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Flow past a plate in the vicinity of a free surface

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ABSTRACT

Two-dimensional transient simulations are performed to investigate characteristics of flow past a plate normal to a stream. Free surface effects on the flow dynamics are the primary focus of this study. Varying plate depths are simulated to examine the variation of force coefficients and vortex shedding patterns. The k–ω Shear Stress Transport (k–ω SST) turbulence model and Volume of fluid (VOF) multiphase model are employed to predict characteristics of free surface flow. Flow past the plates is simulated at distances of 0.75 m, 0.06 m, 0.05 m, 0.045 m, and 0.03 m below the free surface with corresponding local Froude numbers (Fr) of 0.18, 0.65, 0.71, 0.75, and 0.92. As the plate gets closer to the surface the drag coefficient decreases from 3.86 (Fr=0.18) to 2.18 (Fr=0.92) and the Strouhal number increases from 0.125 (Fr=0.18) to 0.355 (Fr=0.92). A jet-like flow formed from the surface is observed on top of the plate. Vortices from the top surface of the plate dissipate into smaller eddies due to the free surface presence, resulting in asymmetric vortex shedding downstream. Flows presented here are beneficial for designing and optimizing systems that harvest energy from marine currents.

1. Introduction

Proper numerical simulations are a valuable proxy for studying fluid flow characteristics while minimizing costly experiments. Understanding the flow around a rectangular bluff body is of practical importance in various fields of engineering. Structures such as bridge decks, platforms, offshore pipelines, and hydropower systems often interact with the free surface. The normal rectangular prism is a simple geometry used to understand complex phenomena such as flow separation, wake instabilities, the unsteady vortex shedding formation, and the force acting on the cylinder. Estimating structural hydrodynamic forces is an important design consideration for offshore structures under unsteady flow conditions. Hydrokinetic turbines for river current applications typically operate near surfaces and the effect of the free surface on the performance of these energy harvesting devices could be profound.

Hydrokinetic power is an alternative clean energy source to conventional power such as fossil fuels and nuclear power. Hydrokinetic turbines have been studied by various research groups; however, these engineering designs are limited by water depth. In general, the blades are placed perpendicular to the flow path in order to extract the energy from rivers. A single flat plate submerged at different water depths is investigated as a preliminary study for marine current systems, where the power extracted is directly proportional to the drag force exerted on the blades. Maximizing the drag force is therefore equivalent to maximizing the power extracted. The free surface effect is studied to determine a proper plate depth so sufficient power can be generated while the hydropower system is operated near the free surface.

Free surface flows are challenging hydraulic engineering scenarios. For instance, when a cylinder is placed closer to the free surface, the forces acting on the cylinder become increasingly complicated due to the interaction between the free surface and the cylinder. Also, the wake behind structures and water surface deformation are altered in such free surface scenarios as well. Several researchers approached this problem numerically (Miyata et al., 1990; Arslan et al., 2013) and experimentally (Miyata et al., 1990; Sheridan et al., 1997; Reichl et al., 2005; Malavasi and Guadagnini, 2007; Negri et al., 2010; Arslan et al., 2013) by employing circular or rectangular cylinders.

Generally, hydrodynamic forces acting on the object decreased when the object is closer to the surface, as described in Miyata et al. (1990) and Malavasi and Guadagnini (2007). A simultaneously occurring abrupt drop in drag coefficient and increase in Strouhal number is reported by Miyata et al. (1990) when the depth–radius ratio was down to 1.7. Malavasi and Guadagnini (2007) experimentally investigated a rectangular cylinder submerged in a water channel at various depths. They found that the drag coefficient decreases drastically and Strouhal number

