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Transient Development of the Leading-Edge Vortex and its Role in Unsteady Aerodynamic Load Variations

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Large eddy simulations are conducted for a pitching National Advisory Committee for Aeronautics 63(3)418 airfoil section at a reduced frequency of $K = 0.4$ and a chord-based Reynolds number, $Re_c = 100,000$. The goal of this work is to understand how transient stall flutter dynamics are affected by initial flow field conditions associated with a high incidence angle. Perturbation starting times are varied parametrically to investigate both the differences in the transient dynamic stalling processes over a single pitching cycle. It is found that Kármán vortex shedding associated with an initially static airfoil interferes with the leading-edge vortex detachment and dynamic lift stall as per large variations in the post-stall unsteady aerodynamic loading. Monitored leading-edge vortex trajectories and computed Lagrangian averaged vorticity deviation fields both confirm this notion and are utilized to link this phenomenon to the status of a trailing-edge vortex. It is shown that the leading-edge vortex trajectory standard deviation leading up to dynamic lift stall contracts at a singular point in space. This event appears to be weakly connected to the leading-edge vortex circulation during its maturation stage. The leading-edge vortex morphology is also investigated near its detachment location through several morphometric quantifiers such as the area, aspect ratio, and eccentricity. It is found that the leading-edge vortex morphology undergoes a similar contraction in the aspect ratio and eccentricity standard deviations. Finally, near-surface measurements of the u and v signals grant an indirect quantification of the leading-edge vortex strength and position as it advects over the airfoil chord.

I. Introduction

Stall flutter remains to be a complex aeroelastic phenomenon that can be detrimental to flexible lifting body structures like wind turbine blades, for example. It is widely accepted that this single degree of freedom instability is permissible due to a negative aerodynamic damping coefficient associated with the pitching moment hysteresis at high amplitudes. In general, this phenomenon is attributed to the formation, advection, and severance of a strong leading-edge vortex (LEV) along the airfoil chord [1,2]. This ensemble of events is often consolidated into ‘dynamic stall processes’ or an ‘LEV lifecycle’ for brevity. The coupling of both viscous and inviscid interactions throughout this LEV life cycle gives rise to highly nonlinear dynamics that are not well represented by classical aeroelastic theory. Furthermore, design considerations like the mean incidence angle, reduced frequency, leading-edge radius, and airfoil chord thickness are known to be sensitive bifurcation parameters that can further exaggerate this nonlinearity [3,4]. Other parameters like the Reynolds number have been shown to have a logarithmic scaling effect on the cycle-averaged energy extraction indicating a less severe dependency [5]. A relatively unexplored parameter in the context stall flutter is the perturbation or starting time of the airfoil motion. This is because stall flutter is known to form a limit cycle oscillation (LCO) where transient initial conditions are effectively washed out by the attractor at long time scales. Though, starting cycles and the conditions leading up to these stable orbits are of interest from the purview of

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phenomenon like transient energy growth and subcritical bypass transition. Furthermore, as a precursory state to sustained pitching oscillations, the transient stall flutter regime is critically important when attempting to leverage flow control methods for the purpose of flutter suppression like active blowing, deformable flaps, or camber morphing. This is because the dynamic stall processes during this initial timeframe can vary dramatically from a limit cycle oscillation regime. Thus, an in-depth analysis of the transient stall flutter regime is crucial for understanding how stall flutter is triggered and how it can be suppressed/delayed.

Ref. [6] demonstrated via computational methods that at high mean incidence angles, the timing of an applied perturbation in angle of attack to their stationary airfoil significantly affects transient aerodynamic loading. This timing, given as a phase angle in the unsteady vortex shedding oscillation, was shown to either exaggerate or suppress the unsteady variations in the time-resolved aerodynamic pitching moment, C_M . In some cases, they demonstrated non-monotonic growth prior to a stable convergent state indicating non-normality. Ref. [7] investigated the interaction between Kármán vortex shedding and a ‘motion-induced vortex’ due to heaving and torsional profiles for a rectangular cylinder. They demonstrated that beyond a free stream speed, $\frac{1}{St}$, the amplitude of the pitching motion was significantly decreased when compared to the case with an attached splitter plate. Thus, the Kármán vortex shedding can destructively interfere with the LEV development at long timescales. Ref. [8] also showed that the Kármán vortex shedding has a damping effect during dynamic stall when the pitching frequency exceeds the vortex shedding frequency. This indicates that the Strouhal number is potentially a high frequency bound for stall flutter to occur. Similar vortex interaction studies have explored the role of bluff body wake ahead of a dynamically stalled airfoil. Ref. [9] demonstrated that a phase offset between the unsteady wake and airfoil limit cycle oscillation (LCO) can also lead to either amplitude growth or decay. The phenomenology of constructive/destructive fluid dynamic interactions within the LEV life cycle remains to be a broad and open area of investigation within the aerodynamics community. Thus, in this work we aim to explore the sensitivity of transient dynamic stall processes when operating at a high incidence angle. Specifically, how unsteady aerodynamic loading can vary due to the transient LEV development in a stall flutter starting cycle.

Here, we explore the transient dynamic stall processes over a single pitching cycle for a NACA 63(3)418 airfoil via large eddy simulations (LES). Starting from an initially static condition at $Re_c = 100,000$ and $\alpha = 15^\circ$, the aeroelastic system is given a small perturbation in angular velocity at eight different starting times corresponding to the shed Kármán vortex phase angle, $\varphi = [0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ, 315^\circ]$. We investigate the effects of this parameter space through time-resolved measurements of the aerodynamic loads and instantaneous pitching angle. Both qualitative and quantitative variations in the LEV life cycle are also addressed via vortex core tracking, Lagrangian averaged vorticity deviation (LAVD) fields, and field probes are employed to elucidate how interference plays a role in unsteady loading during starting cycles. Different from previously mentioned investigations, this work focuses primarily on short-time scales where the relationship between periodic shedding and LEV development is highly transient in nature.

II. Setup

A. Large Eddy Simulation

Large eddy simulations are conducted using an in-house finite-volume based Navier-Stokes solver called SUSAN. This code has been extensively applied and validated for a wide range of case studies including a turbulent channel [10], canopy flows [11], flat plate boundary layer [12], and static high angle of attack airfoils [12]. The filtered incompressible momentum equation is given canonically by equation 1 where τ_{ij} is an unresolved turbulent stress term that requires modelling.

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + f_i \quad (1)$$

$$\tau_{ij} = \bar{u_i u_j} - \bar{u}_i \bar{u}_j \quad (2)$$

Here, an integral length scale approximation (ILSA) model is utilized for turbulence closure in our large eddy simulations [13]. This model leverages a ‘sub filter’ scale eddy viscosity term that is explicitly decoupled from the

mesh grid spacing. C_m is a user defined weighting factor, Δ is the eddy filter width, and $\overline{S_{ij}}$ is the resolved strain rate tensor denoted by an overbar.

$$\tau_{ij} - \frac{\delta_{ij}}{3} \tau_{kk} = -2\nu_{SFS} \overline{S_{ij}} \quad (3)$$

$$\nu_{SFS} = (C_m \Delta)^2 |\overline{S_{ij}}| \quad (4)$$

Δ is determined by approximating the integral length scale as per equation 5. L_{approx} is computed by the total eddy dissipation rate, ε_{tot} , and resolved turbulent kinetic energy, k_{res} . C_Δ is another user defined weighting scalar. The benefit of this filter width definition is that it allows for a mesh independence study to be meaningfully conducted when C_Δ is held constant.

$$\Delta = C_\Delta L_{approx} = C_\Delta \frac{k_{resolved}^{\frac{3}{2}}}{\varepsilon_{total}} \quad (5)$$

C_Δ and C_m consolidate into a single user defined variable, C_k , that dictates the degree of turbulence resolution as per equation 6. Values close to zero imply that the majority of eddies are resolved while high values mean most are modelled. Primes denote the fluctuating component of the assigned variable and brackets, $\langle x \rangle$, are applied as a spatial averaging operation in the homogenous z -direction.

$$\nu_{SFS} = C_k^2 \frac{\langle \frac{\overline{u'_i u'_j}}{2} \rangle^3}{\langle 2(\nu + \nu_{SFS} \overline{S_{ij}}) \rangle^2} \quad (6)$$

In general, this model is particularly well-suited for moderate to high Reynolds number flows where a large range of energy containing eddies can be resolved. A schematic computational domain setup for the current work is given in figure 1 where a rotating reference frame is applied to simulate the pitching airfoil behavior. Periodic boundary conditions are imposed in the z -direction to simulate an infinite wing. The airfoil surface is modelled as a wall by imposing no-slip and no-penetration conditions.

