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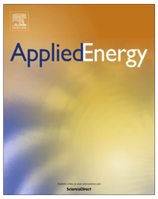

Effects of aerodynamic damping on the tower load of offshore horizontal axis wind turbines ☆

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HIGHLIGHTS

- A load analysis combing aerodynamics, hydrodynamics and structural dynamics.
- Aerodynamic damping model presented for variable-speed wind turbines.
- Study of the effects of aerodynamic damping on offshore wind turbine tower fatigue loads.
- Fatigue load prediction using different aerodynamic damping models.

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ABSTRACT

Aerodynamic damping has an important effect on the dynamic response of offshore Horizontal Axis Wind Turbines (HAWTs). In this paper, an analysis of the loads on offshore HAWTs is presented. The analysis combines the aerodynamics, hydrodynamics and structural dynamics of the structure, and includes the effects of aerodynamic damping. The aim is to better understand the role of aerodynamic damping during the interaction of wind and wave and the structure, and to quantitatively evaluate the effects of aerodynamic damping on the lifetime fatigue load on offshore HAWT towers. The aerodynamic loads are estimated using the Blade Element-Momentum (BEM) theory, including the effects of dynamic inflow and dynamic stall. The wave dynamics is estimated assuming 'random sea state' described by the JONSWAP spectrum, with wave loads calculated using Morison's equation and water kinematics modelled using linear wave theory. Two aerodynamic damping models are proposed: (1) a model based on the analysis of the rotor aerodynamics incorporating the tower-top motion of a constant-speed wind turbine, which is then modified for variable-speed wind turbines by introducing a correction factor; and (2) a model based on Salzmann and van der Tempel's method (Salzmann and van der Tempel, 2005) to calculate the aerodynamic damping as the increase in the thrust per unit increase in the wind speed. The models are incorporated into a transient load analysis. The effects of aerodynamic damping on the lifetime fatigue loads of the tower are then investigated through load analysis of a 5 MW offshore HAWT. In addition, the influence of different aerodynamic damping calculation methods on the prediction of fatigue loads is studied.

1. Introduction

The use of renewable energy sources has attracted increasing interest over the past decades due to the quest for a low-carbon economy and an increasing awareness of the need for sustainable development [1,2]. Among the various renewable energy alternatives, wind energy is considered to be the most cost-effective, and has seen the fastest growth due to a significant reduction in its operating cost [3–6]. At the end of 2015, wind power reached a global capacity of 433 GW and for the previous 5 years increased in installed capacity by 12–19% per annum [7]. The wind energy market is still growing rapidly and it is expected that by 2020 the global capacity will increase to 792 GW [7].

To date, wind farms are mostly deployed onshore due to the relatively lower cost of construction, operation and maintenance. However, offshore locations generally have higher, more consistent

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Nomenclature

a	axial flow induction factor, dimensionless
a'	tangential flow induction factor, dimensionless
A_w	wave amplitude (m)
b	aerodynamic damping correction factor, dimensionless
B	the number of blades, dimensionless
c	chord length (m)
c_a	aerodynamic damping (N s m^{-1})
$\mathbf{C}$	damping matrix
C_C	chord wise force coefficient, dimensionless
C_D	drag coefficient, dimensionless
C_L	lift coefficient, dimensionless
C_M	hydrodynamic inertia coefficient, dimensionless
C_N	normal force coefficient, dimensionless
d	water depth (m)
D	drag force (N)
D_t	diameter of tower section (m)
f	wave frequency (Hz)
f_p	peak wave frequency (Hz)
F	force (N)
g	gravitational acceleration (m s^{-2})
h	height above sea level (m)
H_s	significant wave height (m)
k	wave number, dimensionless
$\mathbf{K}$	stiffness matrix
L	lift force (N)
$\mathbf{M}$	mass matrix
M	moment (N m)
M_a	Mach number, dimensionless
M_n	n^{th} modal mass (kg)
m	mass (kg)
$\mathbf{P}$	load matrix
Q	torque (N m)
r	radius of blade section on blade (m)
R	rotor radius (m)
t	time (s)
T	axial force (N)
T_p	peak wave period (s)
U	wind velocity (m s^{-1})
U_w	wave induced velocity (m s^{-1})
W	relative airflow velocity (m s^{-1})
z	depth below water surface (m)

Greek letters

α	angle of attack (rad)
β	airfoil twist angle (rad)
ρ	density (kg m^{-3})
Ω	rotor angular velocity (rad s^{-1})
ϕ	inflow angle (rad)
θ	rotor azimuth angle (rad)
χ	shaft tilt angle (rad)
β_0	rotor cone angle (rad)
ω	angular frequency (rad s^{-1})
γ	JONSWAP peak-shape parameter, dimensionless
ξ	modal aerodynamic damping ratio, dimensionless

wind speeds, less turbulence and lower wind shear, so that offshore wind farms can offer more, better quality renewable energy than their onshore counterparts [2,8,9]. Also, 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. In reality, the development of offshore Horizontal Axis Wind Turbines (HAWTs) has never lost the attention of the energy industry. Over the last decade, offshore wind power capacity increased considerably and reached 12.1 GW at the end of 2015, approximately 2.8% of the global installed wind power capacity. Although the advantages of offshore projects are counter-balanced by the higher demand on materials, manufacturing, transportation, construction and maintenance, more and more research is being directed to make the deployment of offshore wind turbines more cost-effective. A substantial growth of offshore wind power installation in the future can offer a possible solution to the problem of providing for future green energy needs [9,10].

Although offshore wind resources are of better quality and more abundant, the more severe environment demands additional design considerations for offshore wind turbines to ensure safe operation. Firstly, larger offshore wind turbines are being considered to enable greater wind energy capture at lower cost. The proposed increase in size introduces significant aeroelastic effects, which are caused by the interaction of aerodynamic loads, elastic deflections and inertial dynamics [11–13]. Another important problem is the combined effect of wind and wave loads on the structure. The coincidence of structural resonance with aerodynamic and hydrodynamic forces on the wind turbine may result in large-amplitude vibrations with the associated stresses and subsequent accelerated fatigue [14]. Therefore, in the design stage, a load analysis that estimates the combined effects of wind and wave on the structure is very important to ensure the safety of the wind turbine components.

To accurately estimate the loading during the lifetime of an offshore HAWT, it is crucial to correctly include the effects of damping in the analysis. This is because damping directly affects the structural response, with the amplitude of vibrations being inversely proportional to the damping [15]. The overall damping of an offshore wind turbine is made up of 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. Soil damping and hydrodynamic damping are usually less than structural damping [14]. Similarly, the aerodynamic damping experienced by a simple stationary structure in air is generally less than structural damping. However, this does not apply to an HAWT, where the aerodynamic damping is induced by the rotor aerodynamics and could be much higher than the structural damping [10,14,16–21].

Although it is recognised that aerodynamic damping plays a key role in restraining vibrations in an HAWT, there is a lack of explicit recommendations on aerodynamic damping in the design guidelines [22,23]. A recommendation published jointly by the American Wind Energy Association and the American Society of Civil Engineers [24] suggests that the design spectra for the support structure of operational turbines should be based on a total damping ratio of 5% to include aerodynamic damping. However, using a constant value for the aerodynamic damping for wind turbines of all sizes may be incorrect, as the aerodynamic design and structural configuration may vary from turbine to turbine. This will surely affect the aerodynamic damping value. In addition, as wind turbines operate in a highly unstable environment [13,22,25] due to the wind turbulence and yawing, pitch and speed regulations of the wind turbine, the associated unsteady aerodynamics may lead to time-varying aerodynamic damping.

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