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Partitioned coupling of fluid-structure interaction for the simulation of floating wind turbines

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Abstract. Fluid-structure interaction problems appear in many different fields of application. An interesting and highly topical field is offshore renewable energy. An increasing energy demand, limited fossil energy sources and the climate change in combination with limited suitable and available space ashore lead to an increased relevance of offshore renewable energy. A promising offshore renewable energy concept is the use of floating wind turbines.

For the simulation of floating wind turbines, the necessary and computationally expensive fluid-structure interaction coupling has to be combined with large domains, highly nonlinear and dynamic structural behavior and complex flow situations. This requires new and innovative techniques in the solution process.

In this work, the partitioned solution utilizing existing field solvers is suitable for this type of problem due to the availability of well-developed fluid and structural solvers.

To manage the partitioned coupling, the in-house C++ library *comana* is employed. This coupling framework is employed to control the iterative solution process and to perform the necessary exchange of surface quantities on the interface between the fluid and structural field of the fluid-structure interaction problem. Through this, *comana* enables the computation of complex strongly coupled fluid-structure interaction problems within a reasonable amount of time. Despite the necessary changes for the partitioned coupling, the modifications to the existing specialized high-fidelity fluid and structural solvers are minimized to maintain their sophisticated solution techniques.

The partitioned coupling procedure is described and simulation results are presented.

Different measures to accelerate, stabilize and improve the solution of this fluid-structure interaction problem are demonstrated. Among these measures are the prediction and the convergence acceleration in the implicit coupling of the fluid and structural field solvers.

In the scope of a future research project, the presented method will be applied to develop the simulation of a point wave energy absorber used for the conversion of wave energy into electric energy.

Introduction

The partitioned coupling strategy is a powerful solution approach for many fluid-structure interaction (FSI)-problems. Due to the partitioned approach, existing specialized field solvers can be used to solve FSI-problems only with the exchange of surface quantities in a fast and efficient way. Among the many applications of this approach are offshore renewable energies of which the most prominent technology are offshore wind turbine plants. Wind blows stronger and more continuously offshore, which is an important advantage of offshore wind energy turbine plants especially with respect to power grid stability in face of the transition to renewable energies. Even though offshore wind energy has many advantages over traditional onshore wind energy plants, it also poses serious challenges. For large water depths, offshore wind energy turbine plants with a foundation in the seafloor are not cost-effective. For these water depths, floating wind turbines are more suitable and economic. The construction and design of floating wind turbines, however, poses serious challenges since the forces on the structure, which are affected by the dynamic motion and structural deformations, are hard to determine with uncoupled structural or fluid simulations. A coupled simulation nevertheless requires well developed solvers able to cover the different physical effects that have to be taken into account for such a complex simulation.

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1 Partitioned solution approach for FSI-problems

For the solution of FSI-problems, fluid and structural equations, which are dependent on each other, have to be solved in a coupled approach. For this, it is possible to solve both subproblems by coupling them in a partitioned (segregated) or in an monolithic (integrated) way [5, p.3252].

To solve the fluid and structural equations in an integrated way, the monolithic approach requires the development of solvers appropriate to the given FSI-problem. Integrated FSI solvers are more robust, but require the labor-intensive development of a dedicated solver for the problem at hand [2, p.140]. They are not easily modifiable in the selection of the discrete equations that describe the structural or fluid problem [3, p. 1119]. Partitioned solution procedures on the other hand allow for an independent and flexible modelling to select the most appropriate techniques for the solution of the structural or fluid side. This enables the usage of highly specialized solvers for both subproblems in a black-box manner, where only the surface quantities have to be exchanged [3, p. 1120].

The in-house software library *comana* has been developed to control this iterative exchange of quantities in multi-physic problems [7].

To compute the displacements and velocities of a solid body under external loads, the finite-element-method (FEM) is among the most popular discretization schemes. For the computation of the flow field in a moving domain, finite-volume-method (FVM) and boundary-element-method (BEM) are widely used methods to compute the pressure and velocity inside the fluid domain.

In order to couple the FEM with the BEM or FVM to account for FSI, the displacements $\vec{d}$ calculated by the structural solver S_s are interpolated to the nodes on the boundary of the fluid solver such that the fluid mesh can be deformed according to the movement of the structure.

The fluid solver F_s can then compute tractions $\vec{t_i} = F_s(\vec{d_i})$ on the interface between the fluid and structural side in the deformed domain. These tractions can be applied to the structure as external loads to compute new displacements $\vec{d}_{i+1} = S_s(\vec{t_i})$.

This procedure can be seen as a fixed-point iteration since the quantity (in this case displacements) that is computed is the same that enters the procedure:

$$\vec{d}_{i+1} = S_s(F_s(\vec{d_i})) \tag{1}$$

The procedure described by equation (1) is repeated until the displacement increment between two subsequential iterations reaches a predefined tolerance. The converged displacements are taken as the solution for the current time step and the structural and fluid solvers are advanced in time such that the procedure can be repeated for the next time step.

In order to speed up and stabilize the fixed-point iteration (1), different measures can be taken.

