

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**USE OF LESP (LEADING EDGE SUCTION PARAMETER) AND EFFECTIVE
ANGLE OF ATTACK MEASUREMENTS FOR GUST MITIGATION**



M.Sc. THESIS

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Department of Aeronautics and Astronautics Engineering

Aeronautics and Astronautics Engineering Programme

JULY 2023

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**SAĞANAK ETKİSİNİN AZALTILMASI İÇİN LESP (HÜCUM KENARI EMME
PARAMETRESİ) VE EFEKTİF HÜCUM AÇISI ÖLÇÜMLERİNİN
KULLANIMI**

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To my family and cats,



FOREWORD

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ABBREVIATIONS

DPIV	: Digital Particle Image Velocimetry
LESP	: Leading-edge Suction Parameter
CFD	: Computational Fluid Dynamics
DDES	: Delayed Detached Eddy Simulation
RANS	: Reynolds Averaged Navier-Stokes
LES	: Large Eddy Simulation
MAV	: Micro Air Vehicles
UAV	: Unmanned Air Vehicles
AR	: Aspect Ratio
GR	: Gust Ratio
PSP	: Polyamide Seeding Particles



SYMBOLS

Δy	: Cross-flow distance between the gust generator and wing model
T	: Half rotation period of the gust generator
C_L	: Lift coefficient
C_D	: Drag coefficient
C_s	: Suction force coefficient
C_f	: Skin friction coefficient
P	: Pressure
τ	: Shear stress
t^*	: Convective time
α_{eff}	: Effective angle of attack
γ	: Vortex sheeth strength
W	: Downwash
V_{LE}	: Theoretically infinite flow velocity



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USE OF LESP (LEADING EDGE SUCTION PARAMETER) AND EFFECTIVE ANGLE OF ATTACK MEASUREMENTS FOR GUST MITIGATION

SUMMARY

This master thesis aims to investigate the initiation of flow separation at the leading-edge during gust encounters by analyzing parameters such as, lift and drag forces, leading-edge suction parameter (LESP), and effective angle of attack, in order to determine the most accurate and practical indicator for the initiation. Experimental method is used for this investigation, which includes measuring forces acting on wing models and using Digital Particle Image Velocimetry (DPIV) technique for flow visualization and vector field analysis. Additionally, numerical method is used to prove applicability and accuracy of the total force measurements from experimental method conducted in this study. For that, sectional lift and drag forces, which are calculated from computationally obtained pressure and shear stress distributions, are compared with total forces obtained from both Computational Fluid Dynamic (CFD) and experimental studies.

The experiments are conducted in the closed circuit, large scaled, free-surface water channel located in the Trisonic Laboratory of the Faculty of Aeronautics and Astronautics of Istanbul Technical University (ITU). For all experiments, free-stream velocity is set to 0.1 m/s, therefore the Reynolds number corresponding to the wing models' chord length is determined as 10,000. The wing models, also known as test models, used for this study are a rectangular sharp-edged flat plate and a NACA0012 airfoil, both with AR=4. A gust generator, which is a rectangular flat plate with wedge shape edges, is positioned upstream of the wing model. During the experiments, force measurements are obtained from a force/torque sensor connected to the leading-edge of the wing model, with 1 kHz sample rate. Simultaneously with the force measurements, quantitative flow field images are recorded using DPIV system.

CFD simulations are performed using the commercial software package of ANSYS Fluent® and k- ω SST-Delayed Detached Eddy Simulation (DDES) hybrid Reynolds Averaged Navier-Stokes (RANS)/Large Eddy Simulation (LES) method had been employed. The wing models and the gust generator are modelled with identical geometrical characteristics and dimensions with the experimental setup. The computational domain is discretized with a combination of tetrahedral and five-sided triangular prismatic mesh. From the CFD analysis, pressure and shear stress distributions around the cross sections located on quarter and mid span are obtained, along with total lift and drag forces acting on the wings. Additionally, for flow visualization, two-dimensional streamline and vorticity images and three-dimensional velocity images are obtained.

During the experiments, a negative vortex gust is generated with the half rotation of the gust generator in the clockwise direction. While both of the wing models are stationary with zero angle of attack, the gust generator is subjected to three different half rotation periods ($T=3, 4, \text{ and } 6 \text{ s}/(1/2\text{rev})$) and two different cross-flow distances

($\Delta y = -36$ & -111 mm) with respect to the wing models. Each case is repeated five times and the results are averaged to reduce the noise and increase the accuracy. The CFD simulations are only conducted to base case ($T=4$ s/($\frac{1}{2}$ rev) & $\Delta y = -36$ mm) of the research for both wing models.

Initially, the sectional lift and drag forces for mid-span and quarter-span cross sections are compared with total lift and drag acting on the wing models, from experimental and CFD analysis. To better interpret the results, the three-dimensionality effect of the flow is studied using CFD data. Additionally, C_f distributions from the upper and lower surfaces of the wing models are compared with the vorticity images from CFD and experimental. This allowed for the determination of detecting vortex formation through C_f and the observation of similarity with experimental data. After discovering a strong correlation between the sectional results and the forces acting on the wing, the study proceeds to a comprehensive investigation of flow separation prediction parameters. In this comprehensive investigation, parameters such as C_L , C_D , LESP and effective angle of attack are compared to determine the most accurate and applicable indicator for the initiation of flow separation at the leading-edge. Critical instances from DPIV are studied alongside these parameters. It is observed the location of the stagnation point and the formation of a leading-edge vortex are crucial steps in the development of flow separation at the leading-edge. The location of the stagnation point is linked to the effective angle of attack and C_L . Since LESP is calculated from the axial force, a mostly symmetrical behavior is observed between LESP and C_D results. When the instantaneous LESP reached to the critical LESP value, LESP generally indicated the initiation of flow separation at the leading-edge.

SAĞANAK ETKİSİNİN AZALTILMASI İÇİN LESP (HÜCUM KENARI EMME PARAMETRESİ) VE EFEKTİF HÜCUM AÇISI ÖLÇÜMLERİNİN KULLANIMI

ÖZET

Havacılık araştırmalarında tarih boyunca, akışın kararsızlığı ve öngörülemez doğası çözülemeyen bir sorun olmuştur. Son yıllarda, mikro hava araçları (MAV) ve insansız hava araçları (UAV) dahil olmak üzere küçük hava araçlarına olan ilginin artması sonucunda, bu sorun yeniden gündeme gelmiştir. Bu küçük ölçekli uçaklar, sıklıkla zorlu atmosfer koşullarına maruz kalır ve yoğun manevralara girerler, bu da yukarıda bahsedilen sorunu ortaya çıkarmaktadır. Bu sorunun öncelikli olarak küçük ölçekli uçakları etkilediği belirtilmektedir, ancak spesifik durumlara bağlı olarak helikopterlerde veya büyük uçaklarda da ortaya çıkabilir. Bu sorunun kökeni daimi olmayan aerodinamiktir ve sağanak karşılaşmaları önemli bir rol oynamaktadır. Basitçe söylemek gerekirse, bir hava aracının sağanak karşılaşması nedeniyle akış hızında ve yönünde ani bir değişiklik yaşadığı durumlarda gözlemlenir.

Gerçek hayat koşullarında, en yaygın ve karmaşık sağanak karşılaşma türü, girdap tipi sağanak karşılaşmasıdır. Girdap tipi sağanak karşılaşması, hem akış yönünde hem de enine yönlü hız bileşenleri içerdiğinden, akışın kararsızlığını ve öngörülemezliğini artırır. Bu hadise genellikle atmosferik türbülanslarda ve daha spesifik olarak, girdap kopmasının meydana geldiği yüksek binalar ve gemiler gibi küt cisimlerin iz bölgesinde gözlemlenir. Girdap tipi sağanak karşılaşmasının bir sonucu olarak, yukarıda belirtilen hava araçları, akış ayrılması yaşayabilir ve bu da stall (tutunma kaybı), kontrol kaybı ve en kötü senaryoda uçak kazalarına yol açabilir.

Mevcut araştırmalar, akış ayrılmasını önlemek veya geciktirme niyetiyle daimi olmayan akışları anlamak ve öngörü yöntemleri geliştirmeyi hedeflemektedir. Çoğu çalışma, akış ayrılmasının öncesini, sırasını ve sonrasını inceleyerek ayrılmayı önceden tahmin etmeye odaklanır. Ana amaçları, çeşitli durumlarda akış ayrılmasını doğru bir şekilde belirleyebilen evrensel bir kriter bulmaktır. Böyle bir kriter geliştirilerek, her uçağa bir öngörü sistemi entegre edilebilir ve sağanak karşılaşmalarının etkilerini etkili bir şekilde azaltmak ve istenmeyen sonuçları önlemek için karşı önlemler uygulanabilir.

Bu amaç doğrultusunda, kanat profilinin hücum kenarında ölçülen emme kuvvetinin boyutsuz bir formu olan hücum kenarı emme parametresi (LESP) adı verilen bir kriter geliştirilmiştir. LESP, kritik LESP aracılığı ile akış ayrılmasının başladığı anı belirlemek için bir gösterge görevi görür. Kritik LESP değeri, her kanat modeli ve Reynolds sayısı için önceden belirlenmesi gereken belirli bir LESP değeridir ve kanat hareketinden bağımsız olması ile birçok senaryoda kullanılabilir. Bu yöntem, anlık LESP değerinin kritik değere ulaştığı anda akış ayrılmasının başlaması prensibine dayanır. Böylece, anlık LESP'nin izlenmesi ve kritik değere ulaştığında sistemin uyarılması, uçuş sırasında akış ayrılmasını tahmin etmek için pratik bir yöntem olabilir.

Efektif hücum açısı, lokal kanat profili kesitinin veter hattı ile lokal bağıl akış arasındaki açı olarak tanımlanmaktadır. Girdap tipi sağanak karşılaşmalarında, kanat hem akım yönünde hem de enine yönde hız bileşenlerinin etkisi altında olacağından efektif hücum açısı oluşabilir. Bu açı, lokal kesitsel taşıma katsayısı ile doğru orantılı olduğundan, akış ayrımı başlangıcını tahmin etmek için kullanılabilir. Açının artmasıyla taşıma katsayısı da artar ve firar kenarındaki ayrılma noktası, hücum kenarına doğru ilerlemeye başlar. Daimi olmayan akış koşullarında, efektif hücum açısı statik stall açısını yeterince hızlı geçtiğinde akış hücum kenarından ayrılmaya başlar. Böylece hem hücum açısı hem de hızdaki bu büyük değişimler, istenmeyen dinamik stall olayına yol açabilir. LESP yönteminde bahsedildiği gibi, efektif hücum açısının izlenmesi, uçuş sırasında akış ayrılmasını tahmin etmek için kullanılabilir. Anlık efektif hücum açısı, hücum kenarının yukarı akışını ölçen bir pitot tüpü monte edilerek elde edilebilir. Pitot tüpünün konumu nedeniyle, akış daha kanat profiline ulaşmadan önce akış ayrılması tahmin edilebilir. LESP, kanat profili üzerinde etki eden basınçlardan veya kuvvetlerden elde edildiği için efektif hücum açısı metoduna göre geç tahminde bulunma ihtimali vardır. Bu nedenle, bir uçuş sistemi için hangi yöntemin daha doğru, pratik ve uygulanabilir olduğunun araştırılması ve belirlenmesi önemlidir.

Bu yüksek lisans tezi, şiddetli sağanak karşılaşmaları sırasında hücum kenarında akış ayrılmasının başlamasını, taşıma ve sürüklenme kuvvetleri, hücum kenarı emme parametresi (LESP) ve efektif hücum açısı gibi parametreleri analiz ederek araştırmayı böylece en doğru ve pratik göstergeyi belirlemeyi amaçlamaktadır. Bu araştırmada deneysel yöntem kullanımı ile, kanat modellerine etki eden kuvvetler ölçülmüştür ve aynı zamanda akış yapılarını görselleştirme ve vektör alan analizi için Dijital Parçacık Görüntüleme Hızölçer (DPIV) tekniği kullanılmıştır. Ayrıca, sayısal yöntem, bu çalışmada kullanılan toplam kuvvet ölçümlerinin ve deneysel yöntemin uygulanabilirliğini ve doğruluğunu kanıtlamak için kullanılmaktadır. Bunun için, Hesaplamalı Akışkanlar Dinamiği (CFD) analizinden elde edilen basınç ve kayma dağılımlarından hesaplanan kesitsel kaldırma ve sürüklenme kuvvetleri, hesaplamalı ve deneysel çalışmalardan elde edilen toplam kuvvetlerle karşılaştırılmaktadır.

