A study of the dynamic performance of the multi-system involved in the offshore floating type wind turbine

This thesis is submitted for the degree of

Doctor of Philosophy

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Certificate of original authorship

I, Kan Ye declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical and Mechatronic Systems, FEIT at the University of Technology Sydney. And this research is supported by the Australian Government Research Training Program.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Contents

Nomenclature

For Chapter 5

c	damping coefficient of the bearing
dr	displacement of the rotor
f_m	nonlinear unbalanced magnetic pull force
m, m_r, m_h, m_s	total mass of the rotor system, and masses of its three components
h	length of the air-gap
I	moment of inertia of the drive train system
I_p	polar moment of inertia of the rotating system
k	stiffness of the bearing
L	length of the shaft
l_i	distance from the centre of gravity to a specific position along the shaft
p	number of pole pairs of the generator
Δr	average air-gap between the rotor and stator
R_r	outer radius of the rotor
R_s	inner radius of the stator
S_s	linear current density in the stator

u_r	displacement of the centre of the rotor from its rotating axis
U_r	displacement of the centre of the stator from its rotating axis
x, y, θ_y, θ_x	displacements and rotating angles of the rotor system
μ	permeability of the magnet in the air-gap
Δe	relative eccentricity
β	angle between the principal axis and the direction of the unbalanced mass
ω	rotating speed of the rotor system
τ	skew angle of the rotor unbalanced mass

For Chapter 6

X, Y, Z	moving-local coordinate system (the rotor)
$y, z,$ θ_y, θ_z	displacements and rotating angles of the moving-local coordinate system
X', Y', Z'	fixed-global coordinate system (the platform)
$x', y',$ θ_x', θ_y'	displacements and rotating angles of the fixed-global coordinate system

m	total mass of the rotor system
L	length of the shaft
Rs	inner radius of the stator
Δr	average air-gap
h	length of the magnet
Ip	polar moment of inertia
I	moment of inertia
p	number of the pole pair
$l_{oo'}$	horizontal distance between the CG of the drive-train system and the CG of the platform
$h_{oo'}$	vertical distance between the CG of the drive-train system and the CG of the platform
$V_{(z)}$	mean wind speed at the altitude z
V_H	reference wind velocity at the reference altitude H (normally $H = 10$ m)
α	wind shear exponent ($\alpha = 0.11$)
F_w	drag force of fluids passing through structure
ρ_a	air density
$V_{r(z)}$	relative velocity of the wind and the structure

C_d	drag coefficient of the structure
$A_{(z)}$	equivalent characteristic surface area
$E(H_s)$	expected value of the significant wave height
$E(T_p)$	expected value of the peak period
$S_{\eta\eta}(\omega)$	JONSWAP spectrum
η	function of water surface elevation
γ	peak enhancement factor ($\gamma = 3.3$ for deep-sea)
ω_p	peak wave frequency
ω	circular wave frequency
T_m	mean wave period
T_z	zero-up-crossing wave period
T_p	peak period
$p(z,t)$	wave force acting on the structure at location z at time t
$f_{wave}(t)$	total wave force acting on the spar-support
d_w	water depth
z	vertical coordinate axis
C_m	inertia coefficient of the spar structure

d_e	equivalent characteristic diameter of spar-support
ρ_w	sea water density
k	wave number
λ	wave length
$v(z,t)$	horizontal velocity of the sea wave
$\dot{v}(z,t)$	acceleration of the sea wave
V_c	average current velocity of the sea wave
$F_c(z)$	force per unit length acting on the spar platform structure
$F_{buoyancy\_z'}$	buoyancy force acting on the structure in the z direction
$M_{buoyancy\_x'}$	buoyancy moment acting on the structure about the x direction
$M_{buoyancy\_y'}$	buoyancy moment acting on the structure about the y direction
l_{b-CG}	distance of the buoyancy force to the CG of the spar platform structure in the z direction
$F_{interaction\_z'}$	total interaction acting on the structure in the z direction
m'	total mass of the wind turbine including the nacelle
θ_{wc}	angle between the wind and the surge direction

For Chapter 7

$EI_{(z)}$	bending stiffness of the tower
$N_{(z)}$	normal force in the vertical direction
$m_{(z)}$	mass density per unit length of the tower
$r_{(z)}$	radius of gyration
$f_{(z,t)}$	resultant force of various loadings applied on the tower
ω_e	angular frequency
ω_n	nth natural frequency
$w_{(z)}$	displacement in the horizontal direction at the tower height z
$\dot{w}_{(z)}$	slope of the tower at the tower height z
k_1	torsion spring stiffness
α_1	rotating angle
L	tower length
D	tower average diameter
t	thickness
M_1	total mass of the platform
I_1	moment of inertia of the platform about its centre gravity (CG)