The prediction of the displacements at the beginning of a time step is used to provide a good initial guess for the displacements entering the fixed-point iteration. A polynomial of order p depending on time t can be constructed based on the previous $m = p + 1$ time steps by requiring that the polynomial is equal to the displacements at the previous m time steps.

$$\tilde{d}(t_j) = \sum_{i=0}^{p} a_i t_j^i \qquad \text{for } j = -1, ..., -m \tag{2}$$

The resulting system of equations (2) can be used to determine the parameters a_i. With these parameters a_i the prediction of the displacements for the current time step $\tilde{d}(t_0)$ can be computed based on the previous time steps. The dependence on the previous time steps is constant in the case of a constant time step size.

While the prediction operates on the solution of previous time steps, the results within the implicit iterations of one time step can also be improved based on the solution of previous iterations in the same time step. To accelerate and stabilize fixed-point iterations, a variety of methods exist. The simplest method is the constant relaxation which just multiplies a constant factor to the increment between two iterations. For FSI-problems, advanced methods like Aitken or quasi-Newton methods are more suitable. Among quasi-Newton methods, the quasi-Newton least square method has shown good convergence behaviour for many FSI-problems [9][4].

2 Floating wind turbine

To demonstrate the benefits of the simulation of FSI using partitioned coupling, complex real world problems like the simulation of a floating wind turbine is well suited. The floating wind turbine presented here was developed within the joint research program 'Hydrodynamic and Structural Optimization of a Semi-submersible Offshore Wind Turbine'. The related FSI simulations were carried out in the subproject 'Fluid-Structure Interaction and Optimization of a Floating Wind Turbine'.

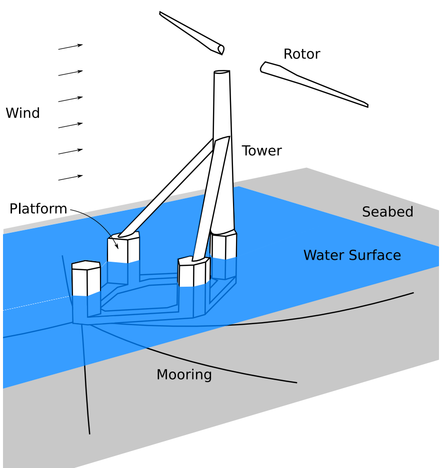

Figure 1. Schematic overview [6, p. 219]

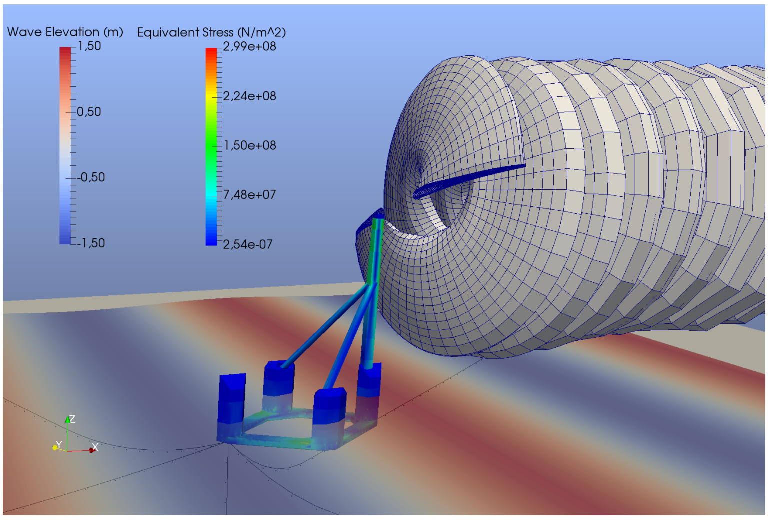

Figure 2. Stresses inside the structure and elevation of the water surface

In Figure 1 an overview of the floating wind turbine is given. This floating wind turbine consists of a platform to lift and stabilize the whole structure and a tower on which the rotor is mounted. To prevent drifting, the platform is anchored in the seabed such that it is self-aligning in the wind [10].

The deformation of the platform, the tower and the rotor is simulated with FEM using the commercial software package ANSYS [1]. The fluid simulation is performed using the boundary element method implemented in the in-house software *pan*MARE [8]. *comana* [7] is used to control the iterative solution procedure and exchange tractions and displacements between ANSYS and *pan*MARE.

In Figure 2 the result of a coupled FSI simulation is shown. Not only the forces on the tower and rotor due to the wind but also the effects of the ocean current and waves is taken into account. Suitable techniques like sub-structuring with large rotations [10] available in the structural solver can be used without modifying the partitioned coupling procedure.

The partitioned simulation allows for the evaluation of deformations and stresses at all points in the structure in every time step taking the important dynamic and nonlinear effects into account. Not only the structural integrity of the platform but also the orientation of the platform in the wind and waves can be evaluated.

3 Conclusion and outlook

The partitioned approach turned out to be suitable for FSI simulations. In a recent research project, the motion and the structural behaviour of a floating wind turbine was successfully investigated. A precise stress analysis is possible and effects of the structural deformation on the motion behaviour can be evaluated [10].

Even though the simulation of the floating wind turbine showed good results, the boundary element method can not fully account for the flow separation and turbulence in the wake of the rotors. To

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increase the solution accuracy, the region where turbulence effects and flow separation occur can be modelled by the FVM, which is more accurate but at the same time computationally more expensive. The FVM can be applied to the wake region of the rotor while the outer region which exhibits non of these effects could be modelled with BEM.

The techniques which have been applied to the floating wind turbine can also be transferred to other floating offshore plants. An example for such an application is the point wave energy converter. The approach is promising for every type of floating structures which is subjected to external forces.

Acknowledgments

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