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Influence of the vibration of large-scale wind turbine blade on the aerodynamic load

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Abstract

The blades of a large wind turbine are subjected to significant vibrations during operation. The vibrations will impact the dynamic flow field around the blade and consequently alter the aerodynamic forces. In order to better understand the influence of blade vibrations on the aerodynamic loads, the dynamic stall characteristics of an S809 airfoil undergoing various types of motion were investigated using Computational Fluid Dynamics (CFD) techniques. Simulation results indicated that the in-plane and out-of-plane translational motions of the airfoil affect the aerodynamic forces significantly. Furthermore, the influence of vibrations on the aerodynamic loading on the blade of a 5 MW wind turbine was investigated using the Blade Element-Momentum (BEM) theory and the Beddoes-Leishman (B-L) dynamic stall model.

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Keywords: Wind turbine; Aerodynamics; Dynamic stall; CFD modelling

1. Introduction

Along with the rapid growth of the application of wind power in recent years, increasingly large wind turbines have been developed, with much longer and more flexible blades than ever before. Inevitably, the blade of large-scale wind turbines will experience more severe vibrations during operation. In the design stage of wind turbines, a critical task is to accurately predict the unsteady aerodynamic loads generated due to the unsteady nature of the environment in which they typically operate [1,2]. Turbulence and

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turbine regulations can lead to dynamic variations of the Angle Of Attack (AOA) of the airfoil, resulting in dynamic stall phenomena. The associated unsteady airloads are usually calculated using a dynamic stall model. The vibrations of the blade can also affect the dynamic change in the AOA, especially for large-scale wind turbines with more flexible blades. However, the airfoil vibrating velocities are usually ignored in the calculation of the AOA of blade sections in the wind turbine simulation codes.

Dynamic stall phenomena of pitching airfoils have been studied for many years and a number of semi-empirical models have been developed, such as the Boeing-Vertol model [3], the Beddoes-Leishman (B-L) model [4], the ONERA model [5] and the Øye model [6]. Of these, the B-L model is the most popular and has been widely used in wind turbine analysis. Due to the availability of enhanced computing resources, Computational Fluid Dynamics (CFD) techniques have also been used to study the unsteady aerodynamics of airfoils in recent years [7-9].

This paper investigates the influence of blade vibrations on the unsteady aerodynamic loads on a wind turbine blade. CFD models designed to simulate the dynamic stall behavior of an S809 airfoil undergoing translational as well as pitching motions are presented. In addition, the aerodynamic loading on the blade of a 5 MW wind turbine is investigated, with considerations of blade vibration using the Blade Element-Momentum (BEM) theory and the B-L dynamic stall model.

2. Numerical method

The dynamic stall behavior of three types of airfoil motion was investigated, including pitching motion, out-of-plane motion, and combined pitching and in-plane motion (Fig. 1). The pitching motion was set up in accordance with the configuration of experiments carried out by Ramsay et al. [10], intended to validate the performance of CFD models. The pitch oscillation about the ¼ chord is governed by:

$$\alpha = \alpha_0 + \alpha_m \sin(2\pi f t) \tag{1}$$

where α_0, α_m and f denote mean AOA, pitch oscillation amplitude and oscillation frequency respectively. The 'reduced' frequency often used in the study of oscillating airfoil is defined by:

$$k = (\pi f c)/U_\infty \tag{2}$$

where c is the chord length, U_∞ the free stream wind velocity.

The out-of-plane motion case is to investigate the dynamic stall magnitude caused by translational motion in the out-of-plane direction, since it is in this direction that the blade experiences the strongest vibrations. Assuming that the out-of-plane motion is governed by:

$$x = x_m \sin(2\pi f t + \varphi) \tag{3}$$

the resulting effective AOA (Fig. 1) is

$$\alpha_e = \arctan\left(\dot{x}/U_\infty\right) \approx \dot{x}/U_\infty \tag{4}$$

If the initial AOA is α_0, the overall AOA is obtained as:

$$\alpha = \alpha_0 + \alpha_m \sin(2\pi f t + \varphi - \pi/2) \tag{5}$$

Here

$$\alpha_m = -2\pi f x_m / U_\infty \tag{6}$$

In the combined pitching and in-plane motion case, the pitching motion is described by Eq. (1) and the in-plane motion is defined as

$$y = y_m \sin(2\pi f t) \tag{7}$$

where y_m is the in-plane motion amplitude. This case is intended to investigate the influence of vibrations in the in-plane direction on the dynamic characteristics of a pitch oscillating airfoil.

