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Free-surface flow modeling and simulation of horizontal-axis tidal-stream turbines

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ABSTRACT

A computational free-surface flow framework that enables 3D, time-dependent simulation of horizontal-axis tidal-stream turbines (HATTs) is presented and deployed using a complex-geometry HATT. Free-surface flow simulations using the proposed framework, without any empiricism, are able to accurately capture the effect of the free surface on the hydrodynamic performance of the turbine, as demonstrated through excellent agreement with the experimental data. To carry out the free-surface computations, we have developed a novel level-set redistancing procedure compatible with the sliding-interface technique used for handling the rotor-stator interaction in the HATT full-machine simulations. To illustrate the versatility of the proposed approach, additional computations are carried out where the HATT is subjected to wave action.

1. Introduction

Renewable energy technologies based on wind and solar energy heavily rely on the weather, which, depending on the geographical location, may exhibit high degree of unpredictability or temporal variation. In contrast, tidal currents present a more predictable resource of renewable energy, and, in recent years, a number of technologies have been developed in the academic and commercial sectors that enable conversion of the energy available within tidal currents into electrical power [38,41,49,50,56,63]. Among them, horizontal-axis tidal-stream turbines (HATTs) present the most mature and promising technology. Examples of HATTs include a twin-rotor SeaGen turbine from Marine Current Turbine that is currently undergoing testing near the coast of Northern Ireland [1], and a single-rotor turbine from Verdant Power that has been operating successfully in the East River near New York City [2,36,40,53].

Current research on HATTs is mostly focused on improving their power-generation efficiency. As a result, numerous computational and experimental approaches have been proposed and explored to accurately predict and improve their hydrodynamic performance [9,10,12–14]. Although HATTs make use of the same mechanical principles as the horizontal-axis wind turbines (HAWTs), there are a number of fundamental differences between the two, especially when it comes to modeling and simulation challenges involved. In particular, HATTs are subjected to hydrodynamic loading (in contrast to HAWTs that are subjected to aerodynamic loading), the effect of free surface becomes important for the cases of shallow-tip immersion, and cavitation may occur for the cases of higher flow and rotor speeds.

Traditionally, reduced-order numerical techniques such as the vortex-element and blade-element-momentum methods have been used to predict the performance of tidal stream turbines [11,54,55,57,58]. Although results from these numerical simulations were occasionally shown to be in good agreement with experimental measurements, the aforementioned methods rely on empirical correlations and may not be suitable for a wide range of operating conditions. Furthermore, due to the computational challenges involved, only a few of the numerical studies considered the free-surface effect, which, as shown in the experimental studies of [7,8], can significantly affect the performance of HATTs. Finally, the analyses presented focused on the rotor only, without taking into account the other turbine components, such as the tower and nacelle.

In this paper, we present our computational free-surface flow framework that enables 3D, time-dependent simulation of HATTs. In addition, we make use of the framework to investigate how the presence of the free surface affects the HATT hydrodynamic performance. The level-set method [3–5,48,60,61] is adopted to track the evolution of the free surface, which is treated as an air-water interface. The aerodynamics and hydrodynamics are governed by the Navier–Stokes equations of incompressible, two-fluid flows, in which the fluid density and viscosity are defined by means of the level-set function. The finite-element-based

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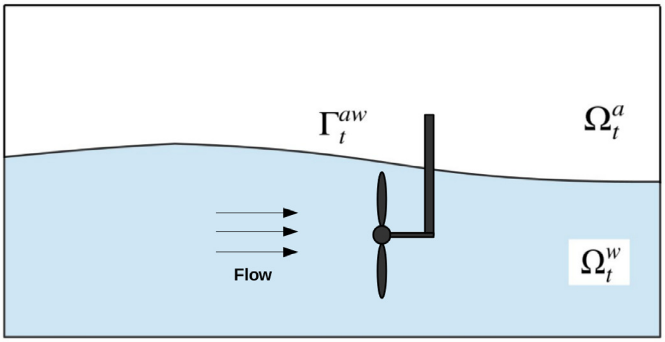

Fig. 1. Illustration of the problem spatial domain separated by the free surface into air and water subdomains.

Arbitrary Lagrangian–Eulerian Variational Multiscale (ALE–VMS) [21,30,31,33,66–68] formulation enhanced with weakly enforced of essential boundary conditions [15,22,28] is employed to discretize the free-surface flow equations. The sliding-interface formulation [23] is employed to account for the presence of tower and nacelle, thus enabling the so-called "full machine" simulation [43]. The sliding-interface formulation is augmented to include level-set redistancing. This augmentation of the sliding-interface formulation is reported for the first time, and presents a stable and robust technology that allows the air-water interface to cross the sliding interface. The overall method is in the framework of the Mixed Interface-Tracking/Interface-Capturing Technique (MITICT) [86,88], which was primarily introduced for fluid–object interaction with multiple fluids [73,74].

In Section 2 we introduce the governing free-surface-flow equations at the continuous level, summarize the key ingredients of the discrete free-surface-flow formulation, and present the sliding-interface level-set formulation with redistancing. In Section 3 we describe the HATT design employed in the present work, and present simulation results corresponding to different inflow conditions and tip-immersion depths. In Section 4 we draw conclusions.

