DEVELOPMENT OF A FULLY COUPLED AERO-HYDRO-MOORING-ELASTIC TOOL FOR FLOATING OFFSHORE WIND TURBINES

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Introduction

As one of the fastest growing renewable energy sources, wind energy is playing an increasingly important role in addressing the climate change and energy crisis issues the world is currently facing. The abundance of wind resource in offshore areas makes them a popular choice for turbine installation. In the past few years, several floating wind projects have emerged by installing wind turbines far offshore in deep-water sites on moored platforms. Compared to land-based or offshore fixed-bottom wind turbines, a floating offshore wind turbine (FOWT) is a fully coupled system where the wind turbine with flexible blades and the floating platform with its mooring system interact with each other in wind and waves, which makes existing design tools inadequate to accurately predict its responses. This paper presents a fully coupled high-fidelity aero-hydro-mooring-elastic analysis tool developed for FOWT applications. The numerical techniques adopted in the present tool are firstly described. Simulation results from a series of case studies are then shown to demonstrate the capabilities of the developed tool.

Numerical Methods

In the numerical tool developed in this work, OpenFOAM is coupled with an open source MultiBody Dynamics (MBD) code MBDyn (https://www.mbdyn.org) to solve the structural dynamics of an FOWT with flexible turbine blades. This is achieved by establishing an interface library to exchange data between these two codes. Additionally, a mesh motion solver is developed in OpenFOAM to tackle complex mesh movement in FOWT simulations. A mooring system analysis module is also implemented to simulate mooring lines in an FOWT. Figure 1 depicts the structure of the present FSI analysis tool, where built-in features in OpenFOAM and MBDyn are indicated in black; the wave modelling module marked in red is incorporated from the naoe-FOAM-SJTU solver [1, 2]; new functionalities implemented in this work are highlighted in blue which are described in the following sections.

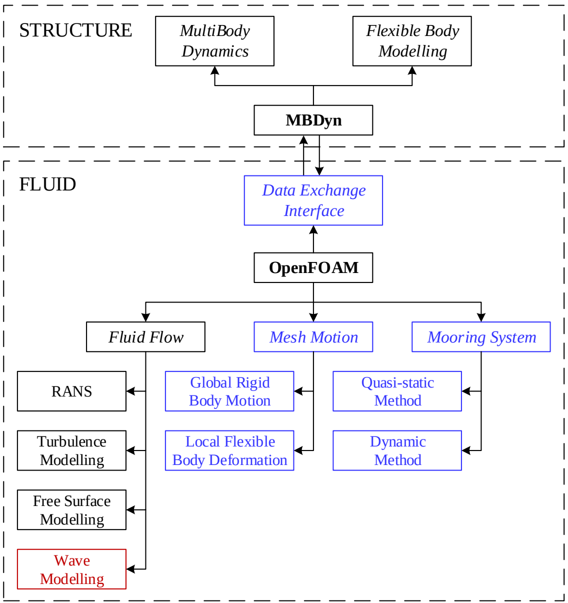


Figure 1: Structure of a fully coupled FSI analysis tool for FOWTs (Black–Built-in, Red–Incorporated, Blue–Developed)

- ***Structural Dynamics***

Dynamic structural responses of an FOWT are solved using MBDyn, which adopts a Lagrange multiplier formulation for a multibody system consisting of both rigid and flexible bodies connected by kinematic constraints [3]. For each body of the constrained system, Newton-Euler equations of motion are established in the differential-algebraic form as a set of first-order equations together with constraint equations.

MBDyn models a flexible body as a series of three-node beam elements based on a nonlinear beam theory formulated within a multibody framework [3]. As illustrated in Figure 2, a three-node beam element is divided into three portions by two evaluation points (squares). Each portion is associated with a reference point (circles), which represents the elastic axis of the beam. These reference points do not necessarily need be on a straight line and can be offset from the geometrical nodes (triangles) where equilibrium equations are established considering both external and internal forces. External forces are integrated over every beam element portion related to a reference point and later translated to its corresponding geometrical node. Meanwhile, internal forces are evaluated at cross sections of evaluation points and are related to geometrical strains and curvatures via constitutive laws.

