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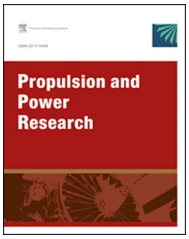

ORGINAL ARTICLE

Local vibrations and lift performance of low Reynolds number airfoil

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Abstract The 2D incompressible Navier-Stokes equations are solved based on the finite volume method and dynamic mesh technique is used to carry out partial fluid structure interaction. The local flexible structure (hereinafter termed as flexible structure) vibrates in a single mode located on the upper surface of the airfoil. The Influence of vibration frequency and amplitude are examined and the corresponding fluid flow characteristics are investigated which add complexity to the inherent problem in unsteady flow. The study is conducted for flow over NACA0012 airfoil at $600 \leq Re \leq 3000$ at a low angle of attack. Vibration of flexible structure induces a secondary vortex which modifies the pressure distribution and lift performance of the airfoil. At some moderate vibration amplitude, frequency synchronization or lock-in phenomenon occurs when the vibration frequency is close to the characteristic frequency of rigid airfoil. Evolution and shedding of vortices corresponding to the deformation of flexible structure depends on the Reynolds number. In the case of $Re \leq 1000$, the deformation of flexible structure is considered in-phase with the vortex shedding i.e., increasing maximum lift is linked with the positive deformation of flexible structure. At $Re = 1500$ a phase shift of about $1/\pi$ exists while they are out-of-phase at $Re > 1500$. Moreover, the oscillation amplitude of lift coefficient increases with increasing vibration amplitude for $Re \leq 1500$ while it decreases with increasing vibration amplitude for $Re > 1500$. As a result of frequency lock-in, the average lift coefficient is increased with increasing vibration amplitude

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for all investigated Reynolds numbers (*Re*). The maximum increase in the average lift coefficient is 19.72% within the range of investigated parameters.

1. Introduction

Recently, the use of flexible structure has increased in aerospace vehicles and micro-air vehicles because of its ability to adapt to severe flow conditions resulting in a positive influence on the aerodynamic performance. However, in the case of fully flexible structure there is a risk of damage in the case of long chord or at high Reynolds number. Therefore, local flexible structure can be promising and safe alternative. Vibration of flexible structure gives rise to complex phenomena due to its particular wake dynamics structure. This study is dedicated to investigate the influence of controlled local vibrations of flexible structure on the lift coefficient of airfoil and the corresponding flow field.

In regard to airfoils and other slender bodies, it is well known that as the angle of attack increases or decreases beyond a certain limit, vortices start shedding from the trailing edge. The vortex pattern can be changed if the airfoil or its surface vibrates in the cross-flow direction. Amplitude and frequency of vibration play an important role in flow structure downstream of the airfoil; typically, when the vibration frequency is close to the vortex shedding frequency. It results in frequency synchronization or lock-in between the two frequencies where the natural vortex shedding frequency is dominated by the vibration frequency. Extensive work has been done on vibrating cylinders, airfoils and the underlying flow-structure interaction. Circular and square cylinders are the representative examples of bluff body with non-fixed and fixed point separation, respectively. Sarpkaya [1,2], Bearman and Graham [3] Bearman [4] and Williamson and Govardhan [5] have presented nice overview of fluid-structure interaction and extensively studied the lock-in phenomenon long ago. Ongoren and Rockwell [6] experimentally investigated the flow structures in the near wake region of various cross-sectional cylinders with controlled frequency and amplitude. They examined the synchronization phenomenon and the phase shift at the same condition between vortex formation and body motion. In separate works, Anagnostopoulos [7] and Pham Anh-Hung et al. [8] numerically studied 2D cylinders with a range of oscillating frequencies and amplitudes. They found that when the oscillation frequency exceeded the natural vortex shedding frequency, there appeared a secondary vortex shedding frequency with a value less than the natural frequency. Similarly, considerable work has also been done on the aerodynamic characteristics of plunging airfoils and slender plates. For instance, experimental and numerical work by Cleaver et al. [9] and Amiralaei et al. [10,11], respectively, investigated the flow field around a plunging airfoil and showed the effects of the Strouhal and Reynolds numbers on its aerodynamic performance. Esfahani et al. [12] investigated plunging with forward and backward motion. Young and Lai [13] observed the lock-in phenomenon for plunging airfoils and found that for a frequency higher than the natural vortex shedding frequency, lock-in is expected to occur at low amplitude in the wake of the airfoil. Gostelow et al. [14] identified similarities between the vortex shedding from an oscillating cylinder (bluff body) and oscillating airfoil in low speed flow and the wake structure of turbine cascade in transonic flow. Lua et al. [15] investigated the wake structure formation of heaving elliptic airfoil from the interaction of leading and trailing edges vortices. Furthermore, Lam and Leung [16] experimentally investigated the flow past an inclined flat plate at high incidence to capture the vorticity distribution in the wake. They gave control lateral vibrations to the flat plate near its natural frequency which improved the regularity and periodicity of vortex shedding.

Actuation is widely used to control the flow separation around slender bodies, for example, Greenblatt and Wygnanski [17] and Seifert et al. [18] outlined the various methods and the aspects of flow separation control from airfoils and other solid surfaces. They demonstrated that unsteady actuation near the separation point can reattach the flow, suppress vortex shedding or shorten the separation bubble. In regards to the airfoils, flexible membranes have been introduced for flow control and enhancing the aerodynamic performance. Shyy et al. [19] have presented the salient features of design and aerodynamics of flexible membranes and their inclusion in air vehicles. Gordnier [20] numerically studied two-dimensional flexible airfoil for various parameters. The dynamic motion of membrane surface alters the unsteady flow with a corresponding improvement in the mean lift. Hui et al. [21] experimentally investigated four flexible membrane airfoils with different number of rigid ribs to adjust the flexibility of membrane. They found that performance of the most flexible airfoil i.e., membrane with a single rib, has the best performance at higher angle of attack. Similarly, Albartani et al. [22] carried out experimental work in a low-speed wind tunnel on three distinct structures: a rigid, a batten reinforced and a perimeter reinforced. Batten reinforced structure has shown improved performance over rigid structure in terms of stall delay while perimeter reinforced structure has increased the lift and longitudinal stability. However, substantial geometric twist was observed in reinforced structures. The high

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