# Numerical investigation of the effect of plane boundary on two-degree-of-freedom of vortex-induced vibration of a circular cylinder in oscillatory flow 

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## ARTICLE INFO

## Keywords:

Vortex shedding
VIV
Circular cylinder
Plane boundary
Oscillatory flow


#### Abstract

The laying of subsea pipelines often produces situations where the pipeline is suspended above the seabed due to local erosion of sediment. In this paper, flow induced vibration of a circular cylinder close to a plane boundary in an oscillatory flow is studied through two-dimensional numerical simulations. The circular cylinder and the plane boundary represents a pipeline and the seabed, respectively. It is found that the plane boundary affects the vibration amplitude in the cross-flow direction significantly. The vibration in the vertical direction ceases if reduced velocity exceeds 6 for $K C=5$ and 12 for $K C=10$, respectively. The vibration in the cross-flow direction stops when the reduced velocity exceeds a critical value because the effective $K C$ number and the effective reduced velocity, which are both based on the relative velocity of the cylinder to the fluid motion, are extremely small. For $K C=10$, the vortex shedding is found to be in one pair regime for most of the reduced velocities and non-vortex shedding regime exists at large reduced velocities. Because the shear layers generated from the plane boundary attract the vortices generated from the cylinder, vortex shedding occurs only at the bottom side of the cylinder.


## 1. Introduction

In offshore oil and gas engineering, subsea pipelines are generally laid on the seabed and will be suspended when local scour (i.e. the erosion of the seabed sediment below the pipeline) occurs. The suspension of a pipeline may cause the vibration of the pipeline. The vibration of a suspended pipeline, caused by waves and currents, can lead to a catastrophic pipeline failure (Low and Srinil, 2016). Because the vibration is generated by the vortex shedding flow, the vibration of cylindrical structures in fluid flows are generally called vortex-induced vibration (VIV). The aim of this paper is to investigate the VIV of a circular cylinder close to a plane boundary in oscillatory flow.

While many experimental and numerical studies have been performed to understand the dynamics of VIV in steady flow, VIV of a circular cylinder in an oscillatory flow has received much less attention. Vortex-induced vibration of cylinders in the cross-flow direction has been discussed extensively in review articles (Bearman, 1984; Parkinson, 1989; Sarpkaya, 1979, 2004; Williamson and Govardhan, 2004). The classic experimental study of VIV of an elastically mounted cylinder in wind by Feng (1968), where the mass-damping parameter (the
product of mass ratio and damping ratio) is quite high, shows that the response can be divided into two branches, namely, the initial and the upper branches. Williamson and Roshko (1988) conducted experiments of forced vibration of a cylinder in the cross-flow direction in a fluid flow and found the relation between the amplitude of the cylinder and the vortex shedding characteristics. By conducting experiments of vibration of a cylinder in water flows, Khalak and Williamson (1999) identified three branches of the response when the mass-damping is low.

Blevins and Coughran (2009) and Jauvtis and Williamson (2004) studied two-degree-of-freedom (2DOF) VIV of a circular cylinder in steady flows and found that the trajectories of the cylinder vibration were strongly dependant on the reduced velocity. Laneville (2006) found that the vortex shedding modes were influenced by the $X-Y$ motion of the circular cylinders. Govardhan and Williamson (2006) found that the effect of the Reynolds number should be taken into account in addition to the mass-damping when evaluating VIV. In the offshore oil and gas engineering, cylindrical structures such as subsea pipelines are subject to oscillatory flows. Very limited experimental and numerical studies of VIV of cylinders in oscillatory flow are available in literature. Kozakiewicz

[^0]https://doi.org/10.1016/j.oceaneng.2017.11.022
Received 23 September 2016; Received in revised form 4 September 2017; Accepted 8 November 2017

| Nomenclature |  |  |  |
| :--- | :--- | :--- | :--- |
|  |  | $S_{i j}$ | Mean strain tensor |
| $a_{\mathrm{i}}$ | Nodal point displacement in $x_{\mathrm{i}}$-direction | $T$ | Period of oscillatory flow |
| $C$ | Damping of cylinder | $U_{\mathrm{m}}$ | Velocity amplitude |
| $C_{\mathrm{A}}$ | Added mass coefficient | $u_{i}$ | Fluid velocity in $x_{\mathrm{i}}$-direction |
| $D$ | Diameter of Cylinder | $\overline{u_{i}^{\prime} u_{j}^{\prime}}$ | Reynolds stress tensor |
| $e$ | Gap between the cylinder and the plane boundary | $\widehat{u}_{j}$ | Moving mesh velocity |
| $F_{\mathrm{i}}$ | Hydrodynamic force | $V_{\mathrm{r}}$ | Reduced velocity |
| $f_{\mathrm{n}}$ | Natural frequency in vacuum | $v$ | Kinematic viscosity |
| $f_{\mathrm{nw}}$ | Natural frequency in still water | $\nu_{\mathrm{t}}$ | Turbulent viscosity |
| $K$ | Stiffness of cylinder | $\omega$ | Specific dissipation rate |
| $K C$ | Keulegan Carpenter number | $X$ | Cylinder displacement in $x$-direction |
| $k$ | Turbulent energy | $X_{\mathrm{i}}$ | Cylinder displacement in $x_{\mathrm{i}}$-direction |
| $m$ | Mass of the cylinder | $x$ | Cartesian coordinate parallel to plane boundary |
| $m^{*}$ | Mass ratio | $Y$ | Cylinder displacement in $y$-direction |
| $\rho$ | Density | $y$ | Cartesian coordinate perpendicular to plane boundary |
| $R e$ | Reynolds number | $y^{+}$ | Nondimensional distance from wall |
|  |  |  |  |

