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Dynamic vibrations in wind energy systems: Application to vertical axis wind turbine

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ABSTRACT

Dynamic analysis of Darrieus turbine bevel spur gear subjected to transient aerodynamic loads is carried out in the present study. The aerodynamic torque is obtained by solving the two dimensional unsteady incompressible Navies Stocks equation with the k–ω shear stress transport turbulence model. The results are presented for several values of tip speed ratio. The two-dimensional Computational Fluid Dynamics model is validated with experimental results. The optimum tip speed ratio is achieved, giving the best overall performance.

In this study, we developed a lamped mass dynamic model with 14 degrees of freedom. This model is excited by external and internal issues sources. The main factors of these excitations are the periodic fluctuations of the gear meshes' stiffness and the unsteady aerodynamic torque oscillations. The vibration responses are obtained in time and frequency domains. The originality of our work is the correlation between the complexity of the aerodynamic phenomenon and the non-stationary dynamics vibration of the mechanical gearing system.

The effect of the rotational speed on the dynamic behavior of the Darrieus turbine is also discussed. The present study shows that the variation of rotor rotational speed directly affects the torque production. However, there is a small change in the dynamic vibration of the studied gearing system.

1. Introduction

Wind energy is one of the most promising renewable energy resources, which receives a great consideration. There are generally two types of wind turbines; a horizontal axis wind turbine (HAWT) and a vertical axis wind turbine (VAWT). The VAWT has received more attention due to its efficiency in urban regions compared to HAWT. In fact, the wind flow speed in urban regions continuously changes direction and is extremely turbulent. The inherent characteristics of omni-directionality of VAWTs make them more suitable to harnessing this kind of flow. Other advantages include the simplicity in construction and low noise. The Darrieus turbine is the most common VAWT, fitted with high-performance symmetric profile blades. It

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Nomenclature

CFD	Computational Fluid Dynamics
BEM	Blade Element Momentum
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
SST	Shear Stress Transport
Cp [–]	power coefficient
Ct [–]	torque coefficient
P [W]	power
T [Nm]	torque
D_{rotor} [mm]	rotor diameter
H_{rotor} [mm]	rotor height
c [mm]	blade chord
$H_{wind\ tunnel}$ [mm]	computational domain height
$W_{wind\ tunnel}$ [mm]	computational domain width
$\{F(t)\}$	load vector
N [–]	number of rotor blades
R [mm]	rotor radius
V_∞ [m/s]	unperturbed wind velocity at computational domain
A [m^2]	swept area of the rotor
$\{q\}$ [–]	generalized vector of degrees of freedom
$[K_s]$	average stiffness matrix
$[M]$, $[K(t)]$,$[C]$	mass, stiffness and damping matrix
σ [–]	rotor solidity
α [rad]	angle of attack
ω [rad s^{-1}]	rotor angular velocity
Θ [°]	azimuth angle
λ (TSR) [–]	tip speed ratio
ρ [kg/m^3]	air density
$\delta(t)$ [m]	dynamic transmission errors (teeth deflection)

works on the principle of lift in order to generate torque. The majority of wind power research is focused on accurately predicting the performance of VAWT.

Since our study has faced a methodological difficulty consisting in combining the aerodynamic study and the bearing dynamic vibration, we opt for dealing with them separately in the literature reviews. In a second step we combine both to produce our suggested model when coupling the two parts.

The literature is rich in theoretical and numerical models achieved on the aerodynamic performance modeling. The most well-known models can be classified into two approaches: the momentum theory and the Computational Fluid Dynamics (CFD) model. BEM (Blade Element Momentum) theory, first introduced by Glauert [1], adopts the lift and drag coefficients of two-dimensional airfoils obtained by a wind tunnel test [2,3]. Then, a single-streamtube model is adapted by Templin [4] for a vertical-axis wind turbine. Templin's approach is extended by Strickland [5] into multiple-streamtube model by considering a number of adjacent and aerodynamically independent smaller streamtube. This approach is also developed by combining the multiple streamtube models with the double actuator disc theory [6,7]. Despite the simplicity of the analytical method based on momentum theory, all the classical aerodynamic tools are unable to predict the complexity of the flow around the turbine. They need experimental data to be validated using wind tunnel test, which is expensive in terms of time and cost. Other researchers try to develop the modeling of the VAWT performance using experimental wind tunnel test [8–10]. These conventional experimental approaches are expensive and have complicated measurement systems. They are unable to provide a comprehensive picture of the complex aerodynamic behavior of VAWTs. To overcome the limitations of the empirical methods and experimental wind tunnel tests, we seek to investigate the wind performance of a VAWT using a numerical method based on a CFD approach, whose integration into industrial appliances and research is continuously rising. The computational method achieves considerable improvements in the understanding of the VAWT thanks to its inherent flexibility for analyzing complex unsteady flow around wind turbines. The CFD codes can also surmount the limitations in low Reynolds number by the integration of the Navies Stokes equations around the blade profile. The most important advantage of the CFD analysis is its ability to simulate the configurations at the wind tunnel test conditions and to generate results that are compared favorably with experimental data [9]. In this context, M. Raciti Castelli et al. [11] perform a numerical simulation validation for a Darrieus wind turbine by a systematic comparison with wind tunnel experimental data. This is more economical than the costly wind tunnel test. The (CFD) method has been widely used in the literature to fully characterize the behavior of the vertical axis wind turbine [11–15]. Performing CFD calculations provides operating torque curves and useful graphical presentations, such as contour and flow lines.

As far as the bearing dynamic behavior is concerned, the work of Ferreira [16] allows us to deduce that the Darrieus wind turbine is characterized by an inherently unsteady aerodynamic behavior caused by the continuous variation of the blade angle of attack with the azimuthal position during the blade rotation. The non-stationary behavior of the VAWT increases vibration. These aerodynamic vibrations are transmitted to the gearing mechanism.

There still exists a large knowledge gap in the simulation of the VAWT completed mechanism. Unlike the empirical method, analyzing an unsteady flow around the blade airfoil in a turbulent regime describes approximately the real behavior of the VAWT and leads to predict the dynamic vibration of the bearing in a non-stationary regime. There are several different works commonly known in the literature modeling the bevel-gears transmission. Most of the research works use simple lumped parameter models involving a spring–mass–damper system [17–19]. Some of these models try to develop the dynamic behavior of the bevel-gear system with flexible bearing that are excited only by the gear meshes stiffness fluctuation [20,21]. Another research studies the vibration of the gear train used in a wind turbine and excited by fixed wind speed [22], which is far from the case of the actual wind turbines with randomly varying wind speed. This kind of analysis is limited due to the empirical torque excitation.