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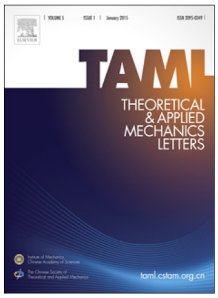

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Numerical simulation of vortex-induced drag of elastic swimmer models

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Abstract

We present numerical simulations of simplified models for swimming organisms or robots, using chordwise flexible elastic plates. We focus on the tip vortices originating from three-dimensional effects due to the finite span of the plate. These effects play an important role when predicting the swimmer's cruising velocity, since they contribute significantly to the drag force. First we simulate swimmers with rectangular plates of different aspect ratio and compare the results with a recent experimental study. Then we consider plates with expanding and contracting shapes. We find the cruising velocity of the contracting swimmer to be higher than the rectangular one, which in turn is higher than the expanding one. We provide some evidence that this result is due to the tip vortices interacting differently with the swimmer.

Keywords: swimming, fluid-structure interaction, thrust generation, numerical simulation

Swimming organisms exploit bending waves to produce propulsive force, an effect which has been extensively studied. Predicting their cruising velocity, however, remains challenging, as the drag force has to be taken into account. In this work, we numerically simulate simplified "swimmers", which consist of a chordwise flexible plate with an imposed pitching motion at the leading edge, immersed in a viscous, incompressible fluid. The solid is fully coupled to the fluid, i.e., we deal with a fluid–structure interaction problem. The emphasis is placed on the longitudinal tip vortices, which result from the finite span of the plate, and their contribution to the drag force.

The usage of flexible foils for thrust generation as a simplified model for swimming organisms is common in both experimental and numerical contributions. Dewey et al. [1] for instance studied flexible pitching panels experimentally. They found the efficiency, i.e., the ratio of thrust to power coefficient, to be maximized if the Strouhal number is in the range $0.25 < St < 0.35$ and the pitching frequency is tuned to the structural resonant frequency of the foil. The former result is supported by a variety of contributions [2, 3, 4]. The connection between the driving frequency f and the resonant frequency f_0 is subject to some controversy in the community. Kang et al. [5] state that operating at or near a structural resonant will enhance performance, a fact which is widely accepted. However, different studies found the precise relation f/f_0 to vary appreciably. For example, Ramananarivo et al. [6] state optimal performance around $f/f_0 = 0.7$. Two-dimensional data [7] points in the same direction, although the difference to the resonant is smaller. Yeh and Alexeev [8] found two regimes which maximize cruising speed and efficiency at $f/f_0 \approx 1.1$ and 1.6, respectively. However, they normalized by the resonant frequency in fluid, which can be derived analytically [9]. Contrarily to these findings, Vanella et al. [10] provided evidence for peak efficiency in flexible insect wings around 0.33. The proposed argument is the usage of superharmonic resonances, also stated in Ref. [6]. Collectively, these findings indeed suggest an important role of the resonant frequency, though the exact relation remains not fully understood.

The total drag acting on these swimming organisms or robots can be decomposed into the contributions of the friction drag and the vortex induced drag. The former contribution has been relatively well explored. Theoretical studies have considered the laminar boundary layer, which is either compressed or stretched by the undulatory motion of the swimmer [11]. This effect is usually referred to as the "Lighthill boundary-layer thinning hypothesis". More recently, Ehrenstein et al. [12] employed high-quality numerical simulations using body-fitted meshes to quantify and verify this hypothesis.

The vortex induced drag, which may play a significant role, has only recently gained attention of experimentalists. In the context of simplified mechanical swimming robots, Raspa et al. [13] established a basic model to explain the influence of the finite aspect ratio by the formation of trailing longitudinal tip-vortices. The present numerical study is inspired by these experiments, and should be seen as complimentary approach, given the difficulty of experimentally measuring the instantaneous flow field appropriately. In a first step, using rectangular swimmers,

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