Renewable Energy 99 (2016) 936–959

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Effect of mass-ratio, damping, and stiffness on optimal hydrokinetic energy conversion of a single, rough cylinder in flow induced motions

Hai Sun [a, b, *, 1], Eun Soo Kim [b, e, 1], Gary Nowakowski [c], Erik Mauer [c, d], Michael M. Bernitsas [b, e, f]

[a] Harbin Engineering University, Post-doctoral Fellow MRELab, University of Michigan, Ann Arbor, MI, USA
[b] Marine Renewable Energy Laboratory, Dept. of Naval Architecture & Marine Engineering, University of Michigan, 2600 Draper Road, Ann Arbor, MI 48109-2145, USA
[c] U.S. Department of Energy, Wind and Water Power Technologies Office, Golden Field Office, USA
[d] Allegheny Science & Technology Contractor to US-DOE, USA
[e] Department of Mechanical Engineering, University of Michigan, USA
[f] Vortex Hydro Energy, Ann Arbor, MI, USA

ARTICLE INFO

Article history:
Received 15 January 2016
Received in revised form
10 July 2016
Accepted 11 July 2016

Keywords:
Hydrokinetic energy
Virtual spring-damping
Flow induced motions
Vortex induced vibrations
Galloping
VIVACE converter

ABSTRACT

Flow Induced Motions (FIMs) of a single, rigid, circular cylinder with end-springs are investigated for Reynolds number $30,000 \leq Re \leq 120,000$ with mass ratio, damping, and stiffness as parameters. Selective roughness is applied to enhance FIM and increase the hydrokinetic energy captured by the VIVACE (Vortex Induced Vibration for Aquatic Clean Energy) Converter at higher Reynolds numbers. The second generation of virtual spring-damping system Vck, recently developed in the Marine Renewable Energy Laboratory (MRELab), enables embedded computer-controlled change of viscous-damping and spring-stiffness for fast and precise oscillator modeling. Experimental results for amplitude response, frequency response, energy harvesting, and efficiency are presented and discussed. All experiments were conducted in the Low Turbulence Free Surface Water (LTFSW) Channel of the MRELab of the University of Michigan. The main conclusions are: (1) The oscillator can harness energy from flows as slow as 0.3946 m/s with no upper limit. (2) Increasing the spring stiffness, shifts the VIV synchronization range to higher flow velocities, resulting in reduced gap between VIV and galloping, where the harnessed power drops. (3) In galloping, the harnessed power increases with the mass ratio. (4) Local optima in energy conversion efficiency appear at the beginning of the VIV upper branch and at the beginning of galloping. (5) Local optima in power appear at the end VIV upper branch and at the beginning of galloping.

1. Introduction

Alternating Lift Technologies (ALT) provide an environmentally compatible way for harnessing marine hydrokinetic (MHK) energy even from slow flows [34]. Flow Induced Motions (FIMs) present a source of challenge for diverse structures in steady flows such as heat exchangers, bridges, buildings, offshore structures, or power-transmission cables. The most common FIM phenomenon is Vortex-Induced Vibration (VIV), which was first observed by Leonardo da Vinci in 1504. The first mathematical formulation was done by Strouhal in 1878. Comprehensive reviews of VIV have been published by Refs. [4,5,9,27,35,38,40]. VIV occurs over a broad range of velocities, called synchronization range. It is due to vortex lock-in with the motion of the oscillating cylinder. The amplitude of VIV is self-limiting.

Galloping is another form of flow induced motion. It is an aero/hydro-elastic instability characterized by lower frequencies and larger amplitudes than VIV and is perpendicular to the flow [1]. It is more vigorous and destructive than VIV, yet not as complex a phenomenon. Galloping occurs above a critical flow speed and does not depend on vortex formation. Amplitude is not self-limiting, and increases with velocity till structural failure.

Typically, as flow velocity increases, VIV appears first, followed

* Corresponding author. College of Aerospace and Civil Engineering, Harbin Engineering University, No.154 Nantong Ave, Harbin, Heilongjiang, 150001, China
E-mail address: sunhai2009@gmail.com (H. Sun).
[1] Co-first authors.

http://dx.doi.org/10.1016/j.renene.2016.07.024
0960-1481/

by galloping. Fig. 1 shows the various branches of FIM for a single cylinder with distributed surface roughness to induce galloping. Each branch represents a different sub-region of FIM within which the wake-vortex mode or the underlying driving mechanism remains constant resulting in distinct amplitude response from adjacent branches. The cylinder is rigid on elastic supports in a cross-flow. As velocity increases, FIM is initiated as VIV due to vortex shedding, alternating from the two sides of the cylinder, resulting in transverse movement of the cylinder. Vortex shedding locks onto the cylinder oscillation over a broad range of synchronization starting with the initial branch as shown in Figs. 1 and 2. This response amplitude increases with the velocity of the flow in the upper branch. It is followed by the lower branch with smaller response, then the desynchronization zone, and then the end of the VIV synchronization range. The various branch characteristics may differ significantly depending on whether the flow in the Transition in Shear Layer (TrSL) is flow regime TrSL2 or TrSL3 [41,42]. Williamson and Govardhan [40] conducted experiments for Re about 3800 in TrSL2 ($1000 < Re < 20{,}000$) and response amplitude reached one cylinder diameter. The Marine Renewable Energy Laboratory (MRELab) has conducted experiments for $16{,}000 < Re < 140{,}000$ in the TrSL3 ($20{,}000 < Re < 300{,}000$) flow regime. They showed that: (a) the dependence of VIV on Reynolds number is strong; (b) in the upper branch in TrSL3, the amplitude increases reaching 1.8 diameters; and (c) the upper branch overtakes almost completely the lower branch. Fig. 1 shows all the VIV branches; the damping and stiffness values have been selected in such a way that the full range of VIV synchronization is shown. That is, the amplitude of oscillation nearly reaches zero before the onset of galloping.

