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Simulation of large-amplitude motion of floating wind turbines using conservation of momentum

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ABSTRACT

A new method is presented to directly derive the nonlinear equations of motion (EOMs) of a floating wind turbine system using the theorem of conservation of angular momentum and Newton's second law. The methodology considers the system as two rigid bodies: the tower and the rotor-nacelle assembly (RNA). The large-amplitude rotation of the tower is described by the 1-2-3 sequence Euler angles, which offer accurate nonlinear coupling between motions in 6 degrees of freedom (DOFs). Two additional DOFs of the RNA relative to the tower, nacelle yaw and rotor spin, are prescribed by mechanical control and are also included in the EOMs of the entire system. Results from the EOMs are transformed among different coordinate systems at every time-step for use in the computation of hydrodynamics, aerodynamics and restoring forces, which preserves the nonlinearity between external excitation and structural dynamics. The new method is verified by critical comparison of simulation results with those of the popular wind turbine dynamics software FAST. The concept of highly compliant floating wind turbines is introduced. The large-amplitude motions and gyroscopic moments of one of these smaller, lighter structures is simulated in an example.

1. Introduction and background

Environmental, aesthetic and political pressures continue to push for siting offshore wind turbines beyond sight of land, where waters tend to be deeper, and use of floating structures is likely to be considered. Design of a floating wind turbine support structure capable of maintaining a near-vertical tower requires buoyancy far exceeding the weight of the equipment being supported. Savings could potentially be realized by reducing hull size, which would allow more compliance with the wind thrust force in the pitch direction. The loss of blade swept area has been shown to have a modest effect on energy capture (Wang and Sweetman, 2011). Increased dynamic motions does not necessarily correspond to increased dynamic load. For sinusoidal motion, the amplitude of the inertial loads is the product of the moment of inertia, amplitude of the motion and the square of the circular frequency. Decreasing the stiffness reduces the pitch and roll natural frequencies, which decreases inertial loading, but may require special consideration in the design of the rotor speed and blade-pitch controllers. Design of these increasingly compliant floating towers will make computation of structural dynamics both more challenging and more important, mainly because of the effects of gyroscopic moments. For conventional, stiff, bottom-founded structures, these moments are primarily generated by mechanical precession of the spin axis into the shifting winds, and so are limited by the maximum yaw rate (Henderson and Vugts, 2001). However, no such limit exists for gyroscopic moments of floating structures because they result from both shifting winds and irregular motions of the tower. New methodologies must be developed and employed to simulate the motions of new design concepts.

The compliant floating wind turbine system can be considered as a multi-body system including tower, rotor, nacelle and other moving parts, which are mechanically connected by the yaw bearing, hub, etc. One conventional analytical method to simulate the dynamics motions of such a system would be the Newton–Euler (NE) equations or Euler–Lagrange (EL) equations (Saha, 1999). The NE equations are usually established by separating the free-body diagrams of each rigid body in the system. For example, Stoneking (2007) presents the derivation of the exact nonlinear dynamic equations of motion for a multi-body spacecraft connected by spherical gimbal joints. Matsukuma et al. (Matsukuma and Utsunomiya, 2008) employ NE equations combined with constraint conditions associated with the joints between rigid bodies to analyze the dynamic response of a 2-MW downwind turbine mounted on a spar-type floating platform

Abbreviation: EOMs, equations of motion; DOFs, degrees of freedom; RNA, rotor-nacelle assembly.

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for pitch amplitudes up to around 10° in steady wind, but no waves, and conclude that the platform motions are meaningfully influenced by gyro moments associated with rotor rotation. The EL equations apply energy methods to establish equations of motion for generalized degrees of freedom. Overall, the commonly used NE method computes the internal forcing between rigid bodies, and is excellent for applications in which the internal forcing has significant concern. However, for simulation of general motion of a system, these internal forces are not needed at every time step. The EL method is efficient for the solution of motion, while the derivation of partial derivatives of energy about related generalized DOFs is laborious. Additionally, the number of equations is equal to that of DOFs for previous conventional methods: the number of equations of the NE method is six times of number of rigid bodies within the multi-body system; the number of equations for the EL method is just that of the generalized DOFs. Kane's method combines the advantages of both the NE and EL methods. As the well-recognized wind turbine dynamics analysis software, the NREL FAST aero-elastic simulator (Jonkman and Buhl, 2005; Jonkman, 2007) uses Kane's method to derive the EOMs for the floating wind turbine system with rotations of platform less than 20°. In FAST, the hydrodynamic radiation-diffraction analysis package WAMIT (WAMIT 6.4, 2008) can be used to provide hydrodynamic forcing in the case of small-amplitude motions.

