University of Technology, Sydney

A study of the dynamic response of wind turbine gearboxes

This thesis is submitted for the degree of

Doctor of Philosophy

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Certificate of original authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

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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Nomenclature

Symbols	**Definitions**
α	pressure angle
α_{pL}	pressure angle of the planet gear at the first planetary gear stage
α_{sL}	pressure angle of the sun pinion at the first planetary gear stage
α_{pH}	pressure angle of the planet gear at the second planetary stage
α_{sH}	pressure angle of the sun pinion at the second planetary stage
α_{GL}	pressure angle of the low-speed gear at the parallel gear stage
α_{GH}	pressure angle of the high-speed pinion at the parallel gear stage
a_g	addendum of the gear
a_p	addendum of the pinion
β	helix angle
β_s	helix angle of sun pinion
b	dedendum
b_i	gear backlash
C	damping matrix
c	radial clearance
$_c$	the subscript representing the planet carrier arm
Cd	center distance of gear pairs
CR	contact ratio
C_p	wind power utilization
c_{rp_L}	damping coefficient of the ring-planet gear pair at the first planetary gear stage

c_{sp_L}	damping coefficient of the sun-planet gear pair at the first planetary gear stage
c_{rp_H}	damping coefficient of the ring-planet gear pair at the second planetary gear stage
c_{sp_H}	damping coefficient of the sun-planet gear pair at the second planetary gear stage
c_{GHGL}	damping coefficient of the parallel gears at the parallel gear stage
c_{cH_sL}	damping coefficients of the shaft that links the sun pinion in the first planetary gear stage and the planet carrier arm of the second planetary gear stage
c_{GL_sH}	damping coefficient of the shaft that links the sun pinion in the second planetary gear stage and the low-speed gear of the parallel gear stage
E	modulus of elasticity
e_i	static transmission error
e_{ai}	alternating term of the static transmission error
F_{ai}	fluctuating meshing force caused by the static transmission error e_i
F_{me}	constant external loading
$f(X_i)$	non-linear gear mesh displacement function
$f(q_i)$	nonlinear gear mesh displacement function, with the consideration of gear backlash
F_L	load on rolling bearings
F_a	axial load
F_r	radial load
F_{r_max}	maximum load on rolling element

$_{GH}$	subscript representing the gear at the parallel gear stage
$_{GL}$	subscript representing the pinion at the parallel gear stage
Gr	gearbox gear ratio
h	tooth thickness
I	area moment of inertia
i	the number of the rows of rollers
K	gear mesh stiffness matrix
k_r	radial stiffness
k_{rp_L}	gear mesh stiffness of the ring-planet gear pair at the first planetary gear stage
k_{sp_L}	gear mesh stiffness of the sun-planet gear pair at the first planetary gear stage
k_{GHGL}	gear mesh stiffness of the gears in the parallel gear stage
K_{cH_sL}	torsional stiffness of the shaft that connects the sun pinion in the first planetary gear stage and the planet carrier arm of the second planetary stage
K_{GL_sH}	torsional stiffness of the shaft that links the sun pinion in the second planetary gear stage and the low-speed gear of the parallel gear stage
$k_{ij}(t)$	time-varying mesh stiffness function
k_{mij}	mean term of the time-varying mesh stiffness function
k_{aij}	alternating term of the time-varying mesh stiffness function
L	depth of gear tooth
LA	distance along the line of action between meshing points
L_{we}	effective contact length of roller bearings

m_{gear}	mass of the gear
m_{pinion}	mass of the pinion
M_{cL}	equivalent mass of the planet carrier arm at the first planetary gear stage
M_{pL_n}	equivalent mass of the planet gear at the first planetary gear stage
M_{sL}	equivalent mass of the sun pinion arm at the first planetary gear stage
M_{cH}	equivalent mass of the planet carrier arm at the second planetary gear stage
M_{pH_n}	equivalent mass of the planet gear at the second planetary gear stage
M_{sH}	equivalent mass of the sun pinion arm at the second planetary gear stage
M_{GL}	equivalent mass of the gear at the parallel gear stage
M_{GH}	equivalent mass of the pinion at the parallel gear stage
M	equivalent mass matrix
M_y	aerodynamic bending moment
N_g	gear teeth number, or the teeth number of the ring gear for the planetary gear stage
P	applied load at the tooth tip
P_b	base pitch
P_d	diameteral pitch
p	subscript representing the planet gear
$p_i(t)$	excitation term
ρ_{air}	air density
r_{blade}	radius of blades
r	subscript representing the ring gear
r_{bp_L}	base radius of the planet gear at the first planetary gear stage

