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Evolution of vortex structures over flapping foils in shear flows and its impact on aerodynamic performance

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ABSTRACT

The evolution of vortex structures over flapping NACA0012 foils in shear flows and the corresponding aerodynamic performance are numerically studied using a two dimensional (2D) high-order accurate spectral difference Navier–Stokes flow solver, and further analyzed using the dynamic mode decomposition (DMD) method and vortex theory. Several types of vortex structures over pitching or plunging foils are simulated and analyzed to answer the following questions: (1) how mean flow shear affects the evolution of vortex structures, including both leading and trailing edge vortices, over flapping foils; and (2) how mean flow shear affects the aerodynamic performance under different kinematics. A temporal DMD method is used to analyze vortex structures. It is found that mean flow shear does not modify the dominant temporal frequencies in flow fields, but strong mean flow shear can significantly alter the growth rate, amplitude, and spatial patterns of coherent structures. From simulation results, it is observed that mean flow shear can affect evolution as well as interaction among leading and trailing edge vortices, thus altering the direction of wakes behind flapping foils. The mechanism of shear-induced deflective wakes is explained via qualitative analysis of evolution of simplified vortex street models. Finally, the effects of mean flow shear on aerodynamic performances of flapping foils with different kinematics are studied. By comparing the practical aerodynamic performances with those predicted by the steady aerodynamic theory, it is shown that flapping motion can significantly promote unsteady lift generation in mean flow shear. Furthermore, compared with flapping foils with positive mean angles of attack in a uniform incoming flow, the lift over flapping foils in flows with negative mean flow shear is enhanced without compromising thrust generation.

1. Introduction

Natural flyers or swimmers flap their wings or fins to generate unsteady forces that permit excellent maneuverability under different flow conditions. The last three decades have witnessed remarkable progress in both experimental and numerical studies of evolution of vortex structures over flapping wings or fins (see the reviews by Platzer et al., 2008; Shyy et al., 2010; Triantafyllou et al., 2004, just to name a few). It is found that most previous research was conducted for uniform incoming flow. The unsteady aero-hydrodynamics over flapping wings/fins in complex flow environments (e.g., shear flow) are still less understood. Considering natural flyers and swimmers usually maneuver in complex flow environments, it is of

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Nomenclature

A	excursion of the foil trailing edge in one oscillating stroke, m
C_L	lift coefficient
C_T	thrust coefficient
c	chord length, m
f	flapping frequency, Hz
h	plunge amplitude, m
k	$2\pi fc/U_\infty$, reduced frequency
M_∞	Free stream Mach number
Re_c	$U_\infty c/\nu$, Reynolds number based on chord
St	fA/U_∞, Strouhal number
U_∞	free stream velocity, m/s
U_{pert}	the magnitude of the maximum velocity disturbance in the mean flow shear, m/s
U_{shear}	velocity profile of the mean flow shear, m/s
α, α_0	pitch angle of the foil, and pitch amplitude, degree
β, θ	control parameters of the shear strength
λ_i	growth rate of the ith temporal DMD mode
ν	kinematic viscosity of fluid, m^2/s
ϕ_0	initial phase angle, rad
ω_i	angular frequency of the ith temporal DMD mode, rad/s
ω_z	spanwise (z-direction) vorticity, rad/s

fundamental importance to further explore unsteady flow physics under non-uniform incoming flow conditions (Ortega-Jimenez et al., 2014). In this study, we aim to explore the impact of mean flow shear on the evolution of vortex structures over flapping foils and the corresponding aerodynamic performance. Among many types of vortex structures over flapping foils, we will focus on the asymmetric wake structure, with or without interaction with leading edge vortices, occurred behind a flapping symmetric foil when the dynamic parameters (e.g., Strouhal number, reduced frequency) exceed certain limits. We will numerically study how mean flow shear affects the deflective direction of the asymmetric wake, how the transition of symmetric wakes into asymmetric ones is promoted due to shear flow disturbances, and how the aerodynamic performance of flapping foils will be changed in shear flow.

The asymmetric or deflective wake features dipolar vortex structure in the wake. This phenomenon has been confirmed experimentally by Jones et al. (1998), Heathcote and Gursul (2007), Godoy-Diana et al. (2008, 2009), von Ellenrieder and Pothos (2008), Buchholz and Smits (2008), Cleaver et al. (2010), Yu et al. (2012) and Marais et al. (2012), and numerically by Jones et al. (1998), Lewin and Haj-Hariri (2003), Yu et al. (2010, 2012) and Zheng and Wei (2012). From the perspective of vortex dynamics, the formation of the asymmetric wake is closely related to the distance between two adjacent vortices with opposite spin shed in one oscillating cycle and the strength of these two vortices. In the two dimensional (2D) study, it is found that the interaction of the two vortices near the trailing edge of the foil is crucial for the dipole formation process. Recent work by Marais et al. (2012) demonstrated that the flexible wing can delay the formation of asymmetric wakes by increasing the relative distance between two adjacent vortices near the trailing edge of the wing. In this study, we investigate the effects of the vortical strength, another factor which can affect the formation of asymmetric wakes behind the flapping foil, on the evolution of vortex structures and the corresponding aerodynamic performance. A shear flow is superposed on the uniform flow to dynamically couple with the vortex structure in the wake, as illustrated in Fig. 1. This can be treated as a simple model for natural flyers passing through shear layers in atmospheric flows at urban or suburban environments. We note that effects of mean flow shear on vortical flow have been studied by Zhu and his co-workers (Zhu, 2012; Cho and Zhu, 2014) in the context of energy harvesting using flapping foils. In their work, it is found that shear flow can alter the behaviors of large leading edge vortices, thus affecting the performance of energy harvesters.

As is recognized, the phenomena we proposed to study feature evolving vortices, which are very sensitive to numerical dissipation. Traditional low-order (≤ 2) flow solvers can dramatically dissipate the unsteady vortices. In this study, a high-order accurate spectral difference (SD) method on dynamic unstructured grids developed in Yu et al. (2011) is used to resolve the unsteady vortex-dominated flows. Other recent numerical simulations of the flapping wing aerodynamics using high-order methods include the work by Visbal (2009), Persson et al. (2010), Liang et al. (2010), Ou et al. (2011) and Yu et al. (2013a, 2013b). All these works demonstrate the superior performance of high-order discontinuous numerical methods for vortex-dominated flow simulations.

High-fidelity numerical simulation can generate a large amount of high-resolution data. This poses difficulty on how to effectively extract critical flow features from the large data set. Popular data processing techniques that can be used to analyze big flow data include, but not limited to, proper orthogonal decomposition (POD) (Lumley, 1970; Sirovich, 1987), and dynamic mode decomposition (DMD) (Schmid, 2010; Rowley et al., 2009). DMD is a recently proposed data-based mode decomposition technique. It was first introduced by Schmid and Sesterhenn (2008) and Schmid (2010), and its connection