et al. (1994, 1996) and Sumer and Fredsøe (1988) conducted experimental studies of one-degree-of-freedom (1DOF) vibration of a cylinder in the cross-flow direction in an oscillatory flow for $K C$ numbers ranging from 5 to 100 . The $K C$ number is defined as $K C=\mathrm{U}_{\mathrm{m}} \mathrm{T} / \mathrm{D}$, where $U_{\mathrm{m}}$ is the velocity amplitude, $T$ is the period of the oscillatory flow and $D$ is the diameter of the cylinder. It was found that the response pattern of the cylinder at a constant $K C$ number varies with the reduced velocity. One of the typical characteristics of the response of a cylinder in the oscillatory flow is that the frequency of the vibration is multiple of the frequency of the oscillatory flow. Anagnostopoulos and Iliadis (1998) simulated the in-line vibration of a circular cylinder in oscillatory flow numerically for $\operatorname{Re}=200$ and $K C$ numbers between 2 and 20. It was observed that the large oscillation amplitude at resonance has a significant effect on the flow pattern and the hydrodynamic forces exerted on the cylinder.

Some numerical studies of 2DOF VIV of a circular cylinder in the oscillatory flow show that the trajectory of the vibration is strongly dependent on the $K C$ number and the reduced velocity (Zhao et al., 2013). Zhao et al. (2012) simulated 1DOF VIV of a circular cylinder in the cross-flow direction of the oscillatory flow and showed that the VIV modes observed in the laboratory can be well predicted by the numerical model based on the RANS equations. Lipsett and Williamson (1994) conducted laboratory tests in a U-tube to study the $X Y$-trajectories of vibration by changing $K C$ number from 2 to 60 and the ratio of natural frequency in water to the frequency of oscillation of the U-tube from 1 to 9. Zhao (2013) also performed 2DOF numerical study on VIV of circular cylinder subject to oscillatory flow. It was observed that as the $K C$ number increases, the vibration becomes irregular and chaotic with increasing amplitude of the vibration.

For a fixed cylinder close to a plane boundary in a steady flow, it was demonstrated that the vortex shedding will be suppressed for a small


Fig. 1. Sketch of 2DOF VIV of circular cylinder near plane boundary in an oscillatory flow.
cylinder-to-boundary gap ratio (Bearman and Zdravkovich, 1978; Taniguchi and Miyakoshi, 1990; Buresti and Lanciotti, 1992; Lei et al., 1999; Ong et al., 2010). Vibration of a circular cylinder in steady flow close to a plane boundary was investigated in a few papers (Yang et al., 2008; Zhao and Cheng, 2011; Hsieh et al., 2016). Vibration of a subsea pipeline also has significant effect on the local scour, i.e. the erosion of the seabed sediment below the pipeline (Yang et al., 2008; Zhao and Cheng, 2010; Gao et al., 2006). The results of experimental studies (Tsahalis and Jones, 1981; Tsahalis, 1984) suggested that the cylinder undergoes an ovalshape motion in contrast to the common figure eight of VIV in steady flow if the gap between the cylinder and the plane boundary is equal to cylinder diameter. Fredsøe et al. (1987) found that the transverse vibration frequency is close to the frequency of the vortex shedding of a stationary cylinder if the reduced velocity is less than 3 and the gap ratio is greater than 0.3 . For reduced velocity between $3<V_{r}<8$ and $0<e / D<1$ where $e$ is the distance between the bottom of the cylinder and the plane boundary, the transverse vibrating frequency is quite different from the vortex shedding frequency of a stationary cylinder. Moreover, Jacobsen et al. (1984) and Tsahalis (1984) studied vibration of a flexible cylinder near a plane boundary in combined waves and currents. Chioukh and Narayanan (1997) conducted an experimental study of transverse vibrations of elastically-mounted cylinders over a plane boundary in waves. It was found that a cylinder can vibrate even when the initial gap ratio between the cylinder and the plane boundary is very small.

In this study, two-dimensional numerical simulations are carried out to investigate the effects of a plane boundary on VIV of a circular cylinder


Fig. 2. Computational mesh around the cylinder when the gap ratio $e / D=0.01$.

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