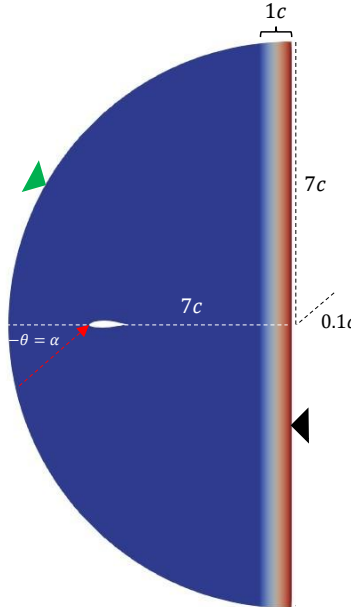


Figure 1. a) Computational domain schematic with periodic boundary conditions imposed in z -direction. Inlet (green marker) and outlet (black marker) definitions update in time based on a near-boundary velocity average.

The green and black triangle markers on the domain schematic in figure 1 imply locations where a Dirichlet and convective outlet boundary condition are applied, respectively. These locations are updated in time based on a near boundary velocity average. If the local spanwise-averaged velocity vector is pointing out of the domain then the corresponding boundary location is assigned as a convective outlet (black triangle). Otherwise, it is given a Dirichlet inlet condition assignment (green triangle). Finally, a sponge region is constructed along the domain outlet boundary to help address stability issues when large scale vortices attempt to penetrate a convective outlet. This sponge region takes the form of a linearly varying source term applied to the u velocity component given by equation 7. This region is applied between $x = 6c$ and $x = 7c$ as indicated by the contour gradient in figure 1. $\vartheta = 6.3$ is a user defined weight that scales the influence of this source term. u_{bulk} is utilized as the target exit velocity for this forcing function and updates in time based on the computed mass outflux.

$$\sigma = -\vartheta \left(\frac{x - x_{start}}{x_{end} - x_{start}} \right) (u(x) - u_{bulk}) \quad (7)$$

The computational domain was generated using Pointwise and segmented into structured x-z slabs where the open MPI communication protocol is implemented for parallel computation. Five candidate grids ranging from ‘coarse’ to ‘very fine’ were assessed on their predictive capabilities of mean aerodynamic loads, C_L and C_D . All tests were conducted at a static angle of attack, $\alpha = 20^\circ$, and chord-based Reynolds number of $Re_c = 100,000$. The turbulence resolution factor is set at $C_k = 0.02$ for all work.

Grid	M1	M2	M3	M4	M5
Type	Coarse	Semi-coarse	Moderate	Fine	Very Fine
Total Cells (N)	9e+6	15e+6	30e+6	42e+6	80e+6
Spacing (x, y, z)	441, 284, 81	661, 284, 81	1,321, 284, 81	1,761, 300, 81	2,001, 500, 81
β_{max}	0.28	0.30	0.28	0.40	0.32
$\overline{x^+}$	45.39	35.00	15.71	14.22	13.55
$\overline{y^+}$	1.01	0.80	0.94	0.938	0.919

Table 1. Grid independence study mesh characteristics ranging from coarse to very fine cell spacing. β_{max} refers to the maximum equiangular skewness angle.

Simulations were conducted for a minimum of $t \frac{U_\infty}{c} = 20$ time units in order to sufficiently purge initial transients that might pollute mean statistics. This corresponds to approximately 6.7 flow times over the airfoil. In some cases, the simulation time was extended as needed to meet a sufficient level of statistical convergence. Details pertaining to the mesh characteristics associated with this convergence study are presented in table 1. The time averaged aerodynamic lift and drag coefficients are presented in figure 2 for varying grid cell count where M5 is considered a baseline and is used to normalize cases M1-M4. It can be observed that the M2, M3, and M4 grids are largely converged for lift while only M3 and M4 are of sufficient quality to accurately predict drag. The M4 predicted lift and drag are within 1.1% and 3.4% of the M5 respective values. M1 was discarded from further analysis due to its massive deviation from M5 in both lift and drag predictions. The boundary layer development was also evaluated for mesh convergence using grids M2 through M5. Discrete probes along the airfoil surface were used to compare the u -component velocity profiles during highly stalled conditions. u is averaged in time and over the homogeneous spanwise direction, z , with values extracted along a linear path extending from the airfoil suction side to $\frac{y}{c} = 1$. For each grid candidate, $\frac{u}{U_\infty}$ is plotted against the respective probe arclength and shifted horizontally for visual clarity (fig. 3).

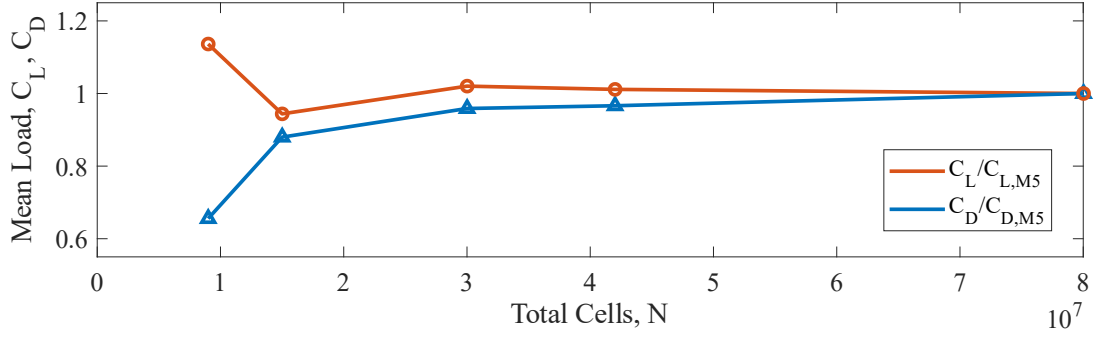


Figure 2. Mesh convergence study of time-averaged aerodynamic loads C_L and C_D for static airfoil section at $\alpha = 20^\circ$ and $Re_c = 100,000$. C_L and C_D are normalised by the respective M5 value.

It can be seen that the grid cases M2-M5 are generally well aligned and exhibit canonical features such as boundary layer growth downstream, flow reversal, and a large separation zone due to a chordwise adverse pressure gradient. Though, the M2 predictions are degraded upstream as indicated by non-physical oscillations attributed to leading-edge grid coarsening. For all cases, errors amplify towards the trailing-edge but are maintained within 4% of the M5 predicted values at $\frac{s}{c} = 1$. Overall, M4 tends to be largely converged at these highly stalled conditions and was deemed as an acceptable balance between computational cost and accuracy for the current investigation.

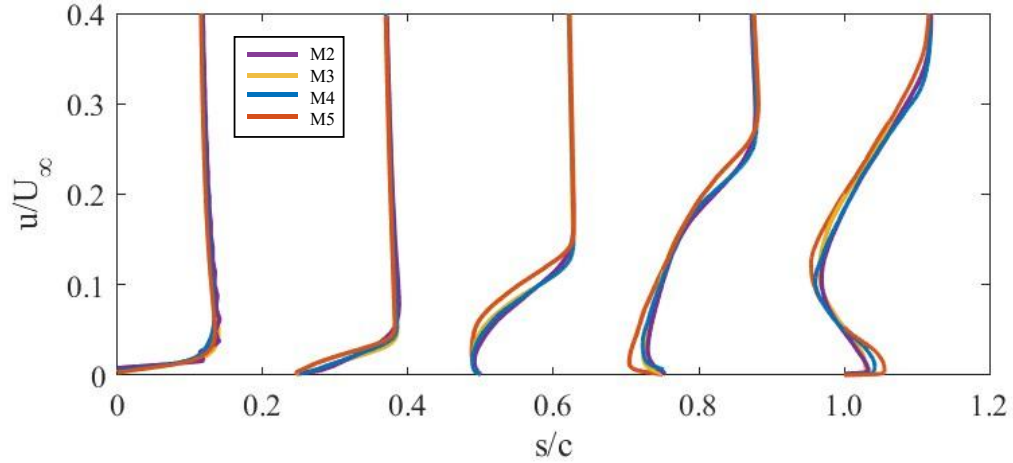


Figure 3. Grid comparison of the time averaged u -component velocity profiles along the airfoil chord. $\frac{s}{c}$ refers to the chord normalized arclength that is shifted along the x-axis for clarity.