Deneyler, İstanbul Teknik Üniversitesi (İTÜ) Uçak ve Uzay Bilimleri Fakültesi Trisonik Laboratuvarı'nda bulunan kapalı devre, büyük ölçekli, serbest yüzeyli su kanalında gerçekleştirilmiştir. Tüm deneyler için serbest akış hızı 0,1 m/s olarak ayarlanmıştır, bu nedenle kanat modellerinin veter uzunluğuna karşılık gelen Reynolds sayısı 10.000 olarak belirlenmiştir. Bu çalışma için kullanılan test modelleri olarak da bilinen kanat modelleri, her ikisi de $AR=4$ olan dikdörtgen şeklinde keskin kenarlı düz bir plaka ve bir NACA0012 kanat profilidir. Kanat modelinin akış yukarısına, kama şeklinde kenarları olan dikdörtgen düz bir plaka olan sağanak üretici yerleştirilmiştir. Deneyler sırasında, kanat modelinin hücum kenarına bağlı olan bir kuvvet/tork sensöründen 1 kHz örnekleme hızıyla kuvvet ölçümleri elde edilmiştir. Kuvvet ölçümleri ile eş zamanlı olarak, DPIV sistemi kullanılarak nicel akış alanı görüntüleri kaydedilmiştir.

CFD simülasyonları, ANSYS Fluent® ticari yazılım paketi kullanılarak gerçekleştirilmiştir olup, $k-\omega$ SST-Delayed Detached Eddy Simulation (DDES) hibrit Reynolds Ortalamalı Navier-Stokes (RANS)/Large Eddy Simulation (LES) yöntemi kullanılmıştır. Kanat modelleri ve sağanak üretici, deney düzeneği ile aynı geometrik özelliklerde ve boyutlarda modellenmiştir. Hesaplama alanı, dört yüzlü ve beş yüzlü üçgen prizmatik ağ yapısı kombinasyonu ile ayrıklaştırılmıştır. CFD analizi sonucunda, kanatlara etki eden toplam taşıma ve sürüklenme kuvvetleri ile birlikte

eyrek ve orta kanat aıklıęında bulunan kesitlerdeki basın ve kayma daęılımları elde edilmiřtir. Ayrıca, akıř grselleřtirmesi iin iki boyutlu akım izgileri ve girdap grntleri ile  boyutlu hız grntleri elde edilmiřtir.

Deneyler sırasında, saęanak retecinin saat ynnde yarım tur dnř ile negatif ynl bir girdap tipi saęanak retilmektedir. Her iki kanat modeli de sıfır hcum aısıyla hareketsiz dururken, saęanak reteci  farklı yarım tur dnř periyoduna ($T=3, 4$ ve $6 \text{ s}/(\frac{1}{2}\text{tur})$) ve kanat modellerine gre iki farklı apraz akıř mesafesine ($\Delta y=-36$ ve -111 mm) tabi tutulur. Her bir durum iin deneyler beř kez tekrarlanır ve sonrasında grlty azaltmak ve doęruluęu artırmak iin sonuların ortalaması alınır. CFD simlasyonları, her iki kanat modeli iin yalnızca arařtırmanın temel durumuna ($T=4 \text{ s}/(\frac{1}{2}\text{tur})$ ve $\Delta y= -36 \text{ mm}$) gre yrtlr.

Başlangıta, orta ve eyrek kanat aıklıęındaki kesitlere ait kesitsel tařıma ve srkleme kuvvetleri, deneysel ve CFD analizlerinden elde edilen kanat modellerine etki eden toplam tařıma ve srkleme kuvvetleriyle karřılařtırılır. Sonuları daha iyi yorumlamak iin akıřın  boyutluluk etkisi CFD verileri kullanılarak incelenir. Ayrıca, kanat modellerinin st ve alt yzeylerinde oluřan C_f daęılımları, CFD ve deneysel analizlerinden elde edilen girdap grntleri ile karřılařtırılır. Bu sayede, girdap oluřumunun C_f aracılıęı ile tespit edilmesi ve deneysel verilerle benzerliklerinin gzlemlenmesi saęlanır. Kesitsel sonular ile kanada etki eden kuvvetler arasında gl bir iliřki keřfedildikten sonra, arařtırma, akıř ayrımı tahmin parametrelerinin kapsamlı bir řekilde incelenmesi ile devam eder. Bu kapsamlı arařtırmada, hcum kenarında akıř ayrılmasının başlangıcının en doęru ve uygulanabilir gstergesini belirlemek zere C_L , C_D , LESP ve efektif hcum aısı gibi parametreler karřılařtırılır. Bu parametrelerle birlikte DPIV'den elde edilen kritik durumlar da incelenir. Durma noktasının konumu ve hcum kenarı girdabının oluřumu, hcum kenarındaki akıř ayrılması aısından nemli adımlardır. Durma noktasının konumu aynı zamanda, efektif hcum aısı ve tařıma kuvveti ile iliřkilidir. LESP, aksiyal kuvvetten hesaplandıęından dolayı, LESP ve C_D sonuları arasında oęunlukla simetrik bir davranıř gzlemlenir. Anlık LESP, kritik LESP deęerine ulařtıęında, genellikle hcum kenarındaki akıř ayrılmasının başlangıcını gsterir.



1. INTRODUCTION

Throughout the course of history in the aerospace research, the unsteadiness and unpredictability nature of the flow has been a pending problem. In recent years, this problem has been back in focus as a result of growing interest in small air vehicles, including micro air vehicles (MAVs) and unmanned air vehicles (UAVs). These small-scale aircrafts frequently experience challenging atmospheric conditions and engage in intense maneuvers, thereby bringing out the aforementioned problem [1-2]. It is important to note that while this issue primarily affects small-scale aircrafts, it can also appear in helicopters or large planes, depending on the specific circumstances. The root of this problem is unsteady aerodynamics, with gust encounters playing a key role. Simply, it is observed in the situation when an air vehicle experiences a rapid change in flow velocity and direction due to gust encounter. In real-life circumstances, the most prevalent and complex type of gust encounter is the vortex gust encounter [3]. Vortex gust encounter intensifies the unsteadiness and unpredictability of the flow as they involve both streamwise and transverse velocity components. This phenomenon is observed generally in atmospheric turbulences and more specifically, wake region of blunt bodies such as tall buildings and ships, where vortex shedding occurs [1-2]. As a results of vortex gust encounter, the above-mentioned air vehicles can experience flow separation, that can lead to stalling, loss of control, and, in the worst-case scenario, air crashes. Current researches aim to understand and develop predictive methods for unsteady flows with the intention of preventing or delaying the flow separation. Most studies concentrate on predicting flow separation at the leading-edge, by investigating the behavior of the flow and wing loading prior to, during, and after the separation [4-12]. Their main purpose is to find a universal criterion that can accurately determine flow separation in various situations. By developing such a criterion, a predictive system can be integrated into every aircraft and countermeasures can be applied to effectively mitigate the effects of gust encounter and prevent any unwanted outcomes. In line with this objective, a criterion called leading-edge suction parameter (LESP) has been developed, which is a non-dimensional form of the suction

force measured at the leading-edge of the airfoil [4-5]. LESP serves as an indicator to identify the instant that the flow separation starts through critical LESP. Critical LESP number is a specific LESP value that has to be predetermined for each wing model and Reynolds number. This critical value is independent of motion but dependent on the geometric characteristics of the wing and the Reynolds number of the flow [5]. This method functions based on the principle that flow separation initiates when the instantaneous LESP reaches the critical value. Thereby, monitoring instantaneous LESP and alerting the system when it reaches to the critical value can be a practical method to predict flow separation during a flight. In addition to the aforementioned method, effective angle of attack can also be used as a flow separation indicator. Effective angle of attack is defined as the angle between the chord line of the local airfoil section and the local relative flow [13]. It can be experienced in vortex gust encounters as the airfoil will be under additional both streamwise and transverse velocity components. Since the effective angle of attack is directly proportional to local sectional lift coefficient, it can be used to predict the flow separation initiation. With the increase of the angle, lift coefficient also increases and the separation point at the trailing-edge starts to move towards the leading-edge. Under the unsteady flow condition, the flow starts to separate at the leading-edge, when the effective angle of attack surpasses the static stall angle rapidly enough. As the increase of the angle continues, a vortex is generated near the leading-edge, subsequently expands and progresses towards the trailing-edge, which causes the unwanted phenomenon called dynamic stall [14]. As it was mentioned with LESP method, monitoring the instantaneous effective angle of attack can be used to predict flow separation during a flight. Instantaneous effective angle of attack can be obtained by mounting a pitot tube that measures upstream of the leading-edge. Due to its location, flow separation can be predicted before the flow reaches the airfoil, which is opposite of LESP method, where LESP is obtained from the pressures or forces acting on the airfoil itself. Therefore, it is important to determine which method will be more practical and applicable for a flight system. The research on flow separation prediction methods consists of numerous theoretical, numerical, and experimental studies so far [4-12]. However, despite these extensive researches, the understanding of flow separation behavior and the development of accurate and more practical prediction methods are still ongoing areas of investigation.

In this thesis, a comprehensive investigation on flow separation prediction hypothesis is conducted by simultaneously recording force measurements and capturing digital particle image velocimetry (DPIV) images for flow visualization. From the force measurements, lift, drag, and LESP are calculated to understand the behavior of the flow and to determine which parameter is an indicator for flow separation. Meanwhile, the DPIV images provided the visualization of the flow separation at the leading-edge through the observation of streamlines and vorticity. Therefore, the images are used to confirm the separation points indicated by force parameters through the comparison of corresponding instances. Additionally, effective angle of attack is calculated using the velocity vectors obtained from the DPIV data, as it is another indicator for flow separation initiation. During the experiments, various vortex gust cases are conducted with the combination of three gust generator rotation periods, two gust cross flow encounter distances with respect to chord line, and two different wing models (flat plate and NACA0012). Before starting the LESP analysis and flow separation detection, the force results along with DPIV streamline and vorticity images are compared with Computational Fluid Dynamics (CFD) results for the base case. This comparison is needed to validate that LESP can be calculated directly from forces acting on the wing, instead of using pressure measurements, which is a common method in literature. From the CFD simulations of both flat plate and NACA0012 airfoil, pressure and shear stress distributions for both mid-span and quarter-span cross sections are obtained. Additionally, the total forces acting on the wing along with streamline and vorticity images are acquired.



2. LITERATURE REVIEW

In this section, a comprehensive literature review about flow separation prediction and LESP is conducted by examining the related main studies. These studies include theoretical, numerical, and experimental research with a specific focus on the development and improvement of flow separation prediction methods and LESP.

Ramesh et al. introduced the Leading-Edge Suction Parameter (LESP) as a practical prediction method to detect flow separation initiation at the leading-edge in unsteady airfoils at low Reynolds numbers [4-5]. Their proposition was that, for a given airfoil and Reynolds number, there is a critical value of LESP that always corresponds to the initiation of flow separation at the leading-edge, and that this critical value is mostly independent of motion of the airfoil.

To formulate the LESP hypothesis, Ramesh et al. used a theoretical method known as large-angle unsteady thin airfoil theory, as the research involved large angle, amplitude, and frequency motions [5]. The lack of the small angle assumption distinguished this theory from the classical thin airfoil theory. However, similar to the classical theory, in large-angle theory, vortex sheet strength distribution, $\gamma(\theta, t)$, is obtained from Fourier series,

$$\gamma(\theta, t) = 2U \left[A_0(t) \frac{1 + \cos\theta}{\sin\theta} + \sum_{n=1}^{\infty} A_n(t) \sin(n\theta) \right] \quad (2.1)$$

where $A_0(t)$ and $A_n(t)$ are the time-dependent Fourier coefficients, c is chord length, U is forward airfoil velocity (negative x direction), and θ is a transformation variable that varies between 0 and π . θ is related to the chordwise coordinate x , which varies between 0 and 1, as shown in the following manner,

$$x = \frac{c}{2}(1 - \cos\theta) \quad (2.2)$$

Narsipur et al. [7] used the reference velocity, U_{ref} , in the equation 2.1 and the following equations are derived from it, instead of the term U , to inform that the

velocity can be defined based on the specific problem. However, in their particular problem, $U_{ref} = U$ as it was defined as the forward velocity.

