Journal of Fluids and Structures 76 (2018) 527–535

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Coupled motion of two side-by-side inverted flags

Cecilia Huertas-Cerdeira *, Boyu Fan [1], Morteza Gharib

Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA 91125, USA

HIGHLIGHTS

- Two side-by-side inverted flags can couple in the flapping regime.
- Five modes are present: in-phase, anti-phase, staggered, alternating and uncorrelated.
- An increase in amplitude and frequency of flapping was observed.
- Flags of different lengths couple for small length differences.

ARTICLE INFO

Article history:
Received 20 June 2017
Received in revised form 6 October 2017
Accepted 14 November 2017

Keywords:
Inverted flag
Coupled dynamics
Synchronization

ABSTRACT

The interaction and coupling between two inverted flags that are placed side-by-side in a uniform flow is investigated in an effort to determine the behavior of systems that are formed by arrays of cantilevered plates. Inverted flags are elastic plates that are free to move at their leading edge and clamped at their trailing edge. We show that placing two inverted flags of equal dimensions side-by-side will cause their motion to couple. In-phase, anti-phase, staggered, alternating and decoupled flapping modes are present, with the anti-phase mode being predominant at small flag distances and low wind speeds. Increases both in amplitude and frequency of flapping are observed in the two flag system with respect to a single flag. Two side-by-side inverted flags of different lengths are found to interact for small length differences, with the longer flag being able to induce a motion on the shorter flag even when the latter is outside of its flapping wind speed range.

1. Introduction

The response of a flexible plate to an impinging flow has been the subject of a wide array of studies. From flexible leaflets in heart valves (Peskin, 1972) to flutter in paper processing (Watanabe et al., 2002) the interaction between thin sheet-like structures and a fluid is pervasive both in nature and engineering. These structures can present many different configurations depending on the boundary conditions of the plate, resulting in a large variety of behaviors. In particular, the flag configuration, where a thin elastic sheet is clamped to a pole and oriented in the direction of the flow, leaving a free trailing edge, has received recent attention (Shelley and Zhang, 2011). A number of engineering applications have arisen for the flag configuration, such as the use of its flapping motion to harvest energy from the wind (Taylor et al., 2001; Tang et al., 2009).

In nature, however, it is more often the case that flags present multiple orientations to the flow. Examples are the leaves of a tree, that are commonly found at varying angles to incoming wind. Considering this, Kim et al. (2013) studied an inverted flag configuration, where an elastic plate is free to move at its leading edge and clamped at its trailing edge. They found

---

* Corresponding author.
E-mail address: chuertas@caltech.edu (C. Huertas-Cerdeira).

[1] Present affiliation: Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA.

https://doi.org/10.1016/j.jfluidstructs.2017.11.005

the existence of three main dynamic regimes as the free stream velocity is increased: a small amplitude oscillation around the zero deflection position (straight regime), a large amplitude flapping motion (flapping regime) and a small amplitude oscillation around a deflected position (deflected regime). In the flapping regime the inverted flag experiences strains much larger than those of the conventional flag, making it particularly useful for energy harvesting (Gurugubelli and Jaiman, 2015). Kim et al. (2013) suggested, based on experimental observations, that this flapping motion is a vortex induced vibration. This conclusion has been numerically and theoretically verified by Gurugubelli and Jaiman (2015) and Sader et al. (2016a), respectively.

Our knowledge of vortex induced vibrations has advanced enormously in the past decades (for a review, see Williamson and Govardhan (2004)), with much of the literature being centered in the study of the vortex induced vibrations of cylinders. Interesting wake dynamics arise when two fixed stationary cylinders are immersed side-by-side in a flow (Zdravkovich (2003) and references therein). Depending on the separation between them, they have been shown to generate either a single vortex street, two wakes of different widths that present a bi-stable gap flow, two equal and synchronized wakes or two completely uncoupled wakes. In the case of cylinders that are flexible or allowed to move the coupling of the wakes can result in the coupling of the motion of the cylinders (Zdravkovich, 1985; Zhou et al., 2001; Liu et al., 2001; Huera-Huarte and Gharib, 2011).