B. Validation

To further validate the predictive capabilities of our in-house solver, an experimental campaign was conducted using the T2 subsonic wind tunnel facility at City St. George's, University of London. The T2 facility is a closed loop recirculating wind tunnel with a nominal operating range of $U_\infty = 7 - 45 \frac{m}{s}$. The wind tunnel has a dual window optical test section and is equipped with an Aerotech force balance for static load measurements. The measurement section dimensions are $L_x = 1.78 m$, $L_y = 0.81 m$, and $L_z = 1.12 m$ which correspond to the streamwise, spanwise, and vertical directions, respectively. To emulate the 2D dominated flow conditions of our CFD studies, a NACA 63(3)418 wing was fabricated to span approximately wall-to-wall in the T2 test section with small gaps ($\sim 1 mm$) at the wing tips to allow for unobstructed pitch rotations. This wing was printed on a Bambu Lab X1 printer using a matte PLA filament in 7 distinct sections due to the printer size. These sections were aligned using male-female inserts (see figure 4) and mated with an epoxy filler to smooth the gaps at each of the sectional interfaces. The wingspan and chord length for the completed assembly are $c = 0.22 m$ and $b = 1.118 m$, respectively.

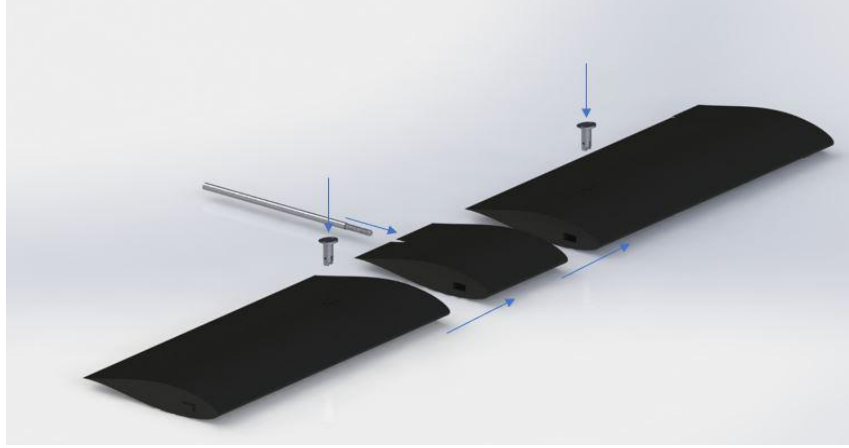


Figure 4. 3D CAD render of NACA 63(3)418 wing with horizontal and vertical sting mounts.

Horizontal and vertical mounts were fabricated using aluminum and are used to transfer aerodynamic loads between the rigid wing, sting mounts, and T2 force balance. The vertical mounts were filed to sit flush with the suction surface of the wing and allow for a large pitch degree of freedom, $\alpha = \pm 35^\circ$. The horizontal sting fits directly into the wing chord line from the trailing-edge to help minimize bluff body interference and vibrations. This horizontal mount is attached to a lever arm that is used to rotate the wing about the $0.5c$ location.

Experimental measurements were conducted at an average wind tunnel speed of $\overline{U_\infty} = 7.9 \frac{m}{s}$ which corresponds to a chord-based Reynolds number of $Re_c = 100,000$. Force balance measurements were taken at discrete positions ranging from $\alpha = -8^\circ - 20^\circ$ at an increment of 2° and corrected for wall, blockage, and sting drag effects as per [14]. The ensemble averaged results for C_L and C_D are shown in figure 5 with error bars to illustrate the measurement load variations sampled over a period of 10 seconds each.

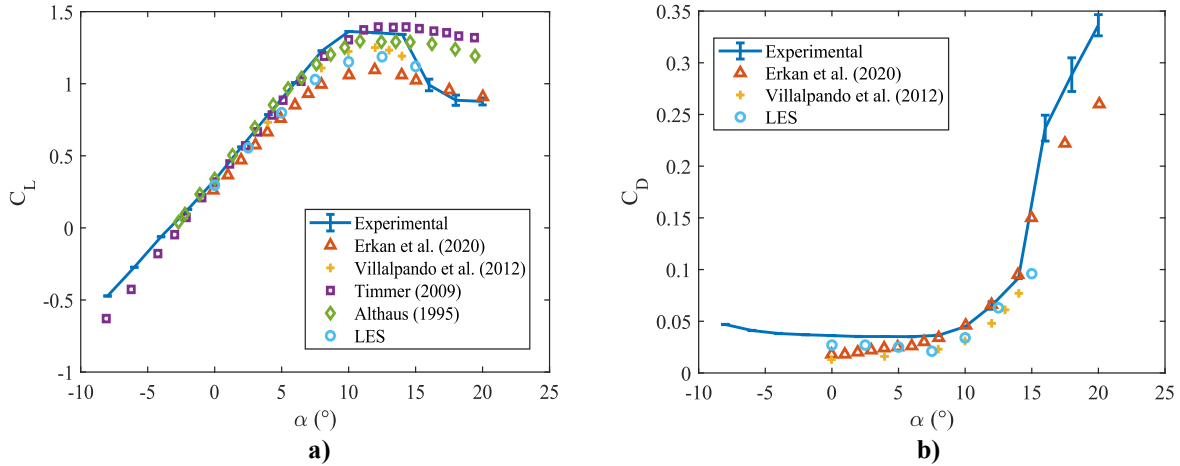


Figure 5. Static load comparison between experimental and LES measurements for a NACA 63(3)418 airfoil. Externally sourced data: Orange triangle, NACA 63415, $Re_c = 1e5$ [15]. Yellow plus, NACA 63415, $Re_c = 3e5$ [16]. Purple square, NACA 63418, $Re_c = 3e6$ [17]. Green diamond, NACA 63418, $Re_c = 3e6$ [18].

Our LES based predictions align well with the experimental measurements and external data sources at low to moderate angles of attack. Beyond $\alpha \geq 10^\circ$, disagreement between the various data sets tend to amplify indicating a familiar sensitivity to the airfoil stall behavior [19]. Overall though, our LES setup is able to capture the general static load characteristics of the NACA 63(3)418 airfoil.

C. Initial Conditions

The aeroelastic behavior of a pitching airfoil was modelled by a forced spring mass damper system where the aerodynamic moment, C_M , is computed about the $0.5c$ location. The non-dimensional form of this governing equation is given by equations 8 and 9 where J , μ , and k are the moment of inertia, damping coefficient, and spring constant respectively. The $' * '$ notation is used to indicate nondimensionalization. ρ , U_∞ , and b are the fluid density, free stream speed, and airfoil span.

$$J^* \ddot{\theta}^* + \mu^* \dot{\theta}^* + k^* \theta^* = C_M(t) \quad (8)$$

$$\frac{2J}{\rho c^4 b} \ddot{\theta}^* + \frac{2\mu}{\rho U_\infty c^3 b} \dot{\theta}^* + \frac{2k}{\rho U_\infty^2 c^2 b} \theta^* = C_M(t) \quad (9)$$

All simulations are conducted at $Re_c = 100,000$ and a mean angle of attack of $\alpha = 15^\circ$. The nondimensional model coefficients are set as $J^* = 0.0765$, $\mu^* = 0.01$, and $k^* = 0.0490$, which corresponds to a semi-chord based reduced frequency of $K = 0.4$ via equation 10.

$$K = \sqrt{\frac{k}{J}} \frac{c}{2U_\infty} \quad (10)$$

Starting from an initially static state, a small perturbation in angular velocity, $\dot{\theta}^* = 0.035$, is imposed to excite the stall flutter instability. The timing of this perturbation varies between 8 different cases based on the Kármán vortex shedding phase angle, φ . To determine these trigger times, time-resolved data was first obtained by setting a point probe within the shedding wake at a downstream location (fig. 6). Time-resolved field measurements were taken for a minimum of $t \frac{U_\infty}{c} = 20$ time units to ensure that multiple shedding events were captured. These field variables were then spatially averaged over the homogeneous spanwise direction.

