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Distribution of turbulent eddies behind a monopile for vortex lock-on condition due to wave current combined flow

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ABSTRACT

The paper presents the results of an experimental study on wave current combined flow around a monopile (partially submerged circular cylinder) for a large Reynolds number. Measured instantaneous time series velocity signals (i.e., the sequence of discrete-time dependent velocity data) were analyzed to evaluate the statistical moments. It was found that vortex lock-on takes place when the forcing frequency of the superimposed surface wave is double that of the natural shedding (NS) frequency. Also, the recirculation region almost disappeared for vortex lock-on condition. The vortices generated due to superimposed surface waves increased the turbulence level near the shear layer at the recirculation region. Moreover, the Reynolds shear stress increased near the shear layer at the recirculation region due to vortex lock-on compared to that of NS condition. Further, the Gram-Charlier type joint probability distributions for two variables were estimated to describe the statistical properties of turbulent velocity fluctuations in different co-ordinate directions. Results from wavelet analysis of phased averaged velocity fluctuation suggested that the wave motion could modulate not only the large-scale eddies in the energy containing region, but the moderate scale eddies for the vortex lock-on condition. At the wake region of the monopile for vortex lock-on condition, it was pertinent that the wave motion induced fluctuating eddies of the background flow gained in strength and showed periodic distribution at the NS frequency (half of the induced wave frequency) in the time domain. The comparative study between NS and vortex lock-on condition showed that the induced wave motion can modulate the instantaneous small amplitude values of stream - wise and transverse velocity fluctuations ($u'v'$) that occur at the recirculation region.

1. Introduction

Understanding the turbulent flow around a monopile is of importance for an extensive range of applications that include, flow past a bridge pier, coastal structures, offshore structures, long marine risers, etc. Lin et al. (2002, 2003) reported that the turbulent flow past a monopile mounted on a rigid plane yields a three-dimensional turbulent velocity field that comprises of recirculation zone, horseshoe vortex, vortex shedding and many others. Most of the coastal structures have piers as their foundation that resemble monopiles mounted on the seabed. The wake region of the monopile experiences vortex shedding that leads to unwanted vibration on it. This vibration is further excited by the wave current combined flow arising out of ocean currents which may synthesize a resonance among the shedding frequency at the cylinder wake and the wave frequency. This resonance is generally known as a lock-on state (Bokaian, 1994; Vandiver et al., 2009).

Bearman (1969) stated that the maximum power spectral value represents the vortex shedding frequency evaluated applying the fast Fourier transform (FFT) of velocity fluctuations at a particular frequency at the coordinate $1d$ downstream from the cylinder (d is the cylinder diameter) at the wake center line. This frequency is also known as the natural vortex shedding frequency f_s for a steady incident flow over a fixed cylinder (no external vibration or rotation imposed on the cylinder). Griffin and Hall (1991) gave a review on the research on the vortex shedding lock-on. As part of this review they reported that vortex lock-on state might be achieved by various types of forcing such as rotational oscillations or forced vibration of the immersed objects. Griffin and Hall (1991) studied the vortex lock-on condition for bluff object oscillations under both normal to and in-line steady incident flow; rotational oscillations of the object; and due to acoustic waves. Griffin and Hall (1991) reported that the lock-on state could arrive when the oscillation frequency (f_o) of transverse and rotational oscillations and the f_s are almost equal

