for validation. The details of the selected data sets are listed in Table 1.

Table 1 Details of selected data sets

| Wind Speed | Tip-Speed Ratio |
|---|---|
| 4.03 m/s | 1.00/1.41/1.87/2.10/2.43 |
| 5.56 m/s | 0.97/1.83/2.50 |
| 6.50 m/s | 0.97/2.08 |

Since the attack angle is not monotonic in one rotational circle, the attack angle-dynamic aerodynamic force coefficient relationship is not one to one relationship, which contradicts to the requirement of establishing an applicable attack angle-dynamic aerodynamic force coefficient relationship. To solve this problem, the experimental data from a monotonic region of attack angle are used. For each set of experimental data, the widest monotonic region of attack angle will be found to guarantee the accuracy in most azimuth angles.

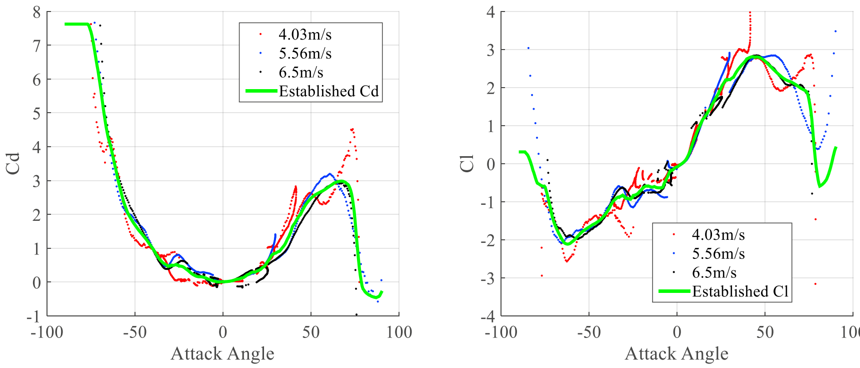


Fig. 4 Dynamic aerodynamic force coefficients in the monotonic attack angle-azimuth angle range

The green line in Fig. 4 is the mean values of the three groups of results, which can be used as the new dynamic aerodynamic force coefficients in the hybrid DMST model.

### *4.2. Hybrid DMST model for high-solidity SBVAWT*

The new dynamic aerodynamic force coefficients obtained from the last section is now used together with the DMST model to testify the availability and accuracy of the so-called hybrid DMST model.

Fig. 5 and Fig. 6 show the comparison results of tangential forces and normal forces predicted by the DMST model and the hybrid DMST model. Compared to the current DMST model, it can be seen that the hybrid DMST model could considerably decrease the discrepancy between the numerical prediction and experimental results. Accurate prediction in the downwind area is still challenging. In general, the hybrid DMST model underestimates the aerodynamic forces in the relatively higher tip-speed ratios.

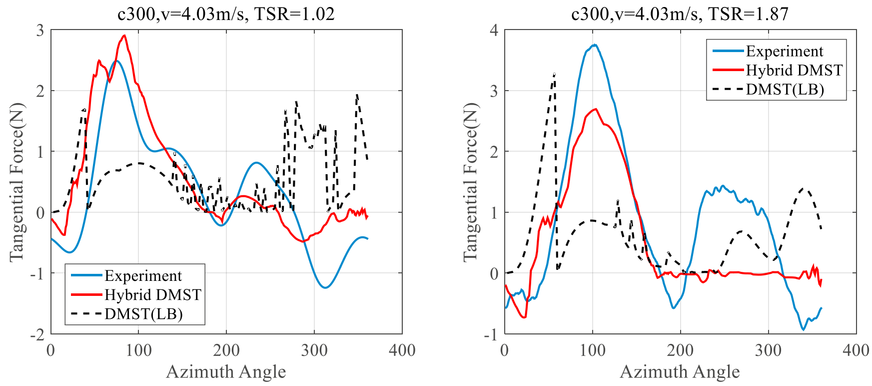


Fig. 5 Comparison of tangential forces

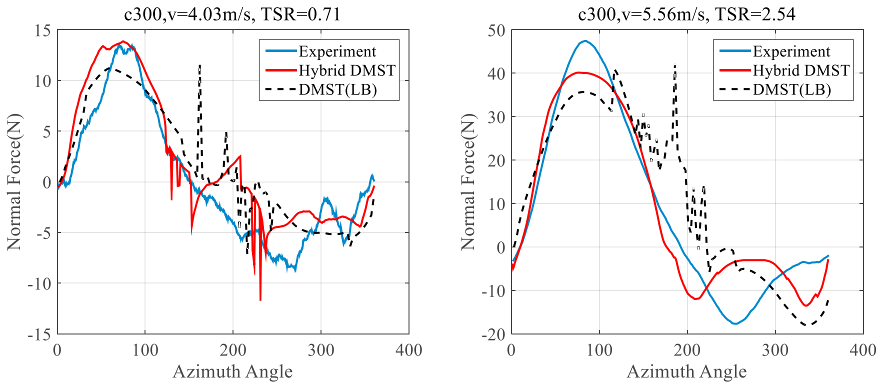


Fig. 6 Comparison of normal forces

## 5. . Conclusions

To obtain an effective analytical tool for predicting and assessing the performance of high-solidity SBVAWTs, the current DMST model, an analytical method that is widely used to predict and assess the performance of SBVAWTs, has been evaluated by means of the direct measurements of aerodynamic forces on the blades of a SBVAWT. However, the current DMST model is unable to provide the good estimation of aerodynamic forces of high-solidity SBVAWTs.

To this end, rather than using static aerodynamic force coefficients in the current DMST model, dynamic aerodynamic force coefficients are defined and found from the experimental results. The new attack angle-dynamic aerodynamic force coefficient relationship has been established and applied in the DMST model, leading to the so-called hybrid DMST model. This hybrid DMST model has been verified that it has considerably increased accuracy compared to the current DMST model in aerodynamic force estimation.

Although the established attack angle-dynamic aerodynamic force coefficient relationship may not be universal to high-solidity SBVAWTs of different airfoils and solidities, the proposed way of obtaining dynamic aerodynamic force coefficients is applicable to any other types of SBVAWTs.

## Acknowledgements

The authors would like to acknowledge the financial support from the Hong Kong Research Grants Council through the Hong Kong PhD Fellowship to the first author and The Hong Kong Polytechnic Endowed Professorship Fund (PolyU-847J) to the second author.

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