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VIV and galloping of single circular cylinder with surface roughness at $3.0\times10^4 \le Re \le 1.2\times10^5$

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ABSTRACT

Passive Turbulence Control (PTC) in the form of selectively distributed surface roughness is used to alter Flow Induced Motion (FIM) of a circular cylinder in a steady flow. The objective is to enhance FIM's synchronization range and amplitude, thus maximizing conversion of hydrokinetic energy into mechanical energy by oscillator in vortex-induced vibration and/or galloping. Through additional viscous damping, mechanical energy is converted to electrical harnessing clean and renewable energy from ocean/river currents. High Reynolds numbers (Re) are required to reach the high-lift TrSL3 (Transition-Shear-Layer-3) flow regime. PTC trips flow separation and energizes the boundary layer, thus inducing higher vorticity and consequently lift. Roughness location, surface coverage, and size are studied using systematic model tests with broad-field laser visualization at $3.0\times10^4 < Re < 1.2\times10^5$ in the low-turbulence free-surface water-channel of the Marine Renewable Energy Laboratory of the University of Michigan. Test results show that 16° roughness coverage is effective in the range (10°–80°) inducing reduced vortex-induced vibration (VIV), enhanced VIV, or galloping. Range of synchronization may increase or decrease, galloping amplitude of oscillation reaches three diameters; wake structures change dramatically reaching up to ten vortices per cycle. Conversion of hydrokinetic energy to mechanical is enhanced strongly with proper PTC.

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1. Introduction

Vortex-induced vibration is a commonly observed and destructive hydrodynamic excitation in slender flexible structures exposed to fluid flow such as ocean or river currents. These self-excited oscillations are due to the formation of a vortex street immediately behind the cylinder. The vortex street is formed by the alternating shedding of vortices from either side of the body, which give rise to periodic changes in the pressure distribution on the body surface leading to time-varying forces at the frequency of vortex shedding. For a spring-mounted rigid cylinder, when the vortex shedding frequency approaches the natural frequency of the system, the cylinder is typically excited to significant amplitudes with the shedding frequency 'locked-on' to the oscillation frequency. For systems with high mass ratios (such as in air), during 'lock-in', the cylinder oscillates at or near the natural frequency of the system and vortex shedding is synchronized with the body oscillation frequency. However, for VIV systems with low mass ratios (such as in water), the oscillation frequency could deviate significantly from the vortex shedding frequency as observed for a fixed cylinder (Khalak and Williamson, 1997). A spring-mounted smooth circular cylinder could only undergo VIV in isolated conditions, but non-circular sections (such as square) could be subjected to large amplitude galloping oscillations (Parkinson and Sullivan, 1979; Bokaian and Geoola, 1984b). Circular sections with attachments (such as splitter plate) could experience galloping (Nakamura et al., 1994). Furthermore, proximity of another cylinder would also induce galloping excitation in circular cylinders (Bokaian and Geoola, 1984a). These studies on galloping of circular cylinders bring to light the fact that a fluid dynamic change brought about by virtue of attachments or proximity to other bodies may cause galloping in circular cylinders.

In this work, a circular cylinder is geometrically modified using straight roughness strips placed on the cylinder surface. Width, roughness, and circumferential location on the cylinder are the parameters tested experimentally. That is, roughness is selectively applied on the surface of the cylinder in contrast to most previous studies where roughness is uniformly distributed over the entire cylinder surface (Achenbach, 1971; Guven et al., 1980; Achenbach and Heinecke, 1981; Nakamura and Tomonari, 1982). Most of these studies aimed to determine the pressure distribution around the cylinder, flow separation, and Strouhal number characteristics. None of these studies focused on the aerodynamic/hydrodynamic excitation of the body. Structural–dynamic

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response is important from the practical point of view of enhancing VIV as needed for hydrokinetic energy harnessing using the VIVACE Converter.

Most publications on single circular cylinder are on VIV at Reynolds numbers O(10^4) or less (Feng, 1968; Sarpkaya, 1995; Khalak and Williamson, 1999; Vikestad et al., 2000; Willden and Graham 2006; Huera-Huarte and Bearman, 2009). There is a scarcity of data for large Reynolds numbers (> 10,000) and especially for high mass-damping conditions in water. Among few studies reported at high Reynolds numbers, the findings of Blevins and Coughran (2009) and Allen and Henning (2001) are noteworthy. At a damping ratio $\zeta=0.02$, close to that of the present study ($\zeta=0.0233$), Blevins and Coughran (2009) report a maximum cross-flow amplitude to diameter ratio of $(A/D)=1.17$ at $Re=2.93\times10^4$ for a 'smooth to touch' cylinder, i.e., an amplitude value lower than that of the current study where $A/D=1.65$. This is due primarily to the higher Reynolds number of this study (Raghavan and Bernitsas, in press) and the lower value of the stability parameter $4\pi m^*\zeta$, which in this paper is 0.505, compared to 1.24 in the case of Blevins and Coughran (2009). Excitation amplitude increases with Reynolds number (Raghavan and Bernitsas, 2010) and reduces with increasing stability parameter (King, 1977). Further, the synchronization range in the present study ($5.5\le U^*\le 13.0$) is broader than that of Blevins and Cougran ($4.0\le U^*\le 9.0$). The reduced velocity $U^*=U/(Df_{n,\text{water}})$ where U is the flow velocity and $f_{n,\text{water}}$ is the natural frequency of the cylinder in water using the constant theoretical value of the added mass. Lower m^* gives rise to broader synchronization range (Khalak and Williamson, 1996, 1999). However, the general trend of oscillation frequency (increasing with respect to reduced velocity) appears to be similar in both cases for smooth cylinders. Blevins and Coughran (2009) report response amplitude values for rough cylinders as well. But, direct comparison is not possible since in their case roughness is applied over the entire cylinder surface whereas in the current study it is selectively applied. They report a drop of amplitude by a factor of two for rough cylinder with roughness/diameter value of 0.005 in contrast to the present study where a significant amplitude gain (1.7 times that of smooth cylinder) is obtained due to the selective application of roughness.