At higher speeds, galloping may be reached depending on the geometric deviation of the cylinder from the circular cross-section [8,10]. Galloping reaches the physical limits of the oscillator in the experimental facility or structural failure [31,32]. VIV and galloping can be fully separated as shown in Fig. 1, or they can overlap resulting in a VIV-to-galloping transition range as shown in Fig. 2. In the latter case, a transition region appears between the two FIM types where both driving mechanisms – the VIV vortex shedding and the galloping instability – coexist.

VIV has a range of synchronization. For mass ratio $m^* = m_{osc}/m_d$ on the order of 1, the VIV synchronization range in terms of the reduced velocity U^* is approximately.

$$\sim 5 < U^* = \frac{U}{f_{n,water} D} < \sim\ 10 \tag{1}$$

where m_{osc} is the oscillating mass, m_d is the displaced fluid mass

$$f_{n,water} = \frac{1}{2\pi}\sqrt{\frac{K}{m_{osc} + m_a}} \tag{2}$$

is the natural frequency in water, m_a is the added mass, and K is the total spring stiffness. That is, the end of the VIV synchronization range increases proportionally to the square root of the spring stiffness K.

On the other hand, galloping initiates at an absolute value of velocity $U = U_{critical}$ given by Ref. [8] as

$$U_{critical} = \frac{2c_{total}}{\rho D \frac{\partial c_y}{\partial \alpha}} \tag{3}$$

where c_{total} is the linear viscous damping, D is the cylinder diameter, and $\partial c_y/\partial \alpha$ is the derivative of the lift coefficient with respect to the angle of attack. $U_{critical}$ is not affected by the spring constant K or

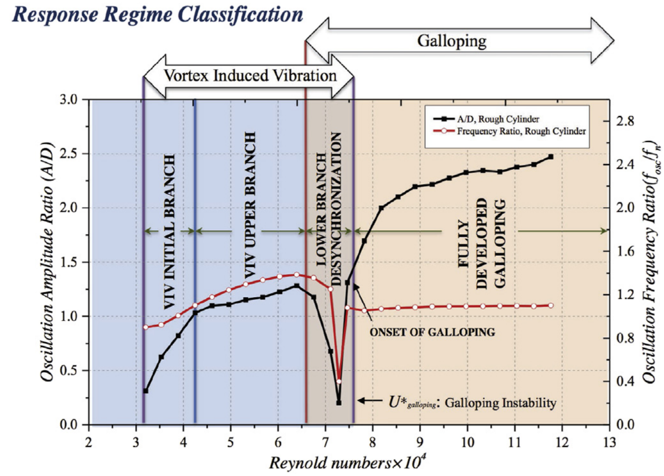

Fig. 1. FIM regions with small overlap between VIV and galloping.

the mass m. That is, initiation of galloping does not depend on K but only on the absolute flow velocity, system damping, and geometric particulars of the oscillator.

Comparing inequality (1) and equation (3), it is observed that the gap between VIV and galloping can be bridged by increasing K, decreasing m, decreasing c_{total}, or increasing D. Thus, an oscillator responding with high amplitude at a range of velocities staring at $U^* \simeq 5$ and having no upper end can be designed. That is, when it comes to energy capturing, the oscillators in the Converter provide a great advantage compared to linear resonators, which have high response within a very limited bandwidth in the vicinity of their natural frequency.

Typically, FIMs are suppressed in engineering applications because of their destructive nature. By enhancing and controlling FIM, the MRELab developed and patented a converter [6,7] to convert the kinetic energy of water flows into electricity. Relevant research on harvesting MHK energy using vortex-induced vibrations has been published in several countries: [2] (Japan); [39] (USA); [12] (Switzerland and France); [3] (Spain); [18] (China); [28] (India) and more.

The research objective of the MRELab is to study FIMs of single or multiple cylinders on springs and find ways to enhance the cylinder response in order to optimize the power output of Converters over a broad range of velocities. Power envelopes as function of flow speed and type of FIM need to be generated. FIMs

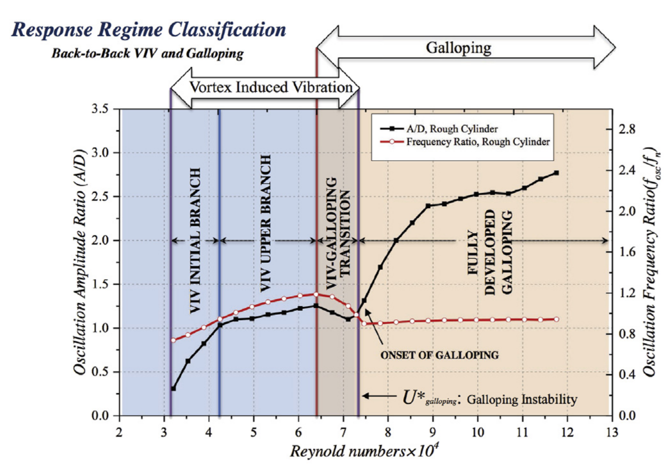

Fig. 2. FIM regions with transition between VIV and galloping.