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Analysis of the aerodynamic interaction between two plunging plates in tandem at low Reynolds number for maximum propulsive efficiency

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The thrust generated by two heaving plates in tandem is analyzed computationally by solving the Navier–Stokes equations for an incompressible and two-dimensional flow at low Reynolds numbers. We consider with detail two particular sets of configurations of interest in forward flight in a wide range of heaving amplitudes and frequencies: a plunging leading plate with the trailing plate at rest, and the two plates heaving with the same frequency and amplitude, but varying the phase difference. In almost all cases the thrust efficiency of the leading plate is augmented in relation to a single plate heaving with the same frequency and amplitude. In the first configuration with a trailing plate at rest, we characterize the range of nondimensional heaving frequencies and amplitudes of the leading plate for which the stationary trailing plate contributes positively to the global thrust. The maximum global thrust efficiency of this configuration, reached for an advance ratio slightly less than unity and a reduced frequency close to 5, is about the same as the maximum efficiency for an isolated plate, reached for slightly smaller frequencies. But for low frequencies the tandem configuration with the trailing plate at rest is more thrust efficient than the isolated plate. We also characterize the nondimensional frequency and amplitude regions for which the flow becomes chaotic. In the second configuration, the maximum of the total thrust efficiency is reached for a phase lag of 180° (counterstroking), particularly for an advance ratio unity and a reduced frequency 4.4. It is almost the same as the maximum thrust efficiency in the other configuration with the trailing plate at rest and that of a single plate. We discuss the flow structures and the aerodynamic interaction between plates responsible for the optimal thrust configuration in both cases.

1. Introduction

Within the flight mechanics strategies of the different insect taxa, it is well known the propulsion efficiency and maneuverability of dragonflies (Alexander, 1984; Azuma et al., 1985; Azuma and Watanabe, 1988; Rüppell, 1989; May, 1991; Wakeling and Ellington, 1997a, 1997b; Thomas et al., 2004; Wang, 2008), with two pairs of slender flapping wings in tandem extending to each side of the thorax. These extraordinary flight capabilities, both in hovering and in forward flight, are to a large extent due to the unsteady forewings–hindwings aerodynamic interaction, which has been the subject of

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many studies (see, e.g., Lehmann, 2009). Some of the recent interest on the unsteady aerodynamic interaction of flapping wings is not only aimed at the understanding of dragonfly flight capabilities, but come from their possible application to the design of more efficient Micro Aerial Vehicles (MAVs) (e.g., Yamamoto and Isogai, 2005; Hu et al., 2009), and to the design of devices for energy extraction by the hindwing from an oscillating flow such as the wake of the forewing (Xiao and Zhu, 2014), which are also inspired by the energy saving mechanism of fish schooling (Liao, 2003; Bao and Tao, 2014). Aerodynamic interactions between dragonfly flapping wings are quite complex (e.g., Chen et al., 2013). However, controlled parametric studies show that, provided that the aerodynamic nondimensional parameters are appropriate, even simple plunging rigid plates can reproduce the detailed features of the flow seen in dragonflies (Thomas et al., 2004), and be a convenient guide to the design of efficient MAVs and energy extraction devices. The hydrodynamic interaction between the flapping of the different sets of fins is also very relevant for the propulsion efficiency of many fish species (Drucker and Lauder, 1999; Akhtar et al., 2007), but here three-dimensional and foil flexibility effects are much more relevant.

