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Dynamic behaviour of a wind turbine gear system with uncertainties

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In this paper, a new methodology for taking into account uncertainties in a gearbox transmission system of a horizontal-axis wind turbine is proposed. Gearbox transmission is the major part of the wind turbine's drive train. For a more reasonable evaluation of its dynamic behaviour, the influence of the uncertain parameters should be taken into consideration. The dynamic equations are solved by using the Polynomial Chaos method combined with the ODE45 solver of Matlab. The effects of the random perturbation caused by the aerodynamic torque excitation on the dynamic response of the studied system are discussed in detail. The proposed method is an efficient probabilistic tool for uncertainty propagation. For more accuracy, the Polynomial Chaos results are compared with direct simulations.

1. Introduction

Wind energy is one of the most efficient renewable energies. Wind turbines harvest the kinetic energy of air and convert it into a usable power such as electricity power. For this, the capacity of wind turbines has increased and they have become the fastest-growing new sources of electricity generation.

Many scientific studies have investigated the dynamic behaviour of wind turbines [1–3]. In their analysis, gear power transmission was considered as the perfect system. However, the gearbox system presents constantly precocious failures [4]. Therefore, in a wind turbine, an adequate knowledge of the dynamic characteristics of gearboxes system is necessary.

In this context, several studies have been developed to study the dynamic behaviour of wind turbines. The dynamic behaviour of a two-stage gear reducer in the presence of aerodynamic excitation has been investigated by Abboudi et al. [5] and a lamped mass dynamic model with 12 DOFs has been developed. Under wind speed fluctuations and system disturbances, the dynamic behaviour and transient stability of fixed-speed wind turbines has been studied by Rahimi et al. [6]. The combined effects of gravity, input torque, bending moment and bearing clearance of planetary wind turbine gearboxes are reported by Guo et al. [7]. In 2011, Helsen et al. [8] investigated the modal behaviour of a wind turbine gearbox using flexible multi-body modelling techniques.

All previous studies have investigated the dynamic behaviour of the wind turbine considering the deterministic parameters as the system's parameters. However, the instability of rotor inflow caused by the atmosphere creates persistent

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Nomenclature

$k_1(t)$	Meshstiffness of the first stage	C_L	Lift coefficient
$k_2(t)$	Meshstiffness of the second stage	C_D	Drag coefficient
x_j and y_j	Translations of each block j ($i = 1$ to 3).	a	Axial induction factor
θ_{ji}	Angular displacements of the component i in block j ($i = 1$ and 2, $j = 1$ to 3).	a'	Tangential induction factor
α	Pressure angle (generally adopted equal to 20°)	V_0	Wind velocity far up stream
rb_{ji}	Base radius of the gear (m)	k_{xj}	Stiffness to bending according to the X direction (N·m)
I_{ji}	Moments of inertia of gears	k_{yj}	Stiffness to traction – compression according to Y direction (N·m)
$\delta_1(t), \delta_2(t)$	Displacements along the line of action	k_m	Average mesh stiffness (N·m)
r	Radius of the rotor (m)	$k_{\theta j}$	Torsional stiffness of the shaft (Nm/rad)
n_p	Number of blades	$Z_{(12)}, Z_{(21)}$ $Z_{(22)}, Z_{(31)}$	Number of teeth
c	Chord (m)	$\varepsilon_{\alpha 1}, \varepsilon_{\alpha 2}$	Contact ratio
ϕ	Inflow angle (rad)	$C_g(t)$	Electromechanic torque
D	Rotor diameter (m)	$Q_{aero}(t)$	Aerodynamic torque
ρ_{air}	Air density (Kg/m^3)		
Ω	Turbine rated speed (rad/s)		

variations of blade loads and rotor torque. Therefore, an increased penetration of wind turbine systems calls for a suitable modelling of the system parameter and incorporates the model into various uncertainty parameters. Until now, system parameters present a random parameter and suffer from a lack of accuracy focusing on the measurement of the parameters. The choice of the design parameters is very critical to optimise the performance of the system. Therefore, it becomes necessary to take into account uncertainty parameters [9,10]. In this context, advanced techniques and methods of uncertainties are developed. Monte Carlo simulation is a well-known technique in this field [11]. For reasonable accuracy, it requires a great number of samples; therefore, it is too costly. The Polynomial Chaos (PC) method is considered as the best framework in dealing with uncertainty quantification. This method is more attractive and more efficient compared to other methods such as Monte Carlo approaches [12,13].

Ghanem and Spanos [14,15] have used successfully the Polynomial Chaos (PC) method in their study of uncertainties in the structural mechanics and vibration fields. The PC method represents the random state and input parameter variables as a probability distribution in the stochastic system state governed by the differential equations of motion. Indeed, the PC method is defined as a spectral representation of the uncertainty in random space in terms of an expansion of orthogonal polynomials that are functions of the random input variables.

The computational accuracy and efficiency supplied by the Polynomial Chaos method in nonlinear problems is reported through scientific works in many fields such as in fluid dynamics [16–19], in solid mechanics [20,21], in chemical reactions [22], in terramechanics [23,24], etc. Due to the accuracy and efficiency of the Polynomial Chaos method in previous studies with different fields, this method is considered to investigate the dynamical behaviour of a wind turbine taking into account the parameters of the uncertainty system.

The originality of this study is to investigate the effects of the uncertainty input gear system parameter of a horizontal-axis wind turbine. The main objective is to capture the dynamical behaviour of a two-stage spur gearbox transmission system subjected to an uncertain input parameter. In order to calculate the dynamical response of the studied model, the PC method is used to deal with uncertainty and to discuss the capabilities of this new methodology. Monte Carlo simulations are reserved to the treatment of reference examples in order to test the validity and the properties of the Polynomial Chaos method.

2. Dynamic model

The wind turbine is composed by the rotor, the transmission power system and the generator. The transmission model implemented in this work is a two-stage spur gearbox system with twelve degrees of freedom (12 DOF) and three main blocks ($j = 1$ to 3) as shown in Fig. 1.

Each block is supported by a flexible bearing characterised by two stiffness parameters k_{xj} and k_{yj} according to the x and y directions, respectively. The connecting shafts admit a torsional stiffness parameter $k_{\theta j}$ according to the x direction. The four gears (gear 12, gear 21, gear 22 and gear 31) are considered as spur gears.

The gear system is subject to a random aerodynamic torque $Q_{aero}(t)$, which represents the effect of wind on the three-bladed rotor. The aerodynamic torque expression is given in paragraph 3. The output electromechanic torque is defined by $C_g(t)$.

In addition to the external excitation, the system is also submitted to two internal excitations, which are the periodic fluctuations of mesh stiffness $k_1(t)$ and $k_2(t)$. In fact, every contact is modelled by a variable stiffness represented by a linear spring following the line of action, whose temporal expression is described in paragraph 4.

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