Scaling of vorticity annihilation during leading-edge vortex formation

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Due to the high performance of wings in bird and insect flight, their aerodynamics are frequently addressed in current research. A broad variety of wing shapes and three-dimensional movements of such have been investigated to identify the significant quantities for the formation and shedding of the dominant lift increasing flow feature: the leading-edge vortex (LEV).

LEVs on flapping wings can be characterized by the dimensionless quantities Rossby number (Ro), Strouhal number (St) and Reynolds number (Re) [1]. The long-term LEV-stability is mainly depicted by centripetal and Coriolis forces due to rotational accelerations of the wing and is only possible for certain Rossby-numbers ($Ro<4$) [2], which describe the ratio of Coriolis to inertial forces. The plunging and pitching kinematics are characterized by the Strouhal number St. Also here a narrow band of values $St=0.2$-0.4 [3] tends to deliver maximum efficiency. In contrast, a large range of flyers and swimmers (from fruit flies to mammals $Re=10^2$-10^8[4]) use LEVs for efficient propagation. The existence of LEVs in nature from the laminar to the highly turbulent regime suggests a small Reynolds number influence [1]. However, with increasing Reynolds number multiple instability mechanisms such as centrifugal instabilities (CI) [5] and Kelvin-Helmholtz instabilities (KHI) [6] appear in the LEV and can influence the coherence of the lift-enhancing structure [2].

Recent publications [7, 8] quantify the circulation budget of nominally two-dimensional LEV during their formation. Hereby, the constant growth of circulation in the LEV is partially counteracted by vorticity fed through the boundary layer on the suction side of the wing. This introduction of opposite signed vorticity results in two phenomena: vorticity annihilation in the LEV and vorticity accumulation near the leading-edge. The latter can lead to the formation of a counter-rotating secondary vortex, which is suggested to coincide with the shedding of the primary LEV [9]. Thus, the introduction, the convection and the annihilation of opposite signed vorticity could be crucial to the LEV stability. It is hypothesized that this process of vorticity flux and annihilation/accumulation is influenced by a possible transition of the suction side boundary layer. Therefore, this study aims towards a deeper understanding of the aforementioned instability mechanisms (KHI and CI) on the vorticity annihilation and accumulation in the LEV. Nominally two-dimensional leading edge vortices are investigated for a broad range of Reynolds numbers. Thereby, particle image velocimetry (PIV) and pressure measurements are applied to quantify and visualize the boundary layer development and its effects on the LEV formation and the circulation budget.

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