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Freely vibrating circular cylinder in the vicinity of a stationary wall

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ABSTRACT

We present a numerical study on vortex-induced vibration (VIV) of a freely vibrating two degree-of-freedom circular cylinder in close proximity to a stationary plane wall. Fully implicit combined field scheme based on Petrov–Galerkin formulation has been employed to analyze the nonlinear effects of wall proximity on the vibrational amplitudes and hydrodynamic forces. Two-dimensional simulations are performed as a function of decreasing gap to cylinder diameter ratio $e/D \in [0.5, 10]$ for reduced velocities $U^* \in [2, 10]$ at $\mathrm{Re}_D = 100$ and $\mathrm{Re}_L = 2900$, where Re_D and Re_L denote the Reynolds numbers based on the cylinder diameter and the upstream distance, respectively. We investigate the origin of enhanced streamwise oscillation of freely vibrating near-wall cylinder as compared to the isolated cylinder counterpart. For that purpose, detailed analysis of the amplitudes, frequency characteristics and the phase relations has been performed for the isolated and near-wall configurations. Initial and lower branches in the amplitude response are found from the gap ratios of 0.75 to 10, similar in nature to the isolated cylinder laminar VIV. A third response branch has been found between the initial and the lower branch at the gap ratio of $e/D \le 0.60$. For near-wall cases, phase relation between drag force and streamwise displacement varies from close to 0° to 180°. Between $e/D \in [5, 7.5]$, the effect of wall proximity on the frequency response tends to disappear. The effect of mass-ratio is further investigated. Finally, we introduce new correlations for characterizing peak amplitudes and forces as a function of the gap ratio for a cylinder vibrating in the vicinity of a stationary plane wall.

1. Introduction

The offshore industry is increasingly considering designs of deepwater pipeline system traversing across escarpment, trough or depressions over the seafloor. The uneven nature of seafloor topography and randomness of scouring result in the formation of free spans that usually would exceed the allowable stress and fatigue limits required for the safety of pipelines (Tsahalis, 1983; Sumer and Fredsøe, 2006). In the presence of steady current close to the seafloor, free span pipelines can undergo severe flow-induced vibrations. In the short run, small amplitude vibrations with high frequencies may not be detrimental but they can lead to serious fatigue damage in the long run. The challenge is then to understand the coupled dynamics of free span pipelines undergoing vibrations in the vicinity of seabed. The problem of a free span vibration along

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Nomenclature

$\alpha^{\mathrm{f}}, \alpha^{\mathrm{f}}_{\mathrm{m}}$	fluid generalized-α parameters
$\alpha^{\mathrm{s}}, \alpha^{\mathrm{s}}_{\mathrm{m}}$	solid generalized-α parameters
δ	boundary layer thickness
$\Gamma^{\mathrm{f}}_{\mathrm{h}}$	non-interface fluid Neumann boundary
$\Gamma^{\mathrm{s}}_{\mathrm{h}}$	non-interface solid Neumann boundary
Γ	interface between fluid and rigid body
Γ^{f}	non-interface fluid domain boundary
μ^{f}	fluid dynamic viscosity
ν	fluid kinematic viscosity
Ω^{f}	fluid domain
Ω^{s}	rigid body
ρ^{f}	fluid density
ρ^{s}	solid density
$\boldsymbol{\sigma}^{\mathrm{f}}$	fluid Cauchy stress tensor
τ_m, τ_c	Galerkin least square stabilization parameters
$\boldsymbol{b}^{\mathrm{f}}$	body force acting on fluid
$\boldsymbol{b}^{\mathrm{s}}$	body force acting on rigid body
$\boldsymbol{c}$	damping vector per unit length
$\boldsymbol{F}^{\mathrm{s}}$	fluid traction acting on rigid body
$\boldsymbol{k}$	stiffness vector per unit length
$\boldsymbol{m}$	mass vector per unit length
$\boldsymbol{u}^{\mathrm{f}}$	fluid velocity
$\boldsymbol{w}$	mesh velocity
A_x^{rms}/D	nondimensional root-mean-squared stream-wise displacement of rigid body
A_y^{max}/D	maximum nondimensional transverse displacement of rigid body
$C_{\mathrm{D}}^{\mathrm{rms}}$	root-mean-square drag coefficient
$C_{\mathrm{L}}^{\mathrm{rms}}$	root-mean-square lift coefficient
C_D	drag coefficient
C_L	lift coefficient
C_P	pressure coefficient
C_{p0}	forward stagnation pressure coefficient
D	cylinder diameter
e	gap between cylinder and wall
f_n	natural frequency of the cylinder in vacuum
k	spring stiffness
L_u, L_d, H	computational domain parameters
M	mass per unit length of cylinder
m^*	structure to fluid mass ratio
p	fluid pressure
p_∞	freestream fluid pressure
Re_D	Reynolds number based on cylinder diameter
Re_L	Reynolds number based on upstream distance
U	free-stream velocity
U^*	reduced velocity

