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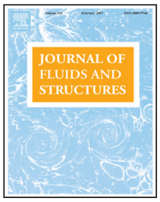

Dynamic response of a semi-free flexible filament in the wake of a flapping foil

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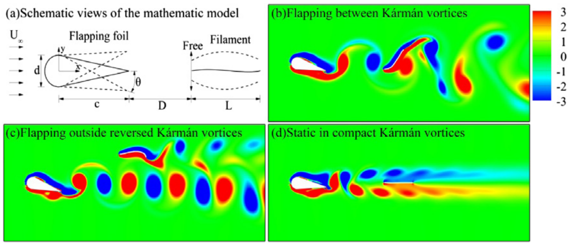
HIGHLIGHTS

- Three flapping states are observed for the filament in different vortex streets.
- The filament flaps between the vortices in the von-Kármán vortex streets.
- The filament flaps outside the vortices in the reversed von-Kármán vortex streets.
- The filament is static in the compact Kármán vortices.
- Vertical dipole-induced velocity and vortex transportation speed affect the states.

GRAPHICAL ABSTRACT

Three distinct flapping states are observed for the semi-free flexible filament in different vortex streets: flapping between Kármán vortices, flapping outside reversed Kármán vortices and static in compact Kármán vortices. Both the vertical dipole-induced velocity and the transportion speed of the vortices determine the filament's flapping motion. A significant drag reduction is obtained for the filament when flapping outside reversed Kármán vortices compared to flapping between vortices. Moreover, the pitching foil has decreased drag when the downstream filament is static.



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ABSTRACT

The passive response of a semi-free flexible filament in the wake of a flapping foil is studied numerically Three distinct flapping states are observed for the filament in different vortex streets: flapping between Kármán vortices, flapping outside reversed Kármán vortices and static in compact Kármán vortices. Both the vertical dipole-induced velocity and the transport speed of the vortices determine the filament's flapping motion. A significant drag reduction is obtained for the filament when flapping outside reversed Kármán vortices compared to flapping between vortices. The pitching foil has decreased drag when the downstream filament is static. These passive flapping motions of the filament in different wakes may be beneficial for achieving a better understanding of fish swimming mechanics and behaviors in schools.

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1. Introduction

Hydrodynamic interactions of two flapping bodies in fluid flows is interesting to biologists and physicists for several decades (Cushing and Jones, 1968; Larsson, 2012). The hydrodynamic interaction is crucial for understanding the intrinsic mechanism characterizing fish schools (Krebs, 1976) since each individual is swimming in the complex flow and altered by the other members (Liao, 2007). For example, a diamond formation, in which fish are swimming at the midway between two front partners, is considered as energetically advantageous for individuals (Weihs, 1973). However, it remains unknown how individuals interact with each other to form the shape of diamond (Partridge and Pitcher, 1979). The energetic advantage is also found in many different arrangements such as line, phalanx, diamond, and rectangular arrangements (Hemelrijk et al., 2015). Therefore, a physical understanding of the hydrodynamic interactions in fish schools remains worthwhile.

Hydrodynamic interaction of two flapping bodies is usually studied by use of flapping foils or passive flexible filaments in regular arrangements. The hydrodynamic interactions of undulating foils in tandem and side-by-side formations have been studied (Deng et al., 2007; Dong and Lu, 2007; Khalid et al., 2016), but there is no dynamic reaction to the surrounding flow since the foils are artificially arranged and undulating. A passive flexible filament can oscillate according to the fluid–structure interaction (Zhang et al., 2000). Therefore, in order to include the effects of flexibility, the hydrodynamic interaction is modeled as a number of flexible filaments which arranged in tandem or paratactic formations (Kim et al., 2010; Uddin et al., 2013). It is found that the flexible deformation also affected the wake patterns, as compared to a rigid foil, the flexible filament with moderate flexibility achieves faster and more economical propulsion (Zhu et al., 2014a; Wang et al., 2016). Moreover, the in-phase and anti-phase flapping states of two paratactic flexible filaments are studied (Zhang et al., 2000); which state occurs depends on the separation distance (Zhu and Peskin, 2003). The inverted drafting of two tandem filaments is investigated (Zhu, 2009), in which the drag of the downstream filament is larger than that of the upstream body (Ristroph and Zhang, 2008). Furthermore, the destructive interaction between two tandem filaments, in which the follower is subject to less drag than the leader, is observed at a certain separation and the Reynolds numbers (Kim et al., 2010). Moreover, the fluid–structure interaction of multiple flexible filaments has been studied, whose flapping motions and drag variations are closely related to the separations (Favier et al., 2015; Uddin et al., 2013).

A fish's self-adjustment of position and undulation following the fluid environment has been observed in laboratory, in which a live trout was slaloming between vortices shed from the ahead cylinder at lower cost (Liao et al., 2003). Thus, using a model that can adjust won position and movement according to the dynamic reactions is beneficial for fully understanding fish schooling. However, the leading edge of the flexible filaments used in the previous studies is fixed; self-adjustment according to the dynamic interactions does not occur. Recently, a model of a self-propelled filament whose horizontal position can self-adjust was used to study the flow-mediated interactions in fish schools, a stable tandem configuration was formed spontaneously by locking the follower's trajectory onto the vortex centers, and some energy benefit was achieved by the follower (Zhu et al., 2014b). However, the vertical direction of self-propelled filament is restrained; thus, some vertical dynamic interactions may be ignored. Although the passive oscillation of a vertical free filament in the Von-Kármán vortex street has been studied experimentally (Jia and Yin, 2008), only minimal Kármán wake generated by a fixed flexible filament was investigated; the passive oscillations of a vertical free flexible filament in different vertical wake patterns are not well understood. However, there exist different wake patterns behind fish in school, the reversed Von-Kármán vortex streets formed in the rear region of a swimming fish, but the normal Von-Kármán vortex streets occurred behind two paratactic swimming fish (Weihs, 1973). Moreover, Liao et al. observed that the trout was slaloming between vortices in the Von-Kármán vortex street behind a D-cylinder (Liao et al., 2003), but Marras & Porfiri reported that the live fish also hold station side behind the robotic fish (Marras and Porfiri, 2012). The observations of Marras & Porfiri and Liao et al. indicated that fish behaviors were different in different flow patterns. In order to fully investigate the passive dynamic response in fish school, and inspired by the experiments of Marras & Porfiri and Liao et al. (Marras and Porfiri, 2012; Liao et al., 2003), the model of a vertical free flexible filament placed behind a flapping foil is proposed in this paper, in which the different flow patterns occurred in fish school can be generated by the flapping foil through changing its flapping parameters (Godoy-Diana et al., 2008).

In this paper, a flexible filament is immersed in the wake of a flapping foil, and the two-dimensional incompressible viscous flow over the flapping foil and the flexible filament is simulated numerically by the immersed boundary method (Peskin, 2003). The leading edge of the filament is fixed in the flow direction but remains free laterally, and the other parts of the filament are free. Different wake patterns are generated by the flapping foil by changing the pitching parameters, including the normal Von-Kármán vortex streets and the reversed Von-Kármán vortex streets (Godoy-Diana et al., 2008). In addition to the slaloming motion between vortices, as studied previously (Jia and Yin, 2008), two other flapping motions are observed in different wake patterns: flapping outside vortex streets and static in the Von-Kármán vortex streets. The filament experiences decreased drag when flapping outside the vortex street, and the pitching foil is subject to reduced drag when the filament is static. The remainder of this paper is organized as follows. Section 2 presents the physical model and the numerical method. Section 3 addresses the simulation results in detail with discussion. Finally, some conclusions are drawn in Section 4.