The Kutta condition, which specifies zero vorticity at the trailing-edge, is indirectly satisfied through the structure of the Fourier series. Even though Narsipur et al. [7] points out the recent advancements on the Kutta condition, these updates are not incorporated into the equation for this particular problem. Moreover, Fourier coefficients are calculated based on instantaneous local chordwise downwash, $W(x, t)$, on the airfoil by applying the boundary condition that the flow must remain tangential to the surface of the airfoil. The Fourier coefficients equations are given as,

$$A_0(t) = -\frac{1}{\pi} \int_0^\pi \frac{W(x, t)}{U} d\theta \quad (2.3)$$

$$A_n(t) = \frac{2}{\pi} \int_0^\pi \frac{W(x, t)}{U} \cos(n\theta) d\theta \quad (2.4)$$

Using Fourier coefficients, two primary forces acting on the airfoil, the normal force and the leading-edge suction force, are derived as coefficients [4],

$$C_N = 2\pi \left[\left(\cos\alpha + \frac{h}{U} \sin\alpha \right) \left(A_0 + \frac{A_1}{2} \right) + \frac{c}{U^2} \left(\frac{3}{4} \frac{\partial}{\partial t} (UA_0) + \frac{1}{4} \frac{\partial}{\partial t} (UA_1) + \frac{1}{8} \frac{\partial}{\partial t} (UA_2) \right) \right] \quad (2.5)$$

$$C_S = 2\pi A_0^2 \quad (2.6)$$

The thin airfoil theory assumes zero airfoil thickness and therefore zero leading-edge radius. Since the flow has to turn 180° around the leading-edge as shown in Figure 2.1, this assumption leads to a theoretically infinite flow velocity at the leading-edge, known as V_{LE} .

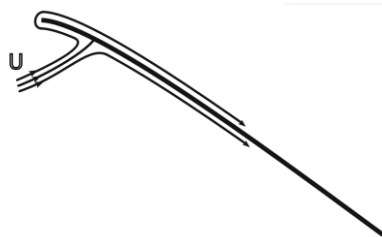


Figure 2.1 : Illustration of flow around the leading edge of a thin airfoil [6].

This theoretically infinite flow velocity, V_{LE} , is obtained from Garrick [15] and von Kármán and Burgers [16] as,

$$V_{LE}(t) = \lim_{x \rightarrow LE} \frac{S}{\sqrt{x}} \quad (2.7)$$

where, S is the leading-edge suction force. Leading-edge suction force can be derived using vortex sheet strength as,

$$S = \lim_{x \rightarrow LE} \frac{1}{2} \gamma(x, t) \sqrt{x} \quad (2.8)$$

At the leading-edge, while $\gamma(x, t)$ is infinite because of its relation to $1/\sqrt{x}$, S is finite. From that S can be derived as,

$$S = \sqrt{c} U A_0(t) \quad (2.9)$$

For given values of c and U , LESP can be defined as it is equaled to $A_0(t)$,

$$LESP(t) = A_0(t) \quad (2.10)$$

because it is a non-dimensional parameter of leading-edge suction force.

Ramesh et al. used combinations of pitch and plunge motions with the variation of pivot location, amplitude, frequency, wing models and Reynolds Number to study these parameters effect on critical LESP and flow separation prediction [5]. Critical LESP values are determined for specific cases. In the initial studies, Ramesh et al. [4] used experimental dye flow images to determine the critical LESP, however, in their following research, they used experimental, CFD, and literature [5-6]. Theoretical LESP results for flow separation initiation is also validated with experimental (flow visualization and wing loading) and CFD (flow visualization, wing loading, skin friction, and pressure) data [5-6].

Narsipur et al focused on continuing and improving the LESP concept and therefore, investigated the effect of airfoil shape, Reynolds number, pivot location, and pitch rate on the LESP analysis using CFD method and compared the results with experiments from literature [7].

From CFD, Narsipur et al. obtains pressure distributions around the airfoil [7]. Using the pressure distributions suction force is calculated. To calculate the suction force, pressure data is integrated from leading-edge up to the 30% chord, which is the maximum thickness location of the NACA0012 airfoil. The integration beyond this point is excluded, as the suction values did not show noteworthy changes. In Figure 2.2, forces acting on the leading-edge is shown and $(x/c)_{max}$ expression stands for the location of the maximum thickness of the airfoil, which is where the pressure integration for the calculation of leading-edge suction is stopped.

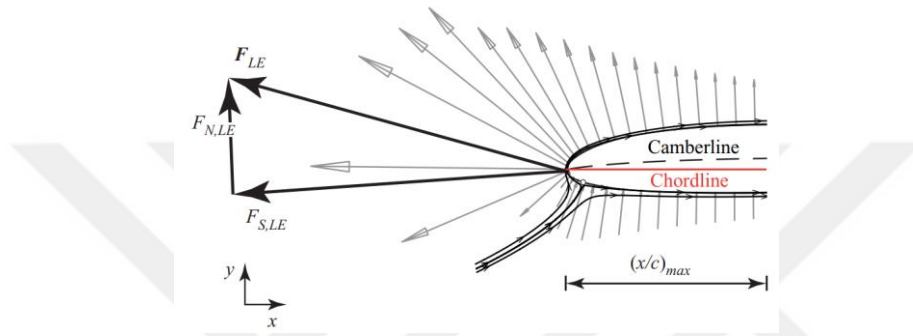


Figure 2.2 : Leading-edge resultant force with suction and normal components [7].

LESP can be derived as a function of suction force coefficient by replacing A_0 term in equation 2.6 with the equivalence in the equation 2.10, which is given as,

$$LESP = \sqrt{\frac{C_s}{2\pi}} \quad (2.11)$$

However, Narsipur et al. does not directly use this equation for their solution. They point out that, the leading-edge suction force cannot have a negative direction but considering the imperfect nature of CFD, small negative results can be obtained. To prevent any confusion, they equaled any negative result to zero. In addition, to provide clear assessment, the sign of the LESP was set to be equivalent to the sign of the normal force. Therefore, the positive normal force and LESP will indicate that the stagnation point is located on the lower surface of the airfoil, while the negative will indicate the opposite as shown in Figure 2.3. According to this information the modified LESP equation is given as [7],

$$LESP = \begin{cases} \text{sign}(C_N) \sqrt{\frac{C_S}{2\pi}}, & \text{for } C_S > 0 \\ 0, & C_S \leq 0 \end{cases} \quad (2.12)$$

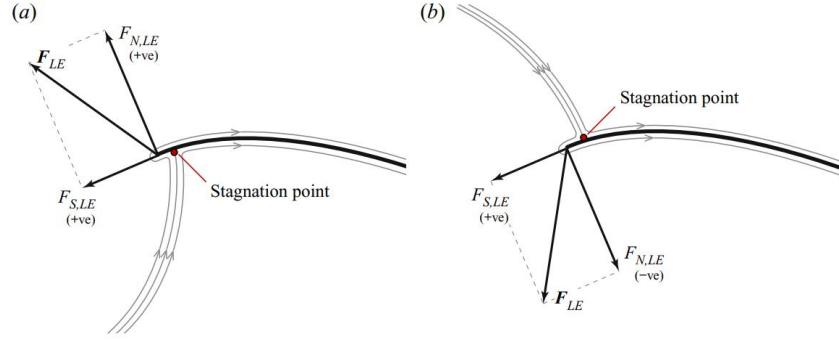


Figure 2.3 : Forces acting on the leading-edge of a thin airfoil, for flow conditions with upper surface (a) and lower surface (b) stagnation points [7].

Narsipur et al. observed that large LESP variations at high Reynolds number cases, which does not support motion independent characteristic of LESP. Therefore, a correction to the LESP equation is developed, as the original equation neglects the wake vortices. While the original equation uses a single U_{ref} velocity as forward speed, under high pitch and plunge motions the magnitude of the net velocity, U_{net} , is expected to have a significant difference. The updated LESP is given as,

$$LESP_{net} = \frac{LESP_{ref}(t)}{(U_{net}(t)/U_{ref})} \quad (2.13)$$

where, $LESP_{ref}$ is calculated using the equations from Ramesh et al. [5]. The derivation of $U_{net}(t)/U_{ref}$ is explained detailedly in Narsipur et al. [7].

Obtaining successful results from previous researches, Narsipur [8] continued research on improvement of critical LESP value with the variation of airfoil thickness and Reynolds number, using CFD results. They observed that for the same airfoil geometry, increasing Reynolds number causes the critical LESP number to initially decrease and then increase. Yet, for a constant Reynolds number, increasing airfoil thickness caused the increase of the critical LESP number.

Jenkins et al. investigated a static airfoil encountering vortical disturbances and its effect on LESP and effective angle of attack using CFD method [9]. They employ the LESP method from Narsipur et al. [7] and use pressure distributions to calculate

instantaneous LESP. Vorticity images are used to determine the timing of the leading-edge vortex (LEV) initiation, which occurs after flow separation at the leading-edge. Then LESP and effective angle of attack results are compared to decide which parameter is more accurate to detect the LEV initiation. As for the outcome, while effective angle of attack results did not show consistency, LESP results gave accurate and precise results, which supports the reliability of LESP as a predictive method.

Deparday and Mulleners studied the development of dynamic stall, caused by flow separation, on an airfoil undergoing pitching motion [10]. They use velocity field data from DPIV and local surface pressure measurements at leading-edge. For the calculation of leading-edge suction force, they use pressure data from the leading-edge up to 10% chord location. Then, to calculate leading-edge suction parameter, which is defined as first coefficient of the Fourier series, they use the following equation,

$$A_{0,exp} = \sqrt{\frac{2}{\pi}} |S_{LE}| \cos(\lambda - \alpha) \quad (2.14)$$

where, S_{LE} is leading-edge suction force, λ is an angle relative to inflow velocity direction, and α is angle of attack.

Additional to experimental research, Deparday and Mulleners also developed an upgraded version of the theoretical model for the leading-edge suction parameter based upon the thin airfoil theory [10]. This equation covers the influence of shear layer growth during separation, while accounting for the increase in effective camber and the decrease in effective angle of attack as shown,

$$A_{0,theor} = \sin \alpha_{eff} + \dot{\alpha} \frac{c}{4U} - K_{\eta} \cos \alpha_{eff} - \Delta z^* \cos \alpha_{eff} \quad (2.15)$$

where, α_{eff} is effective angle of attack, $\dot{\alpha}$ is unsteady pitch motion, K_{η} represents the influence of airfoil camber, and Δz^* is the dimensionless chord-wise average of the shear layer height (experimentally determined from velocity field).

The research concludes that the leading-edge suction parameter is an effective parameter for stall or flow separation initiation indication [10]. In addition, the newly developed theoretical leading-edge suction parameter model accurately predicts both

the magnitude and the instant of the maximum leading-edge suction value on the pitching airfoil.

Deparday et al. develops another mathematical LESP model using the partial circulation around the leading-edge, leading-edge radius, and the location of the stagnation point [11]. Unlike other researches, in this method, LESP is obtained from CFD and experimental flow field data. This LESP model is suitable for the flows that separates at the trailing-edge because, unlike classical thin airfoil theory, this model does not consider Kutta condition at the trailing-edge. They show that using this method with local flow measurements, it is possible to evaluate the flow separation at the leading-edge and detect the separation of the leading-edge vortex.

While the suction force can give information about the state of the flow and, more importantly, indicate the initiation of the flow separation at the leading-edge, it is only applicable until the start of the flow separation at the leading-edge. In Figure 2.4, the behavior of the leading-edge suction force during potential and separated flows is shown. In Figure 2.4(c), the flow separates at the leading-edge and passes over a vortex that is generated at the leading-edge, then accelerates towards to the downward attachment point. Due to the reattachment of the flow, a similarity between the separated flow over sharp edge (Figure 2.4(c)) and the potential flow over round edge (Figure 2.4(b)) is established. It is assumed that the total force acting on the sharp-edged wing, which is related to the pressures that are necessary to sustain equilibrium of the flow over the vortex, is basically equivalent to the leading-edge suction force, which is affiliated with the pressures at the leading-edge that are necessary to maintain the flow around the large leading-edge radius of the rounded edged wing [17]. Nevertheless, for the sharp-edged case, the total force acting on the wing will be concentrated on the upper surface of the wing, rather than on the leading-edge, where there is insufficient surface area. Hence, a normal force equal to the theoretical leading-edge suction force is observed on the sharpened-edged wing. Moreover, the normal force related to the separated flow and vortex is expected to be equal to the leading-edge suction force, as the theoretical leading-edge suction force is fundamentally independent of the leading-edge radius. As a result, it is insignificant to examine the suction force, hence LESP, after the initiation of separation because it is not possible to use axial force during separation, as it becomes normal force.

