Journal of Fluids and Structures 82 (2018) 1–15

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Passive locomotion of freely movable flexible fins near the ground

Young Dal Jeong, Jae Hwa Lee *

School of Mechanical, Aerospace and Nuclear Engineering, UNIST, 50 UNIST-gil, Eonyang-eup, Ulsan 44919, Republic of Korea

ARTICLE INFO

Article history:
Received 12 March 2018
Received in revised form 15 June 2018
Accepted 25 June 2018

Keywords:
Ground effect
Fluid–structure interaction

ABSTRACT

We numerically examine the hydrodynamic interaction between a flexible fin and surrounding fluid near the ground when four relevant parameters of initial position, bending rigidity, mass ratio and Reynolds number are varied. The leading edge of the fin is fixed in the streamwise direction, whereas the lateral motion is freely movable by the fluid–flexible body interaction near the ground. When the fin is initially positioned far from the ground, the fin passively migrates toward another wall-normal position near the ground for an equilibrium state due to larger positive deflection angle for the fin than the negative angle by the effects of vorticity generated by the lateral velocity gradient near the ground. In addition, as the flapping amplitude of the fin is small for large bending rigidity and small mass ratio, the great asymmetry between the positive and negative deflection angles reduces the transient time of the fin to reach the equilibrium position near the ground, and thus the fins can quickly take the hydrodynamic benefits with low drag at an equilibrium state without any energy consumption for lift force due to local balance between the flapping motion and the ground. The most important observation is that the equilibrium position of the fin is invariant to the initial position, bending rigidity and mass ratio of the fin. However, the equilibrium position of the fin is dramatically affected by the Reynolds number. The present results provide new insights into the functional role of the relevant parameters in passively flapping-based locomotion near the ground.

1. Introduction

It is known that river fish (e.g., freshwater darters) or benthic fish (e.g., flatfishes, sculpins and rays) hold station near the ground with a low-speed region and in a wake behind a blunt body to take advantage of the hydrodynamic benefit (Fausch, 1993; Webb, 1998). The station-holding fish often inhabit the boundary layer region near the ground for feeding ecology or reproductive biology and they tend to utilize both active swimming and powerless (passive) gliding to save energy expenditures (Weihs, 1974; Carlson and Lauder, 2010, 2011).

In an effort to examine the influence of ground effects on active motions of rigid bodies within a boundary layer flow, Tanida (2001) utilized analytical approach by applying the linearized Euler equations on an active fluttering plate in a wind tunnel and showed that the propulsive efficiency of thrust is increased by the ground effect. In addition, Liang et al. (2014) employed a potential flow based discrete vortex method to explore the ground effect in heaving and self-exited oscillating airfoils above the surface wave and reported that the magnitude of the regular waves has a significant influence on the lift coefficient and equilibrium position of the airfoils when the initial distance between the foil and surface is given. Based on

* Corresponding author.
E-mail address: jhlee06@unist.ac.kr (J.H. Lee).

https://doi.org/10.1016/j.jfluidstructs.2018.06.015
0889-9746/

a numerical study using the unsteady potential flow method, Quinn et al. (2014b) showed that ground effect can efficiently enhance thrust at low cost for a pitching airfoil near a solid boundary, and found that when the airfoil is placed at an equilibrium location for zero lift force, the thrust is increased by approximately 40%. In addition to the studies with the inviscid flow above, both experimental and numerical investigations with viscous effects have been performed recently due to significant importance of the viscosity on the aerodynamic performance of heaving and pitching rigid airfoils at relatively low Reynolds number (Molina and Zhang, 2011; Quinn et al., 2014b). Furthermore, an experimental study of Quinn et al. (2014a) for active motions of flexible bodies in a boundary layer flow near the ground showed that the swimming speed of oscillating fins gradually increased when they approached the ground, whereas Blevins and Lauder (2013) found little influence of the ground effect on undulating fins in their experiment. Very recently, Ryu et al. (2016) simulated the flapping motion of a flexible body with heaving motion in a viscous Poiseuille flow to explore the hydrodynamic benefits of the body near the ground when the heaving frequency varies. They showed that the back flow generated between the body and ground increases propulsive efficiency and swimming speed of the body.