The work presented here is also a combination of the NE and EL methods for the computation of the general motion using only six equations no matter how many DOFs the system has. It makes direct use of the known interactions between mechanical components in the wind turbine, which are directly controlled or explicitly defined, to derive the rotational equations of motion of the entire wind turbine system. The conventional Euler dynamic equations are normally applied to only one rigid body, while the known relationships between the rigid body components enable the application of the theorem of conservation of angular momentum to the entire system. Transformation matrixes are used to transfer the angular momentum of each rigid body to a unified coordinate system to obtain the total angular momentum of the entire system, the derivative of which is equal to the sum of external moments applied to the system. The resulting rotational EOMs are combined with translational equations governed by Newton's second law of the entire multi-body system to develop a system of six equations. A key advantage of the new methodology is that the EOMs use fewer equations than previous conventional methods because only three rotational DOFs of the base body (tower) described by Euler angles and three translational DOFs need to be solved. Known relative DOFs along the rigid-body chain (nacelle yaw and blade spin) do not require additional EOMs. Structural flexibility of individual bodies cannot be considered using this method. However, neglecting these effects is reasonable for compliant design in cases where the global motions are dominated by first order rigid-body motions that are much larger than the higher modes allowed by structural flexibility. Mechanical systems with known geometric relationships between components are common, especially in rotating machinery. Thus, the methodology here is developed for floating wind turbine systems, but is broadly applicable to other types of interconnected dynamic mechanical systems.

The nonlinearities of various external forces and moments due to their coupling with structural motions are addressed in this work. Aerodynamics and hydrodynamics are calculated including the motion of body through the fluid, and the instantaneous position of the structure is accurately computed to incorporate nonlinearities of both the mooring and hydrostatics. In the numerical simulation, the motions and external excitation (including both external forces and moments) are transformed between various coordinate systems at each time step using matrices developed in terms of Euler angles for the rigid body. Thus, the full nonlinear coupling between external excitation and large-amplitude motion of the tower is preserved.

2. Coordinate systems and Euler angles

The methodology considers the system as two rigid bodies: the tower is the complete structural assembly, including the buoyant hull, that supports the rotor-nacelle assembly (RNA); the RNA is the complete assembly that can mechanically yaw relative to the tower. The implementation of the new method requires use of several coordinate systems to derive the EOMs for the complete system. The external excitation applied in the dynamic equations is computed consecutively and projected into the corresponding coordinate systems. Fig. 1 shows both the (X,Y,Z) and the (X_M,Y_M,Z_M) systems, which are earth-fixed global coordinate systems with the origin located at the center of mass (CM) of the entire system and still water level respectively in case of equilibrium status of the system with zero displacements. The (x_t,y_t,z_t) and the (A,B,C) systems are body fixed and originate at the CM of the tower and RNA, respectively. The CM of the RNA, G_R, is assumed to be on the centerline of the tower to guarantee that the CM of the system, G_s, is fixed on the tower. The (x_s,y_s,z_s) system is parallel to (x_t,y_t,z_t) and originates at the instantaneous CM of the entire system, which is also assumed to be on the centerline of the tower. Thus (x_s,y_s,z_s) coincides with the (X,Y,Z) system for zero displacement.

The (X,Y,Z) and (x_s,y_s,z_s) coordinate systems are used for application of both the Newton's second law and the theorem of moment of momentum on the entire system. Two body-fixed

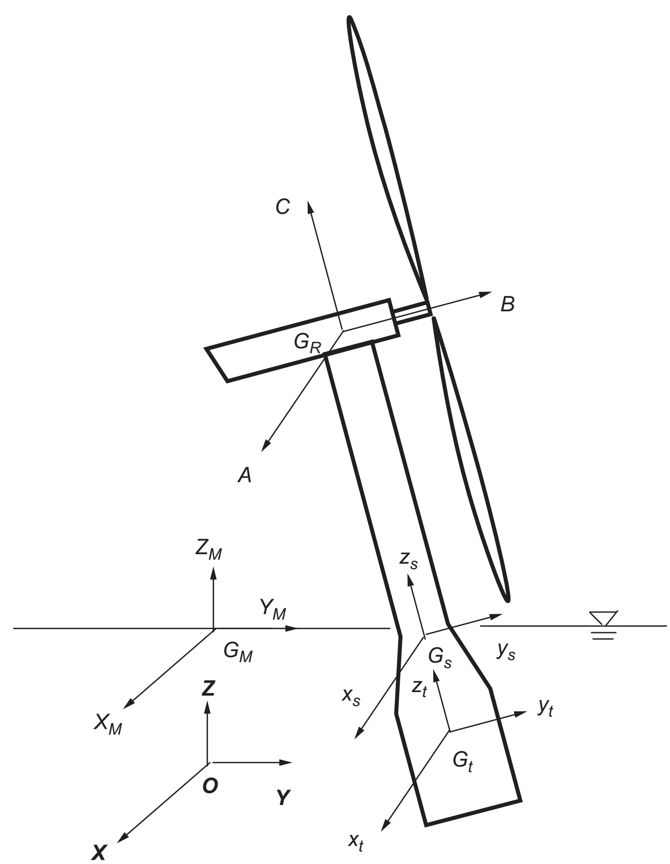

Fig. 1. Coordinate systems used in the application.