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Numerical Investigation on Transverse-Gust-Induced Dynamic Stall

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ABSTRACT

With the development of Urban Air Mobility (UAM), understanding atmospheric disturbances near the ground has become increasingly important. These disturbances significantly impact low-altitude, low-speed flight vehicles, particularly in urban or mountainous environments where gusts are frequent. Flows resembling transverse gusts can alter the effective angle of attack (AOA), potentially triggering dynamic stall. Dynamic stall is a fluid dynamics phenomenon that occurs when the AOA of an airfoil alters around a high value that causes the airfoil to enter and exit the stall regime, leading to unsteady flow phenomena such as delayed vortex shedding and hysteresis effects that differ significantly from those in steady conditions. The phenomenon had been extensively studied using pitching wings. In our recent research, the transverse-gust-induced dynamic stall was confirmed experimentally by employing a stationary NACA0012 wing encountering transverse gusts (maximum amplitude ~ 7 deg) at transitional Reynolds numbers (Re ~ 10^5, Mach ~ 0.03) at the low-speed wind tunnel of the Royal Military College of Canada (RMC).

To model the gust-induced dynamic stall, two-dimensional (2D) Large Eddy Simulations (LES) were first performed using an in-house code of the National Research Council Canada based on the RMC experimental setup. The Smagorinsky sub-grid scale model was implemented in the code, and a hybrid upwind/centred scheme was used for discretization. The split-velocity method was employed to introduce gusts in incompressible viscous flows. These numerical results, validated against experimental data, successfully reproduced the flowfield associated with the gust-induced dynamic stall process and supported its similarity to pitch-induced dynamic stall. However, a key experimental observation, the secondary lift loop due to delayed vortex shedding, was not captured, which highlighted inherent limitations of 2D LES.

To address this, a three-dimensional (3D) LES study is conducted. The results confirm the presence of the secondary lift loop and demonstrate a similar pattern for the moment coefficient, consistent with experimental findings. Delayed vortex shedding is observed after the effective angle of attack reaches its maximum value. The study provides a comprehensive analysis of the gust-induced dynamic stall process, encompassing flow separation, vortex evolution, and flow reattachment, which are comparable with the experimental observations of pitch-induced dynamic stall. Furthermore, the 3D LES underscores the critical role of spanwise flow effects and vortex structures, which are absent in 2D simulations. These numerical simulations offer valuable insights into the mechanisms of dynamic stall induced by transverse gusts, advancing our understanding of this complex aerodynamic phenomenon.