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Ground-induced lift enhancement in a tandem of symmetric flapping wings: Lattice Boltzmann-immersed boundary simulations

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ABSTRACT

The behavior of a tandem of symmetric flapping wings immersed in a quiescent viscous fluid is numerically dissected. The attention focuses on the effect on the flight performance of a solid surface which idealizes the presence of the ground. A wide numerical campaign is carried out. The author demonstrates that the presence of a solid surface can drastically modify the lift force, thus giving a remarkable advantage for the vertical take-off. Therefore, a proper governing parameter is proposed, which accounts for the ratio between the initial gap from the solid surface and the length of the wing.

1. Introduction

Flapping wing dynamics represents one of the most intriguing topic affecting contemporary numerical modeling within the computation fluid dynamics (CFD) framework. In fact, such problem shows a lot of practical applications, such as the design of micro-air vehicles [1–6] or the improvement of the performance of underwater energy harvesters [7–9]. In the last decade, a lot of works developed aiming at dissecting the dynamics of flapping wings immersed in an unbounded quiescent viscous fluid by considering rigid [10–13], flexible [14–20], and even composite [21–23] structures. An interesting aspect worth to be investigated is represented by the force enhancement induced by the presence of a solid surface, as the ground [24]. For example, the ground effect involving wings composed of single and double elements has been investigated in [25,26], respectively, while the aerodynamics of Gurney flaps has been dissected in [27], showing that the presence of the ground can considerably modify the dynamics of a flapping wing. Motion control, structural design and materials involving the technology of the wing undergoing the ground effect has been reviewed in [28], by devoting with special attention for the mathematical modeling. Moreover, in [29] a wind tunnel investigation of a low aspect ratio wing has been carried out, showing the lift augmentation induced by the ground effect. In addition, it has been demonstrated that the fluid forces acting upon a rigid sharp-edged lamina undergoing harmonic oscillations in a quiescent viscous fluid strongly depends on the gap-over-length ratio, that is the ratio between the distance from the solid surface and the length of the body [30–32].

Aiming at predicting the flow physics induced by the motion of flapping wings in a fluid, numerical methods can be successfully adopted. Among the possible approaches able to compute the fluid flow, the lattice Boltzmann (LB) method [33–35] represents a relatively new, computationally efficient, and accurate alternative to the standard continuum-based CFD solvers. In particular, the author remarks that the LB method recovers the Navier–Stokes equations for incompressible flow with second-order of accuracy [36]. Moreover, the computation of the forces acting upon an immersed solid body represents a quite easy task, as in the numerical simulations carried out in this paper. In order to account for the presence of the wings which are immersed in the fluid domain, the Immersed Boundary (IB) method [37–40] is employed. Such method has been preferred to the well consolidated interpolated bounce-back scheme [41–43], due to its superior properties in terms of stability and involved computational effort, as recently demonstrated by the author [44]. Once the forces that the fluid exerts upon the wings are computed, wings solid dynamics is predicted through the time discontinuous Galerkin (TDG) scheme, which exhibits superior properties with respect to standard Newmark or α schemes in terms of stability, accuracy and convergence, as discussed in [45]. The LB, IB and TDG methods have been combined by the author within a proper coupling strategy [46], whose effectiveness has already been widely tested against problems involving flapping wings dynamics [13,20], shallow waters [47], multiphase flows [48], hull slamming [49] and even non-Newtonian fluids [50], among the others.

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In this work, findings from numerical simulations concerning a tandem of rigid symmetric flapping wings undergoing harmonic oscillations are discussed. Specifically, wings can move only in vertical direction and the flight performance is elucidated by highlighting the role of the gap-over-length ratio. Moreover, scenarios characterized by different fluid viscosity are investigated, together with the influence of the reciprocal distance between the wings. Results in terms of time history of the position of the centers of mass are discussed, together with considerations about the velocity field. This paper presents new insights with respect to previous efforts carried out by different authors [13,20,51–54]. Specifically, the behavior of a tandem of butterfly-like wings is investigated, whereas the literature focuses mainly on isolated bodies. In this way, the mutual interaction between the wings is highlighted, together with the role of the encompassing hydrodynamics. Moreover, the effect of a solid ground-like surface is widely elucidated, showing its huge impact on the flight performance.

The paper is organized as follows. In Section 2, the problem is stated and the adopted numerical methods are briefly recalled. In Section 3, results of a numerical campaign are discussed. Some conclusions are drawn in Section 4. Finally, in Appendix A the convergence and accuracy properties of the proposed algorithm are discussed.

