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High-Fidelity Simulation of Transitional Flows past a Plunging Airfoil

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This investigation addresses the simulation of the unsteady separated flows encountered by a plunging airfoil under low-Reynolds-number conditions ($Re_c \leq 6 \times 10^4$). The flowfields are computed employing an extensively validated high-fidelity implicit large-eddy simulation approach. Calculations are performed first for a SD7003 airfoil section at an angle of attack $\alpha_o = 4\,\mathrm{deg}$ plunging with reduced frequency $k = 3.93$ and amplitude $h_o/c = 0.05$. Under these conditions, it is demonstrated that, for $Re_c = 10^4$, transitional effects are not significant. For $Re_c = 4 \times 10^4$, the dynamic-stall vortex system is laminar at its inception, however, shortly afterward, it experiences an abrupt breakdown due to the onset of spanwise instabilities. A description of this transition process near the leading edge is provided. As a second example, the suppression of stall at high angle of attack ($\alpha_o = 14\,\mathrm{deg}$) is investigated using high-frequency, small-amplitude vibrations ($k = 10, h_o/c = 0.005$). At $Re_c = 6 \times 10^4$, separation is completely eliminated in a time-averaged sense, and the mean drag is reduced by approximately 40%. For larger forcing amplitude ($h_o/c = 0.04$, $Re_c = 10^4$), a very intriguing regime emerges. The dynamic-stall vortex moves around and in front of the leading edge and experiences a dramatic breakdown as it impinges against the airfoil. The corresponding phased-averaged flow displays no coherent vortices propagating along the airfoil upper surface. This new flow structure is also characterized in the mean by the existence of a strong jet in the near wake which produces net thrust. This study demonstrates the importance of transition for low-Reynolds-number maneuvering airfoils and the suitability of the implicit large-eddy simulation approach for exploring such flow regime.

I. Introduction

UNSTEADY low-Reynolds-number flows are found in natural flyers, as well as in small unmanned air vehicles and micro air vehicles (or MAVs) due to the relatively small size and low flying speeds involved [1,2]. Depending upon the specific conditions, these flowfields may be characterized by extensive regions of laminar flow, by the onset of laminar separation bubbles (even at moderate incidence), and by laminar–turbulent transition zones. For the case of flapping wings, as well as for severe gusts, the highly unsteady forcing induces the formation of dynamic-stall-like vortices whose evolution and interaction with the aerodynamic surfaces have a significant impact on flight stability and performance. Although much has been studied about these unsteady vortical flow features, challenges still remain in understanding their structure, scaling, and implications on flight efficiency, in particular over the broad range of parameters encountered.

From the perspective of analysis and simulation, this nontraditional low-Reynolds-number aerodynamic regime over flapping surfaces poses a severe challenge due to several factors. Difficulties arise by the presence of highly unsteady flows which defy standard quasi-steady characterization. The flowfields are of a mixed laminar-transitional-turbulent type for which high-Reynolds-number analysis tools may not be adequate. Both in nature and in MAV applications, an extensive range of parameters and configurations are encountered. Lastly, for lightweight flexible vehicles, there exists a strong coupling of the unsteady aerodynamics and structural response which requires advanced multidisciplinary approaches. Given the aforementioned difficulties, a hierarchy of increasingly complex canonical model problems can be considered to facilitate progress in the improved understanding and prediction of the physics relevant to small fliers. The simplest of these configurations is a maneuvering airfoil section which has motivated recent experiments and computations of low-Reynolds-number airfoils under both static and dynamic conditions [3–7].

As a point of departure in this research direction, the present work investigates the application of an implicit large-eddy simulation (ILES) approach for the prediction of transitional flows about plunging airfoils. This ILES approach, previously introduced in [8,9], is based on high-order compact schemes for the spatial derivatives and on a Pade-type low-pass filter to ensure stability. The high-order scheme is essential for the accuracy demanded by the transition process, whereas the discriminating low-pass filter operator provides regularization in turbulent flow regions in lieu of a standard subgrid-scale (SGS) model. This method is particularly attractive for the present application wherein a seamless approach capable of handling mixed laminar, transitional, and turbulent flows is needed.

Results are presented for flow over a plunging SD7003 airfoil section, a geometry which has been considered recently in several experimental and computational studies [4–7]. Due in part to the availability of experimental data, as well as to computational requirements, we investigate initially the case of fairly high reduced frequencies and small plunging amplitudes. Low-frequency, large-amplitude cases of more relevance to flapping flight will be reported in a follow-up study.

In this paper, two different situations are examined for the plunging SD7003 airfoil. In the first category, the airfoil is set at a small static angle of attack $\alpha_o = 4\,\mathrm{deg}$, and the imposed reduced frequency and nondimensional plunging amplitude are $k = \pi f c / U_\infty = 3.93$ and $h_o = \hat{h}_o / c = 0.05$, respectively. These parameters result in a maximum excursion in induced angle of attack of 21.5 deg. To explore the impact of transition on the flow structure around the plunging airfoil, several Reynolds numbers are considered ranging from $Re_c = \rho U_\infty c / \mu = 10^3$ to 4×10^4. Emphasis is placed on the results for $Re_c = 10^4$ and $Re_c = 4 \times 10^4$ corresponding to the recent particle image velocimetry (PIV) measurements of [7]. Similar experimental studies for a NACA 0012 airfoil performing either

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