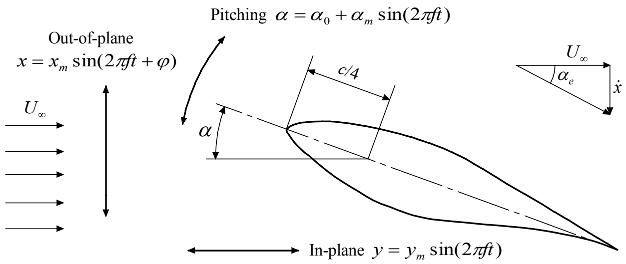
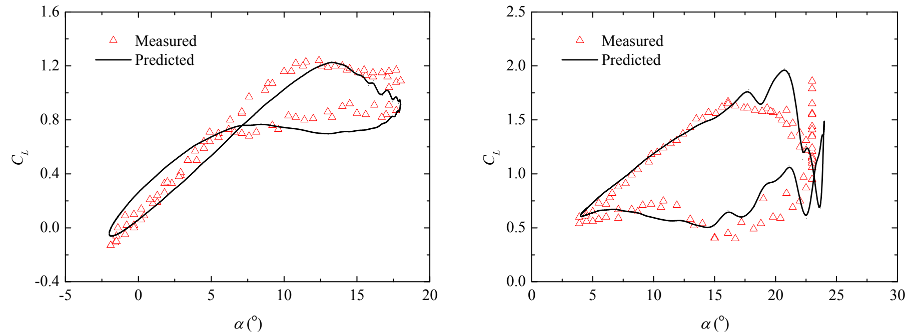


Fig. 1. Schematic of airfoil motion types

The CFD software ANSYS Fluent v14 was employed to simulate dynamic stall of the airfoil. The oscillations of the airfoil were defined by User-Defined Functions [11] describing Eqs. (1), (3) and (7).

3. Simulation results

Two cases were simulated for the S809 airfoil undergoing pitching motion. In the first case, the AOA of the airfoil was assumed to vary in the stall development regime, with α_0 = 8º, α_m = 10º, k = 0.033 and U_∞ = 25.91 m s^{-1}, while in the second case, dynamic stall in the deep stall regime was investigated, with α_0 = 14º, α_m = 10º, k = 0.08 and U_∞ = 32.98 m s^{-1}.



a. α_0 = 8º, α_m = 10º and k = 0.033

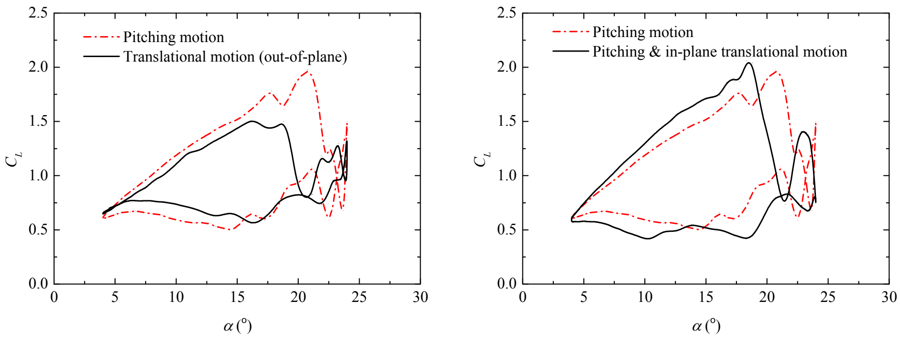
b. α_0 =14 º, α_m = 10º and k = 0.08

Fig. 2. Lift coefficients for pitching airfoil – predicted vs measured

Figs. 2(a) and 2(b) present the lift coefficient hysteresis loops (C_L) in the stall development regime and deep stall regime respectively. Overall, the CFD models showed a satisfactory performance. The trends in the simulation results are consistent with the measured trends. The range of variation of the lift coefficients was successfully estimated and there is mostly good agreement between the predicted and measured hysteresis loops.