2. Problem statement

A fluid of viscosity ν and density ρ surrounds a tandem of two symmetric flapping wings. The following parameters are adopted, which correspond to a *Pieris melete* butterfly [55,56]: wing mass 3.5×10^{-6} kg, body mass 5.0×10^{-5} kg, hinge-wing distance 5.0×10^{-3} m, wing length $L = 3.0 \times 10^{-2}$ m. Making reference to Fig. 1, each wing undergoes a harmonic motion, that is

$$\theta(t) = \Delta\theta \cos\left(\frac{2\pi t}{T}\right), \quad (1)$$

where $\Delta\theta = 46.8^\circ$ is the amplitude, $T = 0.1$ s is the period of the harmonic oscillation and t is the time. Notice that the total mass $M = 5.7 \times 10^{-5}$ kg is considered to be concentrated at the hinge. This means that the update of the position of the wings reduces to the one of the corresponding center of mass. At the bottom-most section, a rigid solid surface is enforced, whereas outflow boundary conditions are prescribed at the remaining edges. The fluid and the wings are initially at rest. Wings are initially horizontally aligned. Moreover, the initial distance between the wings and the solid surface is denoted by g. Thus, it is possible to define a governing parameter, the gap-over-length ratio, as $\mathcal{G} = g/L$. The dependence of the solution of the problem on $\mathcal{G}$ is discussed in the following, together with the influence of the Reynolds number $\mathcal{R}e$ and the incidence of the reciprocal distance between the wings. The problem set-up is sketched in Fig. 2.

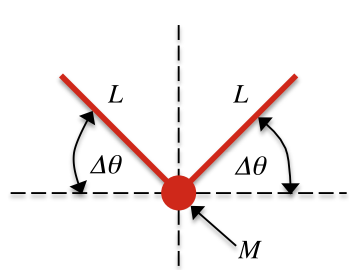

Fig. 1. Symmetric flapping wings of length L and mass M undergoing a harmonic motion of maximum amplitude $\Delta\theta$. The total mass M is concentrated at the hinge (red circle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

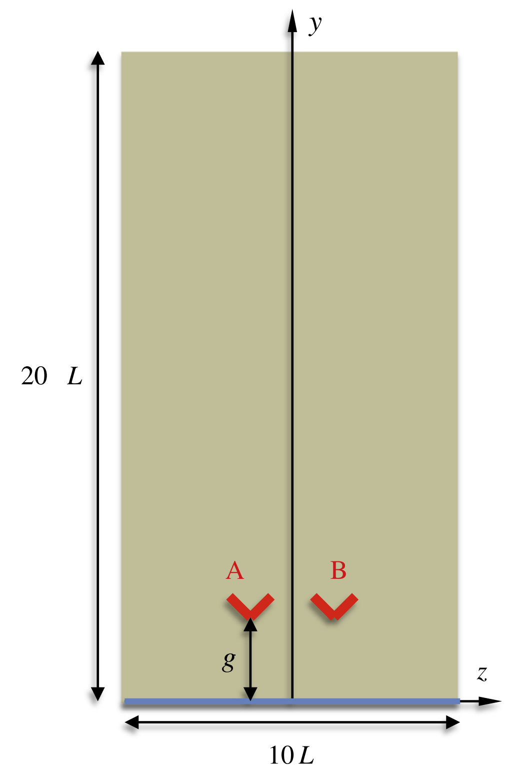

Fig. 2. Sketch of the problem set-up. Two symmetric flapping wings (A and B, red solid lines) of length L and mass M are immersed in a viscous fluid. These are placed symmetrically with respect to the vertical axis y. A solid surface is prescribed at the bottom-most section (blue solid line). Outflow conditions are enforced at the other boundaries. The centers of mass are initially horizontally aligned and these are placed at a distance g from the solid surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1. Governing equations

The flow physics is predicted by solving the Navier–Stokes equations for an incompressible flow, which can be written as

$$\nabla \cdot \mathbf{u} = 0, \quad (2)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)(\mathbf{u}) = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u}, \quad (3)$$

where $\mathbf{u}$ is the flow velocity and p is the fluid pressure. From the solid dynamics point of view, the wings (i.e the center of mass) is forced to move only in the vertical direction according to equation of the solid motion, that is

$$M\ddot{y}(t) = F(t), \quad (4)$$

where y is the vertical component of the displacement of the center of mass of the wings, $F(t)$ is the time-dependent vertical component of the external forces which are exerted by the encompassing fluid on the solid body. Superimposed dots indicate the time derivatives. At the fluid-wing interface and at the bottom section, i.e. at the solid surface, the no-slip condition is prescribed, i.e. $\mathbf{u}(y = 0) = 0$. The following initial conditions complete the definition of the problem: $y(t = 0) = 0, \dot{y}(t = 0) = 0$ and $\mathbf{u}(t = 0) = 0$.

2.2. Numerical methods

The lattice D2Q9 model [35] is adopted to compute the space–time evolution of the particle distribution functions f_i, which are