the pipeline length can be modeled as a spring-mounted cylinder near a plane wall. The presence of wall will alter the oncoming flow profile and vortex patterns during oscillations, which in turn will change the hydrodynamic loads and coupled fluid–structure responses.

Most of the existing literature concerning VIV of a circular cylinder have focused on the case of an isolated circular cylinder placed in uniform flow without the wall-proximity effects. Comprehensive reviews have been done by Sarpkaya (2004), Williamson and Govardhan (2004, 2008) and Bearman (2011) for the current state of this area. For the isolated cylinder, Govardhan and Williamson (2000) found that VIV of a one degree-of-freedom (1-DoF) cylinder with high mass damping exhibits two response branches, namely the initial and lower branches. The vortex wake exhibits in 2S mode on the initial branch and 2P mode on the lower branch.

The proximity of a wall introduces complex interactions between the wall boundary-layer and the shear layer over the circular cylinder. One of the earliest experiments studying the wall effects on a circular cylinder was reported in Taneda's experiment (1998), where a circular cylinder was towed through stagnant waters close to a fixed ground. In this experimental study, since both water and ground moved relative to the cylinder, the effects of wall boundary-layer formed on the bottom wall were neglected. Regular alternate vortex shedding occurred at a gap ratio, i.e. ratio of height of gap between cylinder and wall to the diameter of the cylinder, $e/D=0.6$, while only a weak single row of vortices was shed at $e/D=0.1$. Bearman and Zdravkovich (1978) investigated the effect of gap ratio on the vortex shedding in the Reynolds number regime of between 2.5×10^4 and 4.8×10^4, showing that vortex shedding is suppressed if $e/D<0.3$. Studies by Zdravkovich (1985b) and Lin et al. (2005), carried out at Reynolds number Re_D of 3550 and 780 respectively, showed the cessation of regular vortex shedding for a stationary cylinder near a wall, where $\mathrm{Re}_D=UD/\nu$ with U being the freestream velocity and ν the kinematic viscosity. Other studies on a stationary cylinder near a fixed wall include Lei et al. (1999, 2000), Wang and Tan (2008a) and Ong et al. (2010). In Lei et al. (1999), experiments were conducted in different boundary layer thicknesses, $\delta/D=0.14$–2.89, at Re_D from 1.31×10^4 to 1.45×10^5, and they found that both lift and drag are largely affected by e/D and influenced by δ/D as well. They also reported that vortex shedding is suppressed when gap ratio is between 0.2 and 0.3. Numerical studies were preformed by Lei et al. (2000) to study the vortex shedding for different Reynolds numbers ranging from 80 to 1000 at various gap ratios, where the vortex shedding mechanism was analyzed and critical gap ratios were identified at different Re_D. Wang and Tan (2008a) looked into the near-wake flow characteristics of a circular cylinder proximity to a flat bed at $\mathrm{Re}_D=1.2\times10^4$ and $\delta/D=0.4$, observing that the instantaneous flow field highly depends on e/D. These three works concluded that Re_D, e/D and boundary layer thickness, δ/D, are three governing parameters affecting the flow over a cylinder near a fixed wall. In Wang and Tan (2008b), the authors investigated experimentally the flow characteristics in the near wake of a cylinder located close to a fully developed turbulent boundary layer. For small and intermediate gap ratios, the wake flow develops a distinct asymmetry about the cylinder centerline. Similarly, Ong et al. (2010) conducted numerical investigations by k–ϵ model on stationary near-wall cylinder in the turbulent regime. It was found that the drag coefficient increases as e/D increases for small e/D, reaching a maximum value before decreasing to approach a