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Electro-hydrodynamic synchronization of piezoelectric flags

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ABSTRACT

Hydrodynamic coupling of flexible flags in axial flows may profoundly influence their flapping dynamics, in particular driving their synchronization. This work investigates the effect of such coupling on the harvesting efficiency of coupled piezoelectric flags, that convert their periodic deformation into an electrical current. Considering two flags connected to a single output circuit, we investigate using numerical simulations the relative importance of hydrodynamic coupling to electrodynamic coupling of the flags through the output circuit due to the inverse piezoelectric effect. It is shown that electrodynamic coupling is dominant beyond a critical distance, and induces a synchronization of the flags' motion resulting in enhanced energy harvesting performance. We further show that this electrodynamic coupling can be strengthened using resonant harvesting circuits.

1. Introduction

Piezoelectric materials draw from their internal structure their fundamental ability to generate a net charge displacement when they are deformed and to respond mechanically to an electric forcing. This two-way electro-mechanical coupling may be exploited to convert the mechanical energy of a vibrating structure into electrical form, and has become increasingly popular to design energy harvesters based on ambient vibrations (Allen and Smits, 2001; Sodano et al., 2004; Anton and Sodano, 2007; Erturk and Inman, 2011; Caliò et al., 2014).

Such systems critically depend on existing or forced vibrations of the structure. The concept can nevertheless be extended to harvest energy from a steady flow by exploiting fluid–solid instabilities to generate self-sustained motions of a solid body (see for example Xiao and Zhu, 2014). The spontaneous flapping of thin deformable plates in axial flow beyond a critical flow velocity is another example, commonly referred to as the flag instability (see Shelley and Zhang, 2011, for a recent review). This instability has been the focus of intense recent investigations to understand the impact of energy extraction on the flapping dynamics (Singh et al., 2012) and assess the energy harvesting performance when the flag's deformation is converted into electric energy using piezoelectric and other electroactive materials covering the flag's surface (Dunnmon et al., 2011; Giacomello and Porfiri, 2011; Akcabay and Young, 2012; Michelin and Doaré, 2013; Pineirua et al., 2015).

Much of the work on piezoelectric flags has so far focused on single flags connected with simple circuits, such as pure resistors, to understand the effect of the fluid–solid–electric coupling on the system's stability and the energy transfers between the fluid, solid and electrical components (Dunnmon et al., 2011; Doaré and Michelin, 2011; Akcabay and Young, 2012). Michelin and Doaré (2013) further showed that the flapping amplitude and frequency of a piezoelectric flag can be

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significantly modified by the extraction of energy and coupling to the dynamical properties of the output circuit even for a purely resistive output. Using a resonant circuit, Xia et al. (2015a) reported a frequency lock-in phenomenon that considerably increases the flag's flapping amplitude and efficiency: during lock-in, the flapping frequency of the flag is dictated by the circuit to match its resonance frequency therefore enabling large voltage and energy transfers to the output load.

Because of its material properties, a single piezoelectric harvester is still characterized by its small power output (Sodano et al., 2004; Anton and Sodano, 2007). One potential solution to this problem is to combine multiple devices in order to produce the required power. For flapping flags, however, the placement in close proximity of multiple flapping structures significantly modifies their flapping dynamics, and hydrodynamic synchronization as well as modification of the flapping amplitude and frequency have been reported in multiple recent studies (Schouveiler and Eloy, 2009; Alben, 2009b; Michelin and Llewellyn Smith, 2009, 2010; Mougel et al., 2016).