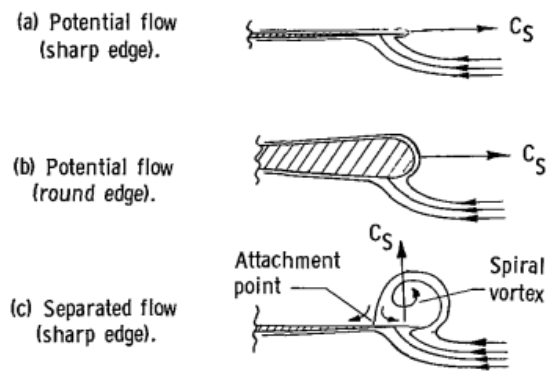


Figure 2.4 : Flow around the sharp edge and round edge wings with corresponding leading-edge suction force [17].

3. EXPERIMENTAL SETUP

3.1 Flow System

The experiments are conducted in the closed circuit, large scaled, free-surface water channel located in the Trisonic Laboratory of the Faculty of Aeronautics and Astronautics of Istanbul Technical University (ITU). The water channel has six main sections: inlet tank, rectification section, contraction section, test section, end tank, and pump. The rectification section consists of honeycomb and five screens to provide a uniform flow with low turbulence intensity. The flow is accelerated uniformly, with 2:1 contraction ratio, at the contraction section, before entering the test section. The test section, where all the experiments are conducted, has transparent acrylic glass walls and floor for DPIV measurements, with the dimensions of 1010 mm width and 790 mm height. The free-stream velocity, which can be ranged between 0 and 0.14 m/s, is controlled by adjusting the RPM settings of the ABB AC drive (ABB-ACS800-01). For all of the experiments in this study, the RPM value was set to 1050 RPM to obtain 0.1 m/s free-stream velocity, therefore the Reynolds number corresponding to the wing model chord length is determined as 10,000.

3.2 Test Models

For the experiments, a gust generator plate and two test models are manufactured using plexiglass material for the DPIV measurements. The test models are a rectangular flat plate and a NACA0012 airfoil. Both test models have dimensions of 100 mm chord length and 200 mm span ($AR=4$), but the flat plate model has a thickness of 5 mm, while the NACA0012 model has a maximum thickness of 12 mm. The gust generator plate, which is positioned upstream of the test models as shown in Figure 3.1, has dimensions of 5 mm thickness, 100 mm chord length, and 400 mm span ($AR=8$). The leading and trailing-edges of the gust generator plate are shaped with 45° angle surfaces to create point tips. The top view of the test section during a vortex gust

generation is illustrated in Figure 3.1, with the dimensions of the gust generator and test models.

The gust generator plate and both test models are mounted to Kollmorgen/Danaher Motion servomotors as shown in Figure 3.2, with gust generator plate mounted from its mid-chord and the test models mounted from their leading-edge. These servomotors are located on top of the water channel test section and they can provide plunge and pitch motions. Pitch motion is used to rotate the gust generator plate 180° in the clockwise direction to generate a negative vortex gust whereas, plunge motion is used to position the gust generator in the cross-flow direction to arrange the vertical distance between the gust generator and test models (Δy), as shown in the Figure 3.1. Also, the invariable horizontal distance between the gust generators trailing-edge and test models' leading-edge (Δx) is given as 55 mm.

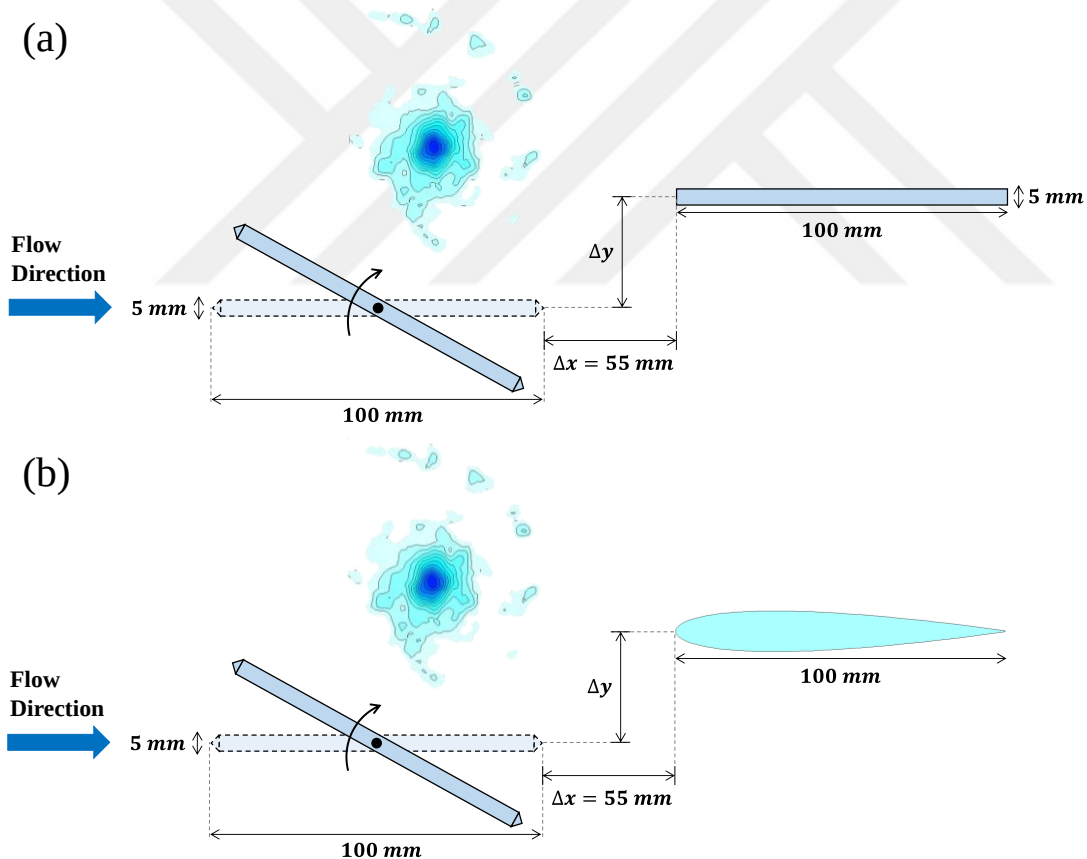


Figure 3.1 : Top view of the test section with dimensions of the test models: a) flat plate and b) NACA0012.

3.3 Force Measurement System

For the force and torque measurements, a six component ATI NANO-25 Force/Torque (F/T) sensor is used. The sensor is located on the mounting beam that is connected to the test models from the leading-edge, as shown in Figure 3.2, and the z axis of the sensor is perpendicular to the plunge plane. The force measurements are obtained with 1000 Hz sample rate, with each case repeated five times and the results are averaged to improve the accuracy and reduce the noise. In addition, 1 Hz low-pass filter is used to further reduce noise. NANO-25 sensor has 1/24 N resolution; the maximum uncertainty of the force coefficients is calculated as 0.2083.

3.4 Flow Visualization System

Quantitative flow field images are recorded using Digital Particle Image Velocimetry (DPIV) system. The flow field is illuminated by a dual cavity Nd:YAG laser with a maximum energy of 120mJ/pulse. Polyamide seeding particles (PSP) with 50 μm mean diameter is used to seed the flow. For the image capturing, a 10-bit camera with 1600 $\times$ 1200-pixel resolution and a Nikon 60mm focal length lens is placed under the water channel, perpendicular to the illuminated plane as shown in Figure 3.2, with leading-edge of the test models located in the center of the images. For each case, 450 images are recorded with 15 Hz trigger rate and 3,000 μs time between pulses. The recording and post-process are done on Dantec Dynamic Studio V4.10.67. At the beginning of the post-process, the gust generator and test models on the captured images are imaged masked. Cross-correlation method is applied with Adaptive PIV algorithm, with a grid step size of 8 pixels, starting from a minimum interrogation area of 16 by 16 pixels up to 64 by 64 pixels. Vector masking is employed along with validation methods such as range validation, moving average validation, and N-sigma validation, and an average filter is applied to the data before vorticity is calculated using scalar derivatives. Each case is repeated five times and the results are averaged to reduce the noise.

Force measurements and DPIV recordings are done simultaneously. To initiate force/torque and DPIV data recordings and control the gust generator plate pitch servomotor, a Labview VI (Virtual Instrument) software that sends a trigger signal is used.

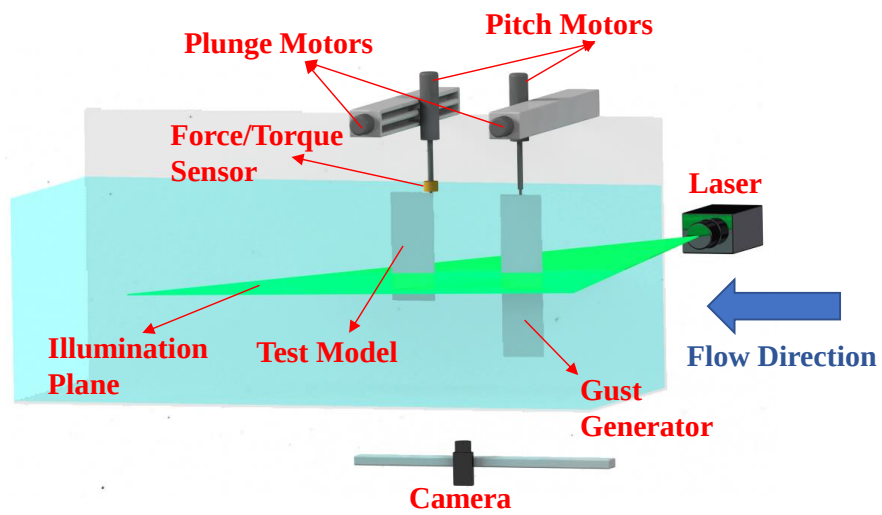


Figure 3.2 : Water channel experimental setup [18].

4. COMPUTATIONAL METHOD

Computational Fluid Dynamic (CFD) calculations are performed using the commercial software package of ANSYS Fluent® and k- ω SST-Delayed Detached Eddy Simulation (DDES) hybrid Reynolds Averaged Navier-Stokes (RANS)/Large Eddy Simulation (LES) method has been employed. Hybrid approaches [19-20] act as a bridge between less accurate and computationally expensive scale resolving methods, such as URANS and LES [21], respectively. Based on the temporal or spatial resolution, these approaches switch between RANS to LES. As a result, when applying hybrid RANS/LES methods, strict mesh criteria of the LES are not required to be satisfied. DDES approach [22] is an advanced version of the Detached Eddy Simulation (DES) method [23]. Using shielding functions [24], the limitations of grid-induced separation (GIS) [25] from the inherent weaknesses of DES and slow transition from RANS to LES in the separating shear layers are mostly overcome by DDES approach. With the recent developments in the computational power and hybrid RANS/LES methods' greater capability of predicting the separated flow compared to URANS, these hybrid methods are extensively used in recent studies [24-29]. Therefore, k- ω SST-DDES turbulence closure model is selected to be used for the CFD simulations in this study, according to the required computational power, fidelity, and accuracy level.

The wing models (flat plate and NACA0012) and the gust generator are modelled to have identical geometrical characteristics and dimensions with the experimental setup. A square prism shaped computational domain is used with the dimensions of 25 chords of length, 20 chords of width and 25 chords of height. The dimensions of the domain, flow direction, and the positioning of the wing models and gust generator is shown in the Figure 4.1(a). The computational domain is discretized with a combination of tetrahedral and five-sided triangular prismatic mesh. Over the wing and gust generator boundary, prismatic elements, with a pre-determined cell height, are generated to resolve the near wall region by satisfying $y^+ \sim 1$ requirement. In the separation region of the models, mesh density is increased to improve the resolution of the flow

structures, as shown in Figure 4.1(b). The boundary conditions for the solution are set as, no-slip condition to the surfaces of wing models, gust generator, and wall sections of the domain, constant flow velocity at the inlet boundary, and constant static pressure to the outlet boundary. During the simulations, the flow is always incompressible and the fluid properties such as density and viscosity are assumed to be constant. For pressure-velocity coupling in the simulations, SIMPLE algorithm [30] has been used. Prior to initiating the unsteady simulations with $k-\omega$ SST-DDES method, a steady-state RANS simulation is performed to obtain the initial values before the gust generator starts to rotate. For the spatial discretization in the solutions, second-order upwind-type schemes is applied, with the exclusion of the momentum equation which bounded central differencing scheme is employed. Also, for the temporal discretization, bounded second order implicit scheme is used. To maintain the stability, the time step size is determined considering Courant number < 0.5 throughout the simulation duration, especially for the cells around gust generator, wing and gust generator..

