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Optimal electromagnetic energy extraction from transverse galloping

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ABSTRACT

A fully coupled electro-fluid-elastic model for electromagnetic energy harvesting from Transverse Galloping is presented here. The model considers a one degree-of-freedom galloping oscillator where fluid forces are described resorting to quasi-steady conditions; the electromagnetic generator is modelled by an equivalent electrical circuit where power is dissipated at an electrical load resistance; the galloping oscillator and the electromagnetic model are coupled appropriately. Two different levels of simplification have been made depending on the comparison between the characteristic electrical and mechanical timescales. The effect of the electrical resistance load on the energy harvested is studied theoretically. For fixed geometry and mechanical parameters, it has been found that there exists an optimal electrical resistance load for each reduced velocity. On the practical side, this result can be helpful to design tracking-point strategies to maximize energy harvesting for variable flow velocity conditions.

1. Introduction

In recent years, Flow-Induced Vibrations like Vortex-induced Vibrations (VIV), Transverse Galloping (TG) oscillations or Flutter have been considered as a new mean to harvest energy from fluid flows (Bernitsas et al., 2008; Barrero-Gil et al., 2010, 2012; Sanchez-Sanz et al., 2009; Grouthier et al., 2013; Abdelkefi et al., 2013; Doare and Michelin, 2011; Allen and Smits, 2001, to name only a few). The basic idea is to take advantage of these phenomena to convert part of the kinetic energy of the flow into oscillatory mechanical energy of the elastic body; thereafter, the mechanical energy of the body may be converted into electrical energy by electromagnetic, piezoelectric, or electrostatic means.

TG potential for energy harvesting has been recently investigated theoretically, numerically, and experimentally by Barrero-Gil et al. (2010), Abdelkefi and co-workers (2012, 2013), Sirohi and Mahadik (2011), or Zhao et al. (2012). Briefly outlined, it can be said that TG is a fluid-elastic instability that appears in some elastic bluff bodies when the velocity of the incident flow exceeds a critical value. Then, a small transverse displacement of the body induces an angle of attack relative to the incoming flow and a fluid force appears in the direction of the displacement in such a way that energy is pumped from the current to the body. Oscillatory motion (transverse to the flow) develops with an increasing amplitude until the energy dissipated per cycle by mechanical damping balances the energy input per cycle from the flow. If the geometry of the body and the elastic properties are appropriate, the instability may appear at low flow velocities and with large excitation

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amplitudes, making TG a very promising way to harvest energy successfully. For an authoritative introduction to TG phenomenology and modelling, the reader is referred to Parkinson (1989), or the books by Blevins (1990), Naudascher and Rockwell (1994), or Païdoussis et al. (2011).

Barrero-Gil et al. (2010) developed a theoretical model to study TG potential for energy harvesting. They considered a one degree of freedom model to describe galloping oscillations and a quasi-steady approximation to describe TG fluid forces. They found analytically the dependence of the energy transferred from the flow to the galloping body as a function of the main governing parameters, namely the mass ratio (i.e. the ratio of the mean density of the galloping body with respect to the density of the surrounding flow), the mechanical damping, the fluid flow velocity, and the geometry of the body. For the sake of simplicity, they just considered a generic viscous damper to dissipate the energy pumped from the flow. Here, a forward step is presented in order to model the TG dynamics when an electromagnetic generator is used to produce electrical current which is dissipated at a generic electrical load resistance. To this end, the model presented at Barrero-Gil et al. (2010) is now coupled with a mathematical model of the electromagnetic generator.

As will be shown in detail later, the electrical generator model may be simplified to a large extent, allowing an analytical solution, if the characteristic electrical timescale of the electromagnet generator T_E is much shorter than the characteristic timescale of galloping oscillations T_N ($T_E \ll T_N$). However, a perturbation approach has also been developed in order to gain deeper understanding of the dynamics when $(T_E/T_N) < 1$ and the inductance of the electromagnetic generator plays a role. In both cases, the effect of the electrical resistance load on the energy harvested is studied theoretically. For fixed geometry of the galloping body and mechanical parameters, it has been found that there exists an optimal electrical resistance load that maximizes the energy harvested for each flow velocity. From the practical side, this result can be helpful when designing some tracking-point strategy to maximize energy harvesting for changing flow velocity conditions.

First of all, in Section 2, an electro-fluid-elastic model is introduced to describe the coupling between the galloping body and the electromagnetic generator dynamics. Section 3.1 presents and discusses analytical results for the most simplified situation ($T_E \ll T_N$), whereas Section 3.2 is devoted to studying the case when the disparity of electrical and mechanical timescales is not so large but $(T_E/T_N) < 1$. In this case, a perturbation approach is introduced to make an analytical treatment. Finally, Section 4 presents some concluding remarks.

2. Mathematical model

Let us consider a simplified dynamical system which consists of a spring-mounted prismatic body, prone to galloping, in an incoming flow. The assembly can be better understood in Fig. 1(a). As it can be seen, the system is composed of a viscous parasite damper, with constant damping per unit length c, a linear spring, with constant stiffness per unit length k, and the electromagnetic generator used as energy harvester, where the magnet is linked to the prism, so it oscillates relative to the coil producing electricity which is dissipated in an electrical resistive load R_L. The prism has a mass per unit length of m and is restricted to move in the y direction (transverse to the incident flow).

Appropriate balance between inertia, damping, stiffness, electromechanical, and fluid forces in the system gives the following ordinary differential equation:

$$m\ddot{y} + c\dot{y} + ky = \frac{1}{2}\rho U^2 D C_Y - F_{FEM}, \quad (1)$$

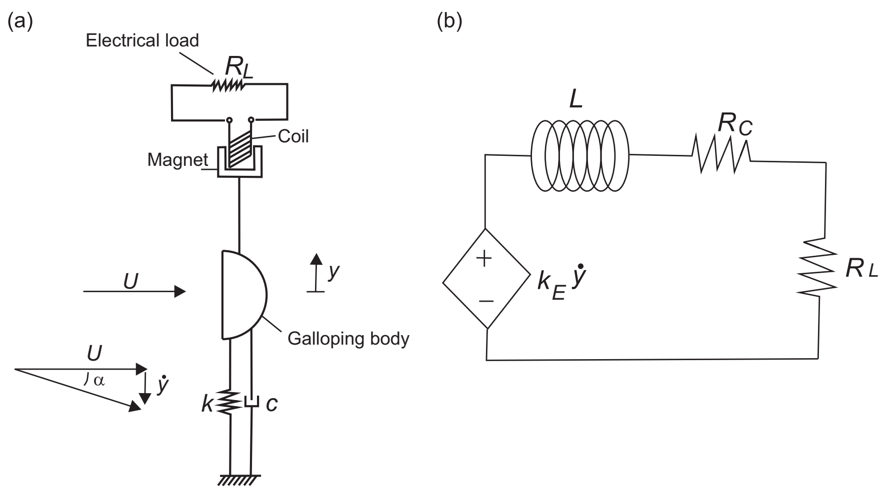

Fig. 1. (a) Sketch of the spring-mounted galloping body in cross-flow and linked to an electromagnetic generator. (b) Equivalent electrical circuit of the electromagnetic generator.