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Spatial and temporal concentration of hydrokinetic energy in the wake of a bluff body

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ABSTRACT

Numerical simulations of a rigid, stationary, bluff body were performed using three-dimensional Computational Fluid Dynamics (CFD) and validated against published data. Bluff body cross sections such as the circle, semi-circle, straight-edged triangle, concave-edged triangle and convex-edged triangle were modelled at a Reynolds number of 10,000 in ANSYS FLUENT (v17.1). The streamwise and transverse wake energy components were investigated using Fourier analysis to analyse the spatial and temporal concentration of bluff bodies. The simulation results of the circular cylinder are compared against known experimental values and there was good agreement for the flow characteristics. The time-averaged energy in the wake, for all the shapes, does not present significant augmentation in the wake, except for a 60% increase in the streamwise kinetic energy near the surface of the cylinder due to a jetting effect (spatial concentration). Maxima for the temporal fluctuations in kinetic energy components (u' and v') occur between a streamwise distance of $1 < x/D < 3$ and a transverse distance of $0 < |y/D| < 1$, and occur mostly at the shedding frequency. Since WIV is vibration that is enhanced by fluctuations in the wake, a cross-section which increases temporal energy can lead to more energy captured by such a system. Changing the cross-section of the cylinder changes the distribution of the wake energy, where the convex-edged triangle and semi-circular cylinders demonstrated the greatest concentration of energy in transverse velocity fluctuations compared to others (1.5 times the freestream energy).

1. Introduction

There is a growing worldwide demand for energy due to the ever-increasing population, increased energy consumption and desire for improved quality of life (Bilgen et al., 2008). Future energy needs and its sources are a popular topic among environmentalists, governments and scientists around the world. A large proportion of energy is produced via combustion of non-renewable fossil fuels which are dwindling due to their limited quantities (Kaltschmitt et al., 2007). The desire to transition to more sustainable energy and low carbon intensity are major drivers of new environmental policies and technology development. Renewable energy sources are expected to play a key role in this transition. However, it is predicted that by the year 2035, global energy demand will increase by 53% over the level in 2008, while renewable energy sources are predicted to increase to only 16% over the same period (USEIA, 2011). Hence there is an interest in exploring other avenues to find viable, clean and abundant energy sources. Besides wind, solar, geothermal and hydro-electric (based on hydrostatic head pressure) energy sources, hydrokinetic energy (based on the kinetic energy in flows and waves) is a widely untapped resource of renewable energy.

Energy convertors for hydrokinetic energy can be classified by the nature of the utilized space in which they operate. Hydrokinetic energy convertors include point absorbers, such as surface buoys (Johnson and Pride, 2010); line absorbers, such as the Pelamis attenuator (Lagoun et al., 2010); horizontal surface patch absorbers, such as oscillating water columns (Heath, 2012); vertical surface absorbers, such as turbines and open propellers (Batten et al., 2006); and three dimensional space absorbers such as devices which operate using Vortex Induced Vibrations (VIV), for example the Vortex Induced Vibration for Aquatic Clean Energy (VIVACE) Converter (Bernitsas et al., 2009). Turbines, which are the most popular hydrokinetic energy convertor, operate at efficiencies of about 20%–55% (Hansen, 2015; Vries, 1983), and usually need high start-up flow speeds (Khan et al., 2009).

Flow energy can be split up in to spatial and temporal energy. The definition arises from the steady component and the unsteady, fluctuating component in the flow. The steady component is defined as the mean component of the flow which gives a steady value over time, whereas the unsteady component arises from fluctuations in the flow. Hence, spatial flow energy concentrators would perform better in

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Nomenclature

x	streamwise direction
y	transverse direction
z	spanwise direction
u	streamwise velocity (m/s)
v	transverse velocity (m/s)
w	spanwise velocity (m/s)
u'	fluctuating component of the streamwise velocity
v'	fluctuating component of the transverse velocity
w'	fluctuating component of the spanwise velocity
fs	vortex shedding frequency of the cylinder
ρ	density of the fluid
P	static pressure
k	turbulent kinetic energy
P_0	static pressure in the freestream, free from any disturbance
ρ_0	density of water in the freestream (998.2 kg/m^3 at 20 °C)
U_0	velocity of fluid in the freestream
$\overline{C}_D$	mean drag coefficient
C_p	pressure coefficient
$\overline{C}_{pb}$	mean back pressure coefficient
C_L	root mean square (r.m.s) lift coefficient
St	Strouhal number
Re	Reynolds number
$E_{\overline{u}}$	mean normalised streamwise energy
$E_{\overline{v}}$	mean normalised transverse energy
$E_{\overline{w}}$	mean normalised spanwise energy
$E_{u'_{fs}}$	normalised energy due to fluctuating streamwise component at fs
$E_{v'_{fs}}$	normalised energy due to fluctuating transverse component at fs
$E_{w'_{fs}}$	normalised energy due to fluctuating spanwise component at fs
$u_{mag\ ps}$	power spectrum magnitude obtained for the streamwise velocity at the primary shedding frequency
$v_{mag\ ps}$	power spectrum magnitude obtained for the transverse velocity at the primary shedding frequency
$w_{mag\ ps}$	power spectrum magnitude obtained for the spanwise velocity at the primary shedding frequency

situations with steady flow conditions (i.e. upstream of turbines), whilst temporal flow concentrators are needed for devices which operate utilising the temporal flow energy.

