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Aerodynamic Analysis of a Localized Flexible Airfoil at Low Reynolds Numbers

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Abstract. A localized flexible airfoil at low Reynolds numbers is modeled and the aerodynamic performance is analyzed numerically. With characteristic based split scheme, a fluid solver for two dimensional incompressible Navier-Stokes equations is developed under the ALE framework, coupled with the theory of shallow arch, which is approximated by Galerkin method. Further, the interactions between the unsteady flow and the shallow arch are studied in detail. In particular, the effect of the self-excited vibration of the structure on aerodynamic performance of the airfoil is investigated deeply at various angles of attack. The results show that the lift-to-drag ratio has been increased greatly compared with the rigid airfoil. Finally, the relationship between the self-excited vibration and the evolution of the flow is analyzed using FFT tools.

AMS subject classifications: 74F10, 76G25, 76D55, 76D05

Key words: Fluid-structure interaction, Navier-Stokes equations, aerodynamic performance, lift enhancement and drag reduction, flow control.

1 Introduction

With the rapid development of the aeronautic technology, the flexible structures (like shell, plate, shallow arch, membrane etc) have been used frequently in the aerospace vehicles, high-performance aircraft and micro air vehicles etc. One advantage of the flexible structures is that it can gain the potential of the shape adaptation for severe flow condition, resulting in delayed separation and what is more, lift enhancement and drag reduction, compared with rigid ones. However, during the flying, the flow and the flexible structures are coupling strongly, giving rise to a rich variety of nonlinear problems

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with respect to stability of airfoil, the dynamic response of the flexible structure, unsteady separation, vortex formation and evolution and so on. Therefore, to understand the behaviors of the coupling systems is one of the important issues for the applications of such structures.

Recent studies have begun to focus on the close interaction between the fluid flow and flexible structure for the aeroelastic problems. In 2007, Persson et al. [1] have investigated both fixed and oscillating membrane airfoils using a high-order discontinuous Galerkin method. More recently, Gordnier [2] presented a viscous aeroelastic computation and analysis for a two dimensional flexible membrane airfoil and highlighted the positive impact of the airfoil flexibility. Experimental flow visualizations have been carried out as well. In 2007, Song and Breuer [3] investigated the aerodynamics of the compliant membrane related to mammalian flight by means of wind tunnel tests. In 2009, Rojratsirikul et al. [4] studied unsteady aerodynamics for a two-dimensional membrane airfoil at low Reynolds numbers with a PIV system. The airfoils in these studies have been considered as fully flexible. However, in the practical cases, the fully flexible structures are mainly used in micro air vehicles. For the structure in normal or large size, fully flexible structures would be sensitive to irreversible damages during the flying with high speed. Moreover, it is difficult to implement active control for such kind of airfoils. Thus, the model of the localized flexible airfoil is presented by introducing the theory of shallow arch in this study, which would be a better choice for airfoil design and flow control.

In order to gain a profound understanding of unsteady aerodynamics of the localized flexible structure, an effective algorithm for the problem of fluid-structure interaction should be established and developed first in such situation. Many approaches have been suggested for this kind of problems (see [5–9]). One of the methods used commonly is the Arbitrary Lagrangian Eulerian method (ALE) [5, 6]. In this study, characteristics based split (CBS) scheme is chosen for fluid-structure interaction under the ALE framework. The CBS scheme was first introduced into the governing equations of fluid by Zienkiewicz in 1995. Its basic idea is the approximation of the characteristics by using a Taylor expansion with a split procedure and it has been successfully used in computational fluid dynamics and computational structural dynamics [10–13]. However, this algorithm is not suitable for the fluid-structure interaction problems and needs to be extended. Hence, a CBS algorithm under the ALE framework is developed to deal with the problems relevant to fluid-structure interaction and an implicit approximation for CBS scheme is implemented consequently in this study.

The purpose of the study is the computational aeroelasticity of the localized flexible airfoil at low Reynolds numbers. The impacts of coupling between the fluid and the structure on the aerodynamic performance are investigated in comparison with the rigid airfoil. The results also show the relationship between the flow evolution and dynamic motion of the flexible structure.