Journal of Fluids and Structures 70 (2017) 390–402

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Energy harvesting from galloping of prisms: A wind tunnel experiment

Pascal Hémon[a,*], Xavier Amandolese[a,b], Thomas Andrianne[c]

[a] LadHyX, Ecole Polytechnique – CNRS, 91128 Palaiseau Cédex, France
[b] Conservatoire National des Arts et Métiers, Paris, France
[c] Aerospace and Mechanical Engineering Department, University of Liège, Allée de la Découverte, 9 Quartier Polytech 1, B52/3, 1, Liège 4000, Belgium

ARTICLE INFO

Keywords:
Galloping
Flutter
Energy harvesting
Wind tunnel

ABSTRACT

We study the energy harvesting from the galloping oscillations of rigid prisms flexibly mounted in a wind tunnel. A square section and a 2/3 rectangular section are tested and the inclination angle of the prisms referred to the flow direction is optimally adapted. The energy harvester is based on magnets moving with the prism in the front of a coil-core at rest. Energy is dissipated in a load resistance for which an optimal value is found. Efficiency of the "prism wind turbine" is weak compared to usual wind turbine due to the physics of the galloping mechanism. However such systems remain interesting for their potential of adaptation to various situations.

1. Introduction

Galloping is a dynamic instability affecting slender structures submitted to a cross flow. It is generally referred to be a one degree of freedom instability, in transverse or torsional motion, for which the motion-induced fluid loading creates a negative added damping that can trig the instability beyond a critical velocity (Païdoussis et al., 2011). As pointed out by Blevins (2001), slender structures with non-circular bluff cross sections are all susceptible to transverse galloping. It is then a matter of great concern in civil and offshore engineering for which bluff structures are submitted to wind and/or water current. Recently the idea emerged that the galloping phenomenon could be used for designing an energy harvester from wind or water current.

The literature on transverse galloping is important and one can find the most significant references in the book of Blevins (2001), the paper of Parkinson (1989) and the recent book of Païdoussis et al. (2011). Energy harvesting from transverse galloping has been previously studied analytically by Barrero-Gil et al. (2010) and Vicente-Ludlam et al. (2014). In the latter, an energy harvesting device model is coupled with a simple galloping non-linear model. Recently, Kiwata et al. (2016) used various cantilevered prisms in a water channel in order to extract energy with a iron-gallium alloy setup. They found that the global efficiency is very small with a maximum of 0.045%, which is much lower than the analytical results proposed by Vicente-Ludlam et al. (2014).

In that context, the objective of this paper is to evaluate and discuss the energy harvesting potential of the galloping mechanism in air with square and rectangular prisms. Although square and rectangular sections may not be the most efficient shapes for harvesting energy, this experimental contribution could allow to improve the mathematical models and assess the performances from a wind engineering point of view.

The paper is organized as follows: after a short review of galloping, the experimental methodology regarding the measurements, galloping section model set-up, and energy harvesting methodology are presented in Section 3. Galloping results and energy

* Corresponding author.
E-mail address: pascal.hemon@ladhyx.polytechnique.fr (P. Hémon).

http://dx.doi.org/10.1016/j.jfluidstructs.2017.02.006
Received 23 June 2016; Received in revised form 2 February 2017; Accepted 13 February 2017
0889-9746/

Nomenclature

A	non dimensional response amplitude of the prism (RMS), $A = Z_{RMS}/D$
B, D	dimensions of the prism section (m)
C_l, C_d	lift and drag coefficients
C_Z	transverse force coefficient
C_Z'	derivative of transverse force coefficient (rad^{-1})
F_Z	aerodynamic transverse force on the prism (N)
f	natural frequency of motion (Hz)
k	stiffness of the elastically supported prism (N/m)
k_E	electromechanical coupling coefficient
L	inductance of the energy harvester (H)
M	total mass of the prism (kg)
m	mass per unit length of the prism (kg/m), $m = M/S$
P_e	electric power (W)
P_g	maximum power available by galloping oscillations (W)
P_w	wind power (W)
R	load resistance (Ω)
R_L	coil resistance (Ω)
Re	Reynolds number
S	span of the prism (m)
S_c	Scruton number, S_c=2$m\eta/\rho BD$
U	mean velocity (m/s)
U_a	apparent velocity (m/s)
U_c	critical velocity (m/s)
U_r	reduced velocity, U_r=U/fD
$V(t)$	load voltage (V)
$Z(t)$	vertical displacement of the prism (m)
θ_0	rotation angle of the prism (°)
μ	efficiency (%)
η	reduced structural damping, referred to critical damping (%)
η_a	reduced aerodynamic damping, referred to critical damping (%)
η_E	reduced electromechanical damping, referred to critical damping (%)
ρ	air density (kg/m^3)
ω	angular frequency of motion (rad/s)

harvesting results are reported in Section 4. Finally, energy harvesting efficiencies are discussed in Section 5.

2. Short review of the galloping phenomenon

The basic mechanism of transverse galloping was first analysed by Den Hartog in 1934 (Den Hartog, 1985), in the context of transmission line vibration when sleet is found on the wire. In his pioneer work, Den Hartog proposed a quasi-static criterion for the onset of this damping driven instability. It is briefly recalled here, following the presentation of Novak (1969) and Blevins (2001) and considering the section model notation that is used in the present study.

Consider a prismatic cross section, Fig. 1, flexibly mounted in order to allow a single degree of freedom motion, Z(t), perpendicularly to a steady flow characterized by a velocity U. The equation of motion is given by (1)

$$\ddot{Z}+2\omega\eta\dot{Z}+\omega^2 Z=\frac{1}{M}F_Z, \tag{1}$$

where M is the mass of the prism,ω its natural frequency, η its damping ratio due to dissipation in the spring-supported setup and F_Z is the transverse aerodynamic force.

Assuming that the fluid force acting on the system is quasi-static, *i.e.* function of the instantaneous apparent velocity seen by the prism, one can express F_z as

$$F_Z=\frac{1}{2}\rho U_a^2 SD\,[C_l(\theta_0+\theta)\cos\theta+C_d(\theta_0+\theta)\sin\theta], \tag{2}$$

where the apparent velocity is the sum of the cross flow velocity and the motion-induced velocity. Its square value and relative angle of attack θ are then defined as

$$U_a^2=\mathrm{U}^2+\dot{Z}^2 \text{ and } \quad \theta=\tan^{-1}(-\dot{Z}/\mathrm{U}). \tag{3}$$

In Eq. (2) ρ is the fluid density, C_l and C_d are the lift and drag force coefficient in and transverse to the direction of the

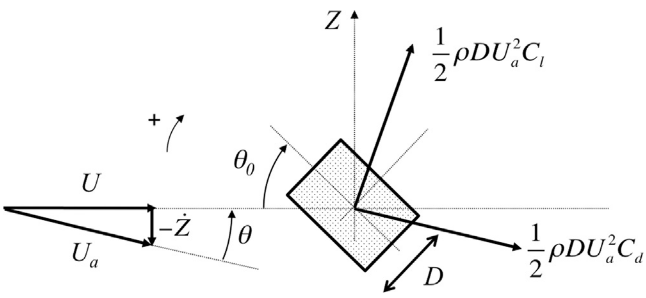

Fig. 1. Cross-section galloping model for one-degree-of-freedom transverse motion.