

FLOW PHENOMENON IN FLAPPING INSECT WINGS

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Abstract. *Exploring the physics of unsteady aerodynamics has general implications on the energetics, control, and production of locomotor forces in flying animals and thus on the design of autonomously flying biomimetic micro-air-vehicles (MAV). The recent progress in analytical and experimental approaches suggests that the elevated performance of biofoils results from the interaction of several distinct aerodynamic mechanisms such as vorticity due to a leading-edge vortex (LEV), rotational circulation, and the recycling of kinetic energy that appears in the wake (wake capture). Two-winged MAVs utilizing flapping wing motion may, moreover, enhance lift by wing-wing interaction during the stroke reversals (clap-and-fling). Although clap-and-fling aerodynamics is limited to a short time fraction of the stroke cycle, it modifies the overall wake structure including the temporal distribution of forces throughout the stroke in a complex manner. Digital Particle Image Velocimetry (DPIV) combined with force measurements in dynamically scaled robotic model wings show that the benefit of LEV induction during fling motion is attenuated by the premature destruction of bound circulation due to wing clapping. A second type of wing-wing interaction occurs in four-winged animals in which the forewing wake passes over the beating hindwing. Measurements on model wings demonstrate that depending on the kinematic phase relationship, the forewing wake is able to either destroy hindwing leading edge vorticity or to enhance hindwing performance even above the performance of a single wing by changing the strength and orientation of the local flow. Clap-and-fling lift enhancement and the changes in flight forces due to changes in kinematic phase relationships are promising tools for establishing enhanced flight stability and maneuverability in certain types of biomimetic MAVs in the future. Compared to conventional mechanisms of flight control such as variations in stroke amplitude and angle of attack, wing-wing based aerodynamic modifications potentially allow both functionally four-winged animals to efficiently manipulate flight forces without elaborate changes in wing beat kinematics, and design-engineers to simplify the construction and control of miniaturized mechanical wing hinges.*

1 INTRODUCTION

The extraordinary evolutionary success of flying insects is largely due to their ability to precisely control their locomotor behavior in response to sensory stimuli. In the past, numerous studies emphasized the complexity of the feedback cascade that allows insects to convert sensory information from the compound eyes, the gyroscopic halteres or the wing's mechanical sensors (campaniform sensilla) into locomotor activity. Behavioral performance may be limited at each step of this cascade including the fluid dynamic processes with which flapping insect wings produce aerodynamic lift and drag. Force production and flight control in insects become most complex when fluid acceleration fields interfere with the flapping wings. Consequently, in a freely flying animal, the production of vorticity and shedding of vortical structures in each stroke cycle depends on several factors such as (i) the instantaneous wake structure produced by the wing's own motion, (ii) wake components produced in a preceding half stroke or preceding stroke cycles, (iii) flow components resulting from force generation of wings flapping in close distance, (iv) changes in fluid velocity at the wings due to the animal's body motion along and around the 3 body axes, and finally, (v) external disturbances in the surrounding air. Altogether, these components determine the instantaneous flow regime around a flapping insect wing and thus lift and drag production. To answer the question of how the neuro-muscular system of flying insects copes with changing fluid environments is intriguing and requires a deeper understanding of the fluid dynamic processes occurring in flapping insect wings [1,2].

A single wing may benefit from wake-wing interaction namely at the beginning of each half stroke. This phenomenon is termed *wake capture* and describes a mechanism by which the animal extracts kinetic energy from the fluid [3,4]. Wake capture at the beginning of the half stroke benefits from an inter-vortex stream produced by the leading- and trailing edge vortex system that accelerates the fluid during wing rotation at the end of each half stroke [5]. However, this interpretation of wake capture force generation has been questioned by computational fluid dynamics modeling of flapping insect wings, suggesting that the rotation-independent lift peak is due to a reaction of accelerating an added mass of fluid and does not rely on a momentum transfer of the fluid [6]. In the past, the effect of inertial reaction forces during the stroke reversals has been well recognized and discussed as a cause for wing rotation, twisting and bending. For example, in two species of dipterans, the blow fly *Calliphora vicina* and the hover fly *Eristalis tenax*, the high stroke frequency ranging from 100 to 200 Hz produces inertial forces sufficiently high to elicit passive wing pitch (angle of attack) changes when the wing reverses its direction of motion [7,8]. Besides this controversial view on the wake capture mechanism, it remains unclear how the benefit of wake capture exactly changes during fast forward or maneuvering flight of an insect when the wings experience additional fluid components produced by the animal's own body motion.

2 DORSAL WAKE-WING INTERFERENCE

The dorsal clap-and-fling mechanism in two- and four-winged insects was first described by Weis-Fogh [9] and has since then been confirmed in many insects at a vast variety of flight modes. It has long been subject to several detailed experimental evaluations. Quite recently, new approaches in the experimental design have provided several new insights, and numerical modeling has much contributed to our understanding of this particular kinematic maneuver. The clap-and-fling is a close apposition of the ipsi- and contralateral wing at dorsal stroke reversal preceding

pronation. During the clap, the insect brings the leading edges of the two wings together, then pronates them until the ‘v-shaped’ gap vanishes and the wings are parallel in close apposition. During the fling, the wings pronate about their trailing edges, creating a growing gap as the leading edge pulls apart. The fling phase preceding the down stroke is thought to enhance circulation due to fluid inhalation in the cleft formed by the moving wings. This causes strong vortex generation at the leading edge, while the development of trailing edge vorticity is inhibited by trailing edge wing contact. Several studies estimated the benefit of the fling part of wing motion using either numerical models or a combined approach incorporating measurements of flow velocities and forces in robotic wings [10-14]. More recently, numerical simulations have been performed on the entire clap-and-fling sequence in both 3D [15] and in 2D across a wide range of Reynolds numbers [16]. Besides this, a dynamically-scaled mechanical model of a 1.2 mg fruit fly demonstrated that alteration in force production due to clap-and-fling wing motion is not limited to the dorsal stroke reversal but may also enhance lift approximately at mid down- and the beginning of the upstroke [17]. Thus, clap-and-fling wing motion should be considered a mechanism that may distort the spatio-temporal structure of the wake during up- and downstroke rather than it affects lift and drag production only in the brief moment during dorsal stroke reversal.

