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Three-dimensional transient flows past plates translating near a wall

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ABSTRACT

Large eddy simulations are conducted to investigate transient three-dimensional flows past arrays of finite plates translating in the vicinity of a wall. Flows around a single plate are examined for a wide range of wall distances at a Reynolds number based on plate height of 50,000. The drag coefficient decreases rapidly when the plate is placed very close to the wall; it reaches a maximum at an intermediate distance and it asymptotes to the value corresponding to unconfined flows as the gap between the wall and the plate is increased. The reduction in drag coefficient is directly related to the pressure drop caused by vortices generated upstream of the plate induced by the close proximity of the wall. Temporal and spatial characteristics of flows past arrays of yawed plates are examined for the wall distance ratio of 1.5 and the spacing ratios of 2.5 and 5. Drag coefficient of the plates is larger than those placed away from the wall. With suitable spacing the wall proximity effects result in an increase of drag force exerted on the plates. The present study aids in optimizing marine energy harvesting systems that have blades translating beneath ocean platforms or floating river docks.

1. Introduction

Flows past rectangular prisms near surfaces are important to hydraulic engineering applications. The flow structure near the prism is expected to be influenced by the presence of the rigid surface. Interactions between the wake flow induced by a plate and the flow inside a wall boundary layer could influence hydrodynamic loadings on the plate. The vortex shedding patterns induced by the prism become asymmetric due to the interference of the solid surface. If the plate is placed in close proximity of the surface, the vortex shedding can be completely disrupted and suppressed. Characterizing flow structures in these systems can be helpful in designing engineering structures, such as marine current energy harvesting systems placed beneath offshore platforms, pipelines near the seabed, tubes close to heat-exchanger walls, and wires near chimneys (Bosch et al., 1996; Shi et al., 2010).

Several researchers (Fage and Johansen, 1927; Knisely, 1990; Najjar and Vanka, 1995; Tian et al., 2013; Hemmati et al., 2016a) have studied flows past a sharp-edged prism immersed in an infinite fluid domain. In several engineering applications, prisms could often be placed near a free surface or a rigid surface. Recently, Malavasi and Guadagnini (2007), and Liu et al. (2016) have documented that hydrodynamic forces acting on a rectangular prism decrease as the prism is placed closer to a free surface. The presence of the free surface breaks the symmetry of vortex shedding, resulting in irregular hydrodynamics. Similarly, when the prism is near a rigid surface, both the hydrodynamic forces acting on the prism and the flow patterns downstream of the prism are altered depending on the distance between the prism and the surface. Bhattacharyya and Maiti (2004), Bhattacharyya and Maiti (2005), Bosch et al. (1996), Mahir (2009), and Shi et al. (2010), have reported that the regular pattern of the vortex street is broken when the sharp-edged plate is in close proximity of a rigid surface. Due to the wall boundary layer influence, characteristics of the top and the bottom shear layers differ significantly, which results in distorted vortex shedding from the top and the bottom of the prism (Maiti and Bhatt, 2014). Bosch et al. (1996), Agelinchaab et al. (2008) and Shi et al. (2010) performed experiments to study flows past a rectangular prism above a plane boundary. Bosch et al. (1996) found that vortex shedding is suppressed at critical gaps less than $0.35D$, where D is the height of the prism. Agelinchaab et al. (2008) and Shi et al. (2010) reported that due to the strong interaction between the wake and the wall, regular vortex shedding becomes very weak or is completely suppressed. The suppression of vortex shedding in flows past a square cylinder near a wall is also documented in the numerical investigation by Bhattacharyya and Maiti (2004). Vortices shed from the wall side of the prism are stretched and migrate away from the wall, resulting in an oblique wake structure. This indicates that vortices near the wall transfer energy in the longitudinal direction (Shi et al., 2010). Recently, Bayraktar et al. (2014) conducted simulations for flows past a rectangular prism under the influence of a wall. They reported that the interaction

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Nomenclature

A	projection area
C_D	drag coefficient
CL	lift coefficient
Cw	WALE constant
D	plate height
D	tip to the centerline distance
FD	drag force
FL	lift force
F	vortex shedding frequency
G	spacing distance
L	plate length
L_s	SGS mixing length
$\overline{p}$	resolved pressure
Re	Reynolds number
S	wall distance
SGS	sub-grid scale
St	Strouhal number
$\overline{S}_{ij}$	rate-of-strain tensor
T	time
Δt	time step size
u_*	friction velocity at the nearest wall
u_i	velocity
$\overline{u}_i$	resolved scale velocity vector
Uw	relative speed between wall and plate
$U\infty$	free stream velocity
V	volume of cell
W	plate width
x_i	position vector
x	upstream length
Y	distance to the nearest wall
$y+$	dimensionless wall distance