The reduced velocity is defined in this paper as

$$U^*=U/(f_{n,w}D), \tag{1}$$

where

$$f_{n,w}=2\pi\sqrt{\frac{k}{m+m_a}}, \tag{2}$$

k is spring stiffness, m is oscillating mass, and m_a is the ideal added mass.

Allen and Henning (2001) present results on flow-induced motions of smooth and rough circular cylinders at very high Reynolds numbers (covering critical and super-critical flow regimes). For smooth cylinder, they report a maximum $A/D\cong$ 0.85 and for rough cylinder $A/D\cong$ 0.7. Direct comparison with results of this paper is hard for three reasons: (a) Allen et al. test cylinder is flexible unlike the one in the present study. (b) Reynolds number range of Allen and Henning (2001) is higher than that of the present study. (c) In their case, the cylinder is free to oscillate both in cross-flow and in-line directions whereas in the present study the cylinder is restricted to oscillate only in the cross-flow direction. Presence of in-line motions make significant difference to the transverse (cross flow) amplitudes of the cylinder resulting in increase of about 50% (Williamson and Jauvtis, 2004).

Apart from its objective of enhancing FIM, the present research, aims to fill as well a gap in VIV and galloping data with turbulence stimulation and at high damping. Enhancing VIV, galloping or other forms of FIM implies increasing the amplitude of oscillation and range of synchronization aiming to extract more hydrokinetic energy from fluid flows, in contrast to most of the previous studies, which focus on low-Reynolds, low-VIV damping or suppression. The concept of extracting hydrokinetic energy from ocean/river currents using Vortex Induced Vibration (VIV), galloping or other instabilities was introduced in 2005 in a patent application, granted in 2009 (Bernitsas and Raghavan, 2009). Relevant data were published in 2006 (Bernitsas et al., 2006a/2008, 2006b/2009). Since then, extensive studies have been conducted by Bernitsas and his associates at the Marine Renewable Energy Laboratory of the University of Michigan, Ann Arbor, on VIV and galloping enhancement at high damping conditions (for energy harnessing) in the Reynolds number range of $8\times10^3<Re<1.5\times10^5$. This range covers flow regimes TrSL2, TrSL3, and TrBL0 for smooth cylinders according to the classification made by Zdravkovich (1997) where 'TrSL' stands for Transition in Shear Layer and 'TrBL' stands for Transition in Boundary Layer. Using Passive Turbulence Control, amplitudes as high as 2.7 diameters have been achieved so far (Raghavan and Bernitsas, 2008). The present study is an extended effort to enhance further the amplitudes of motion enabling extraction of higher amount of hydrokinetic energy.

In this paper, amplitude and frequency characteristics of the flow-induced motions of a single circular cylinder are presented as affected by PTC. The latter is implemented by applying straight roughness strips with certain width and varying roughness glued to the surface of the cylinder at various circumferential locations as described in Section 2 along with the experimental apparatus. The effects of roughness location, roughness height, and coverage area are studied in Sections 3, 4, and 5, respectively, based on experimental measurements. Additionally, in a quest to understand the underlying flow physics, flow visualization is used and results are summarized in Section 6 for smooth cylinders and cylinders with PTC. All tests are conducted in the Low Turbulence Water Channel located in the Marine Renewable Energy Laboratory (MRELab) of the University of Michigan. The present study covers the range of Reynolds numbers of $3\times10^4<Re<1.2\times10^5$ (primarily the TrSL3 flow regime (Zdravkovich, 1997)). Conclusions of this study are presented at the end.

2. Experimental set-up

Section 2.1 describes the Low Turbulence Free Surface Water (LTFSW) Channel where all tests are conducted. In Section 2.2 the flow visualization set-up is described. In Section 2.3 the apparatus and measurements are presented, and in Section 2.4 the application of PTC is explained.

2.1. Low turbulence free surface water channel

The LTFSW Channel provides a continuous flow past the test circular cylinder. About 8000 gal of water recirculate forced by an impeller powered by a 20 hp induction motor. The test section is 2.44 m long, 1 m wide, and 0.8 m deep. The test section walls are made of transparent plexiglass to enable flow visualization and also measurements with optical instrumentation. The length of the cylinder is limited by the width of the LTFSW Channel. The free stream turbulence intensity was reported at 0.098% (Walker et al., 1996). This turbulence intensity refers only to the channel, i.e., free of any test models. Further details of the LTFSF Channel and VIVACE models are provided by Bernitsas et al. (2006b/2009).

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