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Nomenclature

A	cross sectional area
a, a_1	closure coefficient
B	channel width
C	courant number
C_D	drag coefficient
C_L	lift coefficient
d	plate depth
d^*	dimensionless plate depth
f	vortex shedding frequency
F_D	drag force
F_L	lift force
Fr	Froude number
F_1, F_2	blending functions
g	gravity
GCI	grid convergence index
h	water depth
h_b	cylinder elevation above channel floor
h^*	$(h- h_b)/ s$, non-dimensional depth
k	turbulent kinetic energy
l	cylinder cross-section length
L	plate height
$\dot{m}_{12}$, $\dot{m}_{21}$	mass transfer between phase 1 and 2
N_1, N_2, N_3	number of cells
P	pressure
Re	Reynolds number
s	cylinder cross-section width
S	mean rate-of-strain tensor
t	time
Δt	time step size
u_i, u_j	velocity in tensor notation
u_*	friction velocity at the nearest wall
U_∞	water velocity
U_{air}	air velocity
U_f	volume flux through the face based on normal velocity
V	volume of cell
$\forall_{air}$	volume of air within the cell
$\forall_{cell}$	volume of a cell
$\forall_{water}$	volume of water within the cell
$\mathbf{V}$	upstream water velocity
w	plate width
x_i	position vector in tensor notation
Δx	grid width
y	distance to the nearest wall
y^+	dimensionless wall distance

Greek Symbols

α	volume fraction
β, β^*	closure coefficient
δ_{ij}	Kronecker delta
μ	dynamic viscosity
ν	kinematic viscosity
ν_T	eddy viscosity
ρ	density
$\sigma_k, \sigma_\omega, \sigma_{\omega 2}$	closure coefficients
τ_{ij}	stress tensor
ω	specific dissipation rate
Ω	vorticity magnitude

increases with decreasing depth of the cylinder. Both Miyata et al. (1990) and Sheridan et al. (1997) studied the wake structure of flow past a circular cylinder close to the free surface. The presence of the cylinder, which caused the formation of surface waves, altered the dynamics of the free surface and produced a jet-like flow near the free surface. When the cylinder was shallowly submerged, the free surface distortion and asymmetric vortex shedding from the cylinder occurred. Such asymmetric vortex shedding resulted in intense turbulent fluctuations due to the flow confinement on top. Negri et al. (2010) applied a self-synchronized phase averaging technique to PIV velocity fields to study flow past a rectangular cylinder near a free surface. The vortex shedding process and the wake evolution were reported by employing the phase-averaged flow fields. Another study on the free surface deformation and wake behavior with respect to Froude number is presented in Reichl et al. (2005). Results of two-dimensional simulations showed that the surface deformation was sensitive to the Froude number. The surface deformation and the intensity of surface waves became substantial as the Froude number increased from 0.35 to 0.40. Arslan et al. (2013) investigated the flow field of partially submerged rectangular cylinder by conducting large eddy simulations and experimental measurements. They concluded that the magnitude of the drag force is very sensitive to the submergence ratio.

Flow past bluff bodies in an infinite fluid domain has been widely studied both experimentally and numerically. Simple geometries such as circular cylinders, rectangular prisms, and flat plates have been investigated to understand the vortex dynamics and the drag and lift forces. Fage and Johansen (1927) experimentally measured the upstream and downstream pressures for an inclined flat plate with

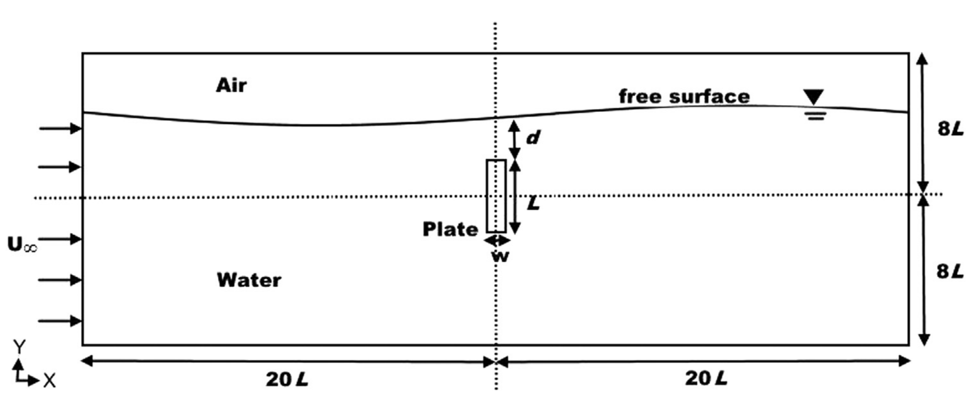

Fig. 1. The schematic of the flow geometry.