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3DFloat: Aero-servo-hydro-elastic computations for offshore wind turbines

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ABSTRACT

This paper describes the in-house code 3DFloat at Institute for Energy Technology (IFE). The core is a general nonlinear Finite-Element-Method (FEM) based on a co-rotated approach. It is particularly suited for structures that can be modeled with a combination of flexible slender beam elements, rigid bodies, taut or catenary mooring lines, springs and dampers subject to concurrent wave- and wind loading. Rigid or flexible rotors, several if so desired, can be applied to the structure. Although the code was developed with offshore wind turbines in mind, other uses, such as strait crossings are currently being explored.

KEY WORDS: Aero-servo-hydro-elastic analysis, offshore wind turbine, strait crossing

INTRODUCTION

3DFloat is an aero-servo-hydro-elastic simulation tool developed from 2006 at IFE and NMBU for the computation of dynamic response of offshore wind turbines. It is coded in FORTRAN90, with linear algebra routines from the LAPACK library (Anderson et al., 1990). 3DFloat was one of the models applied to the OC3-HYWIND floating wind-turbine in the IEA OC3 project (Jonkman et al., 2010), the bottom-fixed space-frame ("Jacket") in the IEA OC4 project (Popko et al., 2012) and the semisubmersible platform in the IEA OC4 project (Robertson et al, 2013). It has been validated against wave tank experiments for 3 different Tension-Leg-Buoys (Myhr and Nygaard, 2015). It is currently being validated against wave tank experiments for a semisubmersible floater (Azcona et al., 2014), several floater shapes in the IEA OC5 project (Robertson et al., 2015) and forced motion of an isolated mooring line. Current verification efforts against other models include a Submerged Floating Tunnel for Bjørnafjorden.

STRUCTURAL MODEL

The core of the model is a general nonlinear (FEM) framework, where computational nodes are interconnected with elements. The elements implemented so far are based on Euler-Bernoulli beams with 12 degrees of freedom (DOF).

The element stores structural properties with respect to the two section principal axes (element y and z axes), and if applicable, for the axial (element x) direction. The user input includes the following properties at each end of the element: Axial stiffness, bending stiffness about the two principal axes, mass per unit length and pre-strain. For conical elements, the user input is simpler, with the material properties and diameter and wall thickness at each end of the element replacing the more general input mentioned above.

Cable elements with reduced bending-stiffness are used for the mooring lines. Geometric nonlinearities are accounted for by a co-rotated FEM approach, where the reference configuration is a recently deformed state. The element equations are stated in a coordinate system attached to the midpoint of the element in the reference state, and then transformed to a common component coordinate system. This allows for the utilization of small-strain elements for large global deflections, as long as the element resolution is sufficient.

LOADS

Loads from gravity, buoyancy, waves, current and wind are applied as distributed external loads on the structure. Forces are evaluated at Gauss points in the elements, and a Galerkin approach is used to evaluate consistent nodal loads. Wind is handled as a nonlinear drag term on the structure above the wave surface, except on the rotor blades, where lift- and drag lookup tables and the Blade Element/ Momentum (BEM) theory are used. The turbulence is modeled with import of turbulence files on the "HAWC" or TURBSIM formats, generated with e.g. the IEC Turbulence simulator or TURBSIM.

The loads for the wet elements are computed from the pressure field obtained from the wave kinematics model. Regular wave kinematics is either linear finite water-depth Airy-theory or stream functions up to order 12 (Chaplin, 1980). Irregular waves, long- or short crested are obtained by superposition of linear Airy wave components. The wave component tables can be computed from JONSWAP or Pierson-Moskowitz spectrum definitions with either constant frequency or constant energy increments. The wave component tables can also be generated directly from time-series of wave height, from e.g. wave tank experiments

Second-order wave kinematics (Sharma and Dean, 1981), long- or short crested is currently being verified. Two options are available for evaluation of wave kinematics. In the 'mean' approach, the mean position of the geometry is used when computing wave forces. In the 'updated' approach, the updated configuration of both the structure and sea surface is taken into account when applying buoyancy and wave loads to the wet elements. For the Airy waves, two approaches are implemented to provide wave kinematics to the wave surface. In the Wheeler stretching approach, the wave kinematics calculated at the Still Water line (SWL) is applied to the wave surface, stretching the distribution between the surface and the bottom. This creates variations in pressure extending further down than in the basic Airy formulation, influencing the heave excitation. In the extrapolated Airy theory, wave kinematics above the SWL is assumed to be the same as at the SWL, and elsewhere (for the wet elements) as in the basic Airy theory. This modifies the kinematics only within the wave crests. The pressure in the stream function formulation is calculated by the Bernoulli equation applied in a reference frame moving with the wave celerity. In this frame, the pressure and velocity fields are steady, and the total pressure height is uniform. The wave kinematics can optionally be updated with a kinematic time step that is different than the structure solver time step. This can give a significant savings on computational speed, without much loss of accuracy. For computations involving wind turbine rotors, a typical structure solver time step is 0.01s. It is then sufficient to update the wave kinematics with a time step of 0.1s.

Wave and current loads for slender beams are computed on the wet part of the structure using the relative form of Morison's equation (Sarpkaya, 1981). Terms involving acceleration (added mass) are added to the mass matrix, while all other loads are kept as applied loads on the right hand side (RHS) of the equation system.