Depending on their relative positioning, two side-by-side flags may flap in-phase (with identical vertical displacements), or out-of-phase (with opposite vertical displacement) (Zhang et al., 2000; Zhu and Peskin, 2003). More complex synchronization was also identified in numerical simulations for both side-by-side and tandem flags (Alben, 2009b; Tian et al., 2011). The synchronization of the flags can modify their individual dynamical properties and their individual performance as energy harvesters. Furthermore, if the flags are to be connected electrically to a single device, for example to increase the available power, the relative phase and amplitude of the generated signals, directly related to their mechanical dynamics, will be critical: the electric interaction might be constructive (resp. destructive) if both signals are in-phase (resp. out-of-phase). Hydrodynamic coupling therefore influences the efficiency of flags that are electrically isolated (Song et al., 2014). Finally, the inverse piezoelectric effect introduces a feedback forcing on the flags' dynamics by the electrical circuit: when multiple flags are connected to the same output loop, this introduces an additional electrodynamic coupling that competes with hydrodynamic effects in setting the relative phase and dynamical properties of the flapping motion.

The motivation for the present work is therefore to investigate the role and relative weight of these different coupling mechanisms and the resulting harvesting efficiency of coupled piezoelectric flags. To this end, we focus on the system consisting of two flags placed side-by-side in an axial flow and connected to a single output circuit, a simple fluid–solid–electric system which provides physical insight on the hydro- and electro-dynamic couplings and performance of a two-flag assembly. In Section 2, the models used to describe the fluid-solid-electric dynamics are presented. Section 3 analyses the relative importance of hydrodynamic and electrodynamic coupling in synchronizing the flags' motion. The role of the output circuit is then discussed in Section 4. Finally, conclusions and perspectives are presented in Section 5.

2. Fluid–solid–electric model

We consider here two piezoelectric flags placed side by side in an axial flow. The flapping dynamics of these structures are coupled both hydrodynamically (each flag modifies the flow field experienced by the other one) and electrodynamically (both flags are connected to the same output circuit). A schematic representation of the coupled system is shown in Fig. 1.

2.1. Piezoelectric flags modeling

Both piezoelectric flags are clamped side-by-side from their leading edge and placed in an axial fluid flow of density ρ_f and velocity U_∞ at a distance D from each other. Both flags are infinitely thin and have a span-wise dimension H much larger than their stream-wise length L, so that the flags' and fluid's motions are purely two-dimensional. Each flag is entirely covered by a single pair of piezoelectric electrodes shunted through the flag with reverse polarity. The piezoelectric material is characterized by an electromechanical coefficient $\chi = e_{31}h/2$, with h the thickness of the piezoelectric flag and e_{31} the reduced piezoelectric coupling coefficient (Erturk and Inman, 2009), and an intrinsic capacitance $\mathcal{C}$. The resulting three-layer plate has bending rigidity B per unit length and mass per unit area μ. In the following, the problem is non-dimensionalized using L, L/U_∞, μL^2 and $U_\infty\sqrt{\mu L/\mathcal{C}}$ respectively as characteristic length, time, mass and voltage scales. Fluid forces are naturally scaled by ρU_∞^2.

The deformation of flag i ($i=1,2$) induces a charge displacement Q_i within the corresponding piezoelectric pair, driven by the change in the patches' length. For a thin patch positioned on an inextensible flag, it is determined by the relative orientations of the flag centerline at both ends of the patch (Doaré and Michelin, 2011). Here, the entire flag is covered by a single pair and the leading edge is clamped: noting $\Theta_i(s)$ the flag's orientation with respect to the flow direction, the charge displacement is therefore completely determined by $\Theta_i(s = L)$. For the i-th flag ($i=1,2$), the charge displacement Q_i is then given by (Ducarne et al., 2012)

$$Q_i = \frac{\alpha}{U^*}\Theta_i(s = L) + V_i, \tag{1}$$

where V_i is the voltage across the piezoelectric pair of flag i, and α and U^* are the piezoelectric coupling coefficient and relative velocity of the fluid flow and of structural bending waves, respectively defined as:

$$\alpha = \chi\sqrt{\frac{L}{B\mathcal{C}}}, \quad U^* = U_\infty L\sqrt{\frac{\mu}{B}}. \tag{2}$$