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An experimental study of a circular cylinder's two-degree-of-freedom motion induced by vortex

Shin-Woong Kim [a], Seung-Jae Lee [a], Cheol-Young Park [a], Donghoon Kang [b,*]

[a] *Dept. of Naval Architecture and Ocean Systems Engineering, Korea Maritime and Ocean University, Republic of Korea*
[b] *Dept. of Ocean System Engineering, Gyeongsang National University, Republic of Korea*

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Abstract

This paper presents results of an experimental investigation of vortex-induced vibration (VIV) of a flexibly mounted and rigid cylinder with two-degrees-of-freedom with respect to varying ratio of in-line natural frequency to cross-flow natural frequency, f^*, at a fixed low mass ratio. Combined in-line and cross-flow motion was observed in a sub-critical Reynolds number range. Three-dimensional displacement meter and tension meter were used to measure dynamic responses of the model. To validate the results and the experiment system, x and y response amplitudes and ratio of oscillation frequency to cross-flow natural frequency were compared with other experimental results. It has been found that the higher harmonics, such as third and more vibration components, can occur on a *certain part of* steel catenary riser under a condition of dual resonance mode. In the present work, however, due to the limitation of a size of circulating water channel, *the whole test o*f a whole configuration of the riser at an adequate scale for VIV phenomenon was not able to be conducted. Instead, we have modeled a rigid cylinder and assumed that the cylinder is a part of steel catenary riser where the higher harmonic motions could occur. Through the experiment, we have found that even though the cylinder was assumed to be rigid, the occurrence of the higher harmonic motions was observed in a small reduced velocity (V_r) range, where the influence of the in-line response is relatively large. The transition of the vortex shedding mode from one to another was examined by using time history of x and y directional displacement over all experimental cases. We also observed the influence of in-line restoring force power spectral density with f^*.

Keywords: Vortex induced vibration; Mode transition; Dual resonance; Restoring force of a cylinder; Higher harmonic components; Power spectral density

1. Introduction

1.1. Background

In general, risers installed on offshore platforms have a long shape along the longitudinal direction. At the first stage of riser design, efficiency and stability are the conflicting issues. For example, as sites are getting deeper, a reliable analysis method and design have become main concerns, while engineers are trying to use minimum materials to improve efficiency (Campbell, 1999; Blevins, 1990). Unfortunately, there are still uncertain factors affecting the dynamic responses of the riser. As such, these uncertainties should be taken into account in a conservative structural design of risers (Assi et al., 2012).

We are in agreement with the premise that one of the main concerns in designing a riser is Vortex-Induced Vibration (VIV) analysis. VIV causes permanent cyclic loading on marine structures, especially risers, and leads to fatigue failure on the risers even though the magnitude of forces is smaller than that induced by waves (Lejlic, 2013). More specifically, when the incident current flows to the riser, the fluid can flow along the surface of the riser. Then, vortices are shed at both sides of the riser, symmetrically or asymmetrically. Because of this self-excited flow, the motion of the riser occurs and the

* Corresponding author.
E-mail address: kangdonghoon@gnu.ac.kr (D. Kang).
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Nomenclature

D	Cylinder diameter
f_{nx}	In-line natural frequency in water
f_{ny}	Cross-flow natural frequency in water
f_{ox}	Stream-wise oscillation frequency
f_{oy}	Cross-flow oscillation frequency
L	Cylinder length
St	Strouhal number
U	Current velocity
ν	Kinematic viscosity of fluid

fluid force acting on the riser is generated (Blevins, 1990). Furthermore, if the oscillation frequency of the riser gets closer to the natural frequency of the riser, the motion of the riser resulting from the interaction between the fluid and the riser will be amplified (Dahl, 2008). This effect in the VIV problem is called 'lock-in'. Many researchers have conducted an experimental investigation of the VIV phenomenon, which is an important issue in terms of designing risers, for many years due to its nonlinearity including its 'lock-in' response.

