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Review

Harnessing hydro-kinetic energy from wake-induced vibration using virtual mass spring damper system

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ABSTRACT

Wake-Induced Vibration (WIV) has been considered as a potential candidate to capture hydrokinetic energy. This paper reports the results of an experimental investigation of the WIV of a circular cylinder, positioned in the wake of an upstream circular cylinder. Investigations were carried out to determine the effects of the arrangement of the cylinders, with respect to each other, and the Reynolds number on the amount of energy, which can be harnessed from the shed-vortices. The upstream cylinder was kept stationary during the experiment, while the downstream cylinder was mounted on a virtual elastic base. The virtual elastic mechanism consists of a motor and a controller, a belt – pulley transmission system and a carriage. In comparison with the more traditional mechanical impedance mechanisms, comprising of a real spring and damper system, the virtual mechanism, utilized in this work, provided greater flexibility and robustness. The Reynolds number based on the diameter of the upstream cylinder was varied between 2000 and 15000. The tests revealed that the power coefficient of WIV power is a function of the Reynolds number and the phase shift between the fluidic force and displacement of the downstream cylinder. The results indicated that the amount of WIV energy, that can be captured, increases in a staggered arrangement, in comparison with an aligned arrangement.

Contents

1. Introduction

Environmental concerns and global warming have motivated scientists to investigate new and alternative methods to produce clean energy. Hydrokinetic energy is one such renewable source and can be captured by turbine or non-turbine converters (Khan

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Table 1
Scaled classification of the vortex induced vibration converters (extracted from Bernitsas et al., 2008).

Scale	Power (MW)	Number of cylinders	D (m)	L (m)	U (knots)
Large	10	1,314	1	20	11.4
Medium	1	526	0.5	10	1.1
Small	0.1	328	0.2	4	0.1

et al., 2009). In contrast to conventional methods (turbine systems), such as dams, where a water head is created, there is a growing trend to produce hydroelectric energy without extensively altering the natural conditions of the water stream. One such relatively new technology is Vortex-Induced Vibration (VIV), typically considered as a non-turbine system. VIV arises from the interaction of a moving fluid with an elastic structure. The method has the potential to harness hydrokinetic energy from the oceans, currents and shallow rivers (Bernitsas and Raghavan, 2004).

For a turbine system the maximum power coefficient is defined by Betz's limit, which is equal to 16/27 for a single and open free blade (Jamieson and Hassan 2008). On the other hand, the actual efficiency of the system reduces due to the efficiency of electrical and mechanical processes and it is limited between 20% and 55% (Vries, 1983).

The VIV converter is a relatively new concept in hydropower generation and its scalability and flexibility make it suitable for a wide variety of applications. It was reported that the VIV converter can be scaled between microwatt and megawatt sizes based on the dimensions of the cylinders, the number of the cylinders and the flow speed (Bernitsas et al., 2008). Table 1 classifies some non-exhaustive VIV converters and highlights the capacity of the produced power extracted from Bernitsas et al. (2008). Here, D and L represent the diameter and length of the cylinder and U is the flow speed.

VIV of an elastically mounted circular cylinder in cross-flow has been well-studied in the literature (Sarpkaya, 1978; Sarpkaya, 1979; Bearman, 1984; Williamson and Roshko, 1988; Govardhan and Williamson, 2000; Govardhan and Williamson, 2004). Bearman (1984) studied the oscillation of a cylinder, due to vortices, in a cross-flow and found that the maximum amplitude of oscillation is achievable over a range of the reduced velocities $U_r = U/(f_nD)$, where, f_n is the natural frequency of the elastically suspended cylinder and D is the diameter of the cylinder. Simultaneous measurements of force and displacement of an elastically mounted circular cylinder was conducted by Govardhan and Williamson (2000). They utilised Digital Particle Image Velocimetry (DPIV) to determine the response of the cylinder with both high and low mass damping ratios ($m^*\zeta$), where the mass ratio is defined as $m^* = 4m/\rho\pi D^2L$, based on the mass (m) of the cylinder, and the diameter (D) and length (L) of the cylinder, respectively. Here, ζ is the damping ratio of the elastically mounted cylinder. With a low mass damping ratio, the authors observed three different types of responses for the amplitude of oscillation, known as *initial*, *upper* and *lower* branches; compared to only the *initial* and *lower* amplitudes observed with high mass damping ratios. As a result, the maximum displacement amplitude of the cylinder was achieved at the upper branch of oscillation using a low mass damping ratio.

