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Dynamics of a flag behind a bluff body

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A B S T R A C T

Flow-induced vibration of an elastic structure such as a flag has drawn attention recently because of its complicated coupling mechanisms and potential application to energy harvesting. For both air and water flows, we experimentally investigate the effect of an upstream bluff body on the dynamics of two types of a downstream flag, a conventional flag and an inverted flag, on and off a midline. In contrast to the conventional flag, the trailing edge of the inverted flag is clamped, and its leading edge is free to move. By using smoke visualization and particle image velocimetry, the interaction of the flag with the vortices shedding from the bluff body was also identified. With the deployment of a bluff body, the conventional flag displays two distinct periodic flapping modes. While synchronization with the vortices shedding from the bluff body and a resultant fundamental mode appear in a low free-stream velocity range for the conventional flag lying on the midline behind the bluff body, the conventional flag off the midline shows a second harmonic mode by flutter instability in a higher free-stream velocity range. Meanwhile, the inverted flag reveals both small-amplitude flapping mode by a lock-in process and large-amplitude flapping mode by divergence stability at a given location on the midline and farther from the bluff body. However, only large-amplitude flapping mode is observed for the inverted flag off the midline. Even though the critical free-stream velocity when the inverted flag starts large-amplitude flapping depends on its relative streamwise and crosswise positions, the flag in flapping mode exhibits similar maximum amplitude and frequency pattern regardless of its relative locations.

1. Introduction

In spite of a simple configuration, a flag experiences complicated physical processes in coupling between an external fluid force and a structural response (Shelley and Zhang, 2011). The stability and non-linear dynamics of a flag have been addressed by many theoretical, numerical and experimental studies (e.g. Watanabe et al., 2002; Connell and Yue, 2007; Eloy et al., 2011). With increasing interest in energy harvesting application, actual energy harvesting performance of a flapping flag has also been evaluated recently by modeling the energy conversion process of elastic strain energy to electric energy through a piezoelectric material (Dunnmon et al., 2011; Giacomello and Porfiri, 2011; Michelin and Doaré, 2013).

In contrast to a conventional flag configuration with a clamped leading edge and a free trailing edge, a flag with a free leading edge and a clamped trailing edge, *an inverted flag*, was recently introduced by Kim et al. (2013). Reversing a clamped position from a leading edge to a trailing edge completely changes the behaviors of a flag. In a low free-stream velocity, the inverted flag maintains a straight mode. However, when the free-stream velocity increases, the inverted flag suddenly starts flapping with a large flapping amplitude. The inverted flag flaps in a finite free-stream velocity range, and thereafter, the flag deflects onto one side and maintains a

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deflected mode. Sader et al. (2016) theoretically obtained non-dimensional free-stream velocity when the flapping motion of the inverted flag abruptly occurs as a function of aspect ratio and showed divergence stability mechanism independent of mass ratio. Numerical simulations were also used to study inverted flag dynamics and flow physics with consideration of bending rigidity and the Reynolds number (Gilmanov et al., 2015; Ryu et al., 2015; Gurugubelli and Jaiman, 2015). Furthermore, Shoele and Mittal (2016) conducted computational investigation on the energy harvesting performance of a piezoelectric inverted flag model by varying an initial inclination angle.

On the other hand, the effect of an upstream bluff body on the dynamics of a downstream thin elastic structure has been investigated recently. Vortices generated by an upstream rectangular plate induce periodic deformation of a downstream thin membrane, leading to a lock-in process, synchronization of vortex shedding frequency and oscillation frequency of the membrane (Allen and Smits, 2001). Akaydin et al. (2010) investigated the performance of a flexible cantilevered beam as an energy harvester behind an upstream cylinder and found that the harvesting performance was affected by the ratio of a shedding frequency to a flapping frequency of the beam and a relative position between the inverted beam and the upstream cylinder. In energy harvesting application, an upstream bluff body was also employed to enhance the efficiency of counter-rotating vertical-axis turbines (Kim and Gharib, 2013, 2014). In their studies, by placing a vertical-axis turbine in a high local velocity region outside the wake of the upstream bluff body, significant increase in power coefficient could be achieved.