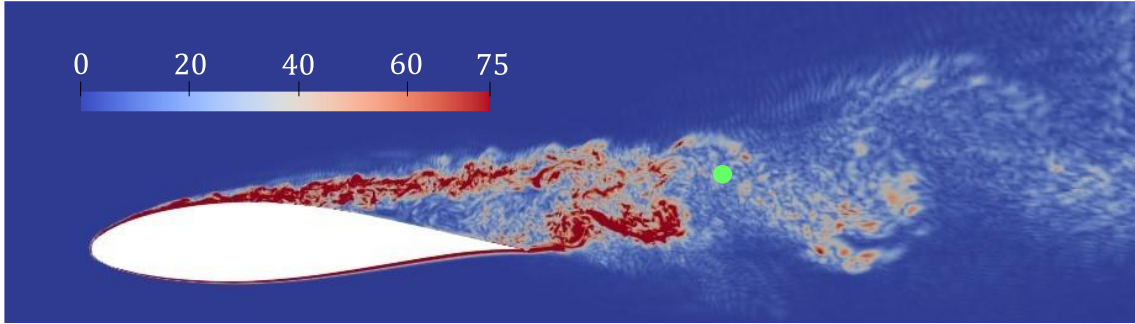


Figure 6. Kármán vortex shedding for NACA 63(3)418 airfoil at $\alpha = 15^\circ$. Contour is colored by vorticity magnitude, $\frac{|\omega|c}{U_\infty}$. Green dot represents a point probe for time-resolved field measurements.

The dominant shedding frequency was obtained by utilizing the discrete Fourier transform to compute the power spectral density (PSD) of two signals, p' and v' , as shown in figure 7. Prime here denotes the fluctuating component of the respective signal. Both signals show strong peaks at a Strouhal frequency of $St = 1.44$ indicating a dominant mode of the vortex shedding instability. The Strouhal number was computed using equation 11 where f is the peak shedding frequency in Hertz.

$$St = \frac{fc}{U_\infty} \quad (11)$$

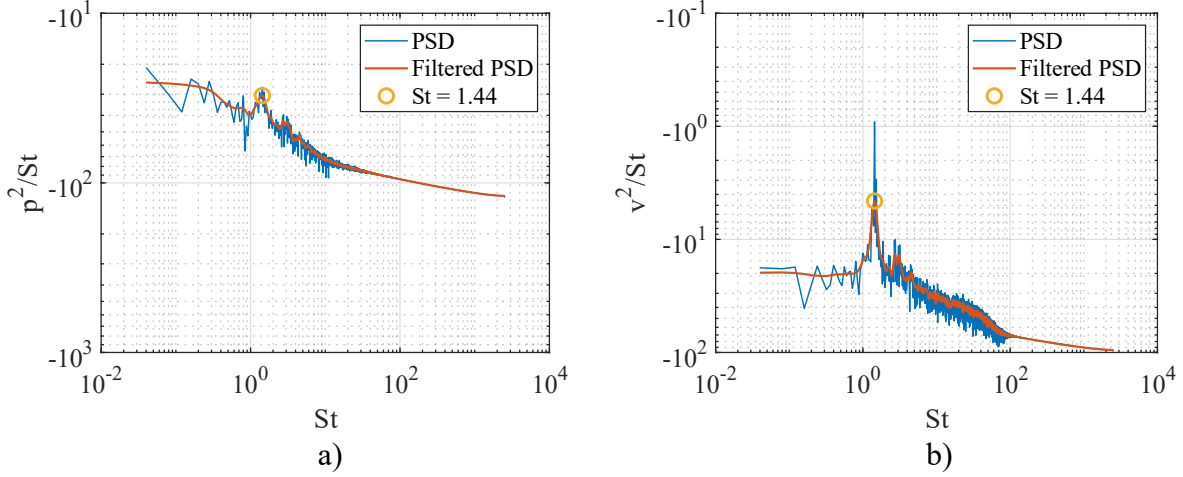


Figure 7. a) Pressure PSD with smoothing. b) v -component velocity PSD with smoothing. Red circle indicates dominant vortex shedding frequency.

The shedding cycle, modelled as a pure harmonic wave, was then utilized to determine 8 different starting times that vary between $\varphi = 0^\circ$ and $\varphi = 315^\circ$ in increments of 45° . These conditions allow for approximately $T = 2.5$ shedding periods to pass over during the initial ramp-up portion of the stall flutter instability. While higher order harmonics are evidently present, we will show in the subsequent sections that these conditions are sufficient to observe strong transient interactions over the first starting cycle.

III. Results

A. Unsteady Aerodynamic Loading

As an opening assessment of the effect of this starting time parameter, the unsteady aerodynamic pitching moment, C_M , and lift coefficient, C_L , were monitored over the first pitching cycle. This is shown in figure 8 where each pitching angle trace and corresponding unsteady load traces are shifted horizontally relative to $\varphi = 0^\circ$ for alignment purposes. It can be plainly observed that the time-resolved aerodynamic loads experience similar augmentation throughout the pitch-up portion of these starting cycles. In contrast, the pitch-down portion exhibits large aerodynamic load variations that greatly alter the pitching dynamics. This is explored by computing the time-resolved standard deviation of both C_L and C_M , respectively (fig. 9). Note that this data was post-processed using a moving window average filter for better clarity. The C_L and C_M windows are approximately 1.3 and 0.8 time units respectively as our solver utilizes an adaptive time marching scheme. Both traces, scaled between zero and one, are maintained close to $\sigma = 0$ up until $t \frac{U_\infty}{c} = 3$ suggesting that the leading-edge shear layer formation and initial roll-up are comparable phenomenon. Between $t \frac{U_\infty}{c} = 5 - 6$, there is a sharp increase in σ_{C_L} that occurs near the time of dynamic lift stall, $t \frac{U_\infty}{c} = 5.65$. This potentially indicates that the LEV detachment and shedding mechanism(s) are largely responsible for transient lift variations across these parametric cases. This assessment is akin to a reduced frequency-based effect reported by ref. [15] where varying K introduces a topological bifurcation in the LEV detachment mechanism. The behavior of σ_{C_M} is much more complicated to diagnose as per the non-monotonic growth between $t \frac{U_\infty}{c} = 3 - 8$.

