Vorticity generation during the clap-fling-sweep of hovering insects

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In 1973 Weis-Fogh [1] studied the flight of different hovering insects, such as some species of moths, flies or wasps, in particular the Chalcid wasp *Encarsia formosa* whose wing span is less than $2mm$. It has two pairs of wings, with a wing chord of about $0.2mm$, which move as a single unit. Weis-Fogh showed that the observed lift coefficient is much too-high to be compatible with steady-state aerodynamics and, by taking movies at frequency 7150 s^{-1}, he decomposed each downstroke, whose frequency is about 400 s^{-1}, into three phases: the wings clap at the end of upstroke, 'fling open' like a book, then sweep and horizontally separate until the end of downstroke. Although the motion is three-dimensional, Lighthill showed the same year [2] that the lift generation can be explained using only two-dimensional inviscid fluid dynamics. We propose to consider Lighthill's two-dimensional model, but using instead viscous fluid dynamics to study how such an unsteady motion generates vorticity, circulation, and lift on the wings.

We perform several numerical experiments, based on the vorticity–velocity formulation of the two-dimensional Navier-Stokes equations computed with resolution $N = 2048^2$, using a Fourier pseudospectral method with semi-implicit time discretization and adaptive time-stepping [6]. We consider a square periodic domain and the no-slip boundary conditions on the wings are imposed using a volume penalisation method [3], whose convergence towards the Navier–Stokes equations with no–slip boundary conditions has been proved in [4].

We study both *double-winged* and *single-winged* configurations, each wing having a chord to thickness ratio of 32 and flapping according to the following protocol. Initially the wings are positioned vertically and parallel –*clap*. The wings start rotating with a linearly increasing and then smoothly decreasing angular velocity –*fling*. When the angle between the wings mounts to approximately 120°, the wings smoothly start translating in opposite directions –*sweep*. The hinge points coincide during the clap and fling phases, such that initially there is no gap between the wings. During *fling* the Reynolds number, based on the chord and the maximum tip-speed, is about 80, while during *sweep* it reduces to about 20, based on the chord and the translation speed.

Fig. 1 (left) shows the vorticity of the *double-winged* configuration at three successive time instants. We observe that strong vortices are formed at the tips of the wings (leading edges), reflecting the fact that the air rushes in the opening, in agreement with [2]. But during sweep, these vortices form a pair which remain localized between the wings, generating a downward jet which is not observed for the single wing, see Fig. 1 (left). Another important feature is that the trailing-edge vortices, formed when the wings separate, are of same sign as the leading-edge vortices in contrast to [7], which followed a slightly different scenario. This increases the downward air flow through the opening gap, supporting the idea of high lift generation and showing how the circulation persists during the sweep phase.

Fig. 1 (right) presents vorticity plots for the *single wing* following the same protocol. Comparison with Fig. 1 (left) shows the importance of the topology change involved in *sweep*. Overall, the single-winged configuration exhibits a typical unsteady-airfoil behaviour which is radically different from the *clap-fling-sweep* mechanism, where a change of topology is involved.

Fig. 2 shows the time evolution of the lift produced by both configurations. For the double-winged configuration, only the force acting on the left wing is shown. During the fling motion the double-winged configuration creates at least double the lift. When the wing stops rotating the lift drops rapidly for both configurations, which is an added mass effect. The lift recovers after the transition and becomes an order of magnitude higher for the double-winged configuration than for the single-winged, confirming the fact that the high circulation survives after the change of topology, which results in an immediate lift (see [2]).

Following [5], local analysis of the flow near the just-opening gap where the local Reynolds number is still small will be given, and its implications discussed.

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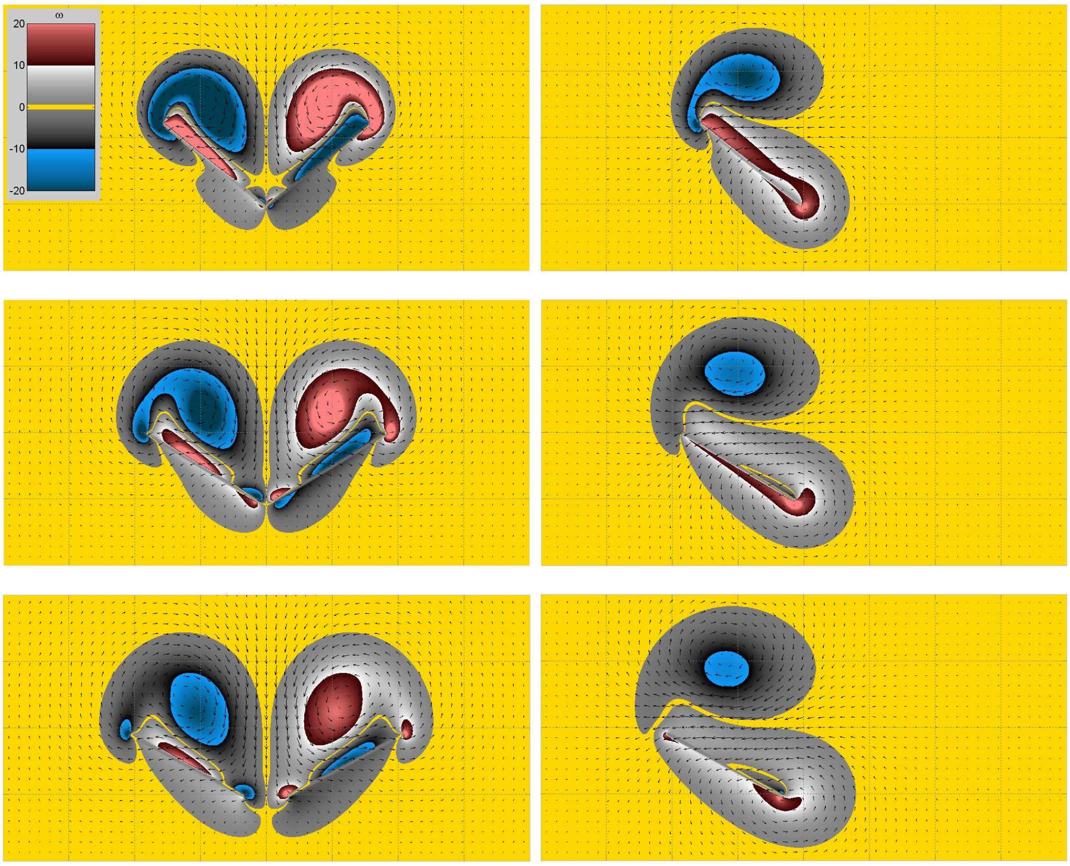

Figure 1: Vorticity plots of the double-winged (left) and single-winged (right) configurations, combined with vector plots of the velocity. Snapshots correspond to the sweep phase, at times $t = 0.32$ (top), 0.42 (middle) and 0.52 (bottom).

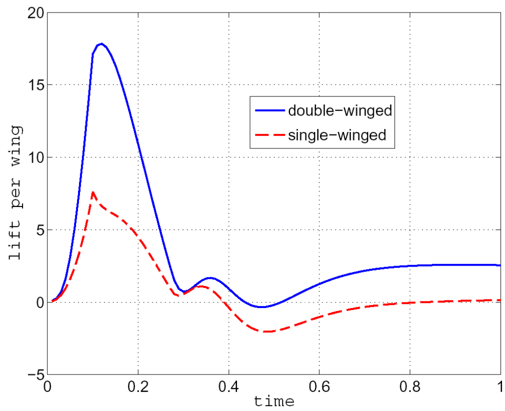

Figure 2: Lift of the double- (half-wing) and the single-winged configurations.

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