In this study, we experimentally investigate the effect of an upstream flat plate on a downstream flag, either inverted flag or conventional flag, immersed in a uniform flow and compare their distinct flapping behaviors. The comparison of these two configurations in the same conditions has not been studied to the best of the authors' knowledge. Both air and water flows are considered in order to evaluate how fluid density affects the flag responses. In most studies on the interaction of a bluff body and a flexible structure, the structure was placed only on a midline behind the bluff body in order to cause the interaction with counter-rotating vortices periodically shedding from the bluff body (e.g. Allen and Smits, 2001; Akaydin et al., 2010). Here, we allocate a flag outside as well as inside a wake region and examine the response of the flag by varying free-stream velocity. Even though several geometric parameters such as the ratio of the upstream plate size to the flag length and the aspect ratio of the flag may be critical to fully understand complicated fluid-structure interaction, we will focus on the change of dynamic responses by mainly varying the relative position of the flag in both streamwise and crosswise directions.

2. Experimental setup

Overall schematics of the experimental setup are described in Fig. 1. Experiments were conducted in an open-loop wind tunnel of a suction type. The cross-section of the tunnel is 0.6 m high and 0.6 m wide. The free-stream velocity U used in this study is between 0.8 m/s and 10.0 m/s. As a flag model, we used a polycarbonate sheet (Young's modulus $E = 2.38 \times 10^9$ N/m^2, Poisson's ratio ν=0.38, and density ρ_s=1.2×10^3 kg/m^3). Length L and height H of the sheet were 15 cm and 20 cm respectively, providing aspect ratio $H/L = 1.33$. Those values were fixed throughout this study. We chose h=0.5 mm as sheet thickness, which was large enough to avoid sagging of the sheet by gravity. For a conventional flag configuration, the leading edge of the sheet was clamped vertically between two long aluminum bars whose width was 2 cm and thickness was 0.8 cm while its trailing edge was free. For an inverted flag configuration, the trailing edge of the sheet was clamped reversely.

In order to obtain images of the sheet, a white plastic tape was attached along the bottom edge of the sheet, and it was captured by a high-speed camera (MINI UX50 160K M1, Photron, Inc.) mounted below the bottom of the test section. The bottom edge of the sheet was illuminated by halogen lamps from both sides of the test section, and the upper side of the test section was covered with black papers to highlight the white line of the flag. Images were recorded at 50 frames per second with a shutter time 1/1600 s.

A rectangular aluminum plate of thickness 5 mm was used as an upstream bluff body (Fig. 1). The width of the plate was fixed at 5 cm, and the plate was vertically long enough to minimize the three-dimensional effects by the plate tip. Since the distance between the bluff body and the sheet is an important parameter to determine the response of a downstream sheet, we varied streamwise distance, D_x, from 5 cm to 40 cm, and crosswise distance, D_y, from 0 cm to 20 cm for the inverted flag experiments; the position of the bluff body was adjusted while the position of the flag was fixed. For the conventional flag experiments, we varied D_x from 5 cm to 30 cm along the midline and chose additional locations of non-zero D_y near the bluff body (D_y=5 cm and 10 cm). For both inverted and conventional flags, D_x is the distance between the bluff body and the leading edge of the sheet in the x-direction, and D_y is the distance between the center of the bluff body and the extended line of the initially straight sheet in the y-direction (Fig. 1). In order to visualize air flow around a flag and a bluff body, a smoke generator (Z-1000II, Antari, Ltd.) with FLG heavy fog liquid was used.

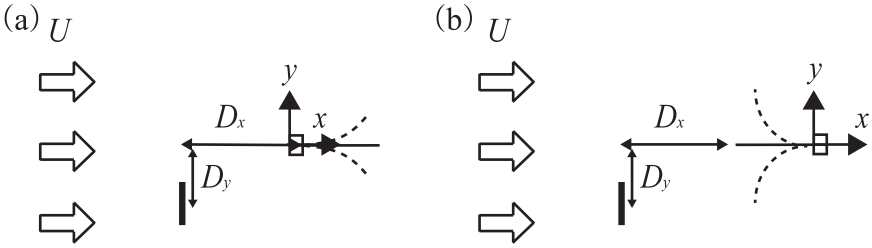

Fig. 1. Schematics of a clamped flag: (a) conventional flag and (b) inverted flag. Dashed curved lines are the shapes of the flag in flapping mode. D_x and D_y are streamwise and crosswise distances between an upstream plate (bluff body) and a flag, respectively.