Renewable Energy 69 (2014) 447–452

Contents lists available at ScienceDirect

Renewable Energy

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

Low-head hydropower extraction based on torsional galloping

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ARTICLE INFO

Article history:
Received 3 September 2013
Accepted 27 March 2014
Available online

Keywords:
Torsional galloping
Flow-induced oscillation
Instability type
Critical velocity
Water current energy extraction

ABSTRACT

The work introduces a new concept of hydropower extraction. The proposed idea is to convert the hydrokinetic energy from an incoming flow to mechanical energy by inducing torsional galloping. The capability of this original device to extract energy is verified through experimental tests. The basic part of the device consists of a rectangular flat plate located vertically in the water current, with an elastic axis in its mid-chord length. The elasticity is provided via a torsion spring. According to the observations in the laboratory, as the current speed exceeds a critical velocity, the system becomes unstable, and as a result the flat plate oscillates torsionally about the elastic axis. The self-sustained torsional oscillation is an instability type flow-induced oscillation and is called torsional galloping. Subsequently a transmission system is added to the turbine to convert the torsional oscillation of the flat plate to a rotation. The rotary motion is applied to lift a weight up to a prescribed height. Each weight is lifted up several times to obtain the repeatability. Through the tests done on the device, its feasibility of hydropower extraction is proved. The simplicity of the construction and its capability for low-head water current energy extraction are the main advantages of the system making it a possible solution for low-head hydropower applications.

1. Introduction

In recent years an international commitment has dedicated to reduce the dependency on the fossil fuels as a result of the environmental problems caused by them and also limitations of their supplies. Several efforts have been made to extract energy from other alternative energy resources that are clean and renewable. One of these resources is hydrokinetic energy, i.e. power derived from the energy of falling and running water. Traditionally, the energy of water currents is extracted using turbines and watermills. However, there are two remarkable disadvantages in regard to use of these rotation-based devices; the structural weakness associated with the centrifugal stress and the need for high Reynolds number current for operation. The structural weakness necessitates high performance materials, and the need for high Reynolds number current requires building dams to get higher hydraulic heads. Despite the environmental destructive effects, both of these problems increase the cost of installation and maintenance. As a result, another family of turbines has recently been developed which use oscillation rather than rotation.

The first oscillation-based turbine was built by McKinney and DeLaurier [1]. This device was a wind turbine with a 2 DOF pitching and heaving oscillating wing operating based on aerodynamic flutter, and was named Wingmill. They tested Wingmill in a wind tunnel and claimed that its measured efficiency can compete with those of conventional (rotation-based) wind mills.

More studies were made to investigate the feasibility of using 2 DOF oscillating foil for energy extraction from the water current [2,3]. Also, various parameters, such as geometry, mechanics, kinematics, mode coupling, and frequency were studied via the analytical and numerical approaches to find the optimized energy extraction performance of the device [4,5].

The energy extraction via 2 DOF oscillating foil is performed from the heaving DOF, whereas the pitching DOF is controlled. The pitching DOF is controlled either through active control systems [6,7], or passively [8]. Furthermore, some studies use a mechanical coupling between pitching and heaving DOFs [9].

In addition to 2 DOF oscillating foil systems explained above, some other studies have used 1 DOF systems to extract energy. VIVACE, a prototype to extract energy of the current, works based on the transversal oscillation of cylinders excited by vortex-induced vibration [10]. Moreover, some studies explored the potential use of transverse galloping, 1 DOF oscillation in elastic bluff body due to instability, in order to obtain energy [11]. The main advantage of 1 DOF systems is their simplicity in control.

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http://dx.doi.org/10.1016/j.renene.2014.03.057
0960-1481/

Nomenclature

A	projected area (m^2)
b	damping coefficient (N.m.s/rad)
B_θ	flutter derivative
c	chord length (m)
C_P	power coefficient
C_θ	flutter derivative
E	total energy (N.m)
f	response frequency of torsional galloping (Hz)
$\hat{f}$	torsional galloping frequency (Hz)
f_n	natural frequency (Hz)
g	gravity acceleration (m.s^2)
h	water depth in the flume (m)
I	mass moment of inertia (Kg.m^2)
I_{66}	added moment of inertia (Kg.m^2)
k_θ	torsional spring rate (N.m/rad)
M	hydrodynamic moment (N.m)
m	weight mass (Kg)
$P_{\text{Take-off}}$	power take-off (N.m/s)
U	water current speed (m/s)
U_{rn}	reduced velocity
z	lifting weight height (m)
$\dot{z}$	lifting rate (m/s)
ζ_s	damping ratio due to structure
ζ_T	damping ratio due to transmission system
ζ_{TO}	power take-off damping ratio
$\hat{\theta}$	torsional galloping amplitude (rad)
θ_0	Response amplitude of torsional galloping (rad)
μ	torsional galloping parameter
ρ	water density (Kg/m^3)
τ	dimensionless time
Ω	frequency ratio