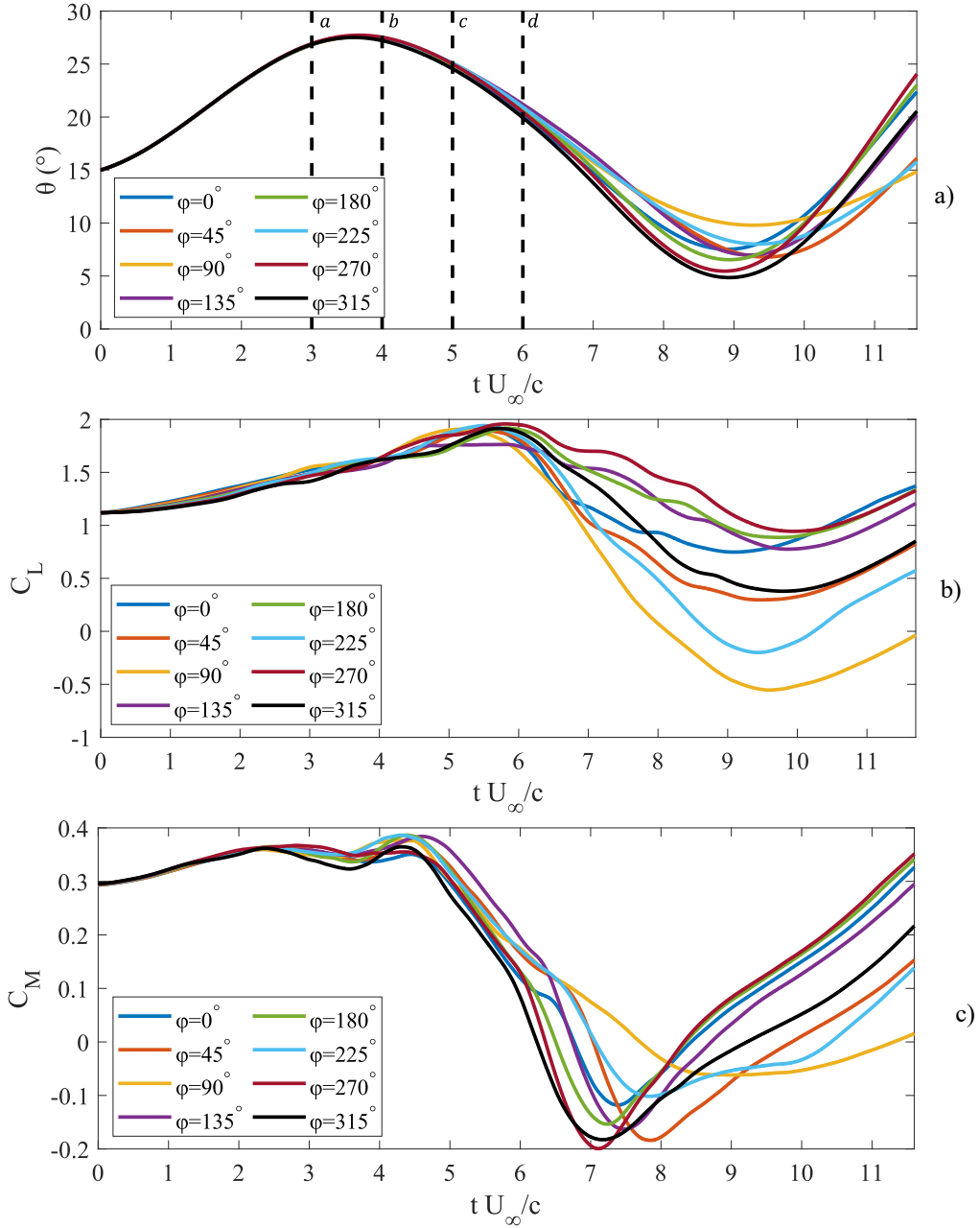


Figure 8. a) Time-resolved pitching angle. b) Time-resolved aerodynamic lift coefficient. c) Time-resolved pitching moment coefficient with flexural axis set at $\frac{x}{c} = 0.5$. All plots vary parametrically via vortex shedding phase angle, φ .

Furthermore, moment stall is not necessarily coincident with LEV shedding but with a chordwise pressure shift corresponding to the LEV migration beyond the flexural axis. Interestingly though, a local minimum in σ_{C_M} also appears to be nearly coincident with the dynamic lift stall. We propose that the respective increases in σ_{C_L} and σ_{C_M} near dynamic lift stall are likely attributed to trailing-edge effects that alter how the LEV detachment process is actuated.

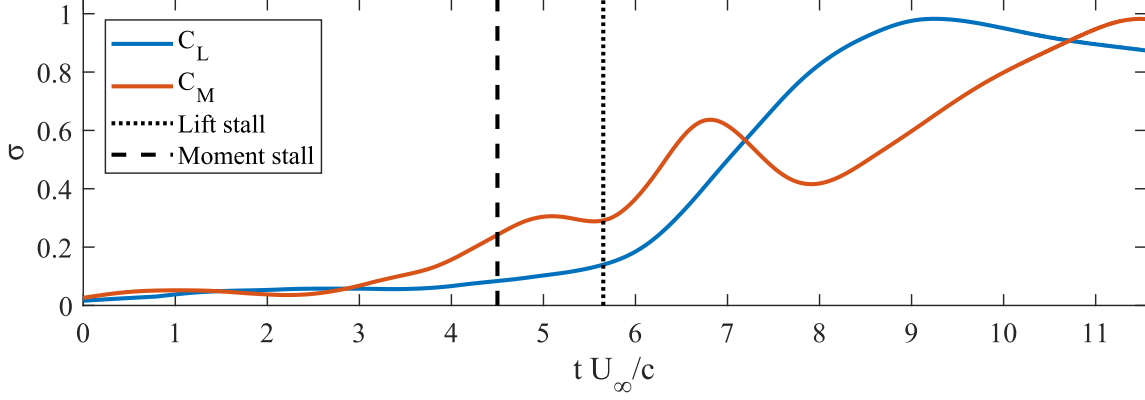


Figure 9. Time-resolved aerodynamic lift and pitching moment standard deviations corresponding to data in figure 8. Dashed lines indicate timestamps associated with lift and moment stall, respectively.

B. LEV Trajectory and Strength

In this section we attempt to rationalize the time-dependent growth in parametric load deviations based on various statistical quantifiers of the LEV in the vicinity of dynamic lift and moment stall. As such, the following analyses are conducted within a truncated time frame that approximately spans timestamps a, b, c, and d in figure 8a. First, an Eulerian vortex core tracking method is utilized to compare how the LEV trajectory varies between each parametric case. An approximate vortex core location is determined via localized thresholding of the out-of-plane vorticity field, ω_z . Next, a smooth spatial distribution is computed using a vorticity (ω_z) weighted kernel density estimate (KDE) of grid points that approximately enclose the target fluid structure. The peak value of this distribution corresponds to a vortex core location. This vortex monitoring procedure is repeated for each parametric case, $\varphi = 0^\circ - 315^\circ$, within a timeframe that captures the LEV detachment.

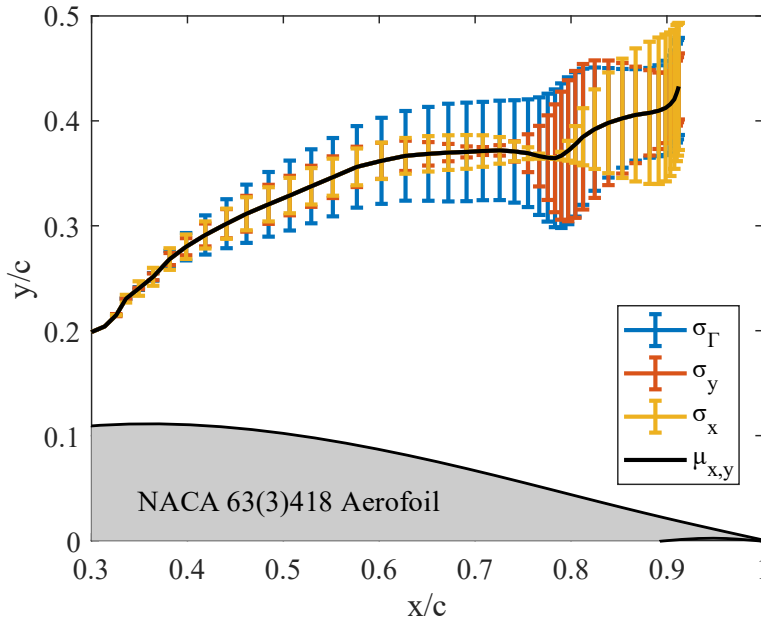


Figure 10. Ensemble averaged trace of LEV core trajectory (black). Error bars correspond to the circulation (blue), $\frac{y}{c}$ (orange), and $\frac{x}{c}$ (yellow) standard deviations at each vortex core position. σ values are range normalized between $[0, 0.07]$ for visual clarity and relative comparison.

