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Tower Load Analysis of Offshore Wind Turbines and the Effects of Aerodynamic Damping

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This study presents an analysis of the loads on offshore Horizontal Axis Wind Turbines (HAWTs). The aerodynamic loads are estimated using the Blade Element-Momentum (BEM) theory, including the effects of dynamic inflow and dynamic stall. The wave loads are calculated using Morison's equation. Models are proposed to account for the effects of aerodynamic damping on the fatigue loading on the tower during its working lifetime. Load analysis of a 5 MW offshore HAWT is carried out and the influence of aerodynamic damping on the fatigue load is investigated.

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Tower load analysis of offshore wind turbines and the effects of aerodynamic damping

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Abstract

This study presents an analysis of the loads on offshore Horizontal Axis Wind Turbines (HAWTs). The aerodynamic loads are estimated using the Blade Element-Momentum (BEM) theory, including the effects of dynamic inflow and dynamic stall. The wave loads are calculated using Morison's equation. Models are proposed to account for the effects of aerodynamic damping on the fatigue loading on the tower during its working lifetime. Load analysis of a 5 MW offshore HAWT is carried out and the influence of aerodynamic damping on the fatigue load is investigated.

Keywords: Offshore wind turbine; Aerodynamic damping; Wave load; Dynamic response; Fatigue load

1. Introduction

In recent years, wind power technology has seen rapid development due to a significant reduction in its operating cost. Currently, wind power has reached a global capacity of 433 GW and for the past 5 years increased in installed capacity by 13-21% each year [1]. The emerging problem is that in some countries the best onshore locations are no longer available, and there is considerable public opposition to a significant increase in onshore wind power installations. Exploitation of the huge offshore wind resource, with considerably less environmental impact than large onshore wind farms, offers a possible solution to the problem of providing for future green energy needs [2].

Although offshore wind resources are of better quality and more abundant, the more severe environment

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demands additional design considerations for offshore wind turbines to ensure safe operation. One important problem is the combined effects of wind and wave loading. To accurately estimate the loading during the lifetime of an HAWT, the effects of damping should be included in the calculations, because damping directly affects the structural response [3]. The damping of an offshore wind turbine consists of a combination of structural damping, soil damping, hydrodynamic damping and aerodynamic damping. Among these, aerodynamic damping plays a key role in restraining vibrations [2-5]. As damping has an important impact on the fatigue damage, research is required to gain more knowledge of the aerodynamic damping effects of offshore wind turbines and to enable accurate lifetime load prediction.

In this study, aerodynamic damping models are presented to incorporate the time-domain load analysis of offshore Horizontal Axis Wind Turbines (HAWTs). Through simulations of a 5 MW offshore HAWT, the influence of aerodynamic damping on the lifetime fatigue load on the tower are investigated.

2. Offshore HAWT tower loading

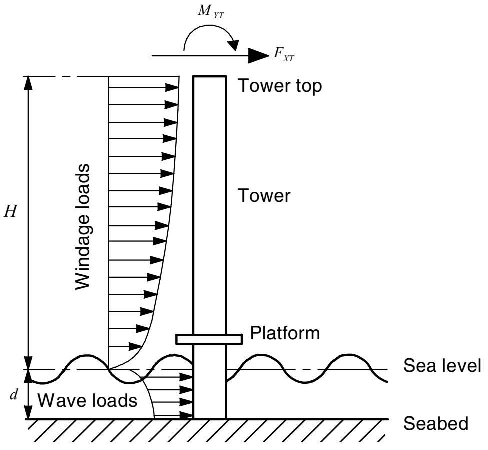


Fig. 1. Loads acting on an offshore HAWT tower.

An offshore HAWT with a tubular tower installed on a monopile foundation was considered. The HAWT tower usually has a large aspect ratio and can be treated as a cantilever. Therefore it can be discretised using two-node beam elements [6] in the finite element model. For an offshore HAWT, the major components of the loading exerted on the tower (see Fig. 1) are the wave loads, the windage loads, the tower self-weight, and the loads acting on the tower top from the rotor and nacelle including aerodynamic and gravitational loads. The aerodynamic damping provided by the rotor mainly affects the tower response in the fore-aft direction and is negligible in the side-to-side direction [2]. Therefore, in the following sections, only the loads affecting tower deflection in the fore-aft direction are analysed.

Aerodynamic loads of the wind turbine blade were calculated using the Blade Element-Momentum (BEM) theory [7]. As the BEM theory was originally developed for a wind turbine operating in steady wind, it was amended by introducing the 'dynamic inflow' [8] and 'dynamic stall' [9] models to account for the transient aerodynamics caused by wind turbulence, yawing, rotational speed regulation and pitch regulation, which are common to a wind turbine operating in the field [10].