The element hydrodynamic (or aerodynamic) properties is given with respect to the two section principal axes (element y and z axes), and if applicable, for the axial (element x) direction. Coefficients can be specified with global defaults, and individually by element. The user input includes the following hydrodynamic properties at each end of the element: Reference lengths along the element x, y, and z axes for use in drag and inertial load calculations, section area for buoyancy calculation, and drag- and inertia coefficients along the element x, y, and z axes. The elements can optionally have end caps exposed to the hydrodynamic pressure. For conical beams, the user input is simpler, with diameter and wall thickness at each end of the element replacing several input parameters for both structural and hydrodynamic properties.

Large rigid bodies, such as the pontoons on a Submerged Floating Tunnel (SFT) and columns of a semisubmersible floater can be modeled with Linear Potential Theory (LPT). For a given body shape, WAMIT (Lee, 1995) or WADAM (DNV, 2005) is used to compute the linear excitation force transfer function coefficients as function of wave direction and period, and the frequency dependent added-mass and damping coefficient matrices. The results can be imported to 3DFloat and associated with bodies attached to nodes on the structure. In the time domain, the excitation forces follow directly from the transfer functions and wave components. The effect of frequency-dependent added mass and damping is computed via retardation functions and convolution integrals.

Point forces can be applied to nodes. A wind turbine rotor load model can associate rigid rotors (or several if so desired) to nodes or provide aerodynamic loads to a flexible FEM representation of a wind turbine rotor. The rotor aerodynamic loads are computed using unsteady blade-element/momentum theory (BEM), with extensions for dynamic inflow and yaw errors.

CONTROL SYSTEM

The generic control system in 3DFloat is for a variable speed rotor, with fixed blade pitch angle below rated wind speed. Above rated wind speed, PI control of pitch angle is used to control rotational speed and thereby power (Hansen et al., 2005). Alternatively, similar controllers developed in the IEA OC3 project for the NREL 5 MW reference rotor are implemented. One of these controllers has been tuned to maintain stability for the OC3-HYWIND floating wind turbine (Jonkman et al., 2010). 3DFloat has a Dynamic Link Library (DLL) interface to proprietary controllers supplied by companies with competition sensitive software, e.g. the Statoil controller for spar-buoy floating wind turbines.

TEMPORAL INTEGRATION

The time domain computations are carried out using either the implicit Generalized-α method, the implicit Newmark scheme, or an explicit central difference scheme (Pai, 2007). For the implicit schemes, modified Newton sub-iterations are used for the convergence of the solution in each time-step, governed by a residual criterion.

EIGEN FREQUENCY ANALYSIS

Eigen-frequency analysis with 3DFloat is handled with all displacement dependent externally applied loads linearized and added to the stiffness matrix at the relevant DOF. This includes the effect of buoyancy, mooring lines and restoring moment due to metacentric height. The results include eigen frequencies, and tables and visualizations of mode shapes.

OPTIMIZATION MODULE INVALS

The ALSIM package at IFE (Sørheim, 2002) contains an optimizer that has previously been used in an inverse procedure to optimize heat transfer coefficients in simulation model vs. experiment comparisons. For the use with 3DFloat, it was enhanced with the new optimization algorithms "Efficient Global Optimization (EGO)", "Genetic Algorithm (GA)", "Bound Optimization BY Quadratic Approximation (BOBYQA)" and "DIviding RECTangles (DIRECT)". General and flexible capabilities were included to allow the module to communicate with other simulation models through text-files or scripts, without the need for linking of models. The design variables with limits are specified in the INVALS input, along with tags for identification of the design variables or derived quantities in the simulation model input templates. INVALS generate the 3DFloat input file from the template. The template is identical to the 3DFloat input file, except some header information, and formulas identifying how the selected input values are evaluated from the design variables. With the generated input, INVALS runs a script, that runs 3DFloat, and subsequently a cost function executable that parses through the output files of 3DFloat. The cost function is evaluated and exported to a text file that is subsequently read by the optimizer. The constraints are implemented as penalty functions in the cost model. INVALS can work on parallel systems, e.g. by sending different instances of design configuration simulations to different processors.

A brief evaluation of the new algorithms in INVALS was performed on a benchmark problem from the casting industry. This confirmed the known characteristics of each of the methods. In the optimization problems applied to 3DFloat and offshore wind turbines, the BOBYQA method (Powell, 2009) seems to work well.

VIZULATIZATION

3DFloat can export geometric information and stresses for visualization and animation with Tecplot, ParaView, and a Python scripts that come with the 3DFloat package.

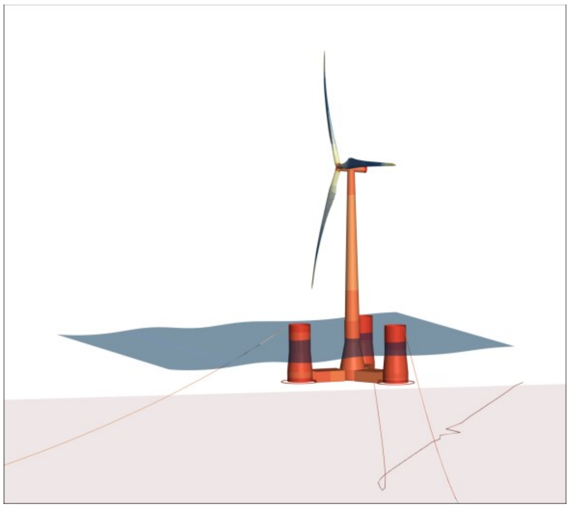
Figure 1: Animation of 3DFloat Results

CATALOGUE OF ROTORS AND FLOATING WIND TURBINE SUBSTRUCTURE DEFINITIONS

3DFloat has been applied to a number of wind turbine rotors. The 3DFloat input for two public definitions are available; the NREL 5MW reference rotor (Jonkman et al., 2009), and the DTU 10MW reference rotor (Bak, C. et al., 2013).

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