The ensemble averaged LEV trajectory is presented in figure 10 with x-component (yellow) and y-component (orange) error bars indicating the relative degrees of spatial variation between each parametric case study. The blue error bars correspond to the standard deviations in circulation determined by equation 12 and using a circular boundary around the manually identified vortex core. The radius of this boundary is determined by growing incrementally until the maximum vortex strength is observed.

$$\Gamma_{LEV} = \int_A \omega_z(x, y) dA \quad (12)$$

Similar to the aerodynamic load data, these error bars have been range normalized for comparing the relative variability of each respective metric, x , y , and Γ , along the trajectory path. The average LEV detachment location occurs at $\frac{x}{c} = 0.78$ as indicated by a core trajectory shift away from the airfoil suction side. This changepoint coincides with both dynamic lift stall and a stark amplification in σ_{C_L} and σ_{C_M} . Furthermore, σ_x and σ_y experience similar relative growth between $\frac{x}{c} = 0.71 - 0.78$ suggesting that the LEV detachment mechanism is correlated to both unsteady lift and moment variations in the post-stall regime. The initial contraction before this LEV changepoint indicates a kind of concentrated focal point across all parametric cases that the LEV reaches prior to detachment. Though, σ_r does not contract in a similar fashion to σ_x and σ_y but instead increases monotonically up until the LEV detachment. Thus, the variations in LEV induced circulation do not appear to be meaningful in specifying why σ_{C_L} surges specifically after dynamic lift stall. This is not to say that σ_{C_r} is non-contributory to σ_{C_L} or σ_{C_M} in the post dynamic stall regime but that a wide range of vortex strengths can exist regardless of LEV attachment or detachment.

B. LEV Morphology

An analysis of the LEV structure is now conducted to identify how vortex morphology differs between the parametric cases due to detachment. More specifically, variations in the LEV boundary are examined via morphometric quantifiers like area, aspect ratio, and eccentricity. To conduct this study, Lagrangian averaged vorticity deviation (LAVD) field contours are computed near the dynamic lift stall event. To generate these LAVD fields, neutrally buoyant particle trajectories are computed by integrating equation 13 from t_0 to t using a 4th order Runge-Kutta method. Discrete field snapshots spanning this temporal evolution are interpolated linearly in both space and time to form a continuous trajectory. Seed particles are initialized at every grid centroid in a sub-domain region enclosing $-0.1 \leq \frac{x}{c} \leq 1.5$ and $-0.1 \leq \frac{y}{c} \leq 1$.

$$\dot{\mathbf{x}} = \mathbf{u}(\mathbf{x}, t) \quad (13)$$

Within this sub-domain, the instantaneous spatial mean of the out of plane vorticity component, $\overline{\omega_z(s)}$, is computed. The LAVD at each grid point is then formulated as the integral of the difference between the point vorticity along a trajectory path, $\omega_z(\mathbf{x}(s; \mathbf{x}_o), s)$, and $\overline{\omega_z(s)}$ given by equation 14.

$$LAVD(\mathbf{x}) = \int_{t_0}^t |\omega_z(\mathbf{x}(s; \mathbf{x}_o), s) - \overline{\omega_z(s)}| ds \quad (14)$$

A rotationally coherent Lagrangian vortex is defined as a nested set of material tubes that each exhibit uniform rotation relative to the mean vorticity. The singular center of this nesting, with radially increasing (inward) LAVD values defines the Lagrangian vortex core as per ref. [20]. Figure 11 illustrates the intra-cycle LAVD contours computed at the timestamps in figure 8a. This timeline coarsely captures the leading-edge shear layer development (11a), its roll-up (11b), LEV saturation (11c), and vortex core trajectory shift associated with detachment (11d). As a visual diagnostic tool, the LAVD contours in figure 11 tend to demonstrate similar leading-edge shear layer development and incipient LEV formation. This is likely because the static separation point is too far aft to interact with the LEV genesis. Topological differences become pronounced at timestamp c) where the LEV feeding shear layer appears weak or severed for the cases $\varphi = 90^\circ, 135^\circ, 180^\circ, 315^\circ$. At timestamp d) there are obvious differences in the trailing-edge vortex (TEV) development across all dynamic lift stall events. For phase angles, $\varphi = 90^\circ$ and $\varphi = 225^\circ$, a strongly coherent TEV forms just aft of the airfoil trailing-edge as indicated by the nested LAVD peak.

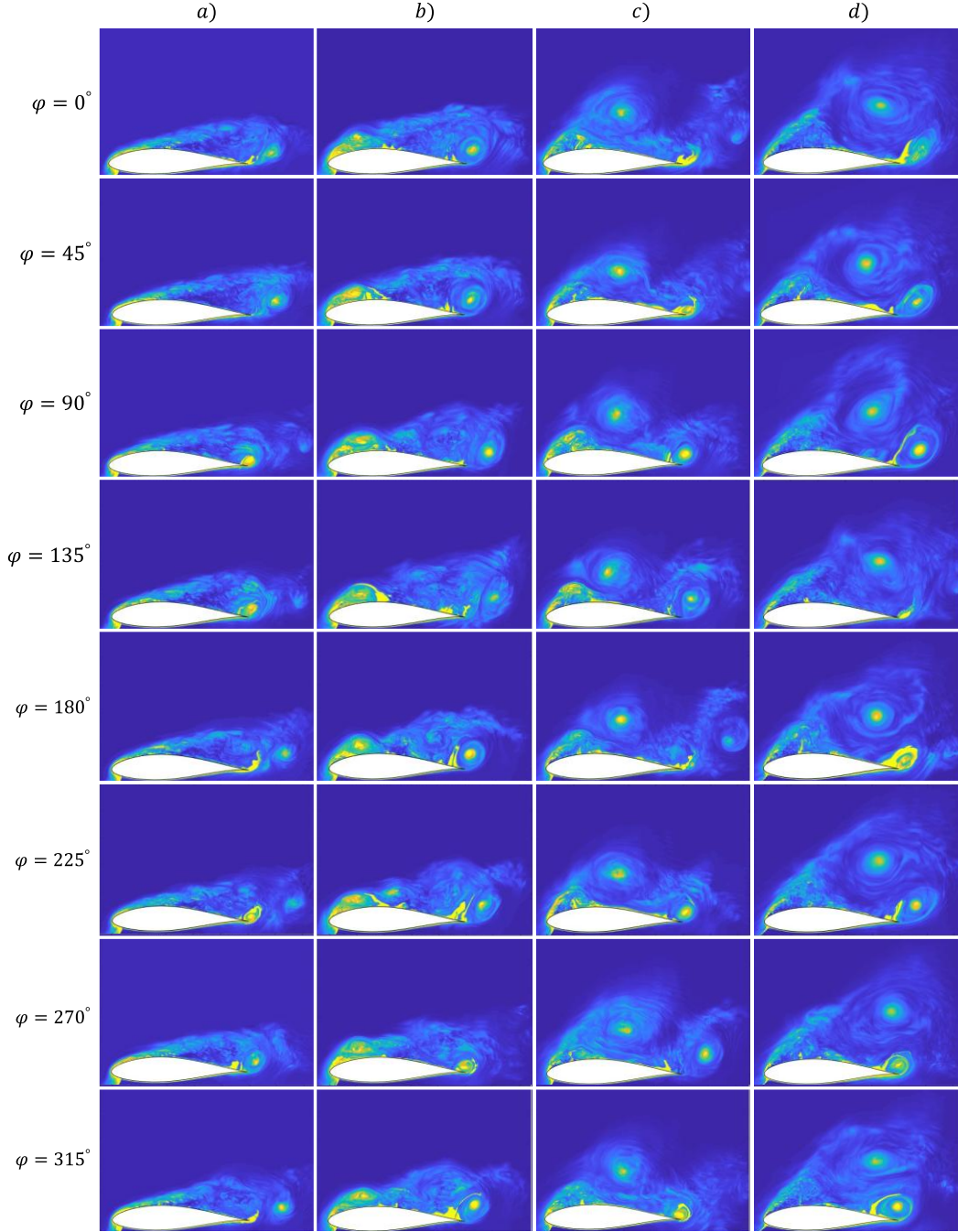


Figure 11. LAVD contours scaled between 0 and 30 are computed at 4 timestamps within the pitching cycle (see figure 8). Each row reflects the parametric variation in Kármán vortex phase angle shifted temporally for column-wise alignment of dynamic stall events.