An experimental study is the best way to analyze and observe uncertainties on responses of a cylinder. A numerical study is also an important method for understanding the responses of a riser. Sarpkaya (2004) reviewed numerical and experimental studies on VIV of a circular cylinder conducted by other researchers. Several researchers have reported the results of VIV responses of a cylinder numerically based on two-dimensional Reynolds-Averaged Navier–Stokes equations. Zhao et al. (2013) have found a relation between cylinder's motion and lock-in regime in a steady flow and an oscillatory flow. Zhao et al. (2012) have proposed a mode-averaging technique and observed a vortex shedding mode transition from one to another mode in an oscillatory flow. Furthermore, a numerical study of four cylinders' motion induced by vortex has been investigated by Zhao and Cheng (2012), and Han et al. (2015). Zhao and Cheng (2012) have observed an influence of an approaching angle on the response of the four-cylinder system numerically. On the other hand, Han et al. (2015) have investigated responses of a square configuration of 2-DOF four cylinders with respect to reduced velocity and Reynolds number. They also have observed a downstream cylinders' motion induced by the wake and their wake patterns.

When it comes to the experimental study of VIV, many studies have been carried out, but an examination of force due to in-line response had been neglected, particularly in fatigue damage analysis. For example, multiple researchers have investigated 1-DOF VIV experiments which allow motion of the cross-flow direction only. In order to get a more accurate response of risers, however, all of the VIV components including in-line response should be considered in designing risers. Recently, some researchers performing VIV experiments have reported that an in-line response is not small, and thus should not be negligible (Jauvtis and Williamson, 2004; Marcollo et al., 2007; Swithenbank and Vandiver, 2007; Baarholm et al., 2006). In addition, the influence of higher harmonic components and interaction between in-line and cross-flow response on designing risers are issues of interest and have been reported by several researchers (Modarres-Sadeghi et al., 2010; Song et al., 2010; Vandiver et al., 2006).

These results play the role of input data in fatigue damage analysis. Although several institutes and classes have codes or guidance for analysis of VIV on risers, they just define a theory of VIV and provide a brief guide for analysis and designing risers (DNV, 2010; API, 2005). As such, it is not sufficient to use these to estimate the entire VIV responses. In essence, a more accurate VIV investigation with variable parameters is necessary. Vandiver et al. (2006) reported that the fatigue damage induced by all VIV components including higher harmonic components is much larger than the fatigue damage considering cross-flow frequency component only.

1.2. Objectives

The main goals of this VIV experiment are to measure and analyze the in-line and cross-flow response amplitude, the 'jump' phenomenon, and the restoring force PSD with variable f^*. Above all, we have focused on the 'jump' phenomenon, particularly the relation between the occurrence probability of 'jump' phenomenon and most influencing parameters such as in-line to cross-flow natural frequency ratio, and damping ratio. The influence of in-line restoring force on restoring force of the cylinder is emphasized in this paper.

Most VIV experiments have been carried out with variable mass ratio and damping ratio (Stappenbelt et al., 2007; Blevins and Coughran, 2009; Assi et al., 2009; Srinil et al., 2013). As mentioned above, the in-line response is not a negligible factor, and it has a significant influence on the VIV phenomenon. In an attempt to understand the interaction between in-line and cross-flow response, the 2-DOF VIV experiments have been carried out with a flexibly mounted and rigid circular cylinder. In this respect, we set the datasets based on in-line to cross-flow natural frequency ratio f^*, mass ratio, and damping ratio. Which are defined as,

$$m^* = \frac{4m}{\rho\pi D^2 L} \tag{1}$$

where m is cylinder dry mass and ρ is fluid density.

$$\zeta = c/2\sqrt{(m+m_a)k} \tag{2}$$

where c is a system damping, $2\sqrt{(m+m_a)k}$ is critical damping in calm water, and m_a is added mass in calm water. The other relevant nominal non-dimensional parameters are defined in Table 1.

2. Experimental set-up

Experiments have been carried out in the Circulating Water Channel (CWC) at the Korea Maritime & Ocean University,