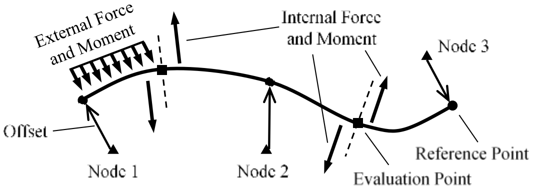


Figure 2: Illustration of a three-node beam element in MBDyn

- ***CFD Mesh Motion***

One of the challenges for a fully coupled FOWT simulation with flexible blades is how to handle the motion of the CFD mesh to represent the complex structural responses of the system, including (a) global rigid body motion, i.e. platform 6DoF motion and turbine rotation; (b) local flexible body deformation, such as deflection of an aero-elastic turbine blade. The current mesh motion libraries in OpenFOAM are unable to cope with both global and local structural responses at the same time. In the present study, a customised mesh motion library is developed by incorporating features of the built-in solid body motion library into the dynamic mesh motion solver displacementLaplacianFvMotionSolver.

The implemented mesh motion library deals with global rigid body motion responses in a solid body motion manner. The computational grid is split into three separate cell zones by two pairs of Arbitrary Mesh Interface (AMI) surfaces as sketched in Figure 3. Different rigid body motions are then applied to these cell zones. When an FOWT is in motion, the outer zone only translates in surge, sway and heave directions. The middle zone experiences three rotational motion responses, i.e. roll, pitch and yaw, as well as the three translational components, while the inner zone undergoes all 6DoF platform motion responses together with prescribed turbine rotation.

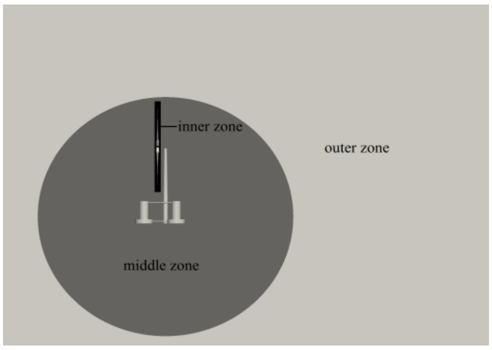


Figure 3: Cell zone decomposition of computational mesh for an FOWT

Mesh motion due to local blade deformation is handled by solving the displacement Laplacian equation for cell centres. In order to maintain grid quality, global rigid body motions are firstly subtracted from the point displacement of turbine surface mesh to obtain a temporary value, which is then used by the mesh motion solver as the boundary condition of the abovementioned Laplacian equation. When the mesh motion equation is assembled, only cells inside the inner zone shown in Figure 3 are considered while those in other zones are kept static by setting their displacement to zero. Once the displacement of cell centres is obtained, interpolation is performed to calculate the displacement of internal mesh points, which is then added to the initial position of all points to determine their updated position resulting from blade deformation. Lastly, points in the inner zone are rotated collectively to take into account global rigid body motion.

- ***Mooring System***

As mooring systems are essential in station-keeping for floating structures, a mooring system analysis module is developed in OpenFOAM to calculate the mooring restoring force provided for an FOWT system. This module includes both quasi-static and dynamic methods.

In the present quasi-static method, instead of employing the analytical catenary equation, a discretised approach is utilised by dividing a mooring line into a number of segments with identical length so that lines of both catenary taut shapes can also be simulated. Equations of static equilibrium are established for each segment in horizontal and vertical directions at each time step. By further applying the relationship between tension and segment elongation as well as geometric constraints between node coordinates and stretched segment length, tension and shape of the line can be computed in an iterative manner. The current method is also able to model mooring lines made of multiple components with different structural properties.

The mooring system analysis module is further extended by implementing a dynamic method based on a 3D lumped mass model, which discretises a mooring line into *n*+1 concentrated masses (nodes) connected by *n* massless springs (segments), as illustrated in Figure 4. Unlike the quasi-static method, equations of motion are applied to every node in the dynamic approach so that dynamic effects resulting from line movement are considered and tension force can be accurately predicted. The hydrodynamic loads exerted on the line are also taken into account by adopting Morison's equation. The Newmark Beta method is then employed to solve the differential equations.