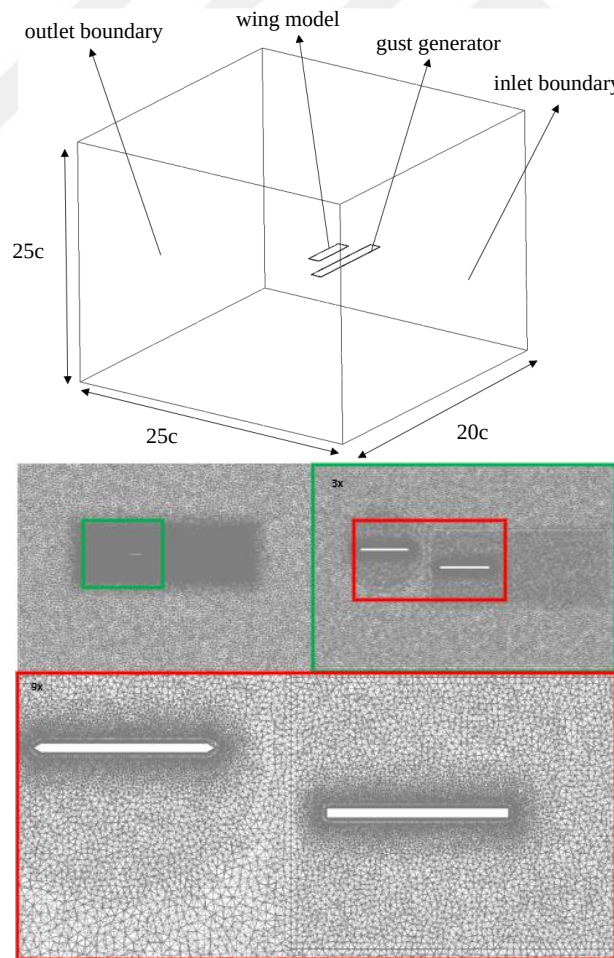


Figure 4.1 : The computational domain and mesh structures [31].

During the simulation, as it is in the experiment, the gust is generated with the rotation of the gust generator. This rotation motion is included into the model by defining the angular velocity of the rotation. To prevent numerical instabilities, the angular velocity profile is smoothed by applying a smoothing function by Eldredge [24]. Then, the rotation of the gust generator is simulated by using non-conformal interfaces and moving mesh feature of the software.

The CFD simulations are performed for the base case of the research for both wing models. From the CFD simulations, pressure and shear stress distributions around the cross sections located on quarter and mid span are obtained, along with total lift and drag forces acting on the wings. Additionally, for flow visualization, two-dimensional streamline and vorticity distribution contours taken at mid-span cross section and three-dimensional velocity distributions are shown on vorticity iso-surfaces.



5. RESULTS

5.1 Investigated Cases

In this thesis, investigated cases are determined in order to investigate the flow separation methods under different vortex gust encounter scenarios. During the experiments, a negative vortex gust is generated with the half rotation of the gust generator in the clockwise direction. While both of the wing models (flat plate and NACA0012) are stationary with zero angle of attack, the gust generator is subjected to three different half rotation periods ($T=3, 4$, and $6 \text{ s}/(\frac{1}{2}\text{rev})$) and two different cross-flow distances ($\Delta y = -36$ & -111 mm) with respect to the wing models. In Table 5.1, experimental investigated cases are given with the varying parameters. The half rotation period of the gust generator controls the rotational speed of the vortex gust and thereby effects the strength of the gust. Additionally, the cross-flow distance of the gust generator controls the trajectory of the generated vortex. The wing models, flat plate and NACA0012, are selected in order to observe leading-edge separation on distinct geometric configurations. While the flat plate has a rectangular shape with blunt leading-edge and sharp corners, NACA0012 has a water drop shape with rounded leading-edge. Each experimental case is repeated five times and the results are averaged to reduce the noise and increase the accuracy. On the other hand, the CFD simulations are only conducted for the base case ($T=4 \text{ s}/(\frac{1}{2}\text{rev})$ & $\Delta y = -36 \text{ mm}$) of the research for both wing models.

The flat plate for $\Delta y = -36 \text{ mm}$ and $T=4 \text{ s}/(\frac{1}{2}\text{rev})$ case is defined as the base case. This particular case has been extensively investigated in previous studies on vortex gust encounters. [18, 32-33]. What makes this case significant is that at the $\Delta y = -36 \text{ mm}$ location of the gust generator, a vortex gust is generated that the wing encounters head-on, while at the $\Delta y = -111 \text{ mm}$ location, the gust moves under the wing models. Furthermore, in previous studies by Tilki et al. [33], a comprehensive gust characterization is conducted, where parameters like velocity and gust ratio is determined. According to this, while there is a flat plate and the gust generator half rotation period is $T=4 \text{ s}/(\frac{1}{2}\text{rev})$, the generated vortex gust's velocity is obtained as

$V=52$ mm/s and the gust ratio, which is the gust velocity divided by free-stream velocity, is $GR=1.25$. In this study, these findings offer crucial background for comprehending the properties of the vortex gust encountered by the wing model.

Table 5.1 : Investigated cases and varying parameters.

Δy [mm]	T [s/($\frac{1}{2}$ rev)]	Flat Plate Case Name	NACA0012 Case Name
-36	3	2A1	2B1
	4	1A1	1B1
	6	3A1	3B1
-111	3	2A2	2B2
	4	1A2	1B2
	6	3A2	3B2

In this study, all the results are given with respect to convective time, t^* . Convective time, which is a non-dimensional parameter, is calculated with the following equation,

$$t^* = \frac{U_\infty t}{c} \quad (5.1)$$

where U_∞ is the free-stream velocity, t is the actual time, and c is the chord of the wing models. When the convective time is calculated, the time is also shifted to align the start of the rotation of the gust generator at $t^*=0$ for all cases.

Therefore, when all of the force results in this study starts at $t^*=0$, it indicates that the rotation of the gust generator begins at that moment. Moreover, the initial steady period before the rotation of the gust generator is not shown in the results, as it is considered unnecessary for the analysis in this study.

5.2 Sectional ΔC_L and ΔC_D Calculations

From the CFD simulations, mid-span and quarter-span sectional pressure and shear stress distributions are obtained, along with total lift and drag acting on the wing. For the comparisons of sectional and total forces between CFD and experimental data, sectional forces are calculated using the sectional pressure and shear stress distributions. The pressure and shear data points for flat plate and NACA0012 airfoil are given in Figure 2.1. The flat plate has four surfaces defined as the leading-edge, pressure side (lower surface), trailing-edge, and suction side (upper surface), whereas

NACA0012 has two surfaces, pressure side (lower surface) and suction side (upper surface).

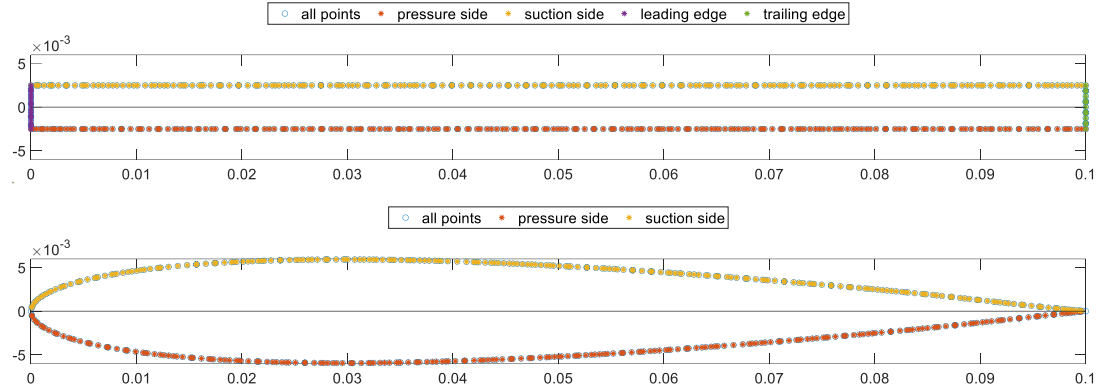


Figure 5.1 : Pressure and shear data points for flat plate and NACA0012.

In Figure 5.2, an illustration of the pressure and shear stress distributions around the flat plate and NACA0012 wing models is shown. The pressure distributions are perpendicular to the surface, while the shear stress distributions are tangential to the surface of the wing models.

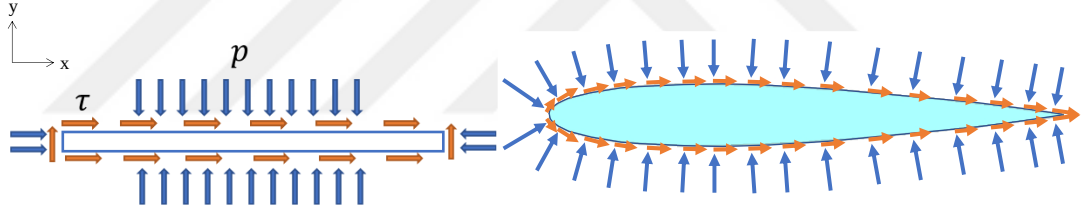


Figure 5.2 : Illustration of pressure and shear distributions around the flat plate and NACA0012.

In theory, the integration of pressure and shear stress distributions give the lift and drag forces. For these calculations, a MATLAB script is used, which includes the following equations,

$$\theta = \text{atan2}(dx, -dy) \quad (5.2)$$

$$L_{sec} = \sum_{n=1}^N (\tau_{sec} * \text{sign}(\tan\theta) * |\cos\theta| - P_{sec} * \sin\theta) \sqrt{dx^2 + dy^2} * s \quad (5.3)$$

$$D_{sec} = \sum_{n=1}^N (\tau_{sec} * |\sin\theta| - P_{sec} * \cos\theta) \sqrt{dx^2 + dy^2} * s \quad (5.4)$$

where N is total number of data points and s is span. These equations are used to calculate both mid and quarter-span sectional lift and drag. Then, non-dimensionalization is performed to sectional lift and drag results to obtain sectional lift and drag coefficients, which are given as,

$$C_{L,sec} = \frac{L_{sec}}{\frac{1}{2}\rho U_{\infty}^2 cs} \quad (5.5)$$

$$C_{D,sec} = \frac{D_{sec}}{\frac{1}{2}\rho U_{\infty}^2 cs} \quad (5.6)$$

Moreover, ΔC_L and ΔC_D are used to compare the lift and drag results of experimental and CFD easier and to focus on the magnitude and phase differences. The calculation of ΔC_L and ΔC_D involves averaging the results from the initial steady period, which occurs before the rotation of the gust generator, and subtracting this average from all of the results. This shifting of the results allows a more straightforward comparison and simplifies the identification of instances where the results align or overlap with each other. For that reason, ΔC_L and ΔC_D makes it easier to compare the differences and similarities in lift and drag between experimental and CFD data. Therefore, sectional and total results from both experimental and CFD lift and drag coefficients are shifted by,

$$\Delta C_L(t) = C_L(t) - \bar{C}_L \quad (5.7)$$

$$\Delta C_D(t) = C_D(t) - \bar{C}_D \quad (5.8)$$

where $\bar{C}_L$ and $\bar{C}_D$ are average of the initial steady period before the rotation of the gust generator plate. For both mid-span and quarter-span cross sections, sectional ΔC_L and ΔC_D results are calculated not only for the entire cross sections of the wing models, starting from leading-edge up to trailing-edge, but also up to various x/c locations, starting from leading-edge. This calculation is performed to distinguish and understand the specific effects of the pressure and shear stress on lift, drag, and later on suction forces. The selected eight integration points are shown in Figure 5.3 and these points are used for both flat plate and NACA0012. The first point, $x/c=0.00$, represents only the leading-edge of the wing models. From the second point to the seventh point ($x/c=0.01-0.75$), the results are integrated from the leading-edge up to those specific

points. Finally, the eighth point, $x/c=1.00$, includes all surfaces around the wing for that cross section.