The complexity of the dynamic response of the cylinder increases considerably by having two cylinders arranged in tandem. Since the longitudinal distance between two cylinders affects the dynamic behaviour of the vortices, even for stationary cylinders (Igarashi, 1981), tandem arrangements of cylinders comprising a stationary and elastically mounted cylinder would alter the response of the downstream cylinder. Brika and Laneville (1999) conducted a series of wind tunnel experiments for flow around two cylinders, with the longitudinal distance of $7 \le x_0/D \le 25$ and Reynolds numbers ranging from 5000 to 27000 (where x_0 is the longitudinal distance between the centre of the cylinders). They reported that smaller longitudinal distances cause larger displacement amplitudes of the downstream cylinder. Similarly, Assi (2009) conducted water channel tests for $4 \le x_0/D \le 20$, in order to study the effects of x_0/D on the WIV of the downstream cylinder. It was observed that the displacement amplitude of the cylinder at low Reynolds number, $Re < 6000$, (or $U_r \le 5$) is independent of the longitudinal distance between the cylinders. While at higher Reynolds numbers, $Re > 6000$, it was found that the amplitude of the oscillation is inversely proportional to x_0/D and that it decreases with increasing longitudinal separation. Although the influence of longitudinal distance was thoroughly investigated by Assi (2009), the effect of the lateral separation between the cylinders was not discussed for the WIV mechanism.

Bernitsas and Raghavan (2004) and Bernitsas et al. (2008) conducted a series of water channel experiments on an array of cylinders and determined an empirical expression for the efficiency of VIV power. They showed that the phase lag of the lift force on the cylinder, with respect to the displacement of the cylinder, would cause a reduction in the overall work production, since work is the product of the force and displacement. Inspired by the initial results, Chang et al., 2011 carried out further water channel tests to investigate the effect of the Reynolds number on the VIV of a circular cylinder with surface roughness. The significance of this study was the identification of the influence of the roughness and high Reynolds numbers, $3 \times 10^4 \le \mathrm{Re} \le 1.2 \times 10^5$ on the flow induced vibration, including galloping and VIV of the cylinder. Surface roughness was changed by placing a strip (one inch wide) on the surface of the cylinder at a different angle relative to the stagnation point of the cylinder. The results indicated that at different strip locations on the surface of the cylinder (20°–64°), the VIV is suppressed by the roughness for $U_r < 10$, while it induced galloping for $U_r > 10$.

Bearman (1984) was the first to postulate that the response of an elastically mounted circular cylinder can be modelled as a Mass Spring Damper (MSD). Following the proposed model by Bearman (1984), Hover et al. (1997), a pioneer of the computer model of Virtual Mass Spring Damper (VMSD), designed and employed a force-feedback controller in real time. The VMSD system allowed the operator to electronically set the desired impedance of the MSD. The advantage of the VMSD is that it allows a wide range of tests to be conducted rapidly compared to the real physical MSD, which requires changes in the physical elements in order to change the impedance. The ease of application of the VMSD allowed Hover et al. (1997) to analyse the effect of damping ratio and the Reynolds number on the VIV response of a cylinder from 60 experiments. Although it was shown that the VMSD is able to record reliable results, such as lift coefficient and the amplitude of oscillation, the system was observed to produce an additional phase lag of 12°. The phase lag between lift and displacement was due to the Chebyshev third-order digital filter (Hover et al., 1997), which can cause a reduction in energy conversion.

The use of VMSD also opened the way for optimisation and further development of energy extraction from VIV. In particular, it was used to explore many unresolved issues including the force-displacement phase lag, the power coefficient of energy harnessing, etc. For example, Lee et al., 2011 developed a VMSD of a VIV converter including a circular cylinder, a timing belt-pulley, a motor, and a controller. They used VMSD to perform a wide range of experiments, in which the spring stiffness was kept constant at 800 N/m and the viscous damping was varied from 0 to 0.16 in increments of 0.04. In this model, they reduced the phase lag between the force and displacement to zero, which could