Two cases were studied for the airfoil with translational motion. In the first case, the airfoil was undergoing translational motion in the out-of-plane direction. The motion was intentionally defined to be equivalent to the cases studied above and here the deep stall regime case was selected. In Eqs. (5) and (6), the values of x_m and φ were obtained as -0.5 and $\pi/2$ respectively. Thus the motion of the airfoil was governed by x = -0.5sin(2πft + π/2), where k = 0.08, making a maximum velocity of 5.8 m s^{-1}. In the second case, the in-plane translational motion was introduced, coupled with the pitching motion. For comparison, the pitch oscillation in deep stall regime studied above was chosen as well. The in-plane motion was defined as y = 0.227sin(2πft), where k = 0.08, giving a maximum velocity of 2.64 m s^{-1}.

Fig. 3(a) compares the predicted lift coefficient loops of the airfoil undergoing out-of-plane motion with those of a pitching airfoil. The overall trends are similar. During the upward motion (equivalent to the upstroke pitching), the lift coefficient of the out-of-plane oscillating airfoil is mostly lower than that of the pitching one, while during downward motion it is mostly higher, resulting in a narrower loop. Generally speaking, the discrepancy between the pitching motion and the out-of-plane motion is limited. In an engineering application, it is feasible to consider airfoil oscillations in the out-of-plane direction by including them in the calculation of the AOA in a dynamic stall analysis.



a. Out-of-plane motion as x = -0.5sin(2πft + π/2)   b. Combined pitching and in-plane motion

Fig. 3. Lift coefficients – pitching airfoil vs airfoil with translational motion

As shown in Fig. 3(b), the combined motion case shows wider lift coefficient hysteresis loops than the 'pitching only' case. This is because during the upstroke, the AOA was increased due to the in-plane motion, resulting in higher lift coefficients; while during downstroke, the AOA was reduced due to the in-plane motion, leading to lower aerodynamic coefficients. The results indicate that the vibrations in the in-plane direction can also affect the aerodynamic forces significantly.

4. Effects of fluctuating velocity

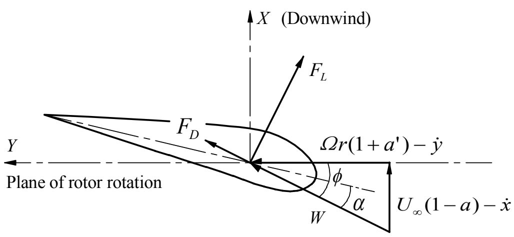


Fig. 4. Velocity diagram for a vibrating blade section

In order to investigate the effects of blade vibration on the aerodynamic loading, aerodynamic analysis of a 5MW wind turbine blade was carried out based on the BEM theory [2,12]. The dynamic stall was evaluated using the B-L model. If considering the out-of-plane and in-plane vibrating velocities (Fig. 4) of the blade, the inflow angle can be obtained as

$$\phi = \arctan \frac{U_\infty (1-a) - \dot{x}}{\Omega r(1+a') - \dot{y}} \tag{8}$$

where r is the radial distance of the blade section from the axis of rotation, Ω the rotor angular velocity, a and a' are the axial and tangential flow induction factors respectively. Using Eq. (8), the AOA time series with the consideration of the airfoil vibrating velocities can then be figured out and fed into the B-L model to obtain the dynamic lift and drag coefficients.

To make the load results comparable, fatigue damage equivalent loads were used to equate the fatigue damage represented by rainflow cycle counted data to that caused by a single load range repeating at a single frequency.

Table 1 Damage equivalent load ranges of aerodynamic forces per unit length on two blade sections (S_X and S_Y are the damage equivalent load ranges of dF_X/dr and dF_Y/dr respectively without considering blade vibration; S_X' and S_Y' are the damage equivalent load ranges of dF_X/dr and dF_Y/dr respectively with consideration of blade vibration. δ represents relative error, $\delta = (S'-S) / S$.)