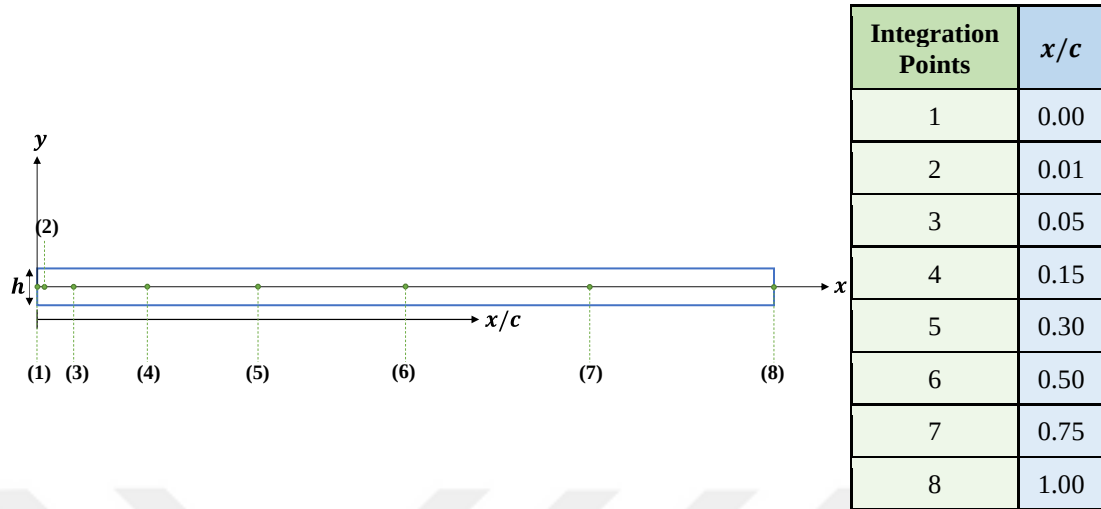


Figure 5.3 : Integration points and their location on the flat plate.

It is important to highlight that when comparing experimental data with CFD, the main objective is to validate the total forces acting on the wing can be used to calculate suction hence LESP. Even though leading-edge suction is theoretically a different force from drag, in this research, it is considered to be equal to negative direction of drag, due to the geometric angle of attack being zero. Therefore, this comparison focuses on lift and drag, and the results will clarify the accuracy of using total drag to obtain leading-edge suction force.

5.3 LESP Derivation

As stated in the Chapter 2: Literature Review, LESP is a non-dimensional parameter that is a function of leading-edge suction. In literature, suction force has been calculated from the pressure distribution around the wing model. However, in this study, the total force acting on the wing is used to calculate suction force. Therefore, before beginning the LESP analysis, the applicability and accuracy of the using the total force instead of pressure are validated with CFD results.

During the experiments, the geometric angle of attack is set to zero. Hence, the axial force is equal to the negative direction of the drag and normal force is equal to lift. Since the suction force is parallel to the camber line (or the chord line for a symmetrical wing), it is equal to the axial force. Suction force coefficient is calculated as,

$$C_s = \frac{F_s}{\frac{1}{2}\rho U_\infty^2 cs} \quad (5.9)$$

where, F_s is the suction force which is total axial force measured on the wing in this study, ρ is density, U_∞ is free-stream velocity, c is chord of the wing, and s is span of the wing.

LESP equation is already derived in the Chapter 2 as equation 2.11. and it is adapted from the knowledge gathered from the literature. In this study, the axial force, hence suction, can become negative, when the wing encounters a negative vortex. Therefore, LESP equation is adjusted to do the calculations without getting errors and matching the sign of the LESP with suction. The adapted version of instantaneous LESP is given as,

$$LESP(t) = sign(C_s(t)) \sqrt{\frac{sign(C_s(t)) * C_s(t)}{2\pi}} \quad (5.10)$$

where sign function is used to multiply the values with the sign of the suction coefficient. It is important to mention that, when calculating force coefficients such as lift and drag coefficients, the raw force data is initially filtered. On the other hand, for the LESP calculations, the process differs. First, the suction coefficient is calculated from raw axial force data, and then LESP is calculated from the unfiltered suction coefficient. After that, the unfiltered LESP results are filtered by a low pass filter with 1.25 Hz cut off frequency. Overall, the instantaneous LESP is calculated from the raw data using equation 5.10, and then it is filtered to obtain final LESP results.

The key aspect of the LESP analysis is the critical LESP value. As explained in the Chapter 2, this value is the indicator for the initiation of the flow separation at the leading-edge. Basically, when the instantaneous LESP reaches the critical LESP value, the flow starts to separate. The critical LESP is dependent on the Reynolds number and wing geometry, however, it is independent to motion [Ramesh 2014]. Once the critical LESP is determined for a specific airfoil and Reynolds number, it can be used in various studies. The critical LESP values for the flat plate and NACA0012 airfoil at a flow condition with a 10,000 Reynolds number are obtained from CFD studies

conducted by Ramesh. For the flat plate, the critical LESP is determined to be $LESP_{crit,FP} = 0.05$ [4], while for the NACA0012 airfoil, the critical LESP is determined to be $LESP_{crit,NACA} = 0.18$ [8].

It is important to highlight that, actually there is no reason to calculate LESP beyond the critical LESP value, as the flow is already separated beyond the critical LESP. This is detailly explained in Chapter 2. Essentially, once the separation of the flow at the leading-edge occurs, the suction force is no longer align with the axial force, as the suction force becomes perpendicular to the chord to sustain the balance of the forces acting on the wing under the influence of the leading-edge vortex. However, in this research, the instantenous LESP is calculated for all the instances during the experiment and the results are plotted accordingly. The results over the critical value will not be discussed, as they are unnecessary and the main focus of this study is the moment when the LESP reaches to critical value.

5.4 Effective Angle of Attack Calculations

Effective angle of attack is another parameter that can detect flow separation initiation, since effective angle of attack is directly proportional to local sectional lift coefficient. Moreover, as the effective angle of attack increases, lift coefficient also increases, while the separation point at the trailing-edge begins to progress towards the leading-edge. Then, when the effective angle of attack surpasses the static stall angle rapidly enough, the flow starts to separate at the leading-edge. Therefore, by tracking the effective angle of attack, it can be used an indicator for the initiation of flow separation.

Effective angle of attack is defined as the angle between the chord line of the local airfoil section and the local relative flow [13]. Therefore, the velocity vector field obtained from DPIV data is used. The velocity vectors inside the red square area, displayed in Figure 5.4, are used for the calculations. This red area has the dimensions of 5 mm width and 5 mm height. The dimensions of this area (width and height) are determined corresponding to high $C_L - \alpha$ correlation, which is 91.9%. The vertical distance between the center of the calculation area and the mid-point of the leading-edge is 2.54 mm, whereas the horizontal distance is 20 mm. Also, there are 36 vectors inside the calculation area. For the calculations the equation is given below,

$$\alpha_{eff} = \tan^{-1} \left(\frac{v}{u} \right) \quad (5.11)$$

where, u and v are the vertical and horizontal velocity components, respectively. Effective angle of attacks are calculated from 36 vectors inside the calculation area. Then to determine one single angle for that case, median is used.

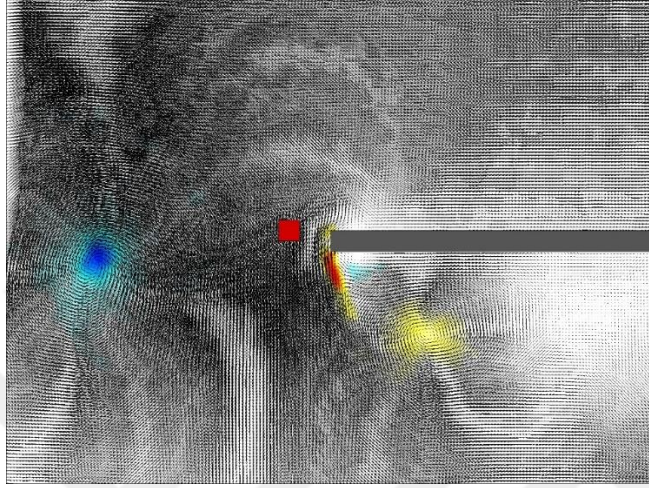


Figure 5.4 : Effective angle of attack calculation area.

5.5 Results

5.5.1 Case 1A1: Flat Plate $\Delta y = -36$ mm, $T = 4$ [s/($\frac{1}{2}$ rev)]

Prior to the analysis of flow separation prediction methods, a preliminary investigation is undertaken to confirm the applicability and accuracy of the measurements of total force acting on a wing for LESP calculations, instead of using sectional force that is calculated from pressure distributions around the cross section of the airfoil as it is in the literature. Therefore, a comparative study is conducted to validate the total force measurements obtained from the experimental method, which also includes total forces acting on a wing obtained from CFD simulations and the sectional forces that are calculated using sectional pressure distributions obtained from CFD. In other words, this comparative study not only provides verification of the total force measurements using different data sources, but also proves the reliability of using this method as an alternative.

The results of Case 1A1 considers a flat plate wing model with $\Delta y = -36$ mm and $T = 4$ [s/($\frac{1}{2}$ rev)] parameters. This case is defined as the base case and only base cases are used for experimental and CFD comparisons.

In Figure 5.5, mid-span and quarter-span sectional ΔC_D results from CFD, calculated by integration up to various x/c locations, along with CFD total ΔC_D for the flat plate are given. For both mid and quarter-span plots, all the sectional ΔC_D results from $x/c=0.00$ to the integration point at $x/c=0.75$ are quite similar, with an extremely slight convergence towards the total ΔC_D as the integration point moves closer the trailing-edge. However, the sectional ΔC_D results for $x/c=1.00$ location is highly converged with the total ΔC_D and displays a close match, especially the small peak at $t^*=0.5$ and maximum positive peak at $t^*=3.3$. The convergence rate of the sectional ΔC_D results is related the dominance between the effect of pressure and shear stress distributions. For $x/c=0.00$, only the pressure at the leading-edge has an effect to ΔC_D . As the integration points move towards the trailing-edge, the inclusion of shear stress distributions from the upper and lower surface of the flat plate in the ΔC_D calculation reveals that shear stress has a relatively smaller effect compared to pressure. This is apparent from the extremely slight converge of the results. However, for $x/c=1.00$, the results converge with the total ΔC_D because the pressure distribution at the trailing-edge is included to the integration and this proves the dominance of pressure over shear stress in calculating sectional ΔC_D . Also, between the mid and quarter span sectional results, quarter span sectional ΔC_D is more similar to total ΔC_D . Although a slight phase difference is observed between the quarter-span sectional ΔC_D and the total ΔC_D at the maximum positive peak, the mid-span sectional ΔC_D does not settle between $t^*=6-7.8$, as observed in both the quarter-span sectional ΔC_D and total ΔC_D results. This topic will be discussed later on in more detail by studying three-dimensionality of the flow.

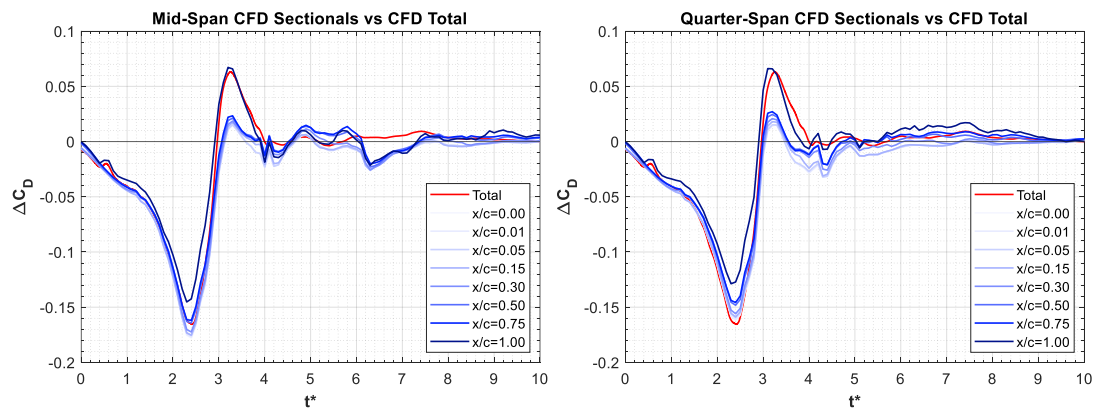


Figure 5.5 : Comparisons of CFD mid-span and quarter-span various sectional and CFD total ΔC_D results for flat plate.

