Large-Eddy Simulation of Unsteady Separation Over a Pitching Airfoil at High Reynolds Number

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Abstract: Large-eddy simulation (LES) of turbulent flow over a pitching airfoil at realistic Reynolds and Mach numbers is performed. Numerical stability at high Reynolds number simulation is maintained using an unstructured-grid LES technology, which obeys high-order conservation principles and employs a global-coefficient subgrid-scale turbulence model. A hybrid implicit-explicit time-integration scheme is employed to provide a highly efficient way to treat time-step size restriction in the separated flow region which is locally refined with dense mesh. Systematic analysis of turbulent flow field is performed to gain physical understanding of quantitative aspects of dynamic stall.

Keywords: Dynamic Stall, Unsteady Flow Separation, Large-Eddy Simulation.

1 Motivation and Objectives

Dynamic stall is a nonlinear and unsteady aerodynamic phenomenon resulting in stall delay during a time-dependent motion of an airfoil at angles of attack higher than its static stall angle. Dynamic stall occurs on the retreating blade of a helicopter rotor experiencing a pitching motion which leads to unsteady flow separation followed by load and pitching-moment overshoots. The unsteady flow separation can, in turn, lead to unacceptably large vibratory loads and acoustic noise, and limit forward flight speeds, load, and maneuverability.

Numerous investigations of unsteady separation associated with dynamic stall have been conducted at chord-based Reynolds numbers in the range of $10^3 - 10^7$, at Mach numbers for incompressible to transonic flow, and for a wide variety of blade geometries. Most experimental studies have concentrated on measurements of aerodynamic forces such as the surface pressure and overall loads or on the flow field visualization. Quantitative measurements of the separated flow field and wake around a pitching airfoil have been difficult using experimental techniques, and therefore, have rarely been reported in the literature.

Computational fluid dynamics has become increasingly useful in studying dynamic stall (see Ref. [1] for a review). Computational works have often been performed, especially at practical Reynolds numbers, using the Reynolds-averaged Navier-Stokes (RANS) equations or its unsteady counterpart (URANS) (*e.g.*, [2, 3]). However, it is known to be challenging for (U)RANS to accurately predict highly unsteady flow involving incipient flow separation, formation and evolution of stall vortices, and reattachment.

The intrinsic capability of large-eddy simulation (LES) for predicting sufficient details of unsteady separating flows has recently been explored by a certain number of researchers. However, LES at higher Reynolds numbers has been difficult mainly due to the numerical instability issue and high computational costs associated with the spatial and temporal resolution requirements. Furthermore, most CFD works including past LES studies so far have focused on the validation of CFD codes and qualitative features of dynamic stall rather than the understanding of the flow physics under realistic flight conditions.

In this work, wall-resolved LES of unsteady separation over a pitching airfoil at realistic Mach and Reynolds numbers is performed. The research focus is on a quantitative understanding of the unsteady separation process rather than validation and qualitative characterization of the flow field. For this purpose, an unstructured-grid LES technology, which maintains numerical stability by obeying high-order conservation principles, is employed. The unstructured grid topology as well as a hybrid implicit/explicit time-integration method provides highly enhanced efficiency in treating spatial and temporal resolution requirements in the dynamically important separated flow region.

2 LES of Flow Over a Pitching Airfoil

The flow configuration corresponds to an experimental setup in [4], which was developed to study dynamic stall penetration at constant pitch rate and realistic combinations of Reynolds $(2-4\times 10^6)$ and Mach $(0.2-0.4)$ numbers. The blade cross section corresponds to the Sikorsky SSC-A09 airfoil

LES of a sinusoidal pitching motion of the airfoil at reduced frequencies, $k = \omega c/2U_\infty = 0.025$, 0.050, and 0.100, where ω, c, and U_∞ are the angular frequency, chord length, and freestream velocity, respectively, is being conducted. In the final paper, results from ongoing LES will be analyzed in detail with comparisons against experimental data such as aerodynamic forces and moment, surface pressure distributions, and transition and separation locations.

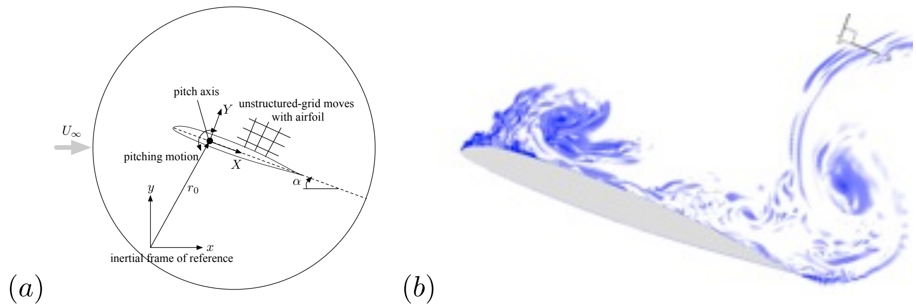

Figure 1: (a) Flow configuration for LES of flow over a pitching airfoil and (b) contours of the streamwise velocity over a pitching airfoil.

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