Mechanical Systems and Signal Processing 98 (2018) 1097–1115

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Design and experiment of controlled bistable vortex induced vibration energy harvesting systems operating in chaotic regions

B.H. Huynh [a], T. Tjahjowidodo [b,*], Z.-W. Zhong [b], Y. Wang [c], N. Srikanth [d]

[a] Energy Research Institute at NTU, Interdisciplinary Graduate School, Nanyang Technological University, Singapore 639798, Singapore
[b] School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore
[c] School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore
[d] Energy Research Institute at NTU, Nanyang Technological University, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 24 November 2016
Received in revised form 25 April 2017
Accepted 4 June 2017
Available online 12 June 2017

Keywords:
Chaotic responses
Bistable spring
Vortex induced vibrations (VIV)
Energy harvesting
Wake oscillator model
Poincaré map
OGY controller

ABSTRACT

Vortex induced vibration based energy harvesting systems have gained interests in these recent years due to its potential as a low water current energy source. However, the effectiveness of the system is limited only at a certain water current due to the resonance principle that governs the concept. In order to extend the working range, a bistable spring to support the structure is introduced on the system. The improvement on the performance is essentially dependent on the bistable gap as one of the main parameters of the nonlinear spring. A sufficiently large bistable gap will result in a significant performance improvement. Unfortunately, a large bistable gap might also increase a chance of chaotic responses, which in turn will result in diminutive harvested power.

To mitigate the problem, an appropriate control structure is required to stabilize the chaotic vibrations of a VIV energy converter with the bistable supporting structure. Based on the nature of the double-well potential energy in a bistable spring, the ideal control structure will attempt to drive the responses to inter-well periodic vibrations in order to maximize the harvested power.

In this paper, the OGY control algorithm is designed and implemented to the system. The control strategy is selected since it requires only a small perturbation in a structural parameter to execute the control effort, thus, minimum power is needed to drive the control input. Facilitated by a wake oscillator model, the bistable VIV system is modelled as a 4-dimensional autonomous continuous-time dynamical system.

To implement the controller strategy, the system is discretized at a period estimated from the subspace hyperplane intersecting to the chaotic trajectory, whereas the fixed points that correspond to the desired periodic orbits are estimated by the recurrence method. Simultaneously, the Jacobian and sensitivity matrices are estimated by the least square regression method. Based on the defined fixed point and the linearized model, the control gain matrix is calculated using the pole placement technique. The results show that the OGY controller is capable of stabilizing the chaotic responses by driving them to the desired inter-well period-one periodic vibrations and it is also shown that the harvested power is successfully improved. For validation purpose, a real-time experiment was carried out on a computer-based forced-feedback testing platform to validate the

* Corresponding author.
E-mail address: ttegoeh@ntu.edu.sg (T. Tjahjowidodo).

http://dx.doi.org/10.1016/j.ymssp.2017.06.002

applicability of the controller in real-time applications. The experimental results confirm the feasibility of the controller to stabilize the responses.

1. Introduction

Vortex induced vibration (VIV) is a fluid-structure interaction phenomenon that can be observed in many engineering structures undergoing fluid flows, e.g. risers, pipes, chimneys, suspended cables, mooring lines, etc. In some cases, VIV is an undesired phenomenon when the induced tremendous kinetic energy may result in disastrous fatigue damage of structures. The collapse of Tacoma Narrows Bridge in 1940 is one of the most notorious examples of the incidents. Nevertheless, it has also been realized that plentiful source of energy can be harvested and converted into other utilizable forms of energy from a structure undergoing the phenomenon. The first energy converter based on VIV from water flows was introduced in 2008 and trademarked as VIVACE [1]. The working principle of this energy converter is rather straightforward. The main component of the converter in a form of circular cylinder is transversely immersed into a water flow. The cylinder is supported by elastic springs, where its motions are constrained in one degree-of-freedom, i.e. translation in the cross-flow direction. When the water flow crosses over the cylinder, due to the flow separation, water vortices are formed and alternately shed into two sides of the wake region. The vortex shedding consequently causes periodic drag and lift forces on the cylinder surface. Since the cylinder is constrained in the cross-flow direction, it will vibrate under the effect of the lift force. Connecting the structure to a transmission mechanism to convert the kinetic energy to electrical energy allows us to utilize the harvested energy.