I_{01}	moment of inertial of the platform about the bottom end of the tower
g_1	distance between the CG of the platform to the bottom end of the tower structure
θ_1	fixed angle between the longitudinal axes of the platform and the undeformed tower
M_2	total mass of the nacelle
I_2	moment of inertia of the nacelle about its axis passing through its CG
I_{02}	moment of inertial of the nacelle about the top end of the tower
g_2	distance between the CG of the nacelle and the top end of the tower structure
$l_{oo'}$	horizontal distance between the CG of the nacelle and the top end of the tower structure
$h_{oo'}$	vertical distance between the CG of the nacelle and the top end of the tower structure
θ_2'	fixed angle between the rotating axis in the nacelle and the undeformed tower

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Abstract

As the utilization of the renewable energy sources has significantly increased over the past decades, offshore wind turbines have been noted for their advantages of more power output and less space limitation than the onshore wind turbines. New prototypes of offshore wind turbines have been developed; not only has the power output been increased but also their sizes have become larger. However, the distinct offshore environmental loads may significantly affect the performances of the offshore wind turbine. The aims of this Ph.D research are to investigate the vibration behaviours of the multi-system involved in a spar type offshore direct-drive wind turbine. First of all, the overview of the main components involved in the offshore direct-drive wind turbine and their dynamic performances related to the mechanical vibration behaviour are presented. Different types of topology of the direct-drive wind turbines are briefly discussed and a comparison of all generator topologies is made based on the criteria of their efficiency, weight and cost. The supporting structures for the wind turbine have been developed from land to transitional-water, then the deep-water. Complex designs have been used to meet the environment requirements. Moreover, the consideration of the nacelle-blade system has been developed from a non-rotating mass to a rotating system with interaction when studying the tower response. The excitation conditions have become more complex. Not only the environmental excitations, such as the aerodynamics and hydrodynamic excitations should be considered, but also the internal excitations, such as the unbalanced magnetic pull force in the generator or tower shadow can be involved.

Three new models about the main components: direct-drive drive-train system, floating platform and the tower structure are presented in this thesis. To start with, the effect of

rotor position and weight adjustment on the vibration behaviour of the drive-train system within a 5 MW direct-drive wind turbine is studied by considering the unbalanced magnetic pull forces. The direct-drive wind turbine, different from the standard geared wind turbine, uses a direct-drive generator to avoid the gearbox failures, in which the direct-drive permanent-magnet generator has been widely used. The unbalanced magnetic pull (UMP) force which is caused by the eccentricity of both rotor and stator of the generator can have an impact on the vibration behaviour of its drive-train system, an up to 30% difference of the tolerance allowable for a safe operation in the generator can be found from the simulation results. The drive-train system which consists of the main shaft, rotor, hub and blades is modelled as a four degree-of-freedom (DOF) nonlinear system. In the present drive-train system, the location of its centre of gravity can be moved along its rotating axis by doing the rotor adjustment in terms of rotor position and mass ratio. Both rotor displacement and bearing forces are obtained for a wide range of rotor positions and weight under different rotating speeds. Such results would provide optimized rotor position and mass ratio to improve the performance of the drive-train system. Then a combined model of a spar-type floating platform wind turbine under deep-sea conditions is developed. The spar-type supporting platform with tower structure is modelled as a rigid body, while the nacelle is considered as a point mass attached on the top of the tower. Then the dynamic interaction between the drive-train system and the nacelle is considered by incorporating the modelling of the direct-drive drive-train system. The hydrodynamic and aerodynamic excitations on the structures are considered, including current, wave, and wind excitations as well as buoyant forces. With the help of the time history and FFT spectrum, the effects of both hydrodynamic and aerodynamic excitations along with the dynamic interaction between the drive-train system and tower structure on the

dynamic behaviour of the spar-type floating platform are investigated under different operating sea conditions. At last, the tower structure is developed using a flexible model. An analytic solution for the free-vibration of the tower structure based on Euler-Bernoulli beam-column theory is presented. The tower structure is modelled as a free-free beam with two end mass components. The platform and the nacelle are considered as two large mass rigid components connected by torsion springs at two tower ends. The stiffness at the connections can be different due to the different joint conditions between the tower and two mass components, such as joint type or crack. The effects of system parameters on the natural frequencies are investigated under a range of variables, including the tower structure parameters, platform and nacelle parameters, and the connecting types. Uniform tower model is presented firstly and then the non-uniform structure is discussed. The non-linear relationships between those variables and the natural frequency of the whole system are numerically found and some design issues are discussed for the spar-type floating wind turbines.