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Fluid–structure analysis of a flexible flapping airfoil at low Reynolds number flow

Ralf Unger [a,*], Matthias C. Haupt [a], Peter Horst [a], Rolf Radespiel [b]

[a] Institute of Aircraft Design and Lightweight Structures, Technische Universität Braunschweig, Hermann-Blenk-Str. 35, 38108 Braunschweig, Germany
[b] Institute of Fluid Mechanics, Technische Universität Braunschweig, Bienroder Weg 3, 38106 Braunschweig, Germany

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ABSTRACT

In this paper, a coupling simulation methodology is applied to investigate the fluid flow around a light and flexible airfoil based on a handfoil of a seagull. A finite element model of the flexible airfoil is fully coupled to the flow solver by using a load and displacement transfer as well as a fluid grid deformation algorithm. The flow field is characterized by a laminar-turbulent transition at a Reynolds number of Re = 100 000, which takes place along a laminar separation bubble. An unsteady Reynolds-averaged Navier–Stokes flow solver is used to take this transition process into account by comparison of a critical N-factor with the N-factor computed by the e^N-method. Results of computations have shown that the flexibility of the airfoil has a major influence on the thrust efficiency, the mean drag and lift, and the location of laminar-turbulent transition. The thrust efficiency can be considerably improved by increasing the plunging amplitude and by using a time dependent airfoil stiffness, inspired by the muscle contraction of birds.

1. Introduction

The development of micro aerial vehicles with flapping wing propulsion and with its broad range of application is a research field, which has a long history of interest. Already over 100 years ago, Lilienthal studied bird's flight for adaption for engineering applications, (Lilienthal and Lilienthal, 1889). In the 1930s, Egloff investigated experimentally the forces and oscillation behavior of examinate wings of birds and of technical model wings to provide a database of characteristics (Egloff, 1937). From the biological point of view, ornithologist have studied systematically the aerodynamic behavior and the performance of different birds in nature since the 1960s (Pennycuick, 1968; Rayner, 1979). Furthermore, the aeroelastic phenomena of pitching and plunging airfoils have been investigated intensively since the 1970s (Dowell, 1977; Garrick, 1976). Recently, aerodynamic effects like laminar separation bubbles have been taken – numerically as well as experimentally – into account to the modeling or airfoils with flapping wing propulsion (Mueller, 2002; Ol et al., 2005; Windte and Radespiel, 2008). With modern computational power and experimental setups, also three-dimensional (3-D) flapping wings have become subject for research interests (Heathcote et al., 2008; Mazaheri and Ebrahimi, 2010, 2011).

The flapping wing concept inspired by bird's locomotion is promising for reaching a high propulsive efficiency. In the context of the flapping flight motion, both necessary flight forces – lift and thrust – are generated by pitching–plunging mechanism in conjunction with a low Reynolds number flow regime. Here, for simplification a 2-D airfoil is investigated

* Corresponding author. Tel.: +49 531 3919925; fax: +49 531 3919904.
E-mail address: r.unger@tu-bs.de (R. Unger).

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first and the question arises, if flexibility of such an airfoil is advantageous for the propulsion efficiency. This issue is addressed in this paper. Further, the aerodynamic behavior of the flapping wing propulsion is still not adequately understood and needs to be investigated. In Heathcote and Gursul (2007), a flexible flat-plate connected to a stiff tear-drop like airfoil was experimentally investigated at low Reynolds numbers and the flexibility of the plate was responsible for improvements of the airfoil propulsive efficiency.

However, the accurate prediction of the flow behavior using computational fluid dynamics (CFD) is still challenging due to the occurrence of a laminar-turbulent transition (Lian and Shyy, 2007; Ol et al., 2005; Radespiel et al., 2007; Yuan et al., 2007). This transition takes place along a laminar separation bubble, which is caused by a strong adverse pressure gradient within the laminar boundary layer and along the smooth aerodynamic surface. The evolution of the flow from laminar to turbulent proceeds in three stages (Yuan et al., 2007). In the first, receptivity stage, external disturbances like free stream turbulence or acoustic waves are transformed into low disturbances with wave characteristics within the boundary layer. In the second stage, a small number of unstable waves (Tollmien–Schlichting waves) are amplified and grow exponentially. Their behavior can be mathematically described by the linear stability theory (Marxen et al., 2004). In the third stage, the amplitudes of the waves increase and a nonlinear interaction with the boundary layer occurs. Thereby, the mean boundary layer profile distorts and the laminar boundary layer breaks down to turbulence.