Greek symbols

Λ	non-dimensional time
$\Delta\lambda$	non-dimensional time step
θ	yaw angle
δ_x	boundary layer thickness
δ_{ij}	Kronecker delta
μ	dynamic viscosity
ν	kinematic viscosity
ν_t	SGS eddy viscosity
ρ	density
κ	von Karman constant
τ_{ij}	sub-grid stress tensor
Ω	rotation tensor

between induced vortices by the plate and vortices induced by the wall dominates flow structures near the plate and downstream of the plate. They also reported that vortex shedding is suppressed when the gap is smaller than the critical value. As the prism is placed away from the wall the wake flow asymptotically approaches that of flows past a plate in an unbounded domain.

Hydrodynamic forces exerted on a prism are sensitive to the proximity of a plate to a rigid surface. Several studies have investigated the wall effects on hydrodynamic forces around a prism. They reported a decrease in drag coefficient, C_D, when the cylinder is placed near the wall. The reduction of drag coefficient is associated with the change of near wake flow structures around the cylinder and base pressure increases as the gap between the prism and the wall decreases. Numerical studies by Kumaran and Vengadesan (2007) and Mahir (2009) and experimental observation by Martinuzzi et al. (2003) showed that both drag and lift in flows past a sharp edged prisms are strongly influenced by the presence of the wall. They concluded that the decrease in drag coefficient is directly related to the suppression of vortex shedding. Bayraktar et al. (2014) also reported a decrease in drag coefficient when the gap between a square cylinder and the wall decreased. In addition to drag force, they also reported intensified vortex shedding when the gap is increased.

There are extensive studies for flows past arrays of prisms placed perpendicular to the incoming flow in a tandem configuration. Interactions between the wake of the upstream and the downstream prism are highly dependent on the spacing between two successive prisms. Different flow regimes are observed based on spacing. These regimes are: single-bluff body regime, intermediate regime, and co-shedding regime. When G/D (ratio of the spacing to the hydraulic diameter) is smaller, the shear layer generated from the upstream prism wraps around the downstream prism and the two prisms generate wake flows as a single body. At intermediate values of G/D, vortices may occur in the space between the two prisms. The shear layer generated from the upstream prism reattaches to the downstream prism. At larger values of G/D, regular Karman vortex shedding is generated from both prisms (co-shedding behavior). The spacing between the two rectangular prisms is large enough that the downstream prism becomes subject to a limited influence of wake flows induced by the upstream prism (Nikfarjam and Sohankar, 2015). When two tandem prisms are placed near a planar wall, wake flow structures become very complicated. Vortices generated near the wall significantly interfere with flow structures around the tandem prisms. As described in Devarakonda and Humphrey (1996), the downstream prism experiences much less drag force in the tandem configuration. When the spacing ratio between the two cylinders is less than two, the drag coefficient of the downstream prism is drastically reduced to a value less than zero. Sohankar (2014) and Nikfarjam and Sohankar (2015) perform simulations to investigate the flow patterns in flows past two tandem square prisms. Different flow regimes are identified with respect to different gap spacing between prisms. Hydrodynamic loadings on the downstream prism are influenced strongly by the gap between prisms. Bhattacharyya and Dhinakaran (2008) conducted numerical studies for flows past two tandem square prisms near a wall at low Reynolds number values. They reported that the shear layer formed near the wall weakens the shear layer generated from the side of the prisms closer to the wall. Harichandan and Roy (2012) conducted simulations for tandem square and circular cross-sectioned prisms placed near a wall. They observed that at a Reynolds number of 100 and 200, and a wall gap ratio of 0.5 and 1, the Strouhal number for both upstream and downstream prisms is identical. With tight spacing of the cylinders, few dominating vortex shedding frequencies are observed. This behavior reflects the presence of complex vortex dynamics and the strong influence on drag and lift coefficients.

Aforementioned studies considered flows past prisms whose axes are perpendicular to the free stream flow. There were few studies that examined flows past an infinite yawed circular cross-sectioned prism. Vortex shedding of yawed prisms becomes irregular and the mean drag coefficient varies significantly with the yaw angle. Although most of the previous studies considered flows past infinitely long prisms, flows past finite length prisms with two free ends are of more practical interest in typical engineering applications. As of today, there are only few studies about flows past finite length prisms with two free ends. Flow structures around a finite prism are highly three-dimensional. Other than the Karman vortex shedding emanating from the sides of the prism, flow can be dominated by the tip vortices generated from the free ends. As reported in Hemmati et al. (2016b), hydrodynamic forces exerted on the prism vary strongly with the length to diameter ratio, L/D, of the rectangular