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An experimental investigation of vortex-induced vibration of a curved flexible pipe in shear flows

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ABSTRACT

Vortex-induced vibration (VIV) of a curved flexible pipe in shear flows was studied experimentally in the concave configuration. The curved pipe was fully immersed into the water with the aspect ratio of 108 and mass-damping ratio of 0.11. The high speed imaging technology was employed to record the pipe's vibration displacements in both in-line and cross-flow directions subject to the shear flows with 15 different velocities. Both amplitude and frequency are presented versus the reduced velocity for a Reynolds number ranging from 165 and 1129. The results reveal that different vibration frequencies exist at different positions of the pipe with the presentation of multi-mode-response, and the excited modes vary with the incoming speed. The highest mode in the in-line direction is the third mode, while it is the second mode in the cross-flow direction. Eight-shape trajectories are presented in the middle part of the pipe, while the trajectories evolve to half-moon format at the two ends of pipe. Flow visualizations show that 2P or P+S wake pattern presents at the locations corresponding to the two peaks of the second-order response, while 2S pattern mainly appears at the position corresponding to the trough. The wake mainly presents a P+S mode at the location corresponding to the peak of the first-order response, while 2S mode is the main pattern in other locations.

1. Introduction

The vortex-induced vibration (VIV) of circular cylinders is a common phenomenon in many fields of engineering such as flow past heat exchanger tubes, offshore risers, chimney stacks and umbilical cords. A considerably large amount of studies have been conducted on this hot topic in last 40 years, as summarized in the comprehensive reviews of King (1977), Griffin and Ramberg (1982), Naudascher and Rockwell (1993), Sumer and Fredsoe (1997), Khalak and Williamson (1999), Sarpkaya (2004), Gabbai and Benaroya (2005), Williamson and Govardhan (2004, 2008) and Bearman (2011). The three branches of amplitude response proposed by Khalak and Williamson (1999) for a straight rigid cylinder with low mass-damping ratio of 0.013, including the initial, upper and lower branches, have been verified by a great many experimental and numerical studies. However, the objects of these studies were short rigid cylinders, and only single mode vibration was excited.

In the past decades, offshore oil and gas development has attracted great attention owing to the depletion of land oil resources and continuous growth in energy demand around the world. As an important oil and gas conveying pipe, riser is usually subjected to strong and complex ocean currents. The flexibility of large-aspect-ratio riser may present large amplitude and high modal response, resulting in an earlier fatigue damage. Therefore, the VIV of a flexible pipe has been a serious concern for ocean engineers and researchers because the fatigue failure of risers may bring about huge loss and environmental catastrophe.

In last decade, the VIV of a flexible cylinder has been studied experimentally and numerically extensively by many researchers as summarized in Table 1. For example, Huera-Huarte and Bearman (2009a, 2009b) have performed experimental investigation on VIV response of a vertical straight flexible cylinder with the aspect ratio of 37.5 in a uniform flow. Five pairs of strain gauges were employed to measure the IL and CF curvatures and to derive the response motion. However, only the first-order vibration has been found owing to the limited aspect ratio and velocity. Huera-Huarte et al. (2014) conducted a series of experiments on VIV of straight flexible cylinders with the aspect ratios of 158 and 187. The maximum amplitude over 3 diameters and responding modes up to 5 were observed. Huang et al. (2011) measured vibration responses of a long straight flexible riser of aspect ratio 502.5 using accelerometers. In their tests, the number of vibration modes was found up to be 20. Sanaati and Kato (2012) have

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Table 1
Analyses of VIV of flexible and curved cylinder in last decade.

Investigators	Year	Pipe/cylinder	Aspect ratio	Flow profile	Inflow direction	Re	Vibrational degrees of freedom	Instrument
(a) Experimental studies								
Huera-Huarte and Bearman	2009	Vertical straight flexible cylinder	93.75	Uniform flow	Perpendicular to the pipe axis	1200–12,000	Two (IL and CF directions)	Strain gauge
Huera-Huarte et al.	2014	Vertical straight flexible cylinder	158, 187	Uniform flow	Perpendicular to the pipe axis	2000–37,400	Two (IL and CF directions)	Strain gauge
Huang et al.	2011	Vertical straight flexible riser	502.5	Uniform flow	Perpendicular to the pipe axis	8000–24,000	Two (IL and CF directions)	Accelerometer
Sanaati and Kato	2012	Horizontal straight flexible cylinder	162	Uniform flow	Perpendicular to the pipe axis	2000–20,000	Two (IL and CF directions)	Strain gauge and accelerometer
Song et al.	2011	Horizontal straight flexible cylinder	1750	Uniform flow	Perpendicular to the pipe axis	3000–10,000	Two (IL and CF directions)	Strain gauge
Morooka and Tsukada	2013	A steel catenary riser (curved cylinder)	940	Uniform flow	Convex	400–600	Two (IL and CF directions)	Accelerometer
Assi et al.	2014	A curved circular cylinder with centerline of a quarter of a ring	25.7	Uniform flow	Convex and concave	750–15,000	Two (IL and CF directions)	Laser displacement sensor
Seyed-Aghazadeh et al.	2015	A curved circular cylinder with centerline of a quarter of a ring	73.8	Uniform flow	Convex and concave	300–2300	One (CF direction)	Laser displacement sensor
Lee and Allen	2010	Vertical straight flexible cylinder	32, 59	Linear shear flow	Perpendicular to the pipe axis	19,367.5–244,769.8	Two (IL and CF directions)	Accelerometer
Chen et al.	2015	Inclined straight cylinder	144.7	Exponential shear flow	Perpendicular to the pipe axis	1872.6–20,064	Two (IL and CF directions)	Accelerometer
(b) Computational fluid dynamic (CFD) studies								
Huera-Huarte et al.	2006	Vertical straight flexible cylinder	470	Uniform flow	Perpendicular to the pipe axis	2800–28,000	Two (IL and CF directions)	
Xie et al.	2011	Vertical straight flexible cylinder	12	Uniform flow	Perpendicular to the pipe axis	1000	Two (IL and CF directions)	
Miliou et al.	2007	A curved circular cylinder with centerline of a quarter of a ring	19.6	Uniform flow	Convex and concave	100, 500	Zero (fixed/static)	
Gallardo et al.	2011, 2013	A curved circular cylinder with centerline of a quarter of a ring	19.6	Uniform flow	Convex	3900	Zero (fixed/static)	
Vecchi et al.	2008	A curved circular cylinder with centerline of a quarter of a ring	19.6	Uniform flow	Convex and concave	100	Zero (fixed/static)	
Vecchi et al.	2009	A curved circular cylinder with centerline of a quarter of a ring	19.6	Uniform flow	Convex	100	One (CF direction)	
Bourguet et al.	2013	Vertical straight flexible cylinder	200	Linear and exponential shear flow	Perpendicular to the pipe axis	330	Two (IL and CF directions)	