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Nonlinear piecewise restoring force in hydrokinetic power conversion using flow induced motions of single cylinder

Chunhui Ma[a,b,c,1], Hai Sun[a,d,e,*,1], Gary Nowakowski[f], Erik Mauer[g], Michael M. Bernitsas[a,h,i]

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

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ABSTRACT

Flow Induced Motions (FIMs) of a single, rigid, circular cylinder with piecewise continuous restoring force are investigated for Reynolds number $24{,}000 \le Re \le 120{,}000$ with damping, and different piecewise functions 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, 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 nonlinear piecewise spring Converter can harness energy from flows as slow as 0.275 m/s with no upper limit. (2) In galloping, the nonlinear spring Converter has up to 76% better performance than its linear spring counterpart. (3) The FIM response is predominantly periodic for all nonlinear spring functions used. (4) Optimal power harnessing is achieved by changing the nonlinear piecewise spring function and the linear viscous damping. (5) VIVACE exhibits local maxima in power conversion at the end of the upper branch in VIV and the highest velocity reached in galloping. (6) The efficiency optima though are at the beginning of the VIV initial branch and at the beginning of galloping.

1. Introduction

Background information on Flow Induced Motion (FIM), alternating lift in harnessing horizontal hydrokinetic energy, nonlinear restoring forces in oscillators, and the research objectives of this study are presented in the Introduction.

1.1. Flow Induced Motions

Flow Induced Motions (FIMs) present a source of challenge for diverse structures in steady flows such as heat exchangers, bridges, buildings, offshore structures, cables, pipelines, 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 Bearman (1984) (2011), Sarpkaya (2004), and Williamson and Govardhan (2004). 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 (Blevins, 1990). It is more vigorous and destructive than VIV, yet not as complex a phenomenon as VIV. Galloping occurs above a critical flow speed

* Correspondence to: 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] Equally Credited Authors.

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Nomenclature

Greek symbols

α_{PTC}	Strip placement angle
θ	Angle coverage of the passive turbulence control
$\zeta_{structure}$	Damping ratio due to losses in the transmission system
$\zeta_{harness}$	Harness damping ratio
$\zeta_{converted}$	Converted damping ratio
ω_{osc}	Angular frequency of oscillation
ρ	Water density
μ	Dynamic Viscosity of water
v	Kinematic Viscosity of water

Roman symbols

A	Amplitude value of the transverse displacement
A^*	Amplitude ratio A/D, average of the 60 highest peaks
c	Total damping
$c_{harness}$	Harnessing damping
$c_{virtual}$	Added linear damping from Vck system
D	Diameter of cylinder
$f_{n,\ water}$	Natural frequency in water
f_{osc}	Oscillation frequency of cylinder
f^*	Oscillation frequency ratio in water
F_{fluid}	Force exerted by the fluid on the cylinder in the y-direction
$F_{nonlinear\_damping}$	Nonlinear damping from the system, containing the friction from structure and Vck system
$F_{controller}$	Force applied by the Virtual system (passive)
K	Spring stiffness
L	Cylinder length
m_{dis}	Displacement mass
m_{osc}	Oscillating mass
m_a	Added mass
m^*	Mass ratio
$P_{harnessed}$	Harnessed hydrokinetic power from the flow
$P_{converted}$	Total hydrokinetic power from the flow
$P_{dissipated}$	Dissipated hydrokinetic power due to structural damping
Re	Reynolds number
t	Time
T_{osc}	Oscillation period
U^*	Reduced velocity
y	Instantaneous cylinder motion in transvers direction
$\dot{y}$	Instantaneous cylinder velocity in transvers direction
$\ddot{y}$	Instantaneous cylinder acceleration in transvers direction

with no upper limit till structural failure. The driving mechanism is an instability related to negative damping caused by asymmetry in the relative flow. The latter can be due to a geometric asymmetry or a flow asymmetry due to an upstream wake. Thus, a smooth circular cylinder in a uniform flow cannot gallop.

Typically, as flow velocity increases, VIV appears first, followed by galloping. Fig. 1 shows the various branches of FIM for a single cylinder with distributed surface roughness to induce galloping. 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 the end of the VIV synchronization range. The various branch characteristics may differ significantly depending on whether the flow in flow regime TrSL2 or TrSL3 (Zdravkovich, 1997), where TrSL indicates "Transition in Shear Layer". Williamson and Govardhan (2004) conducted experiments for Re about 3800 in TrSL2 ($1000 < Re < 20{,}000$) and response amplitude reached one cylinder diameter. Bernitsas and Raghavan (2009) and Raghavan and Bernitsas (2010) 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 spring-stiffness value has been selected low to initiate and end VIV early. The damping value has been selected high to initiate galloping late. That way, the full range of VIV synchronization is shown as VIV ends and the amplitude of oscillation nearly reaches zero before the onset of galloping, the gap between VIV and Galloping increases as the stiffness decreases, decreases as the total damping decreases The relative positioning of VIV vs. galloping is explained in detail by Park et al. (2013a).

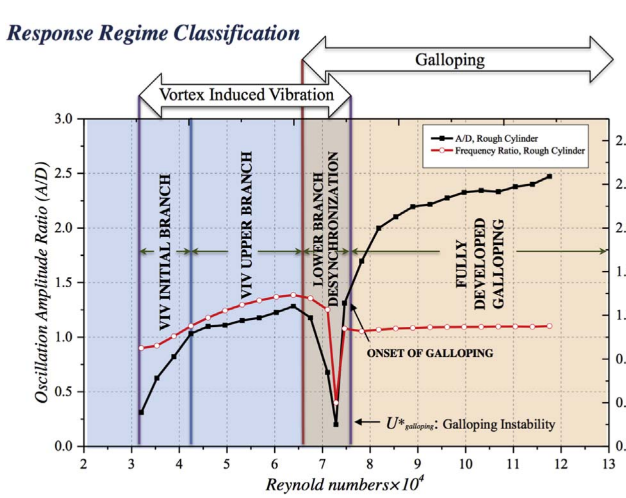

Fig. 1. Flow Induced Motion regions with small overlap between Vortex Induced Vibrations and galloping; K=400 N/m, ζ=0.12 (Sun et al., 2015).

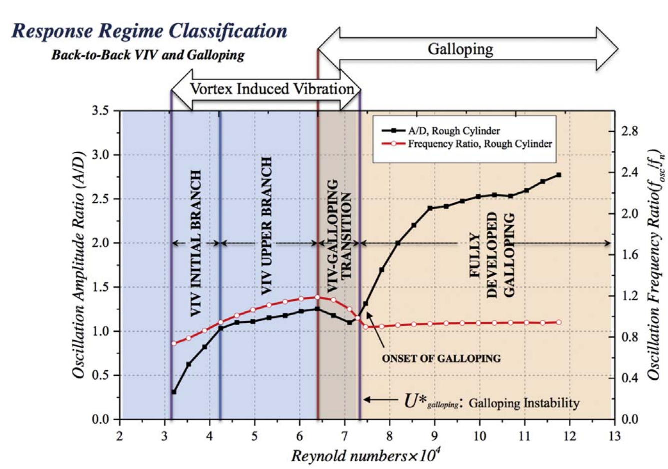

Fig. 2. Flow Induced Motion regions with overlap of Vortex Induced Vibrations and galloping; K=600 N/m, ζ=0.04 (Sun et al., 2015).