For the remaining scenarios, a TEV is either too weak to observe or has migrated onto the airfoil surface. Indeed, the strength, size, and positioning of these observed trailing-edge structures plays a fundamental role in how the LEV is detached. Prior work on the detachment mechanism for varying reduced frequencies showed that it is possible for the TEV to act as a boundary that first impedes the LEV motion then directs it away from the airfoil [21]. Alternatively, the TEV can become entrained between the LEV and suction side surface that severs the supplying shear layer and then pushes the LEV away. As such, it can be concluded that the unsteady load variations beyond dynamic lift stall are largely conditioned by how the TEV is formed. Temporal shifts within the Kármán vortex shedding phase angle

can lead to either a constructive ($\varphi = 90^\circ$) or destructive ($\varphi = 135^\circ$) TEV formation that greatly impacts transient starting cycles.

A key benefit of utilizing LAVD versus other Lagrangian based vortex identification tools is that an explicit vortex boundary is defined as the largest convex member of a nested tubular family associated with a vortex core. This simple definition allows for analyzing the LEV morphology throughout its lifecycle which can reveal fluid dynamic tendencies that are not easily identifiable through indirect metrics like the surface pressure and time-resolved aerodynamics loads. Here, a convexity ratio-based filtration scheme is utilized to identify the LEV boundary. Closed loop polygons around an LAVD peak are first granted candidacy as a potential vortex boundary. Next, a convexity ratio, $CR = 0.95$, is set as a lower limit to filter out boundaries that exhibit sufficient concavity. CR is computed as the ratio of the enclosed area to the hull area as per ref. [22]. Figure 12 exemplifies the results of this boundary detection procedure for the cases of $\varphi = 90^\circ$ and $\varphi = 135^\circ$ at three temporal snapshots, $t \frac{U_\infty}{c} = [5, 5.5, 6]$. All boundaries are centered by subtracting out their respective centroids.

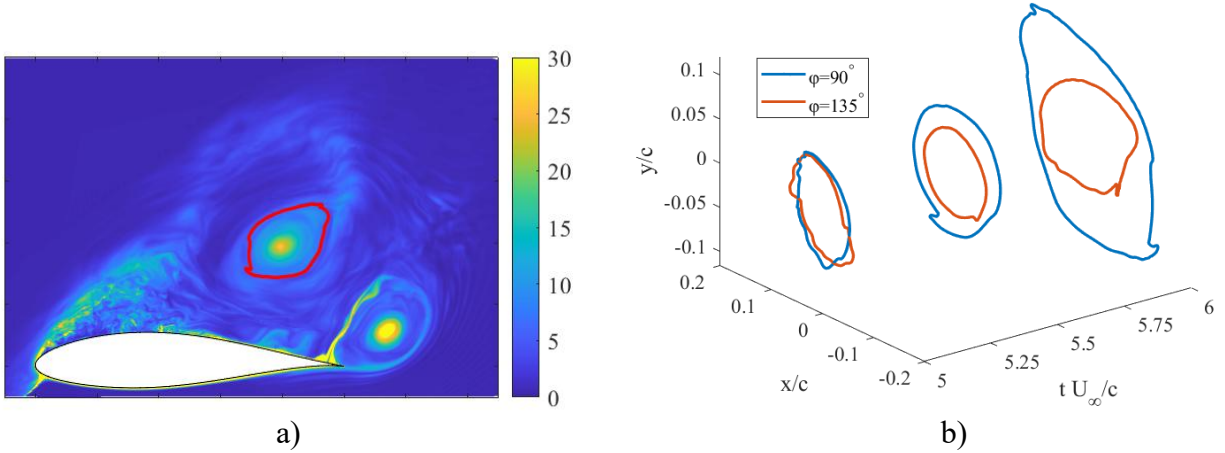


Figure 12. a) LAVD contour for $\varphi = 90^\circ$ and $t \frac{U_\infty}{c} = 6$ with identified vortex boundary around the LEV. b) Comparison of LEV boundaries between $\varphi = 90^\circ$ and $\varphi = 135^\circ$ near dynamic lift stall.

At several snapshots, the LEV boundary area (A), aspect ratio (AR), and eccentricity (e) are computed over the full parametric range, $\varphi = 0^\circ - 315^\circ$, to evaluate morphological variations around dynamic lift stall. These metrics are averaged with respect to φ and plotted at $t \frac{U_\infty}{c} = [5, 5.25, 5.5, 5.75, 6]$ in figure 13. Error bars quantify the φ dependent standard deviations in the LEV morphology due to the previously described trailing-edge interactions. The mean LEV area experiences approximately linear growth between this timeframe with very small deviations at $t \frac{U_\infty}{c} = 5$. As it progresses through dynamic lift stall ($t \frac{U_\infty}{c} = 5.65$), these variations amplify indicating that detachment greatly affects the LEV size. Most notably though, the LEV aspect ratio deviation shrinks dramatically at $t \frac{U_\infty}{c} = 5.5$ in a similar manner to σ_x , and σ_y when approaching detachment. Eccentricity follows a similar mean trend and error contraction to the aspect ratio indicating that the LEV morphology is approximately circular as the pitching airfoil nears dynamic lift stall.

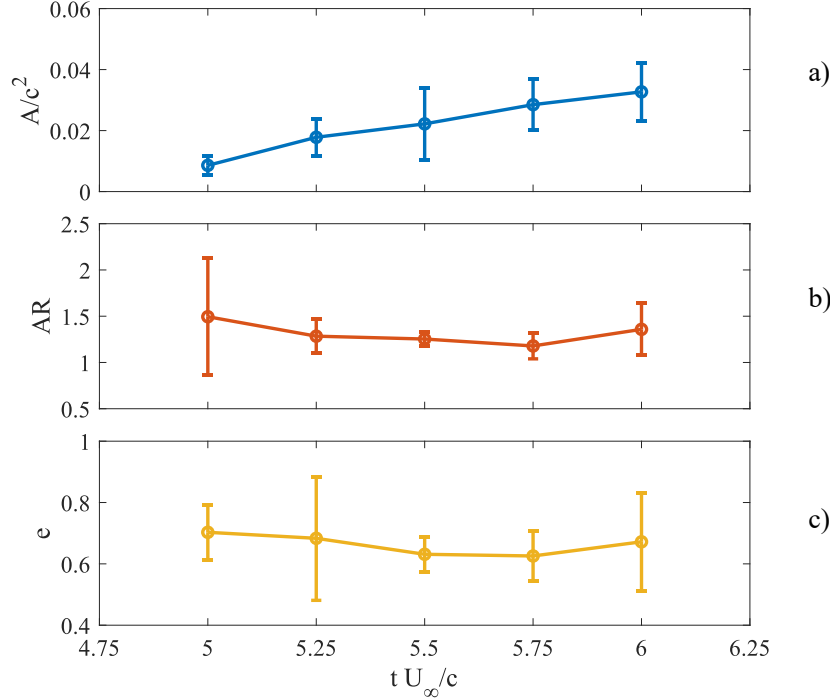


Figure 13. a) LEV boundary area. b) LEV boundary aspect ratio. c) LEV boundary eccentricity. All metrics are averaged in φ and plotted at discrete timestamps around dynamic lift stall. Error bars express morphometric variations across φ .