The hydrodynamic loading on offshore structures is made of several components, including viscous drag loading, inertia loading, dynamic pressure loading, etc. [2]. If a loaded member is small compared with the water wavelength, the water particle motions are only locally affected by the member and the forces can be calculated from the drag and inertia components using Morison's equation [11]. In this study, the diameter of the cross-section of the tower and pile is considered to be less than 1/5 of the wavelength. In this case, using Morison's equation to estimate wave loading is adequate and the other components can be neglected. Thus the horizontal force on the structure per unit length at level *z* can be expressed as [12]:

$$\frac{\mathrm{d}F_w}{\mathrm{d}z} = \frac{1}{4}\pi\rho_w D^2 \dot{U}_w C_M + \frac{1}{2}\rho_w D|U_w|U_w C_D \tag{1}$$

where z is the depth below the mean water surface, ρ_w the density of water, C_M the hydrodynamic inertia coefficient, C_D the hydrodynamic drag coefficient, and U_w the horizontal wave-induced velocity. The horizontal wave-induced velocity and acceleration were estimated using the first-order linear wave theory [11].

3. Aerodynamic damping

For an offshore HAWT the tower motion may be resisted by structural damping, soil damping, hydrodynamic damping and aerodynamic damping. The structural damping is related to the material used. For a tubular steel tower, the structural modal damping ratio is usually less than 1% and in general a value of 0.5% is applied. In this study, the foundation in the sea bed and the pile in the water are assumed to be relatively rigid, so that soil damping and hydrodynamic damping can be neglected. The aerodynamic damping experienced by a simpler structure in the air is generally less than the structural damping. However, this does not apply to a HAWT, where the aerodynamic damping is induced by the rotor aerodynamics and could be much higher than the structural damping [2, 10]. For a variable speed HAWT, the aerodynamic damping ratio for the n^{th} mode can be estimated using Garrad method (Method A) [13]:

$$\xi_n = \frac{c_a}{2M_n\omega_n} = \frac{B\rho\Omega}{4M_n\omega_n}\int_{R_0}^{R} C_L' bcr dr \tag{2}$$

where c_a is the aerodynamic damping, M_n the n^{th} modal mass, ω_n the n^{th} natural frequency, B the number of blades, ρ the density of air, Ω the rotational velocity, C_L' the slope of the lift coefficient, c the local chord length, r the radius, R_0 the blade root radius, and R the rotor radius; $b=\mathrm{d}\phi/(\mathrm{d}U_d/U_r)$ is a correction factor, where ϕ is the inflow angle, U_d the normal velocity component and U_r the tangential velocity component.

In Ref. [5], another method (Method B) was proposed, which calculates the aerodynamic damping as the increase in the thrust per unit increase in the wind speed:

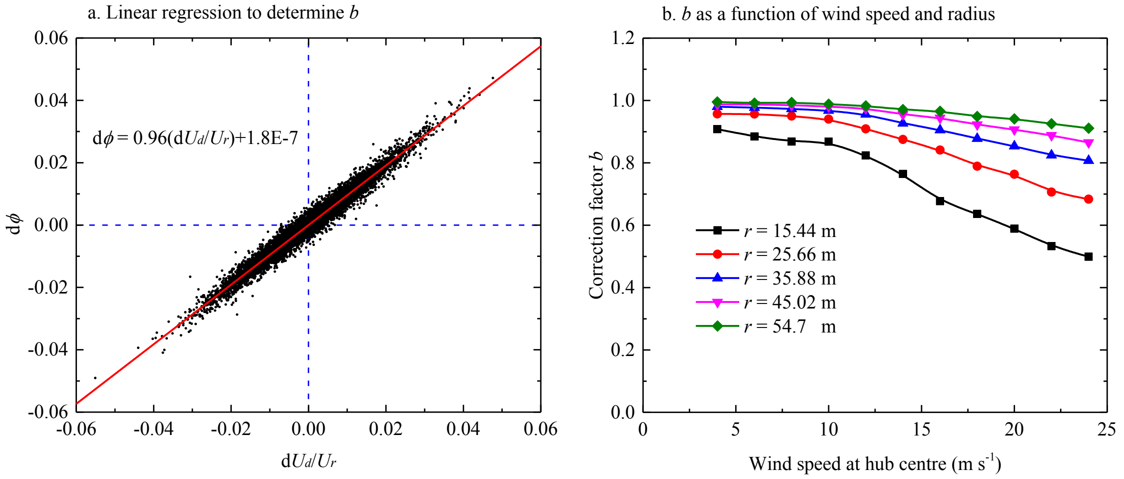
$$c_a = \frac{\mathrm{d}T}{\mathrm{d}U} \tag{3}$$

where T is the thrust force and U the inflow wind velocity.

