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On the dynamics of a tandem of asynchronous flapping wings: Lattice Boltzmann-immersed boundary simulations

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HIGHLIGHTS

- Numerical simulations are performed on a tandem of off-sync flapping wings.
- Scenarios accounting for the presence of a lateral wind gust are investigated.
- Increasing values of the wind gust tend to negatively affect the flight performance.
- For low values of the wind gust the tandem benefits from the asynchronous motion.

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ABSTRACT

In this paper, the flight performance of a tandem of symmetric flapping wings immersed in a viscous fluid is investigated. A harmonic motion is imposed to the wings which can travel only in the vertical direction. Specifically, the attention focuses on the role of the initial phase difference. The fluid domain is modeled through the lattice Boltzmann method. In order to account for the presence of the wings immersed in the lattice fluid background, the immersed boundary method is adopted. Once fluid forces acting upon the wings are computed, their position is updated by solving the equation of solid motion by the time discontinuous Galerkin method according to a strategy already validated by the author. A wide numerical campaign is carried out by varying the initial phase difference. Moreover, scenarios accounting for the presence of a lateral wind gust are shown. The flight conditions and performance are discussed for a wide set of configurations and compared with an in-sync configuration, showing that the wind gust reduces the performance in certain scenarios.
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1. Introduction

An effective computation of the lift generated in flapping wings by a prescribed motion is an attractive issue recently arosen in the computational fluid dynamics framework. In particular, this problem has practical applications in the design of micro-air vehicles and robotic drones which can be used in the mechanics, defense and even civil industry. Huge attention has been devoted to the role of the deformability of the wing. Specifically, Heathcote et al. [1,2] showed that a flapping wing benefits from flexibility, especially within a certain range of the Strouhal number. The impact of the flexibility on the aerodynamics performance was studied in Ref. [3], showing that aerodynamic forces can be controlled by altering the trailing edge flexibility of a flapping wing. More recently, Mountcastle et al. [4] and Kang et al. [5] underlined that the deformability plays a crucial role in the lift generation, enhancing the performance.

Among the possible aspects to be highlighted, one of the most intriguing is represented by the vorticity generated by the tip of the wing, which is responsible for a remarkable modification of the hydrodynamics surrounding the wing itself, thus

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leading to the generation of a useful support during the beat [6]. According to Ref. [7], the leading-edge vortexes represent a flow structure which is largely responsible for the performance of the wings. In Ref. [8,9] the particle image velocimetry technique has been applied to quantify the leading-edge vortexes in insects. The benefit induced by such vortexes has proved to be effective even for slow-flying bats [10]. The dynamic behavior of the tip-induced vortexes has been recently investigated in Ref. [11], showing how the vortex structure arises and develops during the wing beat. Trizila et al. [12] studied the aerodynamics of flapping wings by imposing a translation and a rotation to a rigid wing. Consequently, the induced vorticity and lift coefficient for different scenarios of the imposed motion have been analyzed, focusing on their relationship.

Concerning the flapping wing modeling, the lattice Boltzmann (LB) method [13] has been combined with the immersed boundary (IB) one [14] in a recent work [15], showing interesting results related to the interplay between two in-sync flapping wings. Moreover, the effect of a wind gust has been discussed, leading to the definition of a critical value inhibiting the take-off. The LB method is adopted to predict fluid dynamics, whereas the IB method is used to account for the presence of the wing in the lattice background. The IB method has been preferred to the well known interpolated bounce-back scheme [16,17], due to its superior properties in terms of stability and involved computational effort [18]. Specifically, for a given grid resolution the IB method has proved to be able to solve problems characterized by Reynolds numbers which are higher with respect to the ones achievable by using the bounce-back scheme. Moreover, the computation of the forces acting on a solid body is immediately available due to the intrinsic nature of the IB method, thus avoiding stress integration procedures which are known to involve high CPU time [18]. As discussed in Ref. [15,19], wing dynamics is computed via the time discontinuous Galerkin (TDG) method. This choice over standard Newmark or α schemes is motivated by higher stability, accuracy and convergence, as devised in Ref. [20]. The adopted numerical methods and the coupling strategy have been widely discussed and validated by the author for flow induced vibrations [21,22], blood flow [23], shallow waters [24] and even hull slamming [25]. The interested reader can refer to the above cited works for further details about the numerical methods.

In this work, the motion of a tandem of rigid flapping wings is numerically investigated by imposing a harmonic motion to the wings. Wings can travel only in the vertical direction. Specifically, the attention focuses on the difference in the initial phase angle, thus relating the flight performance to the asynchronous motion. Moreover, the effect of a constant uniform rightward wind gust is discussed, showing how the behavior is affected. A wide numerical campaign is carried out. In particular, the initial phase angle of one of the wings is kept fixed, while the other one varies. In addition, simulations characterized by increasing values of the wind gust are performed. Findings in terms of the time history of the position of the centers of mass are discussed, together with considerations about the velocity field.

Despite previous efforts [26–29], this work presents new insights. 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 the asynchronous motion of a tandem of symmetric flapping wings is discussed here for the first time, showing that the flight performance of the butterfly-like body is considerably influenced by the initial phase angle of the other one, and vice versa. The paper is organized as follows. In Section 2, the problem is stated. In Section 3, the results of a numerical campaign are discussed. Finally, in Section 4 some conclusions are drawn.

2. Problem statement

A tandem of symmetric flapping wings is immersed in a fluid of viscosity ν and density ρ. According to Ref. [30,31], the following butterfly-like physical parameters corresponding to a *Pieris melete* are adopted:

- 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.

Notice that the total mass is equal to $M = 5.7 \times 10^{-5}$ kg. Following the approach recently proposed by Ref. [15], the harmonic motion $\theta(t)$ defined as

$$\theta(t) = \Delta\theta \cos\left(\frac{2\pi t}{T} + \phi\frac{\pi}{180^\circ}\right), \tag{1}$$

is imposed to both the systems sketched in Fig. 1. Notice that $\Delta\theta = 46.8^\circ$ is the amplitude, $T = 0.1$ s is the period of the harmonic oscillation, ϕ is the initial phase angle and t is the time. Simulations are performed by setting $\phi = 0^\circ$ for A, whereas the initial phase angle of B varies.

2.1. Governing equations

The problem is governed by the Navier–Stokes equation for an incompressible flow. Specifically, such equations read as follows:

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

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

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