Effect of Periodic Longitudinal Gusts and Freestream Turbulence on Airfoil Performance Under Separated-Flow Conditions

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Airfoils operate under highly unsteady flow conditions in many applications, such as UAVs, wind turbines, and helicopters. The unsteadiness can manifest through the motion of the airfoil or a gust encounter. This unsteadiness can have two broad effects on the airfoil, wherein in the cross-stream direction, it can alter the operating angle of attack, α. On the other hand, in the streamwise direction, it can influence the dynamic pressure. Prior research has typically employed canonical motion patterns and gust models to simplify the problem and isolate fundamental physical principles. Previous studies using these canonical motions and gusts have shown that in separated flow conditions a coherent leading-edge vortex (LEV) on the upper surface of an airfoil can form, imposing a high amount of transient aerodynamic loading.

Specifically for periodic longitudinal gusts, smoke visualization and numerical simulations have identified the formation of an LEV over an airfoil in the post-stall regime and its impact on the mean and amplitude of the unsteady aerodynamic forces. However, quantitative flowfield measurements in the published literature are currently lacking, and a more comprehensive understanding of the underlying flow topology requires further investigation. The present study seeks to improve the current understanding of the separated flow topology under the influence of periodic longitudinal gusts using phase-averaged Particle Image Velocimetry (PIV).

The measured streamwise velocity u can be decomposed into the mean, $\overline{u}$, periodic, $\tilde{u}$, and fluctuating u' components using the triple decomposition method. The effect of the periodic component (longitudinal gust) is first investigated on the separated flow behavior over the airfoil using PIV. This periodic component is generated using an active grid in the recirculating wind tunnel at the University of Toronto. Subsequently, an additional level of freestream turbulence is introduced by installing a turbulence grid upstream of the airfoil to study the impact of $\tilde{u}+u'$ on the separated flow behavior. The quantitative flowfield measurements are then correlated to the measured unsteady forces to understand the impact of the separated flow behavior on the unsteady force generation.

As expected, the PIV results reveal the formation of an LEV, significantly increasing the mean and amplitudes of the lift, drag, and moment coefficients. The present flowfield analysis facilitates the study of the LEV size, circulation, and trajectory evolution with the cyclic phase of the gust cycle. These results show that the circulation computed inside a control volume bounded by the airfoil chord correlates well with the phase-averaged lift coefficient. It is also found that the turbulence intensities less than 1% show a negligible impact on the separated flow behavior in the post-stall regime. On increasing the turbulence intensity to 4% or higher, however, the extent of boundary layer separation is significantly reduced, and the measured force generation trends differ significantly compared to the laminar gust case.

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