When a static lifting rigid body glides parallel to the ground in a boundary layer flow, it is reported that the body generates more lift force near the ground due to the decelerated flow beneath the body, resulting in higher pressures on the underside (Baudinette and Schmidt-Nielsen, 1974; Rayner, 1991; Park and Choi, 2010). Even though much effort has been devoted to examine the ground effects on the passive gliding of the rigid body, study of interaction between passively flapping flexible body and ground has been limitedly perform thus far. Because real undulatory and oscillatory organisms are expected to experience both active and passive responses to the surrounding environments, system comprising a purely passive flapping motion in a fluid flow can provide insight into how the fluid, flexible body and ground are coupled with relevant physics that apply to the flexible body near the ground to reduce energy expenditure. Such systems with wholly passive flapping flags without ground effects have been extensively studied as simplified heuristic models of swimming fish to investigate flapping dynamics of a single or multiple flexible flags (Zhang et al., 2000; Zhu and Peskin, 2002; Shelley et al., 2005; Connell and Yue, 2007; Eloy et al., 2007; Michelin et al., 2008; Kim et al., 2010; Uddin et al., 2013; Son and Lee, 2017). Indeed, the previous experimental studies of Liao et al. (2003) and Muller (2003) showed that a downstream fish can benefit from energy savings due to reduced muscle activity by swimming in the wake of an upstream obstacle in a manner that resembles passive flapping. Furthermore, an experimental study of Beal et al. (2006) using a dead fish in the wake of D-type cylinder demonstrated that expending energy of a body can be saved by the synchronization between their body and the oncoming vortices, consistent with the finding of Eldredge and Pisani (2008).

In the present study, numerical simulations of flexible fins with powerless gliding in an oncoming flow near the ground are performed to investigate intrinsical fluid–flexible body–ground interaction. We consider freely movable flexible fins along the wall-normal (lateral) direction to resolve several questions near the ground: (1) where does the fin passively take an equilibrium position near the ground, (2) what role do initial position of the fin, flexibility, mass ratio and Reynolds number play on the fin near the ground and (3) how does the fin maintain its optimal position without external energy input? The interaction between the fin and surrounding flow near the ground is classified into distinctive modes based on flapping *amplitude* at transient and equilibrium states. In order to provide an explanation for each mode at the transient and equilibrium states, temporal variation of tail positions, trajectory plot, deflection angle, lift coefficient, drag coefficient, transient time and lateral velocity of the fin are analyzed when the initial position (y_o), bending rigidity (γ), mass ratio (μ) and Reynolds number (Re) are systematically varied. Furthermore, the hydrodynamic forces of a freely movable flexible fin are examined using vorticity, pressure and velocity plots to provide an intuitive comprehension of the lateral migration phenomenon of the fin. This paper is organized as follows. The numerical method used here is briefly described in Section 2, and the results and discussion are presented with four subsections in Section 3. Finally, the summary and conclusion are given in Section 4.

2. Numerical method

The motion of the incompressible viscous fluid is governed using the Navier–Stokes and continuity equations,

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \frac{1}{Re}\nabla^2 \boldsymbol{u} + \boldsymbol{f} \text{ and} \tag{1}$$

$$\nabla \cdot \boldsymbol{u} = 0, \tag{2}$$

where $\boldsymbol{u} = (u, v)$ is the velocity vector, p is the pressure, and $\boldsymbol{f} = (f_x, f_y)/(\rho_f U_c^2/L)$ is the momentum force acting on the immersed boundary due to constrain by the no-slip boundary condition. The Reynolds number Re is defined as $Re = U_c L/\nu_f$, with ν_f the kinematic viscosity of the fluid, U_c the velocity at the channel centerline and L the length of the fin. Eqs. (1) and (2) are solved in time using the fractional step method in accordance with an implicit velocity-decoupling procedure (Kim et al., 2002). Both velocity–pressure decoupling and the decoupling of the intermediate-velocity components are achieved based on block LU decomposition with approximate factorization. In this case, using the Crank–Nicolson method, the terms are initially discretized in time, after which that the coupled velocity components are resolved without iterations. All terms are solved using a second-order central difference scheme in space with a staggered mesh.

The governing equations for inextensible flexible fin motion are non-dimensionalized by the fin density ρ_1, the fin length L, and the centerline velocity U_c. The characteristic scales are expressed as L for the unit of length, L/U_c for the unit of time t,