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The effect of the nonlinear velocity and history dependencies of the aerodynamic force on the dynamic response of a rotating wind turbine blade

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ABSTRACT

Existing models for the analysis of offshore wind turbines account for the aerodynamic action on the turbine rotor in detail, requiring a high computational price. When considering the foundation of an offshore wind turbine, however, a reduced rotor model may be sufficient. To define such a model, the significance of the nonlinear velocity and history dependency of the aerodynamic force on a rotating blade should be known. Aerodynamic interaction renders the dynamics of a rotating blade in an ambient wind field nonlinear in terms of the dependency on the wind velocity relative to the structural motion. Moreover, the development in time of the aerodynamic force does not follow the flow velocity instantaneously, implying a history dependency. In addition, both the non-uniform blade geometry and the aerodynamic interaction couple the blade motions in and out of the rotational plane. Therefore, this study presents the Euler–Bernoulli formulation of a twisted rotating blade connected to a rigid hub, excited by either instantaneous or history-dependent aerodynamic forces. On this basis, the importance of the history dependency is determined. Moreover, to assess the nonlinear contributions, both models are linearized. The structural response is computed for a standstill and a rotating blade, based on the NREL 5-MW turbine. To this end, the model is reduced on the basis of its first three free-vibration mode shapes. Blade tip response predictions, computed from turbulent excitation, correctly account for both modal and directional couplings, and the added damping resulting from the dependency of the aerodynamic force on the structural motion. Considering the deflection of the blade tip, the history-dependent and the instantaneous force models perform equally well, providing a basis for the potential use of the instantaneous model for the rotor reduction. The linearized instantaneous model provides similar results for the rotating blade, indicating its potential application for this scenario, and allowing for the definition of an added damping matrix, applicable for the dynamic analysis of rotating turbine blades.

1. Introduction

With the enhanced interest in renewable energy, the development of offshore wind power has soared. The forces on offshore wind turbines mainly result from environmental interactions – aerodynamic and hydrodynamic – which are coupled through the response of the structure. The coupled analysis requires an integrated model, accounting for the rotor,

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nacelle assembly, tower and foundation. Available commercial and academic software codes allow for a detailed analysis of the aerodynamic interaction [1].

A detailed integrated analysis of offshore wind turbines comes with a high computational price. In order to reduce the complexity of the integrated models, recent research has focussed on the reduction of the foundation structure [2–4]. As an alternative, models can be developed with a reduced rotor representation, in particular when the engineering focus is on the foundation of the structure. This would require a simplified rotor model, accounting for the aerodynamic forcing that results from the operational state. Such a rotor simplification cannot account in full detail for the nonlinear velocity and history dependency of the aerodynamic interaction. The question rises to what extent these interaction characteristics are of importance for the preliminary integrated analysis of offshore wind turbines.

The aerodynamic interaction models for turbine blades stem from preceding developments in the aircraft industry [5–9]. Larsen et al. [10] presented an overview of aerodynamic models for wind turbine application, valid for the lower flow velocities. In the case of unsteady aerodynamics, either through a non-stationary flow or structural motion, a change in the angle of attack results in a brief separation of the flow until again a wake equilibrium – that is, an aerodynamic equilibrium of the near wake behind the trailing edge of the aerofoil – is found, thus delaying the transition to a new aerodynamic state. Hansen et al. [11] presented a modified Beddoes–Leishman model [12], with which experimental data derived for attached-flow conditions was predicted. This model expresses the history dependency in terms of aerodynamic states, through which a delay in the development of the aerodynamic coefficients – lift and drag – is established. Different history-dependent aerodynamic force models have been applied in the study on aero-elastic instabilities of wind turbine blades [13–17].

In many cases, the aerodynamic interaction is described by means of an instantaneous force model [18–20]. Such a model neglects the disturbance of the near wake and the consequent delayed development of the new aerodynamic equilibrium. The validity of this approach can in principle be assessed on the basis of the reduced frequency, a non-dimensional parameter relating the oscillations of the blade to the time required for the air flow to travel across the blade chord [21]. The air flow velocity of wind turbine blades varies along the length of the blade, and so does the reduced frequency. Moreover, the contribution of the structural motion to the relative air flow velocity is not known beforehand. Consequently, the history dependency of the aerodynamic interaction of wind turbine blades cannot straightforwardly be determined.

This paper addresses the aerodynamic interaction of a single rotating blade, with the purpose of assessing the significance of the nonlinear velocity and history-dependent aerodynamic interaction. The blades of a wind turbine are large, flexible and non-uniform elements, twisted along their length. This implies that the flexural modes of vibration are not easily defined, and, moreover, cannot be described within one plane. Given the environmental conditions, the rotational speed can be adjusted, which affects the centrifugal stiffening. To control the aerodynamic interaction, the blades can be pitched towards or away from the direction of the wind. As a result, the coupling between the motions in and out of the plane of rotation depends on the operational state, implicitly affecting the natural frequencies and the modal shapes of the blade. Moreover, added damping and mass are introduced as a result of the aerodynamic interaction, through which the in-plane and out-of-plane blade motions are coupled. Given the nature of the aerodynamic interaction, this coupling is nonlinear.

A geometrically linear model of a twisted non-uniform aerofoil is derived and the true undamped modes corresponding to different operational states are obtained by means of the finite element method. The structural and aero-elastic properties of the blade are based on the conceptual NREL 5-MW turbine [22]. Subsequently, an instantaneous and a history-dependent aerodynamic force model are defined, accounting for the dependency on the structural motion of the turbine blade. These nonlinear aerodynamic models, which are restricted to attached flows, couple the blade motions in and out of the rotational plane. After expanding and truncating the response, by means of the Galerkin decomposition, added damping and the modal and directional couplings are assessed for both a stand-still and a rotating aerofoil on the basis of linearized aerodynamic models. To this end, frequency–response functions of the blade tip motions are computed, which either include or exclude the contribution of aerodynamic interaction terms. Subsequently, the relevance of the nonlinear velocity and history dependency of the aerodynamic interaction is assessed. In a previous preliminary study, the coupled nonlinear system was analyzed with the help of a Volterra series expansion [23]. In the current paper, the full nonlinear response is determined for a turbulent wind signal on the basis of a Kaimal turbulence spectrum, using time integration on the basis of an explicit Runge Kutta scheme. By comparing the blade tip motions derived with the nonlinear and the linearized models, the influence of the nonlinear velocity and history dependency of the forcing on the structural response is addressed.

2. Rotating blade model

2.1. Rotating beam modelling

Numerous examples of the free-vibration analysis of rotating beams can be found in the literature. Many of those have focussed on the linear motion of a uniform Euler–Bernoulli beam [24–31], or a Timoshenko beam [32–35]. Most works are limited to motion either in or out of the rotational plane, while some have specifically addressed the flexural–flexural coupling [24,32,35], the flexural–axial coupling [27,34,29,36,30,37] – introducing the Coriolis effect – or the flexural–torsional coupling [38]. Apart from uniform beams, many studies have focussed on tapered beams [39,25,28,35,40] or non-uniform beams with an axial twist or asymmetrical cross-section [35,36,38]. The finite element method has frequently been