Among the many aspects of the aerodynamic force control by wake–wing interaction (Lehmann, 2008), we focus here only on the thrust efficiency in forward flight using a very simple model of two flapping wings in tandem. In particular, to gain further insight about the effect of the forewing–hindwing interaction on the thrust efficiency in forward flight, and assuming a high aspect ratio, we consider two heaving rigid plates in a two-dimensional (2-D) incompressible flow at the low Reynolds number of interest in insect and MAV flight (between a few hundreds and a few thousands, Dudley, 2000; Wang, 2005; Azuma, 2006). The interaction is first analyzed with detail in the simplest configuration of a plunging leading plate with the trailing plate at rest. This particular airfoil combination in tandem was first analyzed by Schmidt (1965) for a more complicated flapping motion of the leading airfoil, finding that a stationary wing placed in the oscillatory wake of a flapping wing could generated additional thrust by recovering some of the energy released in the wake of the flapping airfoil. It was further considered numerically by Tuncer and Platzer (1996), but for compressible flow and using a turbulence model for a high Reynolds number (Reynolds number three millions and Mach number 0.3). These authors found that selecting the flapping nondimensional amplitude and reduced frequency of the leading airfoil and its separation to the trailing airfoil (both NACA0012) the tandem propulsive efficiency could be augmented more that 40% in relation to a single airfoil. This thrust efficiency improvement, which was computed with pressure forces only (i.e., without taking into account skin friction), was in qualitative agreement with previous experimental and theoretical studies at high Reynolds numbers (Schmidt, 1965; Bosch, 1978). However, it cannot be extrapolated to the much low Reynolds numbers of interest in insect and MAV flight. In fact, later experimental results by Jones and Platzer (1999) with trailing, stationary wings at moderate Reynolds numbers (between 18,000 and 80,000) demonstrate a slight increase in total thrust over the full velocity range, but this benefit was greatly outweighed by the increase in profile drag. We use here this setup with a stationary trailing plate just as a simple configuration to analyze the aerodynamic effects that vortices shed by a plunging airfoil have on a downstream stationary structure.

As a second configuration of interest we consider the two plates heaving with the same nondimensional frequency and amplitude, but varying the phase difference φ (see definition in the next section) between the leading plate (hereafter foreplate, for short) and the trailing plate (hindplate). This is a configuration of interest in dragonfly forward free flight since they usually beat their forewings and hindwings at approximately the same frequency and amplitude, but out of phase (counterstroking), or in phase (parallel stroking), depending on whether they are cruising, or maneuvering or accelerating (Alexander, 1984; Rüppell, 1989; Wakeling and Ellington, 1997a). Using potential flow theory with plates of aspect ratio 6, Lan (1979) showed that, for pure flapping, the maximum thrust can be generated with maximum power efficiency if the hindwing flaps in advance of the forewing by 90°–180°, depending on the reduced frequency and the gap between the plates. Lan (1979) also considered the pitching motion of the flapping plates, which is not considered in the present work, finding that, for a reduced frequency of $k=0.75$ (see definition of k in Section 4) and a wings gap between half and one chord, the best thrust efficiency is obtained when pitching is 90° in advance of flapping, and the phase difference between the flapping plates φ is slightly larger than 90°, but the maximum thrust is obtained when $\varphi \simeq 45°$. Again, these results cannot be extrapolated to the low Reynolds numbers considered in the present work. Numerical simulations at lower Reynolds numbers of interest here were performed by Lan and Sun (2001) for two elliptical airfoils in tandem configurations moving in phase along a straight line at large angle of attack after an initially acceleration from rest. Although it is not an oscillatory heaving motion like the one considered here, these authors explained, in terms of the spacing between the airfoils, the aerodynamics mechanisms by which the thrust and the lift forces on the fore- and the hind-airfoils are both enhanced in relation to a single airfoil at the initial stages of a downstroke. More realistic numerical simulations for a model dragonfly (Sun and Lan, 2004; Wang and Sun, 2005) showed that, both in hovering and in forward flight (i.e., for advance ratios J between 0 and 0.75; see Section 4 for the definition of J), the forewing–hindwing interaction is detrimental to the vertical force generation compared to the case of a single wing with the same motion. This was in part confirmed by experimental studies with an electromechanical model of a pair of dragonfly wings in hovering flight (Maybury and Lehmann, 2004), showing that varying the relative phase difference the performance of the forewing remained constant and the hindwing lift production may be augmented by a factor of two when it leads the forewing by about 90°, but it did not necessarily implied a smaller energetic cost in relation to a single flapping wing. Numerical simulations for the complete range of phase differences (Huang and Sun, 2007) corroborated that for $0 < \varphi < 180°$ (hindwing leads forewing) the mean total vertical force and mean total thrust were only slightly altered in relation to the sum of two single wings, while for $180° < \varphi < 360°$ the mean total vertical force (and in a lesser degree the thrust) was greatly decreased because the interaction reduced the vertical force on the hindwing.

Thomas et al. (2004) were the first to present reliable flow visualizations of dragonflies flying freely in a wind tunnel, showing the relevance of taking into account the two pairs of flapping wings to explain the aerodynamics of dragonfly flight