Application of 3D Nonlinear Beam Theory on Modeling Offshore Wind Turbines

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ABSTRACT

An overview on the development in design of offshore wind turbines concerning modeling of stochastic sea state, extreme waves, breaking wave impact on 2D and 3D structures, stochastic wind, aeroelasticity, particularly for aeroelasticity on rotor blade flow, structural dynamics (in time domain) of the overall structure of an offshore wind turbine and soil elasticity with application to offshore wind turbines is given. For modeling the overall structural dynamics of an offshore wind turbine in time domain the 3D nonlinear beam theory regarding large (unlimited) rotational movement is applied. The governing equations for the 3D nonlinear beam theory are presented. The weak form and a finite element discretization employing a virtual work approach are derived. Unique relationship between structural deformation and inner structural section forces is given, i.e. inner section force timeseries for e.g. the purpose of fatigue analysis for the design of decisive details of the structure can be directly obtained by the numeric approach. The numerical model is applied to represent i) an in-plane rigid rotation of the rotor system of an offshore wind turbine and ii) an in-plane rotation and superposed oscillation and an out-of-plane oscillation of an offshore wind turbine for both i) and ii) long-term simulations of 12000 time intervals with constant time interval size of 0.025 s, i.e. for both i) and ii) a 300 s real time simulation each. Computational results are evaluated with respect to the algorithmic properties of the presented numerical model.

KEY WORDS: offshore wind turbines; structural dynamics in time domain; 3D nonlinear beam theory; finite element method; long-term simulation; combined wave and wind load; modeling the overall structure of an offshore wind turbine at once

INTRODUCTION

Offshore wind turbines are exposed to long-term combined load from stochastic sea state and stochastic turbulent wind. A realistic description of the overall structural dynamics of the complete structure is of main importance for the fatigue design of the different parts of the structure, as there are rotor blades, nacelle, machinery components, azimuth drive, tower segments, ring bolt connections, transition piece, tripod construction, underwater construction and foundation. Sea state load and wind load have up to now been modeled by at-the-time-established approaches. Gravity wave and so sea state modeling ranges back many decades from now (Wave theories by Airy 1845, Stokes 1847, 3rd order Stokes theory Skjelbreia 1959, 5th order Stokes theory Skjelbreia and Hendrickson 1960, stream function theory Dean 1965). A summary on wave theory approaches, on wave-wind correlation mechanisms and on hydrodynamic forces as well as on the dependence of structural dynamic properties of offshore wind turbines on water depth is given in Corte 2003. Extreme wave modeling including breaking waves became applicable as periodicity of waves in space and time was not demanded as assumption anymore and numerical methods (finite element method, boundary element method) were developed for the purpose of nonlinear wave modeling (Longuet-Higgins and Cokelet 1976, Vinje and Brevig 1981, Gravert 1987, Skourup 1989, Grilli, Skourup and Svendsen 1989, Grilli and Svendsen 1990, Grilli 1993, Grilli and Subramanya 1994, 1996, Grilli et al. 2001, 2005, Fochesato et al. 2005a,b,c). Local phenomena as breaking wave impact on rigid structures, e.g. 2D circular structures and 3D cylindrical structures, could be modeled by free surface flow based on potential flow assumptions as well as on viscous fluid flow assumptions (von Kármán 1929, Wagner 1932, Fabula 1957, Goda 1964, Wienke 2001, 2005, Peil and Corte 2005a,b, 2006, Corte and Grilli 2006, Corte 2006). Atmospheric boundary layer modeling was established by logarithmic or exponential average wind speed profiles (Davenport 1961, Telljohann 1998a,b, Peil and Telljohann 1996, 1997, 1999a,b) and 3D wind turbulence modeling (Davenport 1961, Kaimal et al. 1972, Telljohann 1998a,b, Peil and Telljohann 1996, 1997, 1999a,b). Appropriate information on wind data is e.g. given by Troen and Petersen 1990. Application of the 2D blade element theory made it possible to adapt lift and drag force coefficients' description to their transient behaviour for wake flow modeling with respect to the different regimes of flow around aerodynamic profiles of rotor blades (Burbaun 1924a,b, Wagner 1925, Theodorsen 1935, Kássner 1936, 1940, Försching 1974, McCroskey 1981, van der Wall 1990, Meyer 2002, Meyer and Matthis 2004, Corte 2006). At present established models for the design of offshore wind turbines (e.g. BLADED, HAWC2, ADAMS, FLEX5) apply models to consider equilibrium on energy consumption of rotor blades from surrounding flow, tip loss and hub loss aeroelastic force reduction, wake flow evolution behind the rotor blades and steady and dynamic stall within lift and drag force computation. BLADED applies a wake model based on Pitt and Peters 1981; for dynamic stall description BLADED applies a modification of the model of Beddoes (Beddoes 1976, Leishman and Beddoes 1986, 1989); for BLADED see Bossanyi 2003. HAWC2 offers the Stig Òye model (Oye 1990, 1991) and a modification of the model of Beddoes (Beddoes 1976, Leishman and Beddoes 1986, 1989) both for consideration of dynamic stall within aeroelasticity modeling. ADAMS utilizes the AeroDyn module (Moriarty and Hansen 2005) for modeling aeroelastic load. Within AeroDyn two models for wake flow representation are contained that are the blade element momentum approach (BEM) and the generalized dynamic wake approach (GDW) for unsteady wake dynamics; the generalized dynamic wake approach follows the model of Pitt and Peters 1981 and Peters and He 1991; for the description of dynamic stall AeroDyn employs the model of...