Similarly, two conventional flags placed side-by-side in a flow have been shown to interact. Zhang et al. (2000) experimentally studied the motion of two side-by-side filaments immersed in a soap film and observed both an in-phase flapping mode for small flag separations and an anti-phase flapping mode for larger flag distances. The anti-phase mode was observed to oscillate with frequencies 35% higher than those of the in-phase mode. As the distance was further increased, the interaction weakened and the flags moved independently. Analogous results were obtained in numerical simulations by Zhu and Peskin (2003) and Farnell et al. (2004). Farnell et al. (2004), Si-Ying et al. (2013), Sun et al. (2016) observed, in addition to the in-phase and out of phase modes, the existence of a transition mode where the frequencies of both motions co-exist. A different transition mode was reported by Jia et al. (2007), who observed a region where in-phase and out-of phase flapping alternate randomly. In addition to two equal filaments, Jia et al. (2007) studied the motion of two side-by-side filaments whose length varied by a factor of two and observed synchronization with a scattering of the phase around the 0 and π values.

These interactions with neighboring flags and their vortex streets can cause variations in the forces experienced by the flags. Many natural organisms exploit the vortex street of neighboring bodies to enhance their performance; an example are schooling fish (Weihs, 1973). Inspired by this behavior, optimal arrangements of vertical axis wind turbines have been shown to increase energy extraction in wind farms (Whittlesey et al., 2010). Dong et al. (2016) showed that placing two flags side-by-side can produce increased energy extraction efficiency in a potential energy harvesting mechanism. It is expected that inverted flags will show a similar behavior, and placing several flags in close proximity may enhance their energy harvesting capabilities. Changes in phase between the swimming motion of adjacent fish can drastically change the effect of schooling (Weihs, 1973). This implies that in systems such as flags, where the phase between flags is determined by their relative position, the presence and arrangement of surrounding flags plays a double role and is particularly significant.

The purpose of this study is to experimentally investigate the coupling of the motion of two inverted flags when placed in a side-by-side arrangement. Because the amplitudes of oscillation of the inverted flag vary greatly between the different regimes of motion (straight, flapping and deflected), the effective cross-sectional area of the flag undergoes significant changes between them. This causes the synchronization in the motion of the flags to occur at very different flag separations for the different regimes. In this study we have focused on distances at which the flags never collide ($1.7 < T/L < 5.4$ with T the distance between flags and L the flag length), which are pertinent to the coupling of the vortex induced vibrations of the flags in the flapping and deflected regimes.

2. Experimental setup

The experiments were conducted in an open loop wind tunnel of test section 1.2 m × 1.2 m. A square array of 10 × 10 small fans generates uniform wind speeds between 2.2 m/s and 8.5 m/s. The turbulence intensity, measured using a hot wire probe, is under 8.2% for the range of wind speeds studied. The variation in wind speed across the cross section, caused by the multiplicity of fans, is smaller than 2.7%. A schematic of the setup is shown in Fig. 1a. The flags are made of polycarbonate (Young's modulus $E = 2.41$ GPa, Poisson ratio $\nu = 0.38$ and density $\rho_s = 1200$ kg m^{-3}) and have a thickness of $h = 0.254$ mm. They present initial edge deflections smaller than 5° due to the curvature induced by material defects. The flags will be labeled left flag and right flag throughout this article, corresponding to their position when the observer is located downstream of the flags. The first series of experiments was conducted with two flags of equal height $H = 150$ mm and length $L = 100$ mm. In the second series, the height of both flags, $H = 150$ mm, and the length of one of the flags, $L_0 = 100$ mm, were maintained constant, while the length of the second flag, L, was varied. The flags are clamped at their trailing edge by means of two aluminum bars of rectangular cross section of width 6 mm. They are clamped parallel to the flow, within 1° of the zero angle of attack. This error in the clamping angle, together with the initial curvature of the flag, introduce small variations in the motion of the flag (Cossé et al., 2014) and account for the majority of the variability in frequency and amplitude of flapping between the two equal flags. The bars are attached to a rail such that the distance between flags, T, can be varied and are placed vertically such that the deformation of the sheet is primarily in the horizontal plane, with no twisting due to gravity being observed. The motion of the flags is recorded from above at 100 frames per