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# Galloping instability and control of a rigid pendulum in a flowing soap film

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ABSTRACT

A pendulum suspended in a fast flowing soap film may show sustained oscillations. The conditions necessary for self-excited motion to occur are outlined: a flow velocity above a threshold value along with geometrical constraints. The role of vortex shedding is discussed, and the observed instability is shown to be well-described by the galloping instability. Experimental results are supported by numerical simulations. Furthermore, we observe that the instability may be suppressed by attaching a long enough filament to the rear of the pendulum.

## 1. Introduction

The problem of fluid–structure interaction is a highly practical issue as its implications cover a great variety of phenomena, spanning from how organisms swim and harness the energy of diverse flows to the vibrations of vehicles such as a submarine in turbulent water or an airplane in turbulent air. This interaction may be desirable, as in the case of swimming organisms, or detrimental, since it may generate additional drag or cause excessive vibrations in a variety of practical flows and structures. Different approaches and methods have been applied to the study of this problem: experimental observation of swimming strategies of different organisms; numerical simulations of flapping flags; investigation of vortex-induced vibrations on structures of engineering interest, like bridges and airplanes (Spalart, 1998; Williamson and Govardhan, 2004; Shelley et al., 2005; Provansal et al., 2005; Lauga and Powers, 2009; Obligado et al., 2013).

When a flow interacts with rigid or flexible bodies, the resulting dynamics can be unsteady and exhibit an oscillatory behavior. In this situation, the possibility of harvesting energy from the flow becomes possible, e.g., by means of devices that convert mechanical energy into electric current (Allen and Smits, 2001; Boragno et al., 2012; Orchini et al., 2013). Many studies have focused on how a wake affects the shape of deformable structures such as a flexible surface (Allen and Smits, 2001) or a fish body (Liao et al., 2003). In the swimming fish case, an adaptation of the swimming strategy to the presence of vortices has been documented by Liao et al. (2003); even for a passive deformable object some passive propulsion has been observed by Beal et al. (2006). Besides its applicability, the fluid–structure interaction poses fundamental problems. For example, recent studies have outlined a symmetry breaking mechanism that, so far, has eluded our intuitive understanding of how flows affect the shape and conformation of flexible objects (Bagheri et al., 2012; Lacis et al., 2014).

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We investigate the stability of a system formed by coupling a pendulum-shaped rigid structure and a flowing soap film. Soap film flows being two dimensional, their use allows us to limit the number of degrees of freedom of the system, and to use common visualization and analysis techniques to investigate both the flow field and the embedded objects dynamics (Kellay et al., 1998; Kellay and Goldburg, 2002; Rutgers et al., 2001; Amarouchene and Kellay, 2005; Zhang et al., 2000). Fast flowing soap films have been widely used to study fluid–structure interactions in many different situations, e.g., the stability of flexible filaments both in the laminar (Zhang et al., 2000; Jia and Yin, 2008) and turbulent (Amarouchene and Kellay, 2005) regimes, or flag-like instabilities (Zhu and Peskin, 2002, 2003; Argentina and Mahadevan, 2004; Lemaitre et al., 2005). More recent experiments have shown the existence of sustained oscillations of light flexible pendulums due to the vortex shedding from the disk (Bandi et al., 2013). Two main differences characterize our analysis with respect to the one carried out by Bandi et al. (2013): the pendulums considered in this study are rigid and heavy, so that their weight always dominates over added mass effects. Under these conditions, we observe an instability in the quasi-two-dimensional fluid–structure system: for a range of geometrical parameters, and above a well-defined threshold velocity, the system is unstable, and, after a transient behavior, shows sustained, large amplitude, low-frequency oscillations. Although we have mentioned the possibility to harvest energy from the resulting oscillatory dynamics, in this work we will not discuss how the configuration can be optimized for this goal, but will only discuss the origin of the instability and how it can be controlled.

By means of experimental observations and with the aid of a simple analytical model, we show that this instability can be understood in terms of the galloping mechanism, which is characterized by oscillations in the direction transverse to the flow. Galloping arises depending on the slope of the moment coefficient of the structure versus the angle of attack: the latter property strongly depends on the detailed geometrical shape of the pendulum. Numerical simulations have been performed to validate the analytical model. Additional observations on the effects of a flexible filament attached to the rear of the pendulum are also reported. For short lengths, the instability persists, its amplitude does not change, and the filament and the pendulum oscillate in synchrony. However, when the length of the filament is larger than a threshold value, the galloping instability is inhibited and the rigid system comes to rest, whereas the flexible filament continues to flap.

## 2. Experimental setup

The experiments described in this paper were carried out in a soap film channel into which a rigid pendulum was embedded in the flow direction. To perform the experiments we used a vertical setup (see Fig. 1), as described by Kellay et al. (1995, 1998), Rutgers et al. (2001), and Kellay and Goldburg (2002).

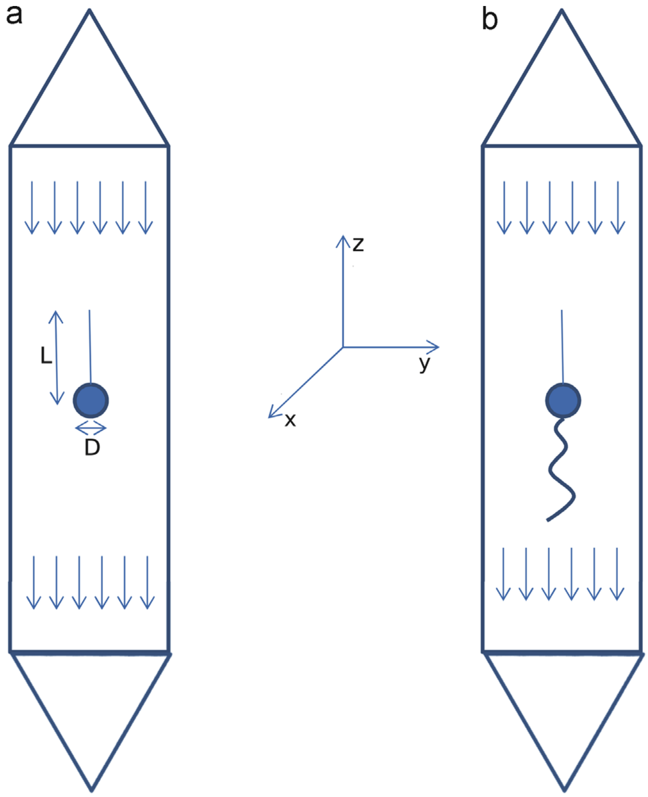

**Fig. 1.** Schematic of the soap film channel where the water–soap solution flows between two nylon wires. Soap water is injected at the top of the channel and the flow direction is indicated by arrows. (a) An embedded rigid pendulum Sections 3, 4, (b) rigid pendulum with a flexible filament attached Section 5.