Spatial flow energy concentrators, such as diffusers, have been analysed ever since the Betz limit was established for turbines and other vertical surface absorbers (Dick, 1984). In theory diffusers can result in a combined system efficiency of 89% (Hansen et al., 2000; Jamieson, 2008), however, in practice duct augmented turbines have not been able to reach such a high power coefficient (Khan et al., 2009). Diffusers fall under the class of spatial energy concentrators, where energy is augmented at specific locations in the flow field.

There are many different types of diffusers, and each has their own merits and limitations (Gaden and Bibeau, 2006; Ohya et al., 2001; Ponta and Dutt, 2000; Ponta and Jacovkis, 2008; Setoguchi et al., 2004). In addition to spatial concentration, temporal concentration can further increase power densities that can be obtained from a hydrokinetic energy convertor system. A combination of spatial and time-dependant energy concentration (i.e. temporal concentration) can be achieved using bluff bodies as shown in previous studies (Assi, 2009; Bernitsas et al., 2008; Derakhshandeh et al., 2014). The concentration is time specific due to the characteristic von-Karman vortex street that forms in the wakes of bluff bodies.

Circular cylinders have received the most attention amongst bluff bodies in a cross-flow. There are numerous review papers on the vibration response of single circular cylinders and the factors that affect it due to early research being focused on mitigating the phenomenon to reduce failure in engineered structures (King, 1977; Sarpkaya, 1979, 2004; Williamson and Govardhan, 2004, 2008). The current state of art has shifted focus to harness the vibrations in bluff bodies exposed to cross-flow, to produce useful, clean and renewable energy (Bernitsas et al., 2008; Derakhshandeh et al., 2014, 2015a; 2016; Hansen et al., 2000). In VIV energy harnessing systems, it has been identified that tandem bodies result in higher power efficiencies when compared to the single bluff body case because they can generate a larger temporal component. A stationary upstream bluff body in a flow produces a vortex street, and hence the downstream body operates in a wake containing spatially and temporally concentrated hydrokinetic energy. Transverse vibration amplitudes, of cylinders undergoing VIV, are about 3 times greater than the streamwise amplitudes, and hence been of more interest for energy generating potential (Bernitsas et al., 2008; Hobbs and Hu, 2012; Wang and Ko, 2010).

There exist two different classes of devices which utilise VIV for energy generation and this is based on the energy output of the device. Many small-scale devices using a combination of VIV and piezoelectric transduction have been investigated to provide power for wireless sensing devices. Although these devices can vary in configuration, most of them use a circular or triangular cross section bluff body to produce vortices which impinge on to a beam containing piezoelectric materials. These devices usually provide power in the order of milli-watts and have very low efficiencies (Hobbs and Hu, 2012; Wang and Ko, 2010; Weinstein et al., 2012).

Larger scale devices which operate using VIV are aimed at providing useful energy to the grid from low speed currents in oceans and rivers. A prototype known as the Vortex Induced Vibration Aquatic Clean Energy (VIVACE) generator was developed by Bernitsas et al. (2008), who pioneered the energy harnessing potential of VIV and have continued to research the field (Bernitsas et al., 2009; Bernitsas and Raghavan, 2004; Bernitsas et al., 2008; Chang et al., 2011; Lee and Bernitsas, 2011). The theoretical efficiency of power conversion for VIV of a single cylinder unit was calculated to be 37% at a Reynolds number of 100,000. However, the maximum power obtained via experiments conducted on a single cylinder system was 22%. This sparked more interest in the field to improve the energy harnessing efficiency from VIV. Very recent experimental work by Ding et al. (2016) demonstrated that higher efficiencies (η = 37%) can be obtained at lower Reynolds numbers (Re = 60,000) using passive turbulence control by attaching roughness strips to the cylinder. Most research on VIV for energy has been performed on circular cylinders due to the abundant research available on the flow features of a circular cylinder (Braza et al., 1986; Cantwell and Coles, 1983; Ong and Wallace, 1996; Williamson, 1996).

Derakhshandeh et al. (2014) have shown the feasibility of Vortex and Wake Induced Vibrations (VIV and WIV respectively) to harness hydrokinetic energy. A transverse spacing of $0 < y/D < 1$ and streamwise spacing of $3 < x/D < 4$, between tandem staggered cylinders provided maximum energy harnessing efficiency (η = 48.4%) for a cylinder with diameter equal to D at a Reynolds number of 65,000 (Derakhshandeh et al., 2014). The power generating potential of VIV has been confirmed by these studies and further work, in particular on the flow field in between the cylinders, is required to identify an efficient and realisable system.

Other bluff bodies have also been tested for the purpose of Flow Induced Motion (FIM). Although the vibration responses of single bluff bodies such as square cylinders (Amandolèse and Hémon, 2010; Barrero-Gil and Fernandez-Arroyo, 2013; Nemes et al., 2012), triangular prisms (Alonso and Meseguer, 2006; Alonso et al., 2005), and a comparison between various bodies (Ding et al., 2015) have been