After observing the similarity between CFD sectional for $x/c=1.00$ integration point and CFD total ΔC_D results, a comparison is made between several CFD sectional and CFD total ΔC_D results with the experimental ΔC_D . In Figure 5.6, mid-span and quarter-span sectional ΔC_D results from CFD, for $x/c=0.30$, 0.50, and 1.00 integration points, along with CFD total and experimental ΔC_D for the flat plate are given. Three specific integration points are selected for this comparison. Firstly, $x/c=0.30$ is selected since it is used in previous research in literature [7], where it corresponds to the maximum thickness location of the NACA0012 airfoil. They had observed that the calculations beyond this location is not necessary as the results already converge for suction. However, considering a flat plate is used in this part of the research, including $x/c=0.30$ is important to provide a later comparison with results obtained from a NACA0012 airfoil, so that their differences will be highlighted. Secondly, as there is no maximum thickness to consider for the flat plate, mid-chord location, $x/c=0.50$, is also chosen for the comparison. Finally, $x/c=1.00$ is selected because it shows the best convergence between the sectional and the total ΔC_D results for the flat plate. In Figure 5.6, despite the presence of a phase difference, it can be observed that experimental ΔC_D result is highly similar to the CFD quarter-span sectional ΔC_D for $x/c=1.00$, as well as CFD total ΔC_D . The observed differences between the experimental and CFD results can be associate with the sensor uncertainty, as the results are in between the uncertainty range. Furthermore, the occurrence of a negative peak at $t^*=5.3$ in the experimental result can indicate the influence of three-dimensionality effects of the flow.

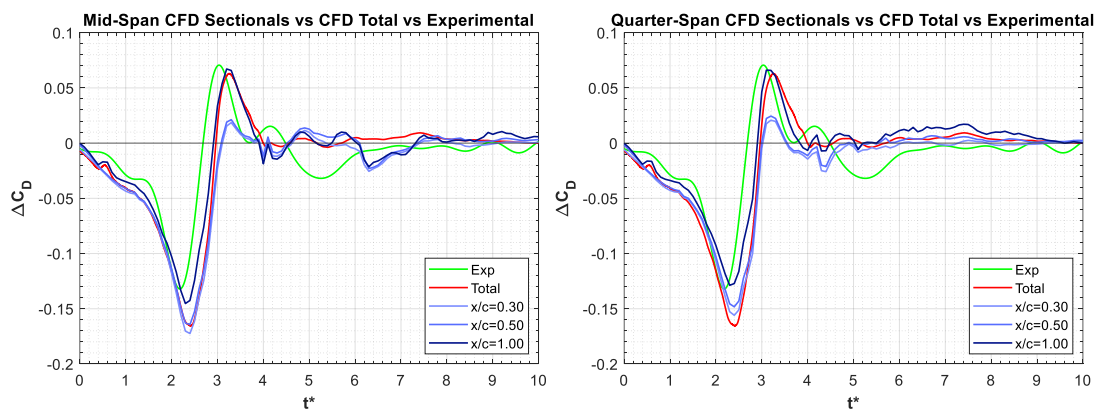


Figure 5.6 : Comparisons of CFD mid-span and quarter-span sectional with CFD total and experimental ΔC_D results for flat plate.

In this part of the research, it was essential to validate the total drag acting on the wing since it is equal to the negative axial force acting on the wing due to the flat plate's constant zero geometric angle of attack. That is to say, validating the drag results

provides insight into the accuracy of the LESP calculation method used in this research, as the axial force is used directly to calculate LESP. Despite the highly satisfying coherence observed between the sectional drag from CFD and total drag acting on the wing from both experimental and CFD, which was sufficient for validating the LESP calculation method, lift results are also evaluated to demonstrate the consistency of the integration calculations and provide understanding into the behavior of the flow.

In Figure 5.7, mid-span and quarter-span sectional ΔC_L results from CFD, calculated by integration up to various x/c locations, along with CFD total ΔC_L for the flat plate are given. Unlike ΔC_D results, for both mid and quarter-span plots, all of the sectional ΔC_L results are profoundly different from each other, for each integration point. Moreover, as the integration point moves from $x/c=0.00$ to $x/c=1.00$, an evolution is observed among the sectional ΔC_L results as they ultimately converge towards the total ΔC_L result. Similar to ΔC_D results, the sectional ΔC_L results for $x/c=1.00$ integration point demonstrates the highest similarity to the total ΔC_L result. Additionally, compared to ΔC_D results, it is evident that the sectional ΔC_L results for $x/c=1.00$ integration point display more similarity to the total. This can be observed from the alignment of the initial positive, maximum negative, and maximum positive peaks. The evolution of the sectional ΔC_L results is also related the dominance between the effect of pressure and shear stress distributions. For $x/c=0.00$, only the shear stress at the leading-edge has an effect to ΔC_L . As the integration points move towards the trailing-edge, the inclusion of pressure distributions from the upper and lower surface of the flat plate in the ΔC_L calculation reveals that shear stress has a relatively smaller effect compared to pressure. This is apparent from the significant lack of convergence in the sectional ΔC_L for $x/c=0.00$ and the subsequent increase in the convergence as the upper and lower surfaces are included to the integration. Furthermore, for $x/c=0.75$, the results nearly converge with the total because the shear stress distribution at the trailing-edge has a minimal effect compared to the pressure distribution over the upper and lower surfaces. This indicates that the dominant factor in calculating sectional ΔC_L is pressure rather than the shear stress. According to this, it can be concluded that the dominant factor in calculating both sectional ΔC_L and ΔC_D is pressure but there is a difference in the specific regions considered. For the calculation of ΔC_L , the pressure distribution over the upper and lower surfaces of the flat plate are used, whereas for

ΔC_D leading and trailing-edges are used. Additionally, between the mid and quarter span sectional results, quarter span sectional ΔC_L is more similar to total ΔC_L . Even though a slight phase and magnitude differences are observed between the quarter-span sectional ΔC_L and the total ΔC_L at the maximum positive peak, the mid-span sectional ΔC_L does not show a tendency to settle between $t^*=4.2-7.4$, as observed in both the quarter-span sectional ΔC_L and total ΔC_L results. Further elaboration on this topic will be discussed later on by studying three-dimensionality of the flow.

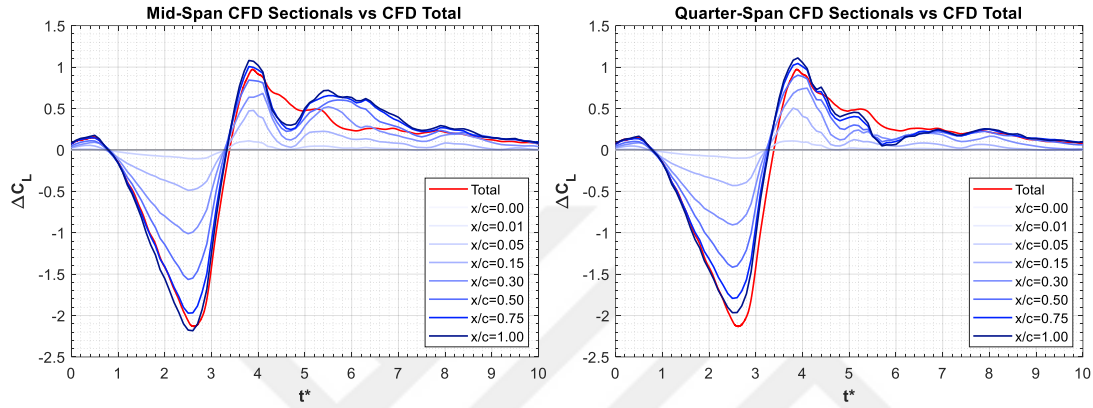


Figure 5.7 : Comparisons of CFD mid-span and quarter-span various sectional and CFD total ΔC_L results for flat plate.

Following the observation of the similarity between CFD sectional for $x/c=1.00$ integration point and CFD total ΔC_L results, a comparison of several CFD sectional and CFD total ΔC_L results with the experimental ΔC_L is conducted. In Figure 5.8, mid-span and quarter-span sectional ΔC_L results from CFD, for $x/c=0.30$, 0.50 , and 1.00 integration points, along with CFD total and experimental ΔC_L for the flat plate are given. The three integration points for the sectional ΔC_L is same with the prior ΔC_D comparison for the same reasons that had been explained. Regardless of the presence of a phase difference, a similarity is observed between the experimental ΔC_L result and the CFD quarter-span sectional ΔC_L for $x/c=1.00$, as well as CFD total ΔC_L . Given the sensor uncertainty, most of the differences between the experimental and CFD results can be attributed to sensor uncertainty. The biggest difference is that the CFD results show a single maximum positive peak, whereas the experimental results show two consecutive positive peaks with similar magnitudes between $t^*=4-6$. This occurrence can be attributed to the three-dimensionality effects of the flow, which is assessed later on with flow image results.

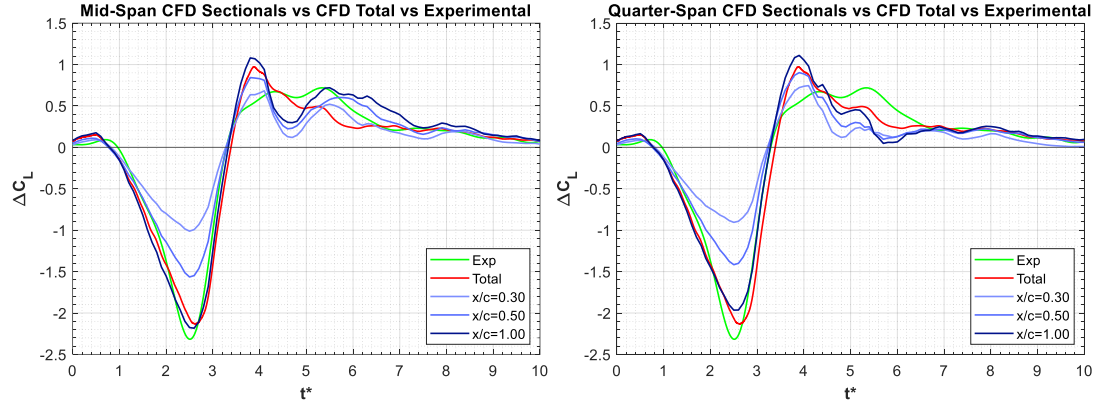


Figure 5.8 : Comparisons of CFD mid-span and quarter-span sectional with CFD total and experimental ΔC_L results for flat plate.

In the previous ΔC_L and ΔC_D comparisons, some discrepancies were found between the mid-span and quarter-span CFD sectional results, and it was mentioned that this could be a result of the three-dimensionality effects of the flow. Therefore, 3-D flow images from CFD are examined. In Figure 5.9, velocity colored snapshots of Q criterion isosurfaces from CFD for flat plate are given with comparisons of ΔC_L and ΔC_D results from CFD mid-span sectional, CFD quarter-span sectional, and CFD total. The instants of the 3-D images are marked on the ΔC_L and ΔC_D plots. At $t^*=1.0$, in the ΔC_L graph, both sectional and total results are overlapping, while in the ΔC_D graph, the total result differs from both sectionals, and the sectional results start to diverge after that instant. This similarity is observed in the 3-D image at $t^*=1.0$, where the vortical structures over the leading-edge, surface, trailing-edge, and in the wake of the flat plate are symmetrical along the span. The small difference at the ΔC_D can be connected to the variations in the left and right tip vortices, which cannot be observed in mid-span and quarter-span results. As the time passes, the sectional and total results start to diverge for both ΔC_L and ΔC_D . Then, at $t^*=2.6$, maximum negative peak of ΔC_L is reached. At this instant, mid-span and quarter-span sectional ΔC_L results have a significant magnitude difference however, for ΔC_D , both sectional results have already passed the maximum negative peak and they converge again during the increase. In the corresponding 3-D image, a leading-edge vortex is not observed over the upper surface of the flat plate, as a large leading-edge vortex is formed over the lower surface. Since the vortical structures over the trailing-edge are symmetrical for mid-span and quarter-span sectionals, the observed differences can be a result of the slight asymmetry in the wake and the large leading-edge vortex, which is not visible from the current perspective. Later, at $t^*=3.2$, ΔC_D results reach the maximum peak

with a small phase difference, and up to that point, both ΔC_L and ΔC_D sectional results progress while overlapping. The symmetry of the vortical structures is observed over the surface of the flat plate, which justifies the similarity between the sectional results, even though a slight asymmetric behavior is observed in the wake region as it moves away from the flat plate. Next, in the 3-D image at $t^*=4.2$, the flow over the surfaces of the flat plate starts to mixed up as various small vortical structures detach. Also, leading-edge vortex starts to lose its symmetrical behavior along the span, as there is an opening formed over the leading of the mid-span section. However, even as the wake vortices move away, they remain attached to the tips. These observations are reflected in the ΔC_L and ΔC_D plots, as the sectional results begin to diverge after this instant, especially in the ΔC_L sectional results. After this moment, ΔC_L and ΔC_D sectional and total results no longer display similarity and do not converge until settlement. This is observed in the $t^*=5.2$ and $t^*=6.4$ instants, where the vorticity structures become even more complex and asymmetric behavior dominates all over the flat plate and the wake region. One reason for these differences is noticeable at $t^*=6.4$ instant, where significantly higher number of vortical structures are detected on the leading-edge of the mid-span sectional compared to the quarter-span. Overall, up to $t^*=4.2$, the three-dimensionality of the flow has minimal effect and can be considered negligible. But, after that moment, the vortical structures get more complex and start to mix up, which indicates a noteworthy influence of the three-dimensionality of the flow.