$\bar{U}_\infty$ (m s^{-1})	Section A at 99% rotor radius						Section B at 75% rotor radius					
	S_X (N m^{-1})	S_X' (N m^{-1})	δ_{SX}	S_Y (N m^{-1})	S_Y' (N m^{-1})	δ_{SY}	S_X (N m^{-1})	S_X' (N m^{-1})	δ_{SX}	S_Y (N m^{-1})	S_Y' (N m^{-1})	δ_{SY}
4	475	590	24.2%	71	110	54.9%	911	948	4.1%	138	141	2.2%
6	1301	1534	17.9%	164	266	62.2%	2274	2346	3.2%	338	351	3.8%
8	2044	2521	23.3%	255	457	79.2%	3881	3813	-1.8%	594	568	-4.4%
10	2506	3230	28.9%	425	700	64.7%	4590	4789	4.3%	972	1024	5.3%
12	3479	4474	28.6%	562	924	64.4%	5769	6120	6.1%	1206	1234	2.3%
14	4097	5171	26.2%	653	1004	53.8%	6879	7107	3.3%	1461	1396	-4.4%
16	4263	5356	25.6%	721	879	21.9%	7112	7512	5.6%	1500	1201	-19.9%
Overall	3588	4530	26.3%	591	857	45.0%	6004	6285	4.7%	1269	1175	-7.4%

The aerodynamic loads were analyzed for turbulent winds with 7 different mean wind speeds ranging from 4 m s^{-1} to 16 m s^{-1}. Three random turbulent seeds were used for each mean wind speed and each of the wind time series lasts 600 s. The damage equivalent load ranges of the aerodynamic forces per unit length on the two blade sections are shown in Table 1. One section (section A) is at 99% rotor radius and the other (section B) is at 75% rotor radius.

Clearly, the blade vibrations have a significant influence on the aerodynamic loads. When considering the vibrating velocities in the calculation of airfoil AOA, the aerodynamic fatigue loads per unit length mostly tend to be increased. At sections closer to the blade tip, larger changes in the aerodynamic fatigue loads were observed. This is due to the blade tip experiencing the maximum deflection and vibration amplitude. The impact reduces towards the rotor center. However at 75% rotor radius, there is still a 4.7% increase and 7.4% reduction of the damage equivalent load ranges of the aerodynamic loads per unit length in the out-of-plane and in-plane directions respectively. This will surely affect the overall aerodynamic loading on the blade.

Calculation of damage equivalent load ranges of bending moments M_x (in-plane) and M_y (out-of-plane) on the blade indicate that, when accounting for the vibrating velocities, the damage equivalent loads of M_x on blade sections at 25%, 50% and 75% rotor radius are increased by 1.1%, 9.8% and 26.3% respectively, while those of M_y are increased by 5.8%, 11.3% and 14.3% respectively. Therefore considering the effects of the blade vibration in the aerodynamic analysis is necessary for an optimum design, especially for the fatigue design of the blade. This analysis may also considerably affect the control system design.

5. Conclusions

(1) CFD models using dynamic mesh can predict satisfactory aerodynamic coefficient hysteresis loops for a moving airfoil.
(2) The translational motion of airfoil can significantly contribute to the dynamic stall. The out-of-plane motion can cause stall of comparable magnitude to its equivalent pitching motion. A relatively small perturbation in the in-plane direction can alter the aerodynamic force considerably. The results suggest that it would be beneficial to include the fluctuating velocities in the calculation of airfoil AOA.
(3) For large-scale wind turbines, it is necessary to consider the blade vibrations in the aerodynamic analysis to obtain an optimum structural strength and control system design.

Acknowledgements

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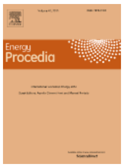

Biography

Xiong Liu is a research fellow in the Faculty of Engineering, University of Wollongong. He holds a PhD in Mechanical Engineering from South China University of Technology. His research interests include computational fluid dynamics, gas pipeline analysis, atmospheric dispersion modelling, and research on wind energy systems.