r_{bs_L}	base radius of the sun pinion at the first planetary gear stage
r_{br_L}	base radius of the ring gear at the first planetary gear stage
r_{bp_H}	base radius of the planet gear at the second planetary gear stage
r_{bs_H}	base radius of the sun pinion at the second planetary gear stage
r_{br_H}	base radius of the ring gear at the second planetary gear stage
r_{bG_L}	base radius of the low-speed gears at the parallel gear stage
r_{bG_H}	base radius of the high-speed gears at the parallel gear stage
r_{pL}	pitch radius of the planet gear at the first planetary gear stage
r_{sL}	pitch radius of the sun pinion at the first planetary gear stage
r_p	pitch radius of planet gears
r_{pH}	pitch radius of the planet gear at the second planetary gear stage
r_{sH}	pitch radius of the sun pinion at the second planetary gear stage
r_{GL}	pitch radius of the low-speed gears at the parallel gear stage
r_{GH}	pitch radius of the high-speed gears at the parallel gear stage
$_s$	subscript representing the sun pinion
T_{in}	driving torque
T_{out}	output torque
V_{wind}	average wind speed
ω_g	rotational speed of the gear, or the rotational speed of the planet carrier arm for the planetary gear stage
ω_i	meshing frequency
ω_e	external excitation frequency
ω_{blade}	rotational speed of blades

x_{cL}	equivalent transverse displacements of the planet carrier arm at the first planetary gear stage
x_{pL_n}	equivalent transverse displacements of the planet gear at the first planetary gear stage
x_{sL}	equivalent transverse displacements of the sun pinion at the first planetary gear stage
x_{cH}	equivalent transverse displacements of the planet carrier arm at the second planetary gear stage
x_{pH_n}	equivalent transverse displacements of the planet gear at the second planetary gear stage
x_{sH}	equivalent transverse displacements of the sun pinion at the second planetary gear stage
x_{GL}	equivalent transverse displacements of the low-speed gear at the parallel gear stage
x_{GH}	equivalent transverse displacements of the high-speed pinion at the parallel gear stage
X_i	relative meshing displacements on the direction of action
X_k	translational displacements
$y_{\max\_gear}$	maximum deflection of the gear tooth
$y_{\max\_pinion}$	maximum deflection of the pinion tooth
Z	number of rollers per bearing row
θ	rotational displacements
θ_{xj}	rotational displacements of gearbox components on x-axis
θ_{yj}	rotational displacements of gearbox components on y-axis

θ_{zj}	rotational displacements of gearbox components on z-axis
δ_a	axial deformation of the cylindrical roller bearing
δ_r	elastic displacement of the cylindrical roller bearing
ξ	damping ratio
γ	contact angle

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Abstract

Gearbox is an important component for large modern wind turbines incorporated either by a squirrel cage induction generator or a doubly fed induction generator. Wind turbine gearboxes have distinct features from standard gearboxes. They are used to increase the rotor speed to a speed suitable for the electricity generation and operate under varying load conditions, while standard gearboxes are designed to step down from high speed to low speed and operate under full load conditions. The modern wind energy industry has been experiencing high gearbox failure rates since its inception. However, the fundamental mechanisms of gearbox failures have not been fully understood yet. Thus, this thesis studies the dynamic response of wind turbine gearbox components in order to provide useful information to the wind energy industry to reduce the possibility of the gearbox failures at an early stage.

The torsional vibrations of wind turbine gearbox are firstly investigated in this thesis. The nonlinear dynamic model developed considers the factors such as time-varying mesh stiffness, damping, static transmission error and gear backlash. Both the external excitation due to wind gust and the internal excitation due to static transmission error are included. With the help of time history, FFT spectrum, phase portrait, Poincare map and the effects of the static transmission error, mean-to-alternating force ratio and time-varying mesh stiffness on the dynamic behaviour of wind turbine gearbox components are investigated by using the numerical integration method. It is found that the external excitation has the most influence on the torsional vibrations of the wind turbine gearbox components. The gear mesh stiffness has more influence than the static transmission error, and the static transmission error has the least influence.

Secondly, the dynamic response of a proposed four-degree-of-freedom (4DOF) wind turbine gearbox dynamic model is studied. The effects of different excitation conditions are discussed. The results show that the external excitation fluctuation has large influence on the dynamic responses of both the gears and bearings, and explain under which conditions the fretting corrosion, as one of the wind turbine gearbox failure modes, may occur.

Thirdly, the effects of bending moments on the dynamic responses of a wind turbine planetary gearbox are analysed. The proposed six-degree-of-freedom (6DOF) dynamic model takes into account the key factors such as the time-varying mesh stiffness, bearing stiffness, damping, static transmission error, gear backlash and bearing clearances. It is found that the bending moments can affect the gear meshes. What is more, the driving torque may have the effect on the bending moments. Furthermore, the bearing clearance has negligible effect in the planetary gear stage.