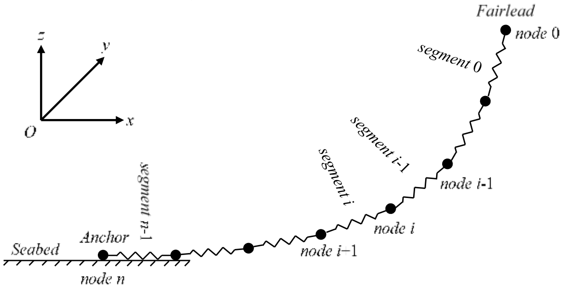


Figure 4: Sketch of a 3D lumped mass model

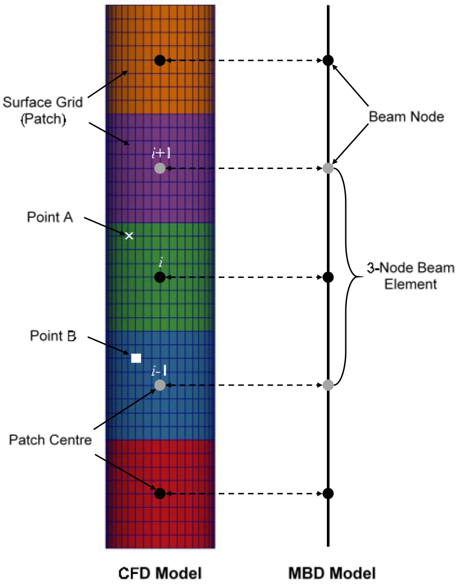
- ***Coupling Procedure***

In MBDyn, a flexible blade is modelled as a series of three-node beam elements, while it is discretised into a surface grid comprising a large number of surface points in OpenFOAM. The gap between the level of complexity in describing the blade by the two codes leads to a pair of un-matched interfaces. A mapping scheme is therefore established to exchange data between CFD and MBD models, as illustrated in Figure 5. In the CFD model, the surface grid of the structure is decomposed into several small patches, each of which is associated with a beam node in the MBD model. A centre is defined for every patch in the CFD grid and has the same kinematics as its corresponding beam node in the MBD model via motion exchange. On the other hand, external fluid force and moment are firstly integrated over every patch of the CFD surface grid with respect to its patch centre and then transferred to MBDyn via force exchange.

In order to maintain smooth transition between patches in the CFD model, a linear interpolation scheme [4] is implemented to calculate position of surface grid points using kinematics from patch centres in the following way:

$$\mathbf{X} = \xi\left(\mathbf{X}_i + \mathbf{R}_i\mathbf{d}_i\right) + \left(1-\xi\right)\left(\mathbf{X}_{i+1} + \mathbf{R}_{i+1}\mathbf{d}_{i+1}\right) \tag{1}$$

where $\mathbf{X}$ represents position of point or patch centre; $\mathbf{R}$ denotes transformation matrix of patch centre due to rotation; $\mathbf{d}$ is distance vector pointing from patch centre to point; $\xi \in \left[0,1\right]$ stands for normalised point location between surrounding patch centres.



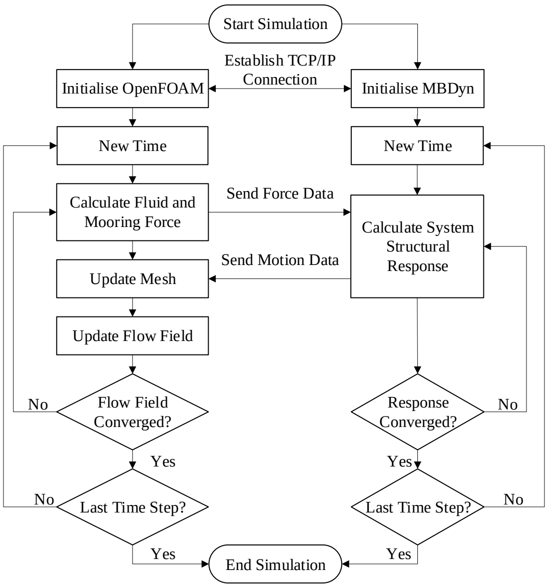


Figure 5: Diagram for mapping between CFD and MBD **Figure 6: Flowchart for coupling OpenFOAM with MBDyn**

Figure 6 shows the coupling procedure used in the present FSI analysis tool. When a fully coupled simulation is performed, both OpenFOAM and MBDyn run simultaneously as individual computer processes. Data exchange between the two codes is achieved with the help of the TCP/IP communication protocol, using a client/server model. An interface library is implemented in OpenFOAM by adopting the motion and force exchange functions provided in MBDyn, serving as the bridge connecting the flow and structural solvers.