Solving Eq. (2) requires the solution of the BEM theory for each wind speed to find the derivative of the lift coefficient over the Angle of Attack (AOA) including the steady-state induction factor for that AOA. The correction factor b also needs to be determined for each wind speed using non-linear time domain load simulations. Compared to Eq. (2), solution of Eq. (3) is much more straightforward if the objective is to calculate the aerodynamic damping as the rate of change of thrust with respect to wind speed.

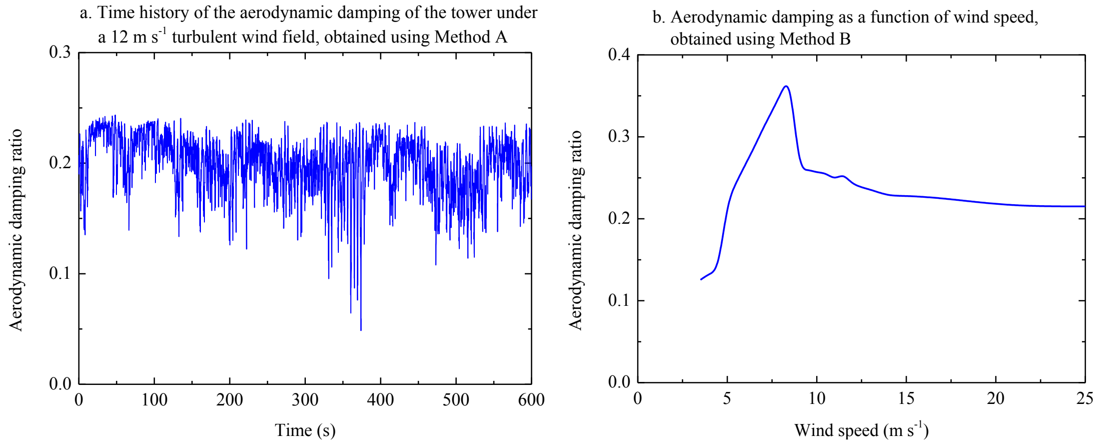
4. Results and discussion

The proposed model was applied to carry out the load analysis of a 5 MW offshore HAWT. For structural dynamics solution, the aerodynamic damping needs to be estimated in advance. Fig. 2a shows the relationship between $\mathrm{d}\phi$ and $\mathrm{d}U_d/U_r$ at a blade section 35.88 m from the hub centre when operating under a 12 m s^{-1} turbulent wind. This can be used to determine the correction factor b in Eq. (2) when using Method A [13]. It is found that linear regression of the data points gives a straight line almost exactly passing through the origin. Thus the slop of the red line in Fig. 2a is the correction factor *b* in Eq. (2) at this blade section for a 12 m s^{-1} wind. Through simulations using a number of turbulent winds with different mean wind speeds, the relationship between correction factor *b* and mean wind speed at different blade sections can be revealed. Fig. 2b shows the correction factor *b* as a function of wind speed at four blade stations. It is observed that higher wind speed corresponds to smaller correction factor, implying more correction. Also, the blade section closer to the hub centre needs more correction. Within the normal operational wind conditions, the correction factor deviates considerably from 1 in most cases, suggesting that the correction factor should be taken into consideration to determine the aerodynamic damping of a variable speed wind turbine.


a. Linear regression to determine *b*

b. *b* as a function of wind speed and radius

Fig. 2. Determination of correction factor *b*.


a. Time history of the aerodynamic damping of the tower under a 12 m s^{-1} turbulent wind field, obtained using Method A

b. Aerodynamic damping as a function of wind speed, obtained using Method B

Fig. 3. Modal aerodynamic damping ratio obtained using Method A and Method B

Fig. 3a shows the time history of the modal aerodynamic damping ratio of the tower during power production under the 12 m s^{-1} turbulent wind, calculated by Method A. It is found that the aerodynamic damping ratio varies between 0.05 and 0.24, with an average value of 0.2. Fig. 3b shows the modal aerodynamic damping ratio obtained using Method B [5]. For a steady wind at 12 m s^{-1} speed, the aerodynamic ratio obtained by Method B is 0.24, slightly higher than the average value obtained by Method

A. When using Method B in a time domain simulation, the instantaneous aerodynamic damping value can be determined as a function of the instantaneous wind speed at the hub centre.

