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Numerical simulation of vortex-induced vibration of a circular cylinder with different surface roughnesses

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ABSTRACT

The effects of surface roughness on the vortex-induced vibration (VIV) performances of a circular cylinder were studied numerically. The VIV response amplitude, response frequency, vortex force, vortex phase and vortex shedding flow pattern with different degrees of surface roughness were compared. The numerical results show that the VIV response amplitude decreases with increased surface roughness. For a smooth cylinder and a cylinder with small surface roughness, the VIV response could be divided into three branches: initial branch, upper branch and lower branch. In the initial and upper branches, the vortex shedding flow pattern displays a 2S mode. However, the VIV response produces a 2P mode vortex shedding pattern in the lower branch. For a cylinder with large surface roughness, the VIV response can be divided into only two branches: an initial branch and a lower branch. In the initial branch, the vortex shedding flow pattern displays a 2S mode, but in the lower branch, the pattern changes to the 2P mode. The transition of 2S mode to 2P mode is caused by the abrupt change of the vortex phase between the vortex force and the VIV response.

1. Introduction

Vortex-induced vibration (VIV) of cylindrical structures is of practical interest to many branches of engineering. For example, it influences the dynamics of marine risers bringing oil from the seabed to the platform. The VIV of the structure is one of the key issues of the structure design. This is because VIV increases the dynamic load on the structure and may cause fatigue damage of the structure. The VIV of cylinders has been studied by many researches in the past few decades [1–9]. In fact, the VIV problem is a typical fluid – solid coupling problem, and is distinctly affected by the nearby flow. However, the surface roughness of the structures is one of the important parameters that strongly influence the flow past the cylinder. As with all marine structures with cylindrical section, marine organisms will grow on the structure surface over a period of time, increasing the surface roughness of the structure.

There have been numerous studies of the effect of surface roughness on the nearby flow around a circular cylinder and the VIV response of a circular cylinder [10–21]. As shown in Table 1, based on the boundary condition of the cylinder, the cylinders that have been studied can be divided into stationary cylinders [10–16], which are completely fixed, and oscillating cylinders [17–21], which are flexibly mounted. The studies of stationary cylinders are directed mainly toward the flow wake region, and include examinations of vortex shedding frequency, vortex shedding flow pattern and hydrodynamic forces induced by vortex shedding. However, in

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Table 1
Experimental analyses of circular cylinders having different degrees of surface roughness.

Investigators	Year	Aspect ratio	Cylinder conditions	Reynolds number[a]	Surface roughness[b]
(a) *In air*					
Achenbach	1971	3.33	Stationary	$4.0 \times 10^4 - 3.0 \times 10^6$	$1.1 \times 10^{-3} - 9.0 \times 10^{-3}$
Achenbach & Heinecke	1981	3.38	Stationary	$6.0 \times 10^3 - 5.0 \times 10^6$	$7.5 \times 10^{-4} - 3.0 \times 10^{-2}$
Nakamura & Tomonari	1982	3.33	Stationary	$4.0 \times 10^4 - 1.7 \times 10^6$	$9.0 \times 10^{-4} - 1.0 \times 10^{-2}$
Ribeiro	1991a,b	6.1	Stationary	$5.0 \times 10^4 - 4.0 \times 10^5$	$1.8 \times 10^{-3} - 1.2 \times 10^{-2}$
Bearman & Harvey	1993	12.26	Stationary	$2.0 \times 10^4 - 3.0 \times 10^5$	$4.5 \times 10^{-3} - 9.0 \times 10^{-3}$
Okajima et al.	1999	1.83	Oscillating	$2.5 \times 10^4 - 3.2 \times 10^5$	$5.0 \times 10^{-3} - 3.8 \times 10^{-2}$
(b) *In water*					
Allen & Henning	2001	84.6	Oscillating	$1.8 \times 10^5 - 6.5 \times 10^5$	$5.1 \times 10^{-5} - 5.8 \times 10^{-3}$
Bernitsas et al.	2008a,b	7.2–14.4	Oscillating	$8.0 \times 10^3 - 2.0 \times 10^5$	$1.4 \times 10^{-3} - 4.2 \times 10^{-3}$
Kiu et al.	2011	8.0	Oscillating	$1.7 \times 10^4 - 8.3 \times 10^4$	$2.8 \times 10^{-4} - 1.4 \times 10^{-2}$
Gao et al.	2015	48.32	Oscillating	$2.5 \times 10^4 - 1.8 \times 10^5$	$1.1 \times 10^{-4} - 1.2 \times 10^{-2}$

