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Wake Structure and Hydrodynamic Performance of Flapping Foils Mimicking Fish Fin Kinematics

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Abstract Numerical simulations are used to investigate the wake structure and hydrodynamic performance of bionic flapping foils. The study is motivated by the quest to understand the fluid dynamics of fish fins and use it in the underwater propulsion. The simulations employ an immersed boundary method that makes it possible to simulate flows with complex moving boundaries on fixed Cartesian grids. A detailed analysis of the vortex topology shows that the wake of flapping foils is dominated by two sets of complex shaped vortex rings that convect at oblique angles to the wake centerline. The wake of these flapping foils is characterized by two oblique jets. Simulations are also used to examine the wake vortex and hydrodynamic performance over a range of Strouhal numbers and maximum pitch angles and the connection between the foil kinematics, vortex dynamics and force production is discussed. The results show that the variety law of the hydrodynamic performance with kinematic parameters strongly depends on the flow dynamics underlying the force production, including the orientation, interconnection and dissipation rate of the vortex rings.

KEYWORDS Flapping foil; Immersed boundary method; Hydrodynamic performance; Wake vortex

1. Introduction

Despite impressive innovations in underwater vehicles, both the military and scientific communities hope to benefit from more maneuverable vehicles. Existing underwater vehicles are mostly propelled by the traditional propeller-rudder system and this has shown poor maneuverability performance and low efficiency in unsteady flow. Based on studies about biofluid mechanics by Xiao (2014) and Zhang (2011), the application of bionic technology in underwater vehicles is becoming a feasible scheme for the improvement. Flapping foil propulsion as a kind of bionic propulsion type is increasingly studied by investigators.

Most of previous studies have assumed that the aspect ratio of the flapping foil is large and have therefore restricted their attention to two-dimensional foils. In Triantafyllou (1992) and Read (2003)'s experimental studies, approximate two-dimensional flow has been accomplished by use of high-aspect-ratio foils and endplates, whereas numerical studies of Lewin (2003) and Lu (2006) explicitly perform two-dimensional simulations that ignore any spanwise variability in the foil geometry and the flow field to achieve this.

On the other hand, a number of studies have examined the hydrodynamic performance of finite aspect-ratio flapping foils/wings. Dong et al. (2006) have investigated the effect of aspect ratio on the vortex topology and hydrodynamic performance of thin ellipsoidal foils. Sane (2011) and Dickinson (2011) have performed detailed experimental studies with a dynamically scaled mechanical model of the fruit fly to discuss the production of unsteady aerodynamic forces in the influence of wing kinematics, and Sun (2002) and Tang (2002) have used this same wing in their numerical simulations to study the lift and power

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