2. Free-surface flow modeling and simulation

2.1. Governing equations of free-surface incompressible flows

We summarize the governing differential equations of free-surface flow posed on a moving domain. Let $\Omega_t \in \mathbb{R}^d, d = 2, 3$ denote the combined air-water domain at time t and let Γ_t denote its boundary. The domain Ω_t is decomposed into the water and air subdomains denoted by Ω_t^w and Ω_t^a, respectively, while Γ_t^{aw} denotes the interface between them. (See Fig. 1 for an illustration.) We utilize the level-set method for incompressible two-fluid flows [3–5,48,60,61], and introduce a scalar level-set function $\phi : \Omega_t \to \mathbb{R}$, which divides the spatial domain into the air and water subdomains and their interface as follows:

$$\Omega_t^a = \{\mathbf{x} | \phi(\mathbf{x}, t) < 0, \forall \mathbf{x} \in \Omega_t\}, \tag{1}$$

$$\Omega_t^w = \{\mathbf{x} | \phi(\mathbf{x}, t) > 0, \forall \mathbf{x} \in \Omega_t\}, \tag{2}$$

$$\Gamma_t^{aw} = \{\mathbf{x} | \phi(\mathbf{x}, t) = 0, \forall \mathbf{x} \in \Omega_t\}. \tag{3}$$

The Navier–Stokes equations of incompressible two-fluid flows on a moving domain may be stated using the ALE description [46] as

$$\rho \left(\left.\frac{\partial \mathbf{u}}{\partial t}\right|_{\hat{x}} + (\mathbf{u} - \hat{\mathbf{u}}) \cdot \nabla \mathbf{u} - \mathbf{f} \right) - \nabla \cdot \boldsymbol{\sigma} = \mathbf{0} \text{ in } \Omega_t, \tag{4}$$

$$\nabla \cdot \mathbf{u} = 0 \text{ in } \Omega_t, \tag{5}$$

where $\mathbf{f}$ is the body force per unit fluid mass, $\hat{\mathbf{u}}$ is the velocity of the fluid domain, ∇^s is the symmetric gradient operator, $\boldsymbol{\sigma}$ is the Cauchy stress defined by $\boldsymbol{\sigma}(\mathbf{u}, p) = -p\boldsymbol{I} + 2\mu\nabla^s\mathbf{u}$, and $\mathbf{u}$ and p are the fluid velocity and pressure, respectively. The fluid density ρ and dynamic viscosity μ of each spatial point are assigned as follows:

$$\rho = \rho_w H(\phi) + \rho_a (1 - H(\phi)), \tag{6}$$

$$\mu = \mu_w H(\phi) + \mu_a (1 - H(\phi)), \tag{7}$$

where $H(\phi)$ is the Heaviside function defined by

$$H(\phi) = \begin{cases} 0 & \text{if } \phi < 0, \\ 1/2 & \text{if } \phi = 0, \\ 1 & \text{if } \phi > 0, \end{cases} \tag{8}$$

and where the subscripts a and w refer to the quantities defined for the air and water subdomain, respectively.

The air-water interface is assumed to move with the fluid material particles, which is modeled by means of a convection equation for the level-set function ϕ, also posed on a moving domain in the ALE description and written as

$$\left.\frac{\partial \phi}{\partial t}\right|_{\hat{x}} + (\mathbf{u} - \hat{\mathbf{u}}) \cdot \nabla \phi = 0 \text{ in } \Omega_t. \tag{9}$$

In the above differential equations, the partial time derivatives are taken holding the referential coordinates $\hat{\mathbf{x}}$ fixed. The space derivatives are taken holding the current-configuration spatial coordinates $\mathbf{x}$ fixed. Provided the appropriate initial and boundary conditions are set, and the motion of the fluid mechanics domain is prescribed, the above equations constitute a complete mathematical model of the free-surface flow on a moving domain at the continuous level.

2.2. Discretization methods

To discretize the free-surface equations, the ALE-VMS method [21,66] and weak enforcement of essential boundary conditions [19,22,28,29,42], which have been applied to a variety of challenging fluid mechanics and fluid–structure interaction problems in [6,25–27,30,31,33,34,91,92], are employed in the present work.

In order to simulate the full tidal-stream turbine configuration, which includes the spinning rotor and stationary nacelle and tower, the sliding-interface method is employed. The approach utilizes a moving subdomain, which encloses the spinning rotor, and a stationary subdomain, which contains the rest of the tidal turbine (See Fig. 2). The two domains are in relative motion and share a sliding cylindrical interface. Because the meshes on each side of the interface are nonmatching due to relative motion of the subdomains, the kinematic, level-set, and traction compatibility conditions are enforced in the weak sense. The sliding-interface technique was originally developed in [23] in the context of Isogeometric Analysis (IGA) [39,45], and successfully applied to simulate offshore wind turbines in [24,43,51,52], hydraulic arresting gears in [90], and kayak propulsion in [91]. The sliding-interface formulation was recently extended to the space–time (ST) VMS method [70,72,75–78,80], and the extension is called the "ST Slip Interface (ST-SI)" method [79,82,84,85].

In the present work, the spatial discretization makes use of linear finite elements, and the generalized-α method [16,37,47] is employed to advance the solution in time. A two-stage predictor-multicorrector algorithm based on Newton's method is used to solve the nonlinear equations arising in the level-set formulation. At each Newton iteration a flexible GMRES algorithm [64,65] is employed to solve the coupled linear-equation systems. GMRES