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Computation of unsteady viscous flow around a locally flexible airfoil at low Reynolds number

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A B S T R A C T

A numerical method for fluid–structure interaction is presented for the analysis of unsteady viscous flow over a locally flexible airfoil. The Navier–Stokes equations are solved by ALE–CBS algorithm, coupling with a structural solver with large deformation. Following the validation of the method, a numerical example for the flight of micro-air vehicles at low Reynolds number is chosen for the computation. The coupling effect of flexible structure with different elastic stiffness on aerodynamic performance is demonstrated. A noticeable camber effect is induced by the deflection of the structure as the elastic stiffness of the structure goes smaller. Moreover, when the vibrating frequencies of the structure with smaller elastic stiffness have a close correlation with the shedding frequencies, the positive impact of the vibration of local flexible surface on the lift of the airfoil is highlighted, which results from the formation of the coherent vortices.

1. Introduction

Flexible structures (e.g. shell, plate, shallow arch, membrane) have been widely used in unmanned air vehicles (UAVs) and micro-air vehicles (MAVs) (Shyy et al., 2010, 1999; Yu et al., 2013). During the flight, unsteady flows and the structures are coupling strongly. The structures may undergo severe vibration and large deformation under the unsteady aerodynamic forces. On the other hand, since the structure is a boundary of fluid domain, the flow over the structure may change or separate. Thus the aerodynamic forces upon the structure will be altered in a feedback loop. The investigation of the coupling system addresses a challenge of multi-disciplinary computational techniques and fundamental understanding of unsteady aerodynamics and fluid–structure interaction.

An extensive study has been conducted on the coupling between the fluid flow and flexible structures. Early studies have paid much attention to modeling of flexible structure and its aeroelastic instability (Dowell and Hall, 2001; Guo and Mei, 2003), such as flutter, limit cycle oscillation, chaotic motion. An excellent review for these subjects is presented in Dowell and Hall (2001)'s work. However, in most of these works (Dowell and Hall, 2001; Guo and Mei, 2003), the flow was modeled by using potential theory or thin-layer flow models, which cannot describe unsteady viscous flow precisely. In recent years, highly coupled fluid–structure systems for MAV at low Reynolds numbers have become of great interest inspired by biological flights. Researchers have attempted to explore the flexibility of structure to gain the potential of shape adaptation for severe flow condition, and to improve aerodynamic performance (Ghommem et al., 2012; Gordnier et al., 2013). Persson et al. (2007) proposed a high-order discontinuous Galerkin method to study fluid–membrane interaction on the flapping flight. Gordnier (2009) presented

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numerical analysis for the aeroelastic model of a two dimensional flexible membrane airfoil. He highlighted the positive impact of the airfoil flexibility, which results from a close coupling between unsteady leading edge vortex shedding and dynamic response of structure. Experiments of flexible wings have also been carried out. Song and Breuer (2007) investigated the effects of aspect ratio and the initial tension of membrane wing on aerodynamic performance in mammalian flight by means of wind tunnel tests. Rojratsirikul et al. (2009) studied unsteady aerodynamics for a two-dimensional membrane airfoil at low Reynolds numbers with a PIV system. The results show that the stall is delayed due to the vibration of flexible structure. In these works, the whole lift surfaces of wings were modeled as flexible structure. Such design demands high quality of structure materials, and may result in irreversible damage during strong fluid–structure coupling. Thus, one part of upper surface of the airfoil is modeled as flexible structure in this study, which would be a preferable choice for airfoil design and flow control.

In present study, a numerical computation of the aeroelastic problem for locally flexible airfoil is carried out in order to gain a profound understanding of coupling between unsteady flow and flexible structure. The focus of the study is viscous aeroelastic simulation of a locally flexible airfoil and to study effect of flexibility of the structure on aerodynamic performance. In Section 2, an aeroelastic model for the flow around the locally flexible airfoil is proposed. Furthermore, a finite element algorithm is presented coupling with a structure solver for aeroelastic model in Section 3. Subsequently, the interaction between the viscous flow and flexible structure at low Reynolds number is studied in Section 4. The effects of flexibility on lift and the related flow evolution are analyzed to investigate coupling nature between fluid and structure. Finally, some conclusions are drawn in Section 5.

2. Aeroelastic model for unsteady flow around a locally flexible airfoil

2.1. Governing equations of unsteady flow

Since low Reynolds number flows for MAV flights are of interest in the study, the flow is considered laminar and incompressible. The governing equations for unsteady, viscous, incompressible flow are Navier–Stokes equations, which are written in the Cartesian coordinates as

$$\begin{aligned} &\nabla \cdot \vec{u} = 0, \\ &\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \frac{1}{\mathrm{Re}} \Delta \vec{u}. \end{aligned} \tag{1}$$

Let the chord of the airfoil c be the characteristic scale, freestream velocity u_∞ be the characteristic velocity, and dimensionless variables are defined as

$$x^* = \frac{x}{c},\; y^* = \frac{y}{c},\; t^* = \frac{u_\infty t}{c},\; p^* = \frac{p}{\rho_\infty u^2{}_\infty},\; u^* = \frac{u}{u_\infty},\; v^* = \frac{v}{u_\infty}, \tag{2}$$

where ρ_∞ is the freestream density.

For the sake of simplicity, the superscript "*" is dropped, and the standard summation conventions are used hereinafter.

In order to deal with fluid–structure interaction, arbitrary Lagrangian–Eulerian (ALE) framework is introduced into the equations. Thus, the dimensionless governing equations for two-dimensional, unsteady, incompressible flow in the ALE configuration are rewritten as follows:

$$\begin{aligned} &\frac{\partial u_i}{\partial x_i} = 0, \\ &\frac{\partial u_i}{\partial t} + (u_j - \hat{u}_j)\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}}\frac{\partial^2 u_i}{\partial x_j \partial x_j}, \end{aligned} \tag{3}$$

where $\mathrm{Re} = \rho u_\infty c/\mu$, $\hat{u}_j$ is the velocity of the grid.

2.2. Governing equation for flexible structure

The cross section of the wing surface with high aspect ratio is of small curvature and subjected to tension and bending moments, which can be analogous to shallow arch. Thus, locally flexible part of airfoil surface is modeled using the theory of shallow arch with large deformation. The effects of large deformation and bending moments are considered in the presented model (Kang et al., 2012; Zhang et al., 2007), which are not included in the membrane model (Gordnier, 2009; Shyy et al., 1999; Smith and Shyy, 1995).

In light of the study of airfoil with dynamically deformable leading edge shape (Chandrasekhara et al., 1997, 1998; Sahin et al., 2003), the position of the structure is chosen near the leading edge of the airfoil. That is because the perturbation induced by the excitations can propagate downstream, which has great influence on flow evolution. In this paper, the flexible section is shallow arch with simply supported boundaries, locating near the leading edge of the airfoil. Fig. 1 shows the schematic diagram of locally flexible airfoil.

The analysis for flexible surface will be carried out under the following assumptions: (1) the deformation is elastic; (2) the inertial effects from deformation are ignored; (3) the geometric nonlinearity is considered; (4) the damping is introduced; (5) the bending effects are considered.