1000 Island Fluid Mechanics Meeting, 2026

Effect of Lock-in on Leading-Edge Vortices During Longitudinal Gust Encounters

Suraj Bansal[1] & Philippe Lavoie[1]
1 Institute for Aerospace Studies, University of Toronto, Toronto, Ontario, CANADA

Airfoils operate under highly unsteady flow conditions in many applications, such as UAVs, wind turbines, and helicopters. For a harmonic longitudinal gust encounter, a stationary airfoil is subjected to a freestream flow with instantaneous velocity $u(t)$ defined as

$$u\,(t) = \overline{u}\,[1 + \sigma_g \sin\,(2\pi f_g t)]\,. \tag{1}$$

Here, $\overline{u}$ is the time-averaged freestream speed, f_g is the gust frequency, and σ_g is the gust amplitude normalized by $\overline{u}$. The reduced frequency, k_g, is defined as $k_g = \pi f_g c/\overline{u}$, where c is the chord length.

Under steady-flow conditions ($k_g \to 0$), extensive boundary layer separation at high angles of attack can result in von Kármán type shedding in the wake, causing large fluctuations in the aerodynamic loads. Then, as k_g increases, a pair of leading-edge (LEV) and trailing-edge vortices (TEV) is expected to form over the airfoil.

Naturally, a few questions arise. Are these two vortex shedding events, one in the steady-flow case and the other in the longitudinal gust case, mechanistically the same but occurring at different frequencies? Under what conditions does a lock-in between the gust frequency and the natural vortex shedding frequency in the steady-flow case occur, and what role does it play in the LEV dynamics and unsteady force generation? The present study seeks to answer these questions using direct force measurements and phase-averaged Particle Image Velocimetry (PIV).

PIV measurements reveal distinct topological differences between the two cases. In the steady-flow scenario, the upper-side vortex remains detached from the airfoil throughout the entire shedding cycle. The separated shear layer is fully turbulent near the separation point, resulting in less organized, highly three-dimensional shedding. In contrast, the acceleration phase of the harmonic gust promotes the production of clockwise vorticity near the leading edge, triggering LEV formation close to the airfoil surface. Additionally, a lock-in facilitates a coherent roll-up of the turbulent shear layer, resulting in a tighter and more compact LEV formation accompanied by outer-flow reattachment on the suction side. This increased coherence, combined with the higher strength and prolonged dwelling time of the vortex near the airfoil surface, augments the mean aerodynamic loads relative to the no-gust baseline substantially. Not surprisingly, the elevated mean lift values are observed over a range of frequencies for which a lock-in is observed. The width of this lock-in frequency range was found to be inversely related to the strength of the natural shedding in the steady-flow case. For instance, increasing the mean Reynolds number ($\overline{Re}$) or freestream turbulence intensity, which weakens natural shedding, generally broadens the lock-in range. Conversely, increasing the angle of attack (α), which results in stronger vortex shedding in the steady-flow case, narrows the lock-in boundaries.

Email address for correspondence: *suraj.bansal@mail.utoronto.ca*