Results

The present FSI analysis tool developed for FOWTs are applied to a series of test cases to validate its various components and features [5-7]. The NREL Phase VI wind turbine is firstly studied to validate the aerodynamic modelling feature of the tool. Turbine aerodynamic torque from present simulations agrees well with experimental results under various wind conditions, as shown in Figure 7. Hydrodynamic modelling is then validated by investigating the DeepCwind semi-submersible of the OC4 FOWT project. Figure 8 reveals good agreement between the motion RAOs of the platform predicted by the present tool and experimental data under regular incident waves. Subsequently, a dynamic analysis is conducted for a flexible hanging riser subject to prescribed surge motion at its fairlead. Figure 9 show that the present prediction of fairlead tension is in perfect agreement with previous results, demonstrating good accuracy of the dynamic mooring line method. Furthermore, the capability of the tool in modelling flexible structures is validated by comparing deflections of a turbine blade under a concentrated loading at its tip, as illustrated in Figure 10.

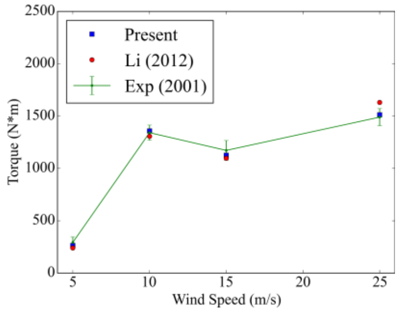


Figure 7: Aerodynamic torque of NREL Phase VI wind turbine

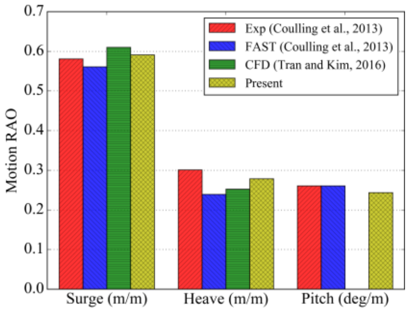


Figure 8: Motion RAO of OC4 DeepCwind semi-submersible

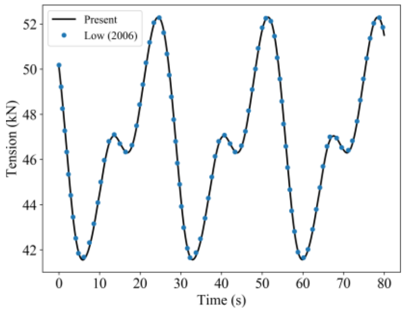


Figure 9: Fairlead tension of a hanging riser subject to surge motion

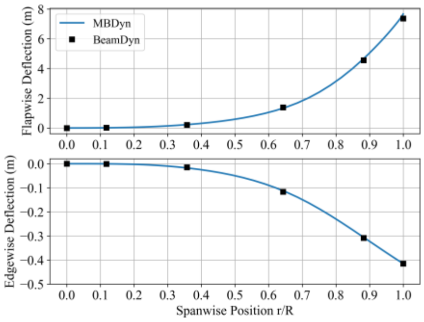


Figure 10: Blade deflections under a concentrated loading at tip

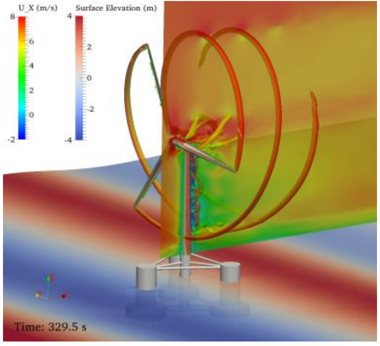


Figure 11: Fluid field around an FOWT

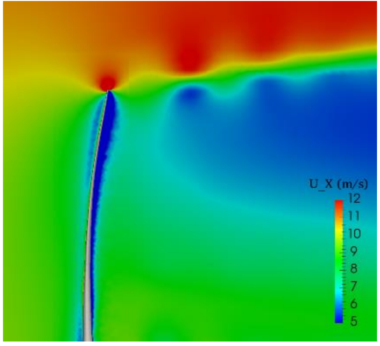


Figure 12: Blade deformation in wind

With the fully coupled CFD-MBD tool implemented in this work, high-fidelity aero-hydro-mooring-elastic analysis can be performed. Figure 11 and Figure 12 depict the complex fluid flow around the OC4 semi-submersible FOWT under combined wind/wave conditions. This tool can be utilised to better understand the underlying physics and sophisticated interaction between fluid flow and an FOWT as well as the influence of different parts of the system on each other.

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