The present study represents the concept of energy extraction from the water current through the torsional galloping phenomenon. Generally, galloping and flutter are similar phenomena in the sense of their negative damping instability. As a result of negative damping, energy is pumped from the current into the structure, and puts it in a self-sustained oscillation. The only difference between torsional galloping and flutter is that galloping has only 1 DOF with relatively high amplitudes, which can be either angular or transversal oscillation.

Basically, torsional galloping is a destructive and robust phenomenon for the structures. The robustness of this phenomenon was the main cause of Tacoma Narrows Bridge collapse in 1940 [12]. It was proved that this event was the outcome of the torsional instability, and occurred due to negative damping in torsional DOF [13]. This study, however, reveals its capability to extract energy.

The energy extraction in this study is performed by converting the torsional oscillation of the flat plate to rotation, using a transmission system, and carrying out a physical work taking advantage of the rotary motion in order to measure the performance. The physical work here is to lift weight. The idea of lifting weight is a preliminary suggestion to approve the concept, whereas the expected vision of this research is to generate electricity. The experimental set-up and the results are presented in Section 2. Then, the torsional galloping thresholds are discussed in Section 3. It is followed by the energy extraction performance in Section 4. Finally, conclusions are made in Section 5.

2. Experimental tests

2.1. Experimental set-up

The experiments were conducted in the current flume of LOC (Laboratory of Waves and Currents) COPPE – Federal University of Rio de Janeiro. The current flume has 22 m length, 1.4 m width and 0.5 m depth, and the maximum current speed attainable in the flume is 0.5 m/s. Through the experiments, two aluminum made flat plates were utilized, each with different chord length ($c = 0.2$ *m* and $c = 0.3$ *m*). For these chord lengths, the maximum Reynolds numbers in the current flume are 10^5 and 1.5×10^5, respectively. The water depth was kept to be *0.45 m* in all the tests. The plates were free to rotate about their elastic axis, which was kept in the mid-chord length of the flat plates. The elasticity for the flat plates was provided by torsion springs. Several torsion springs were utilized to assess the effect of the stiffness on energy extraction performance. The spring coefficients were obtained through calibration tests done in LOC.

In order to find the damping ratios some decay tests were conducted in the air; once without the transmission system in order to find the structural damping ratio ζ_S, and once with the transmission system in order to find the damping ratio due to the transmission system ζ_T. Table 1 shows the estimated values for damping ratios ζ_S and ζ_T.

The instability observation tests were conducted, through which the flat plates were located into the current flume and exposed to the increasing current speed. The current speed was measured using an electronic flow meter. Also, a Qualisys motion capture system (2 Oqus cameras and the QTM software version 1.1) was set up to trace the angular oscillation of the flat plates. It was observed, then, that as the current speed exceeds a critical velocity, the flat plates become unstable and torsional galloping takes place. The instability observation test set-up is shown in Fig. 1, and the transition from the stable still condition to flow-induced instability is shown in Fig. 2. The observed instability, which leads to torsional galloping of the flat plate, is the basic principle of the hydropower extraction in this study.

The energy extraction tests were conducted by installing a transmission system on top of the flat plate to convert its torsional oscillation to rotation. The transmission system was designed and built in LOC. Fig. 3 shows a photograph and a front view schematic of the hydropower extraction test set-up. The energy extraction performance was assessed by measuring the physical work carried out through the rotary motion in the output of the transmission system. According to Fig. 3, the elastic axis is linked to the transmission system via the input shaft, and the output shaft rotates. A sheave is connected to the output axis which twists a string. The physical work is to lift a weight up to a prescribed height ($z = 2.2$ m). The weight connected to the string is lifted up as the sheave keeps turning. During the hydropower extraction tests several weights were lifted up, in a constant current speed (U) of 0.5 m/s and the depth (h) of 0.45 m.

Basically, the uncertainties in the measurements come from three sources; experimental set-up, the data acquisition devices, and truncation error which is not taken into account in the present

Table 1
Damping ratios.

ζ_S	ζ_T
0.100	0.118