For the simulation of such flow phenomena fully coupled with a flexible thin structure, a high qualitative and time resolved coupling schemes nowadays used for fluid–structure interaction problems is utilized (Unger et al., 2008a). The so-called partitioned coupling approach uses well-validated fluid as well as structural solvers, which are linked together within a simulation environment by the aid of flexible data transfer libraries (Haupt et al., 2005). For the flexible airfoil itself, a nonlinear finite element methodology is applied (Bathe, 1996; Zienkiewicz and Taylor, 2005). A thin rigid airfoil based on a parameterized description of seagull's handfoil is numerically and experimentally analyzed in Bansmer et al. (2010). This airfoil is named SG04 and in this paper the flexible version of this airfoil is investigated in terms of motion and structural parameters. The first structural eigenfrequency of the flexible SG04-airfoil is validated against the designed model for the wind tunnel test campaigns in Unger et al. (2008b) and Bansmer et al. (2010).

For the fluid part of the simulation environment, an unsteady Reynolds-averaged Navier–Stokes (URANS) flow solver (Kroll, 2002) is modified to take the transition process into account (Radespiel et al., 2007). Thus, for the second stage of the transition process, the linear stability solver Lilo (Schrauf, 2006) is directly coupled to the flow solver to investigate the flow field and especially the boundary layer of the airfoil. The transition location on the upper and lower side of the airfoil is calculated by comparison of a critical N-factor to the N-factor computed by the e^N-method (Smith and Gamberoni, 1956; van Ingen, 2008). Due to the use of a URANS solver the first stage is empirically considered by a calibration of the critical N-factor. Further it is assumed that the third stage is very short and that therefore the location of the breakdown to turbulence is equal to the end of the second stage (Yuan et al., 2007).

The present paper is intended to be the subsequent work of the paper (Bansmer et al., 2010), where experimental measurements have been conducted and the numerical simulation environment was validated for both, the rigid and flexible SG04 airfoil. Therefore, a comparison of a rigid and a flexible airfoil is not the topic of the present paper. Here, the simulation environment is further applied to a flexible airfoil and numerical flow computations are presented. The question arises how to improve the propulsive efficiency of the flapping airfoil motion by varying certain parameters on the structural side of the coupled fluid–structure system. Thus, the remainder of the paper is organized as follows. In Section 2, the fluid solver and the coupling environment are introduced, which are used for the simulations. The calculation of the structural jig-shape with the aid of the coupling simulation, which come along with steady state fluid solution will be presented in Section 3. Validation of the coupled analysis with given experimental data is the topic of Section 4. In Section 5, parameter studies are accomplished, which focus on improving the propulsive efficiency of the flapping motion.

2. Fluid solver and coupling scheme

For the computation of the flexible airfoil interacting with an incompressible fluid at a low Reynolds number, the Navier–Stokes solver Floweris integrated into the flexible coupling environment *ifls* (Haupt et al., 2005; Unger et al., 2008a). To calculate the transition location along the airfoil, the velocity profiles from the URANS solution are treated with a linear stability solver, which provides the amplification rates of the instability. These amplification rates are used to predict the transition location by comparison with a critical N-factor.

2.1. Description of the fluid solver with transition prediction

The unsteady Reynolds averaged Navier–Stokes equations (URANS) are solved by the flow solver Flower (Kroll, 2002), which uses block-structured grids in conjunction with a finite volume spatial discretization scheme in 3-D. Here, a cell-centered scheme is utilized and the convective fluxes across the cell edges are treated with a second order-accurate central differencing scheme with scalar dissipation. The code is switched to a 2-D mode, i.e. in spanwise direction, periodic boundary condition is assumed. The fluid solution is iterated to steady state by a five stage multigrid scheme. The true transient solution is recovered with the aid of an implicit dual-time stepping approach. Menter's baseline (BSL) turbulence model is used on a single grid basis. Acceleration of convergence is accomplished by a local time stepping, residual