C. Instantaneous Probe Measurements

Near surface measurements of the u and v velocity components are taken at six discrete probe locations along the airfoil chord between $\frac{x}{c} = 0.025$ and $\frac{x}{c} = 0.95$ in equally spaced increments and at a distance $\frac{d}{c} = 0.01$ in the wall normal direction. These instantaneous probe measurements span the first starting cycle in our parametric range, $\varphi = 0^\circ - 315^\circ$, and serve as an indirect quantification of the time-resolved LEV progression along the airfoil surface. At each probe, the velocity component signals are ensemble averaged with respect to, φ . Also, the standard deviation is computed along each probe trace to indicate where the dynamic stall process is sensitive/insensitive to transient conditions. These results are shown in figure 14 where the time-resolved signals have been smoothed using a sliding window filter and plotted with a vertical offset ($\frac{u}{U_\infty} = 2$ and $\frac{v}{U_\infty} = 1.5$) for clarity. Finally, the dynamic lift and moment stall time-stamps are given as the coarse and fine dashed lines, respectively. As the LEV is generated and progresses over the airfoil, flow reversal along the suction side wall is an indicator of both its position and strength. The troughs in figure 14a are evidence of this LEV migration as it passes over the various (near) surface probes. The error bar shade grants insight into which stage(s) of the dynamic process are highly sensitive to initial conditions. At all probe locations, the velocity signal variations between $t \frac{U_\infty}{c} \approx 0 - 2.5$ are near zero indicating that the pre-stall regime is quite comparable regardless of these initial starting time conditions. This behaviour is similar to our observations in the ensemble averaged C_L and C_M traces where the load variations are small during the initial ramp-up portion of the cycle. Beyond $t \frac{U_\infty}{c} = 2.5$, fluctuations in both the u and v component traces tend to start growing as the dynamic stall processes begin to ensue. In particular though, the fluctuations at $\frac{x}{c} = 0.95$ are comparably larger than those at the other probe locations for both u and v traces. This would suggest that the TEV rollup and its induced near-surface velocity during this pitching motion is highly sensitive to φ . This alludes to our previous LAVD based observations where the TEV can have a wide-ranging status based on the unsteady vortex shedding phase angle. As a consequence of this trailing-edge behaviour, subsequent upstream variations at all the probe locations start to grow owing directly to its interaction with the shear layer formation and LEV rollup. Thus, the TEV status is not strictly a local characteristic that can be regarded independently from the LEV. Instead, its influence propagates far upstream to affect how dynamic moment and lift stall occur. It is clear that these respective fluid structures should be analysed

as a coupled pair rather than as stand-alone elements. This is because the upstream dynamic stall processes are directly impacted by the trailing-edge interactions.

As a final observation, the recovery stage of the dynamic stall process occurs when flow reattachment begins starting from the leading-edge to trailing-edge. This happens after the LEV-TEV pair has been completely severed from the airfoil suction side which can be accelerated or delayed based on its detachment mechanism. In general, the recovery portion of this starting cycle occurs after $t \frac{U_\infty}{c} = 9$ when the airfoil begins to pitch back upwards. The u -component standard deviations within this recovery stage are comparably high. We attribute this to delays in the LEV-TEV shedding that causes a lag in the pitching profile trace. As such, the pointwise variations observed here are primarily due to a phase misalignment that is caused by either prolonged or expedited dynamic stall events.

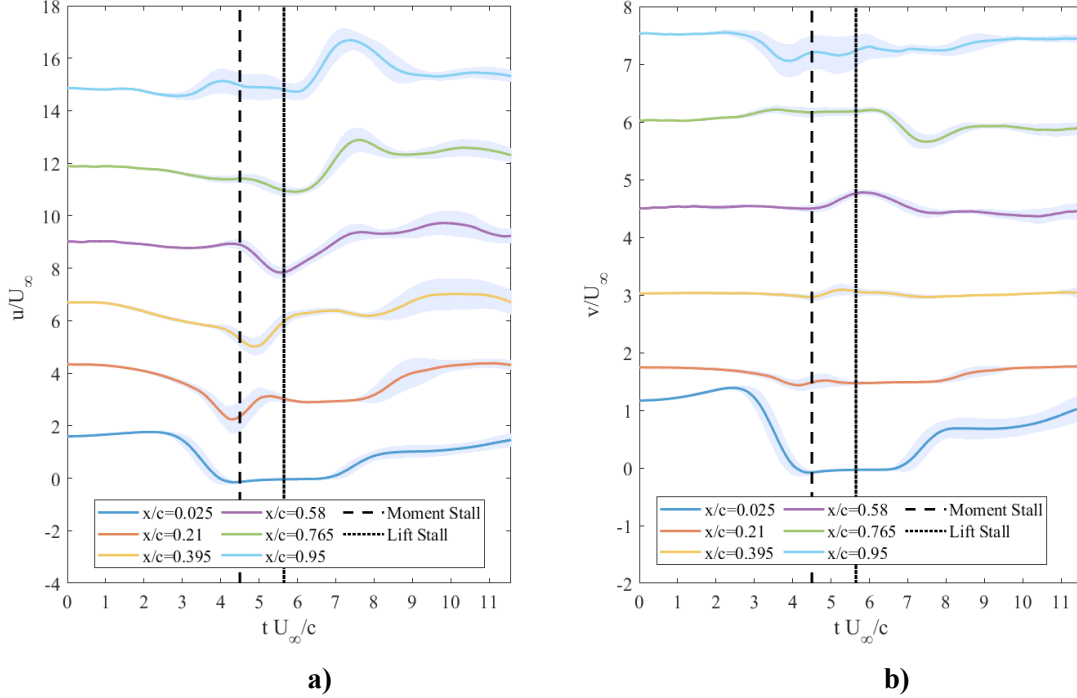


Figure 14. a) Ensemble averaged u -component signals with standard deviation shade at various chordwise probe locations. b) Ensemble averaged v -component signals with standard deviation shade at various chordwise probe locations.

VI. Conclusion

An analysis of the perturbation starting time impact in high mean incidence angle stall flutter is conducted over the first starting cycle. It is found that varying the starting times parametrically within the Kármán vortex shedding phase angle leads to increasingly pronounced deviations in the time-resolved aerodynamic loads, C_L and C_M . Specifically, these deviations tend to amplify sharply near dynamic lift stall which is also coincident with the LEV detachment. Measurements of the ensemble averaged LEV trajectory indicate a spatial changepoint between LEV attachment and detachment. Up to this location, parametric case variations in x and y undergo a significant contraction followed by a rapid expansion in the post LEV detachment regime. It is shown that variations in the computed vortex strength tend to grow regardless of the LEV attachment or detachment. LAVD contours are utilized to investigate how the dynamic stall processes vary with ϕ . In general, the leading-edge shear layer development and initial roll-up phenomenon are largely comparable across all cases. Qualitative differences within this parametric study become apparent when the LEV approaches detachment due to trailing-edge effects. Specifically, the wide-ranging status of a generated TEV tends to dictate how the LEV is being detached from the airfoil suction side. In particular, the TEV can either impede the LEV motion as a kind of inviscid wall or become entrained between the coherent structure and

airfoil with varying degrees of severity. This is specifically documented for the case of $\varphi = 90^\circ$ where the TEV is strongly coherent and has migrated onto the airfoil suction side. This kind of invasive LEV-TEV interaction appears to be energy defeating and rationalizes, in part, why the C_M trace for $\varphi = 90^\circ$ is much higher than the remaining cases. The LEV morphology is also analyzed between $t \frac{U_\infty}{c} = [5, 5.25, 5.5, 5.75, 6]$ by computing the LAVD defined vortex boundary. It is shown that variations in the LEV aspect ratio and eccentricity tend to converge prior to dynamic lift stall. This is akin to the contraction observed in x, y spatial variations of the ensemble averaged LEV trajectory. Beyond dynamic lift stall and detachment, variations in the LEV area, aspect ratio, and eccentricity all grow. Thus, the condition of a TEV and how the LEV is separated from the airfoil appear to be the most influential factors in unsteady aerodynamic load variations beyond dynamic lift stall. By changing the perturbation starting time, the TEV can either grow to be mildly or highly invasive to the LEV lifecycle when operating at stalled static conditions. Finally, near-surface probe measurements of the time-resolved u and v velocity components are analysed throughout the first starting cycle. The u -component traces offer more insight into the dynamic stall processes owing to strong fluid recirculation induced by the LEV. This grants an indication of the LEV strength and its spatial-temporal location. During the ramp-up portion of this cycle, the φ dependent variations at each probe location are near zero indicating comparable fluid dynamic processes. As the airfoil approaches its maximum pitching angle amplitude, stronger variations in these time-resolved traces become evident. This growth in σ_u at upstream probe locations is a consequence of trailing-edge interactions and the TEV status that propagate far upstream. As such, the LEV state and its load augmentation effects are highly coupled with trailing-edge flow dynamics. The coupling between the LEV and TEV is an important interaction that largely dictates the dynamic stall processes in starting cycles.

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Competing Interests Statement

The authors have no conflicts to disclose.

Data Availability Statement

The data that supports the findings of this study are available from the corresponding author upon reasonable request.

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