The ability to operate efficiently in low velocity water flows is a prominent advantage of the VIV energy converter whereas other types of energy converters, e.g. turbines and watermills, require flow velocities higher than 2 m/s for efficient operations [1]. The induced fluid force excites the VIV structure at the vicinity of its resonance frequency, where the frequency of excitation corresponds to the water flow velocity. Therefore, if the VIV structure is designed with a natural frequency that corresponds to the flow characteristic, it can operate effectively, even in low water flows. The relations of the induced fluid forces, flow velocities and resonance range have been comprehensively studied and reviewed in literature (see e.g. [2–4]). Unfortunately, velocities of natural flows, e.g. ocean and river, might fluctuate. For example, based on a flow measurement at the marine test bed facility of Energy Research Institute at Nanyang Technological University located at the Sentosa Boardwalk, Singapore, the flow velocities fluctuate in the range of 0.1–1.2 m/s in day duration [5]. Meanwhile, the VIV energy converter operates efficiently only at a limited flow range depending on the designed parameters, i.e. the support stiffness, effective mass, damping and length of the cylinder. The variation of the water flow velocity beyond the resonance range will result in a poor performance of the converter since considerable amount of vibrational energy cannot be maintained. This adversity is the most challenging barrier for the practical application of VIV energy converters.

Since this issue was revealed, several theoretical and experimental studies have been carried out to improve the performance of a VIV energy converter. They focused on investigating effects of designing parameters including mass, damping, stiffness and surface roughness of the cylinder to improve the vibrating amplitude and broaden the resonance range. A comprehensive review on these studies can be found in [6]. In particular, an apparent benefit from embedding a nonlinear stiffness to a VIV system has been demonstrated in several studies. Experimental studies have been conducted to prove that a hardening stiffness factor has the ability to broaden the resonance range of a VIV energy converter towards the side of high velocity flows [7–9], while theoretical and experimental analyses in [10,11] have indicated that a VIV energy converter enhanced by a bistable spring will improve the resonance range at low velocity flows. The improvement of the performance in the latter case is resulted from the vibrations of the system in the inter-well mode of a bistable oscillator, which in turn allows for larger vibrating amplitude than that with a linear spring. However, it is also shown in these studies that chaotic vibrations (see e.g. [12,13] for more discussions on chaotic vibrations) may occur and lead to a significant drop in the utilizable power at various water flows and diverse ranges of structural parameters, i.e. structural damping, effective mass and bistable gap. In some cases, when a bistable system exhibits chaotic behavior, its utilizable power can drop below 40% of that in the case with a linear spring.

The theoretical and experimental analyses in [10] provide detailed study on the bifurcation of a bistable VIV energy converter from periodic to chaotic responses and vice versa, as well as the evolution of chaotic degree as a function of the bistable gap and structural damping. According to this information, chaotic responses can be avoided when the bistable VIV converter is designed with a small bistable gap, i.e. smaller than the value of $0.05D$, where D is the diameter of the cylinder. However, the desired effect in improving the utilizable power from the bistable spring is becoming minor in a case of a small bistable gap. On the other hand, if the bistable gap is increased, the chaotic responses might appear that will result in a significant power reduction at high water flows. Even though at an excessive large bistable gap, i.e. larger than $0.5D$, chaotic responses are less likely to occur, the inter-well vibrations are hardly maintained and the improvement in the performance by means of the introduction of the bistable spring will not be acquired. In addition, the paper also reported that a high damping value imposed to the system can eliminate the chaotic vibrations. Unfortunately, an excessively high damping value can diminish the vibrating amplitude and, thus, lower energy to be harvested.