[a] Reynolds number is defined as $\mathrm{Re} = V{\cdot}D/\upsilon$, where V is the flow velocity, D is the cylinder diameter and υ is the kinematic viscosity of flow.
[b] Surface roughness is given by K_s/D, where K_s is the dimeter of the particle distributed around the cylinder.

addition to the problems related to stationary cylinders, oscillating cylinders experience other problems that include VIV amplitude, frequency, trajectory and other response parameters, all of which need to be considered.

As shown in Table 1, early studies were mainly focused on the nearby flow in air around cylinders having different degrees of surface roughness. In the experiments of Achenbach [10,11], it was found that as the boundary changes from laminar to turbulent, the drag acting on a cylinder decreases abruptly at a critical Reynolds number. This phenomenon is called the "drag crisis". The critical Reynolds number for this "drag crisis" decreases with increased surface roughness. With the rapid development of ocean engineering, research examining the effect of surface roughness on the VIV response of cylinders in water has received much attention. Kiu et al. [20] found out that as the roughness increases, the maximum VIV amplitude and the mean drag coefficient decrease, tending toward constant values. Compared with those for a smooth cylinder, the Strouhal numbers of rough cylinders are larger.

In contrast to the large number of publications dedicated to the VIV problems of smooth cylinders, significantly fewer studies exist on the VIV problems of rough cylinders, and many VIV characteristics of rough cylinders are not well understood. For example, as the surface roughness increases, how does the vortex shedding flow pattern display with different reduced velocities? Furthermore, what causes different vortex shedding flow patterns?

To answer the above questions, we conducted studies, which are reported in this paper (in Section 4, "Results and Discussion."). In Section 4.1, the mesh independency study and validation of the numerical model are described. In Section 4.2, results of the VIV response amplitude are reported. In Section 4.3, the vortex forces and vortex shedding flow patterns of a circular cylinder with different surface roughnesses are described. In Section 4.4, the response frequencies and the vortex phases between the vortex force and the VIV response are reported. In Section 4.5, the two different modes of the 2P vortex shedding flow pattern are discussed in detail.

2. Problem description

Fig. 1 shows a rectangular computational domain containing a cylinder with diameter D = 0.0381 m. The dimension of this domain is 22D (width) in the cross-flow direction and 32D (length) in the flow direction, resulting in a blocking ratio of 0.045.

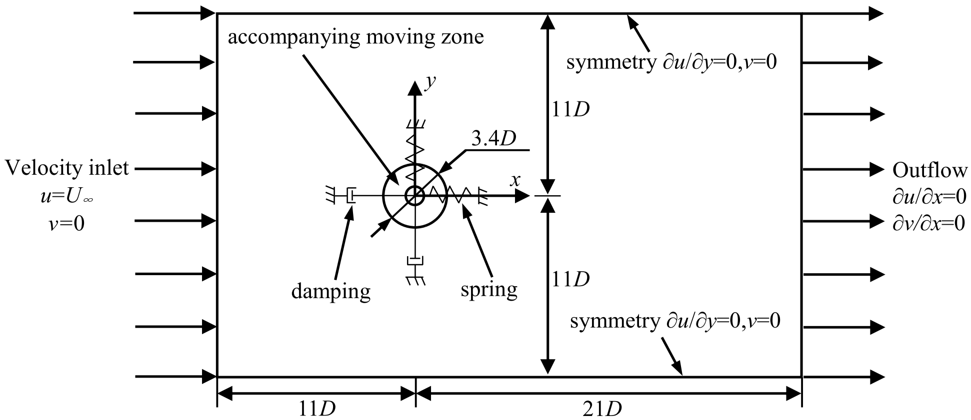

Fig. 1. Computational domain and boundary conditions.