Aerodynamics and Structural Mechanics of Flapping Flight with Elastic and Stiff Wings

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Abstract. The flapping flight mechanism is expected to provide revolutionary operation capabilities for tomorrow’s Micro Air Vehicles (MAV). The unsteady aerodynamics of the flapping flight is vastly different from traditional fixed-wing flyers. Boundary layers with moving laminar-turbulent transition, three-dimensional wake vortices and fluid-structure interaction with anisotropic wing structure are only a few examples for the challenging problems. To get basic understanding of these effects, the authors develop a computational method that is validated with boundary-layer measurements on flexible and inflexible, flapping wings in a wind-tunnel. The computational method solves the unsteady Reynolds-averaged Navier-Stokes equations and is combined with both transition prediction and fluid structure interaction capability. Using generic airfoils shapes inspired by seagulls and hawks, different aerodynamic, structural and kinematic effects are systematically analyzed on their influence on thrust and propulsive efficiency of the flapping flight mechanism. In particular, we demonstrate that a slight forward-gliding motion during the flapping downstroke can increase significantly thrust and efficiency. Wing elasticity however seems to lower the propulsive efficiency in the investigated cruise flight flapping case. Beyond, we show that the wake structure of 3D flapping wings generates an efficiency loss of about 10% compared to equivalent two-dimensional flapping cases.

1 Introduction

Inviscid aerodynamic theory of flapping flight goes back to Theodorson [1] and Garrick [2], who investigated the phenomenon of aerodynamic flutter.
THEODORSEN showed that depending on the flutter - i.e. flapping - frequency, the lift force oscillation has a phase lag with respect to the angle of attack oscillations. The theory is quite simple and nowadays still used for rough estimations of the lift and thrust distribution over one flapping cycle. The flapping flight of birds however takes place in a Reynolds-number range of 100000, where the viscous effects of boundary layers and eddy formation can not be neglected, i.e. the THEODORSEN theory might not give adequate results.

Eminently difficult seems to be the presence of laminar separation bubbles (LSB), which are a phenomenon at the laminar-turbulent transition, according to early observations by HORTON [3]. A pressure increase along the airfoil contour causes the oncoming laminar boundary layer to separate. The separated flow performs the transition process from laminar to turbulent flow following a gradual development of the primary instabilities from TOLLMIEN-SCHLICHTING instabilities towards KELVIN-HELMHOLTZ instabilities. The resulting turbulent fluctuations in the flow enhance momentum transport towards the wall, and the flow reattaches to the airfoil contour. The resulting region of circulating flow is called LSB. LSB’s are usually not desired in airfoil design because they increase the pressure drag of the airfoil due to a higher displacement thickness level of the boundary layer.

Of course, there is no simple ‘formula based’ theory to cover the transitional flow over flapping airfoils. It can not be avoided to solve the Navier-Stokes equations. These equations are derived from the first principles of mass, momentum and energy conservation. Solving the Navier-Stokes equations without further simplifications can be very demanding since even small turbulent structures have to be discretized for the numerical schemes. To minimize the computational effort, RADESPIEL et al. [4] demonstrated that it is sufficient to solve the unsteady Reynolds-averaged Navier-Stokes (URANS) equations, which have to be coupled with a transition prediction method. In the present contribution, we will adopt this methodology and investigate the aerodynamics of naturally evolved airfoils. Seagull and hawk airfoils are used because these birds are known to be efficient flapping flyers, see chapter 2.

2D effects in chapter 6.1 and also 3D aerodynamics effects in chapters 6.3 and 6.4 are discussed. The common objective is to yield information on the propulsive efficiency $\eta_p$, given by

![Fig. 1 Sketch of a Laminar Separation Bubble (LSB) by HORTON [3] (corrected).](image-url)