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FLUID-STRUCTURE INTERACTION SIMULATION OF FLOATING WIND TURBINES INTERACTING WITH COMPLEX, LARGE-SCALE OCEAN WAVES

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INTRODUCTION

The topic of floating wind turbines has recently attracted increasing attention due to its potential to capture part of the large offshore wind energy resource. Numerical simulation is the most viable way to tackle such problem but poses a major challenge due to the need to resolve the coupled interaction of atmospheric turbulence and ocean waves, the arbitrary geometric complexity of floating structures, the inherent two-phase nature of such flows, and the dominant role of complex nonlinear phenomena such as turbulence and free surface effects. In this work, we present a powerful numerical framework to simulate the coupled interactions of complex floating structures with large-scale ocean waves and atmospheric turbulent wind.

NUMERICAL METHODS

The near-field approach solves the spatially-filtered incompressible Navier-Stokes equations using a two-phase flow formulation with the level set method. The flow properties adopt their corresponding values in each phase while there is a smooth transition across the interface, which is determined by a signed distance function ϕ. The governing equations of the flow motion in generalized curvilinear coordinates read as follows

$$J\frac{\partial U_j}{\partial \xi_j}=0,\ \frac{1}{J}\frac{\partial U^j}{\partial t}=\frac{\xi_l^i}{J}\left(-\frac{\partial}{\partial \xi_j}\left(U^j u_l\right)+\frac{1}{\rho(\phi)}\frac{\partial}{\xi^j}\left(\mu(\phi)\frac{\xi_l^j \xi_l^k}{J}\frac{\partial u_l}{\partial \xi^k}\right)-\frac{1}{\rho(\phi)}\frac{\partial}{\partial \xi^j}\left(\frac{\xi_l^j p}{J}\right)-\frac{1}{\rho(\phi)}\frac{\partial \tau_{lj}}{\partial \xi^j}+G_i\right) \qquad (1)$$

where ξ_l^i are the transformation metrics, J is the Jacobian of the transformation, U^i are the contravariant volume fluxes, u_i are the Cartesian velocity components, ρ is the density, μ is the dynamic viscosity, p is the pressure, τ_{lj} is the subgrid-scale stress (SGS) tensor and G_i is the gravitational acceleration. A dynamic Smagorinsky SGS model with wall modeling is implemented for large-eddy simulation (LES) of complex flows. The motion of the air-water interface is modeled by solving a level set equation. Extensive details of this solver are given in Kang and Sotiropoulos [3]. The momentum equations are discretized using a second-order central differencing scheme for the diffusion and advective terms, and a second-order Crank-Nicholson method for the time advancement. A fractional step method is used to enforce the continuity condition. To simulate FSI problems involving geometrically complex immersed floating bodies, we use an extension of the FSI Curvilinear Immersed Boundary method (CURVIB) of Borazjani et al. [1] to carry out LES incorporating free surface effects with the previously discussed level-set formulation. The FSI method is used to solve the structural equations governing the motion of the body coupled with the level-set equation.

The large-scale wave and wind model is based on the two-fluid coupled approach of

Yang and Shen[4], which employs a potential-flow based wave solver using a spectral method for the water motion and a viscous solver with undulatory boundaries for the air motion.

The large-scale ocean waves are incorporated to the near-field solver by adapting the pressure-forcing method of Guo and Shen [2] for the level set method. It consists in applying a pressure force on the free surface, by adding in the momentum equations the following forcing term

$$S_i\left(x,y,t\right)=n_i\left(\phi\right)P_0\delta\left(x,\varepsilon_x\right)\delta\left(\phi,\varepsilon_\phi\right)\sin\left(\omega t-k_y y-\theta\right) \tag{2}$$

where n_i denotes the normal direction of the free surface, P_0 is a coefficient which is determined by the desired wave amplitude, δ is a distribution function of the pressure forcing, and ω, k_y, and θ are the frequency, wave number in the y direction and initial wave phase of the resulting wave, respectively.

The far-field wind-wave solver is coupled with the near-field FSI solver by feeding into the latter the large-scale waves as well as the wind field. The wave field is extracted at every time step from the far-field simulation by performing a Fourier analysis to obtain the energy and phases of surface waves and is incorporated into the near-field simulation by using equation (2). The wind field from the far-field simulation is incorporated to the near-field simulation by feeding the air velocity at the inlet boundary.

RESULTS

The forcing method for wave generation has been first validated for both simple wave trains and 3D directional waves and the results compare very well with experimental and theoretical results. Then it has been tested for incorporating to the near-field solver a JONSWAP wave spectrum from the far-field solver. The free surface elevation compare well with the expected theoretical solution as shown in figure 1a. Finally, we demonstrate the capabilities of the present method by carrying LES of a floating offshore wind turbine platform interacting with realistic ocean waves (see figure 1b). In this particular case, the turbine configuration is allowed to move in 2 DoF, heave and pitch, and the structure responds as a result of the wave field and the thrust force. The rotor is modeled with the actuator disk and both the wind and wave fields are incorporated from the far field solver.

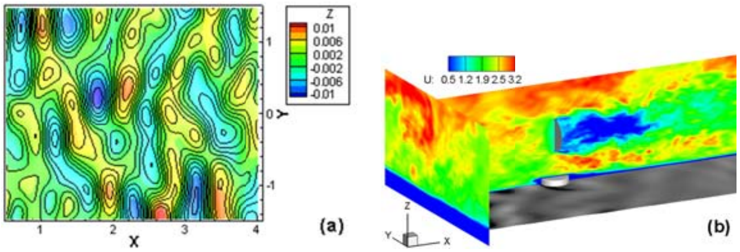

Figure 1: (a) Comparison of wind field from near-field simulation (color contour) and theoretical prediction (contour lines). (b) Contours of the wind stream-wise velocity around a floating wind turbine.

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