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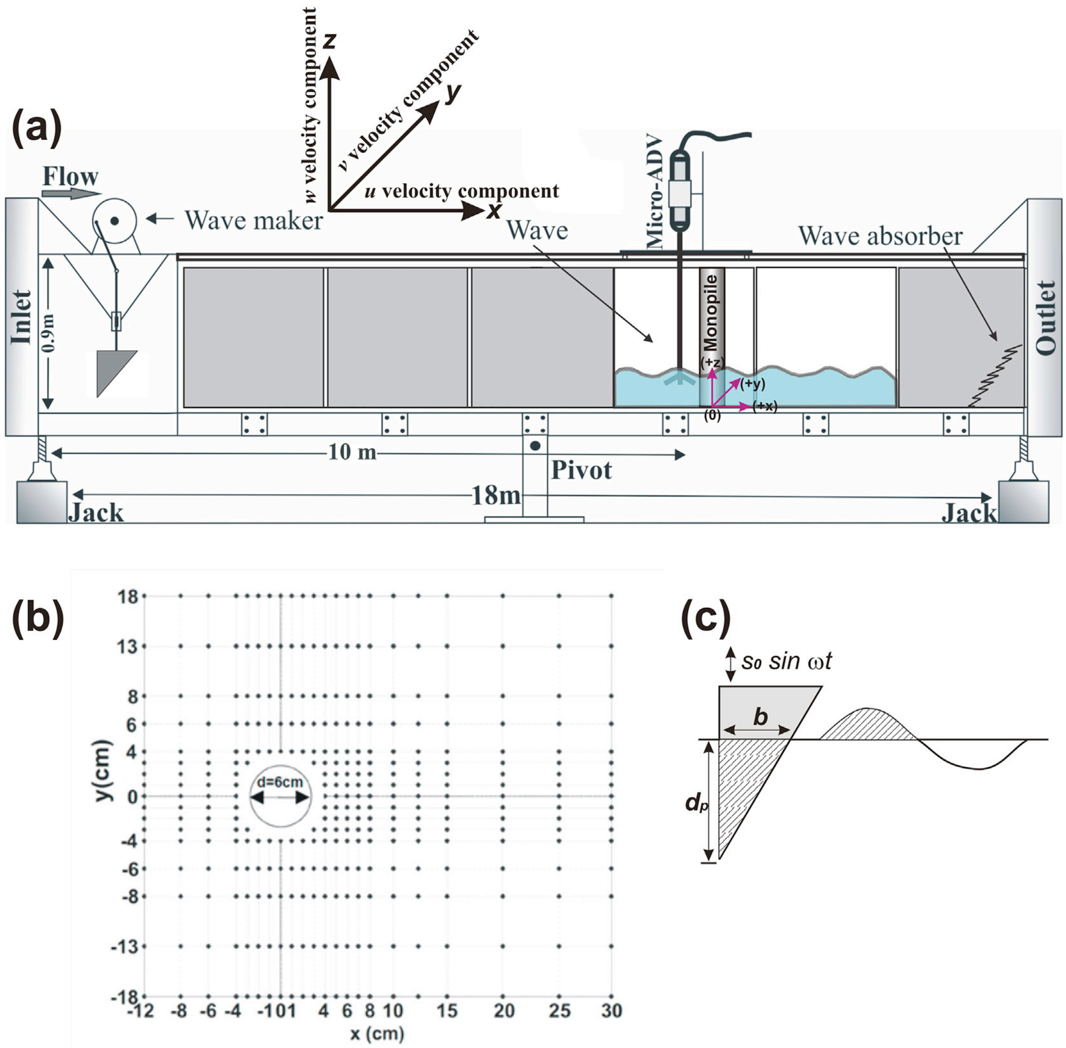

Fig. 1. (a) Schematic diagram of the experimental set-up; (b) grid points on the *xy*-plane, where the velocity measurements are taken; (c) schematic diagram of wave generation by the plunger.

(Bearman, 1984).

Alternatively, resonance appears when the f_o is twice the f_s due to the oscillatory flow and in-line oscillation. Kim et al. (2006) reported that the lock-on condition in the wake region of a submerged horizontal cylinder was achieved when the oscillation frequency of the perturbed flow was twice that of f_s. Further, the vortex lock-on state or vortex-synchronization condition was also reported in Kim et al. (2009) and Feng and Wang (2010). Recently, Feng and Wang (2014) reported that a synthetic jet placed at the upstream stagnation point modifies the vortex shedding at the cylinder wake. They also reported that the vortex shedding modes are affected due to the type of the front envelope of the synthetic jet.

Choi et al. (2008) stated that the vortex shedding at the rear of an object (bluff body) has a significant effect on the increase of mean drag and lift fluctuations including unwanted object vibration due to vortex shedding. Kim et al. (2009) reported that an oscillatory flow is capable of modulating the wake vortex structures behind a cylinder through vortex lock-on, resulting in a reduced object vibration. Bokaian (1994) numerically predicted that the virtual drag coefficient increased along the vertical marine riser at the vortex lock-on state. Thus, it is important to confirm the occurrence of vortex lock-on due to wave current combined flow around a monopole which in turn results in the alteration of the drag coefficient and vibrations. Information on vortex lock-on state may be helpful for the optimization of design parameters towards the stable design of coastal structures such as coastal bridges and docks and marine risers. Thus it can be summarized that based on previous investigations the flow parameters such as, lift and drag coefficients, vortex shedding frequency and mean and fluctuating velocities are significantly modulated due to the vortex lock-on phenomenon (Bokaian, 1994; Vandiver et al., 2009; Kim et al., 2009).

It may be of importance to note that information on eddy scale distribution under vortex lock-on state still remains unexplored. Vortex shedding region behind a monopile comprises of complex turbulent flow structures (turbulent eddies). These turbulent eddies are randomly distributed having different scales and energy content both in the time and frequency domain. The characterization of these turbulent eddies for natural vortex shedding condition as well as for superimposed surface wave condition (which also includes the vortex lock-on state) is the primary goal of the present study. In addition, the study attempts to explore the turbulence statistics under vortex lock-on state. Towards this wavelet transform (WT) has been used as a tool to compare the distributions of fluctuating eddies for NS and vortex lock-on condition.

Previously WT has been utilized in various disciplines of science and engineering for investigating incidental data (e.g., Morlet, 1983; Niu and Sivakumar, 2013; Sehgal et al., 2014a, 2014b; Shoaib et al., 2015; Wang et al., 2016). Panizzo et al. (2002) applied the WT analysis to examine the records of water level surface. They found that this technique can provide the information on the distribution of wave energy in the time-frequency