The strength of wake-wing interaction during clap-and-fling depends on several factors including the thickness of the wing’s boundary layer as well as the strength and direction of the induced flow during stroke reversal. Experiments modifying the distance between two flapping robotic wings show that lift enhancement requires an angular separation between the two wings of no more than 10-12° (Reynolds number=134)[17]. This value corresponds to a distance between the two rotational wing axes of approximately one mean wing chord of the fruit fly model wing. The *relative* benefit of clap-and-fling lift enhancement strongly depends on the stroke kinematics. For example, insects that flap their wings with small stroke amplitudes should benefit relatively more from clap-and-fling force augmentation than insects that produce elevated flight forces by flapping their wings with stroke amplitudes close to the mechanical limit of the thoracic exoskeleton. In fruit fly model wings (160° stroke amplitude), maximum lift augmentation amounts to approximately 17% of the mean lift produced by a single wing flapping free from downwash of an image wing.

3 WAKE-WING INTERFERENCE IN DRAGONFLIES

Another type of wake-wing interaction is found in functionally four-winged insects such as dragon- and damselflies [18-22]. The neuromuscular system allows these animals to actively change many aspects of wing motion in a single wing such as the angle of attack, stroke plane and more conventional parameters such as stroke amplitude and stroke frequency. However, unlike four-winged insects with indirect flight musculature such as butterflies, bees, wasps and ants, dragon- and damselflies may actively control the timing between fore- and hindwing stroke cycles – the kinematic phase relationship [23,24]. In this respect, dragon- and damselflies even differ from other more primitive orders of functionally four-winged insects, such as locusts, in which phase relationship is highly consistent during flight with only little variation during steering maneuvers [25].

According to the bi-plane theory, total lift production in tandem wings depends on the proximity and strength of forewing downwash that interferes with the hindwing. Under such conditions, the hindwing must cope with a potential reduction in effective

angle of attack and the interference between shed vorticity such as the forewing's start vortex and the hindwing's leading edge vortex. Since wake-wing interaction depends on the forewing wake structure and the timing with which the hindwing interacts with the forewing wake, two long and narrow wings working independently should have higher lift-to-drag coefficients than a combined wing with the same area but different aspect ratios. Alexander [26] thus predicted that tandem wings flapping in-phase should produce less lift, because the two wings are always closer together than two wings flapping out-of-phase.

Maybury and Lehmann [18] modeled dragonfly flight, employing an electromechanical flapper and measured forces and wake structure by two-dimensional digital particle velocimetry. While varying the phase relationship between the two horizontally beating wings, the authors showed how the performance of the fore- and hindwing varies in response to kinematic phase-shifting. The most unexpected result in this study was that the hindwing regained aerodynamic performance close to that of a wing without forewing interference, when the motion of the hindwing led the forewing by approximately a quarter stroke cycle. Thus, when the forewing leads wing motion by a quarter stroke cycle, hindwing lift production decreases by approximately 40%, compared to a single wing. The approximately two-fold change in aerodynamic performance of the hindwing follows a sinusoidal curve when phase relationship linearly changes from -50% (forewing leads wing motion) to $+50\%$ stroke cycle (hind wing leads wing motion, counterstroking). This relationship implies that small changes in phase lag of around -25% and $+25\%$ stroke cycle (phase-shifted stroking) only produce moderate changes in hindwing lift production, whereas in parallel stroking, the same phase alterations produce considerably larger modulations in hindwing lift.

Moreover, power estimates of the dragonfly model suggest that flying with two pairs of wings can be highly effective in improving aerodynamic efficiency. This is achieved by recovering energy from the wake wasted as swirl in a manner analogous to coaxial contra-rotating helicopter rotors. With the appropriate fore-hind wing phasing, aerodynamic power requirements can be reduced by up to 22% compared with a single pair of wings, indicating one advantage of four-winged flying that may apply to dragonflies [27].

4 CONCLUSIONS

Caution must be applied when interpreting the biological significance of the above observations. Suggesting an evolutionary advantage of either two-winged or four-winged forms is unwise, considering the success and diversity of the true two-winged flies, and yet the maintenance of the four-winged form by dragonflies since the Carboniferous. However, in terms of engineering, the findings presented here may be particularly valuable. Any energetic benefit from four-winged flapping would be of great interest in the field of biomimetic aircraft design (Stafford, 2007) because flapping-winged aircraft are challenged by the high power requirements of flapping flight (Ellington, 1999). Appropriately phased four-winged flapping, analogous to dragonfly flight, and the use of dorsal wake-wing interaction may thus present aerodynamic tricks to reduce these power requirements, and to improve the endurance of the next generation of flapping micro air vehicles.

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