In the solution of the equation of motion, the overall damping ratio of the tower was introduced by superposition of aerodynamic and structural damping ratios. The random sea state was described using the JONSWAP spectrum [14]. Fig. 4 shows the comparison between the time series of tower-top deflection with and without the effect of aerodynamic damping, when operating under a 12 m s^{-1} turbulent wind. It is clear that the aerodynamic damping significantly affects the tower deflection by reducing the vibration amplitude.

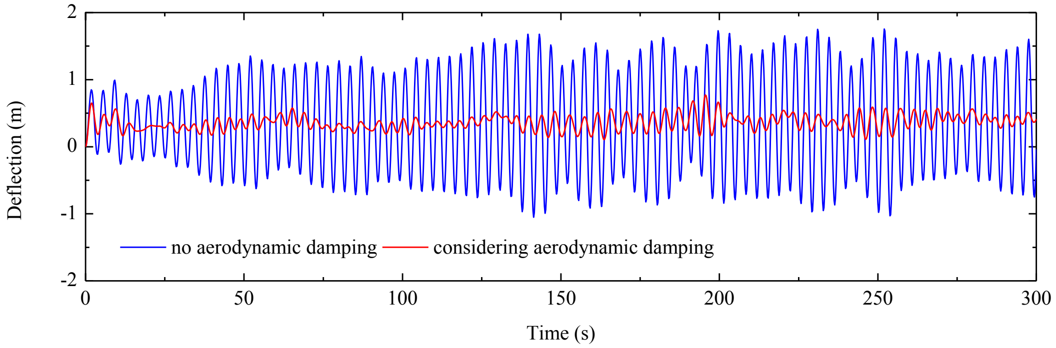


Fig. 4. Tower top deflection during power production (12 m s^{-1} turbulent wind field used)

In order to understand the influence of the aerodynamic damping on the fatigue loading on the tower, load analysis of the wind turbine was performed assuming turbulent winds with 11 different mean wind speeds ranging from 4 m s^{-1} to 24 m s^{-1}. The wind turbine class for the 5 MW machine was considered to be IEC IA [14], with a Weibull wind speed distribution [14] with an annual mean wind speed of 10 m s^{-1} and a shape parameter of 2. The total number of load cases for each mean wind speed throughout the 20 year lifetime was scaled from the corresponding Weibull hours. In order to investigate the influence of aerodynamic damping on the tower fatigue loading, each load case was simulated using three conditions: 1) considering only the wind; 2) considering only the waves; 3) considering both wind and waves. For every 'wind-only' case, tower loads were estimated both with and without consideration of aerodynamic damping.

To enable meaningful comparison, the concept of 'Fatigue Damage-Equivalent Load' (FDEL) was 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. The FDEL was estimated for each load component assuming 1.37×10^8 cycles in the turbine lifetime of 20 years. Table 1 shows the obtained FDEL of tower base moment M_y, which is crucial in the fatigue design of the tower. In the calculation, the slope of the SN curve was chosen as m = 4 [14].

Table 1. FDEL of tower base moment M_y (AD: aerodynamic damping)

	Wind and wave			Wind only			Wave only
	No AD	AD Method A	AD Method B	No AD	AD Method A	AD Method B	
$\boldsymbol{M_y}$ (kNm)	118647	20173	18249	71030	14374	13124	58330

It is clear that aerodynamic damping greatly affects the FDEL of M_y. The value of M_y calculated without considering aerodynamic damping is more than 5 times that considering aerodynamic damping. The actual fatigue load is significantly less than the cumulative fatigue load (sum of 'wind-only' and 'wave-only' loads). Moreover, it is less than the fatigue load of considering only the waves, which means that the introduction of wind does not increase but reduces the fatigue load considerably. This is mainly due to the aerodynamic damping analysed above, which restrains the tower vibrations induced by hydrodynamic forces as the wind and waves are co-directional. Table 1 also shows that using Method B for estimation of aerodynamic damping will underestimate the fatigue load by about 9%, compared to Method A.

5. Conclusions

1) An analysis of the transient load on an offshore HAWT tower is presented. The analysis includes calculation of transient aerodynamic loads, wave loads and structural dynamics. Aerodynamic damping models are introduced to account for the damping caused by the rotor aerodynamics, based on which the influence of aerodynamic damping on the offshore HAWT tower load is investigated.
2) Aerodynamic damping can significantly affect the structural response and the fatigue load of the tower. In the wind turbine design stage, the aerodynamic damping should be taken into account to obtain an optimum design.
3) The two aerodynamic damping prediction methods show considerable difference in the prediction of the lifetime fatigue load of the tower. In order to ensure a safe design, the method for calculating the aerodynamic damping should also be carefully chosen.

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