



# Energy harvesting from galloping of prisms: A wind tunnel experiment



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## 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

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Nomenclature			
$A$	non dimensional response amplitude of the prism (RMS), $A = Z_{RMS}/D$	$R_L$	coil resistance ( $\Omega$ )
$B, D$	dimensions of the prism section (m)	$Re$	Reynolds number
$C_l, C_d$	lift and drag coefficients	$S$	span of the prism (m)
$C_Z$	transverse force coefficient	$S_c$	Scruton number, $S_c=2m\eta/\rho BD$
$C_Z'$	derivative of transverse force coefficient ( $\text{rad}^{-1}$ )	$U$	mean velocity (m/s)
$F_Z$	aerodynamic transverse force on the prism (N)	$U_a$	apparent velocity (m/s)
$f$	natural frequency of motion (Hz)	$U_c$	critical velocity (m/s)
$k$	stiffness of the elastically supported prism (N/m)	$U_r$	reduced velocity, $U_r=U/fD$
$k_E$	electromechanical coupling coefficient	$V(t)$	load voltage (V)
$L$	inductance of the energy harvester (H)	$Z(t)$	vertical displacement of the prism (m)
$M$	total mass of the prism (kg)	$\theta_0$	rotation angle of the prism ( $^\circ$ )
$m$	mass per unit length of the prism (kg/m), $m = M/S$	$\mu$	efficiency (%)
$P_e$	electric power (W)	$\eta$	reduced structural damping, referred to critical damping (%)
$P_g$	maximum power available by galloping oscillations (W)	$\eta_a$	reduced aerodynamic damping, referred to critical damping (%)
$P_w$	wind power (W)	$\eta_E$	reduced electromechanical damping, referred to critical damping (%)
$R$	load resistance ( $\Omega$ )	$\rho$	air density ( $\text{kg/m}^3$ )
		$\omega$	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,  $\omega$  its natural frequency,  $\eta$  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

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

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  $\theta$  are then defined as

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

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

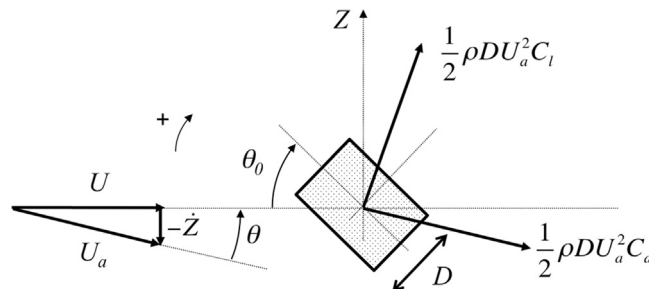


Fig. 1. Cross-section galloping model for one-degree-of-freedom transverse motion.

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