The 3-D images provided explanations for the differences between the mid-span sectional, quarter span sectional, and total CFD of ΔC_L and ΔC_D results, mainly after $t^*=4.2$, as the results diverge the most and the vortical structures become complex and asymmetric. Additionally, to understand the differences between the experimental and CFD total ΔC_L and ΔC_D results, 2-D vorticity and streamline images from DPIV and CFD are studied. In Figure 5.10, DPIV and CFD vorticity and streamline comparisons with C_f distributions over the flat plate are given. C_f distributions are obtained from the CFD simulations, where the red line represents the upper surface friction distribution, and the blue line represents lower surface friction distribution. Even though the distributions are from CFD data, the plots are placed on the DPIV images to compare the results easier. These six images are critical instances, where the total C_L and ΔC_D results from experimental and CFD diverge the most.

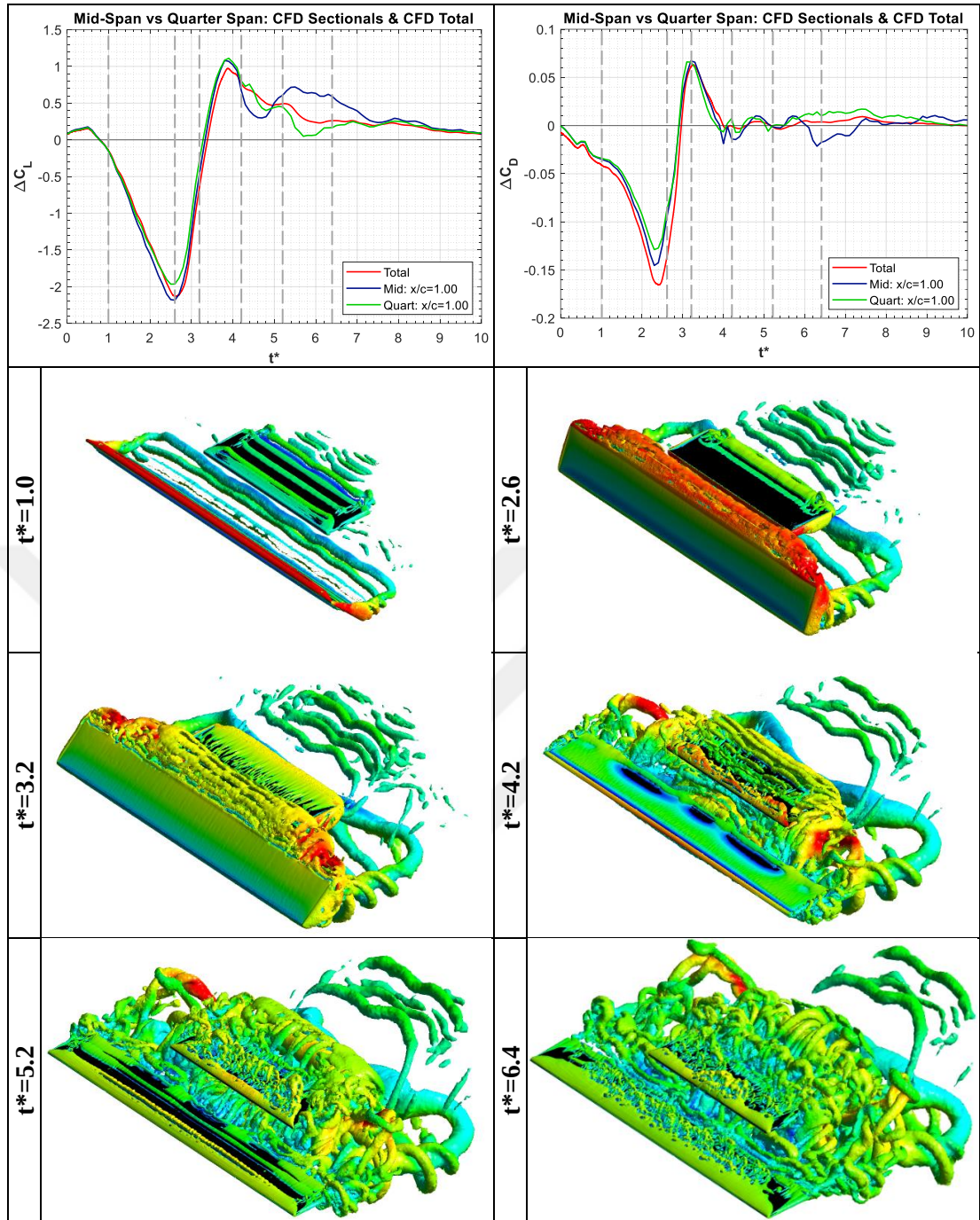


Figure 5.9 : Comparison of ΔC_L and ΔC_D from CFD mid-span sectional, CFD quarter-span sectional, and CFD total, with velocity colored snapshots of Q criterion isosurfaces from CFD for flat plate.

When a vortex forms over the surface of the flat plate, whether on the upper or lower surface, a peak in the corresponding C_f plot can be observed. At $t^*=0.8$, the experimental ΔC_L result reaches its initial positive peak, while the CFD total result has already passed the peak and is decreasing (Figure 5.8). This is observed in the corresponding images, where the leading-edge vortex over the upper surface appears larger than the one over the lower surface in DPIV images. But, in the CFD images, two consecutive

vortices are observed. These vortices are also detected in the C_f plots, with a single peak on the upper surface and two peaks on the lower surface. Next, at $t^*=2.2$, maximum negative peak is observed in the experimental ΔC_D result, while the CFD total result is still approaching it (Figure 5.6). Then, at $t^*=2.4$, both the CFD total ΔC_D result (Figure 5.6) and the experimental ΔC_L result (Figure 5.8) reach their negative peaks. In both of the instances, the DPIV and CFD images show a high degree of similarity, and the experimental vortices align with the C_f plots, where peaks correspond to the vortex locations. The slight phase and magnitude difference of the vortices can be linked to the differences in the force plots. After that, at $t^*=3.0$, the experimental ΔC_D result reaches its maximum positive peak, while CFD total result is still approaching it (Figure 5.6). The slight phase difference is detected also in the images, where the large negative vortex in the experimental image is located closer to the flat plate. However, apart from this difference, the vortices and streamlines are highly similar, which is also observed from the C_f plots as the peaks align with the locations of the vortices. At $t^*=3.8$, significant differences between the experimental and CFD for both total ΔC_L and ΔC_D results are observed (Figure 5.6 and Figure 5.8). In the 2-D images, although the leading-edge vortex on the upper surface of the flat plate appears highly similar in both experimental and DPIV images, supported by the C_f plots, there is a considerable difference in the vorticity and streamlines below the flat plate. In the DPIV image, the large negative vortex is nearly out of the picture, whereas in the CFD image, it is closer to the flat plate. Furthermore, the streamlines below the flat plate in the experimental image are highly fluctuating. Finally, at $t^*=5.2$, there is a positive peak in the experimental ΔC_L result and a negative peak in the experimental ΔC_D result, while the CFD total results are still progressing to settle in both plots (Figure 5.6 and Figure 5.8). In the corresponding images, the differences between the vortices and streamlines are clearly observed. Even though the flow in the experimental images seems to be settling, it is proven in the 3-D CFD images that the 3-D effect of the flow is apparent, especially after approximately $t^*=4.2$, and these effects have an influence on the results.

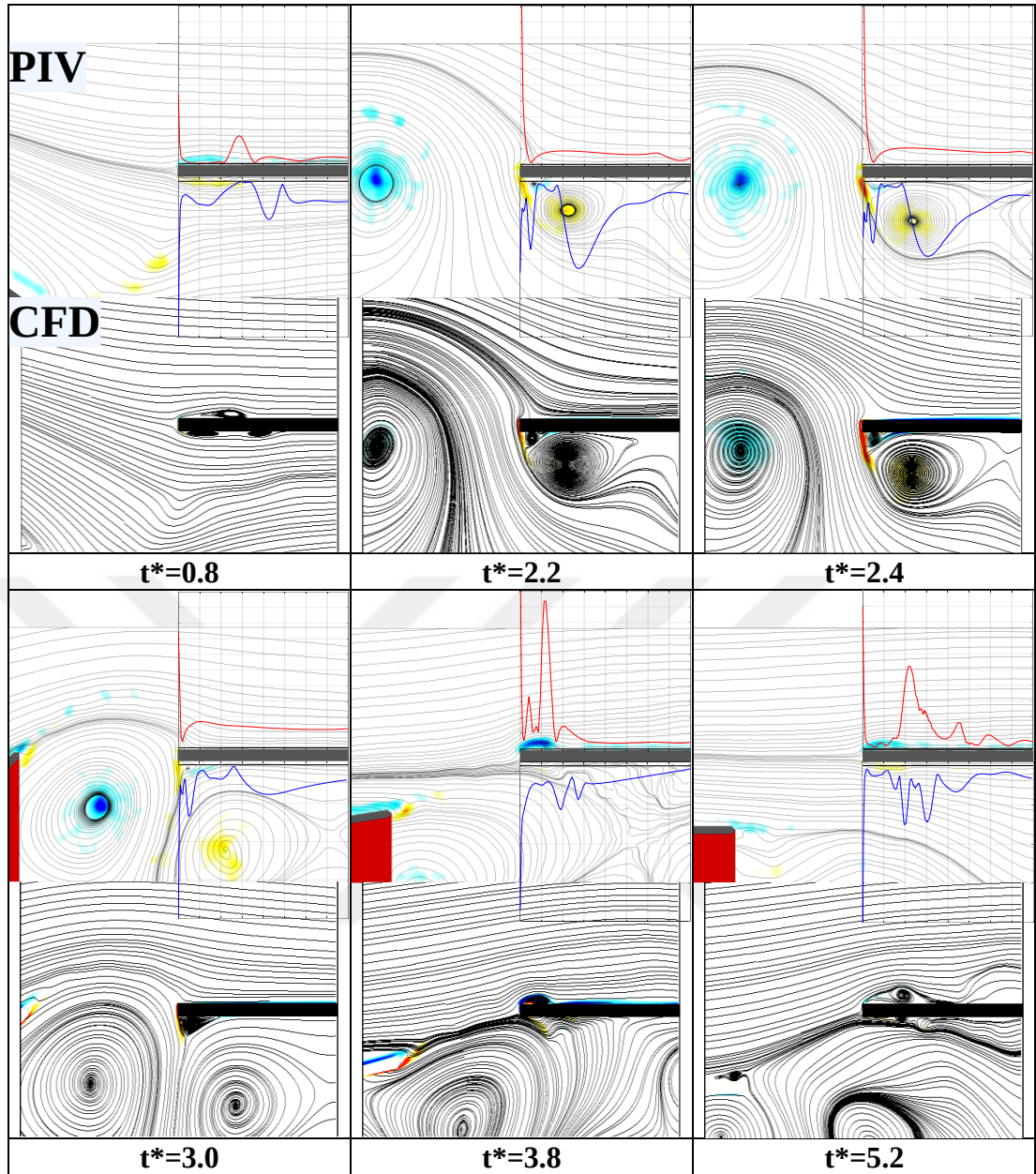


Figure 5.10 : DPIV and CFD vorticity and streamline comparisons with C_f distributions over the flat plate.

From the experimental and CFD comparisons, sufficient similarity is observed between the direct measurements of the total forces acting on the wing and sectional forces calculated from integration of pressure and shear stress distribution. Therefore, for flat plate cases, it is decided that direct force measurements can be used to calculate suction force, hence LESP, and with that the investigation of the ideal flow separation initiation indicator is conducted. Lift coefficient, drag coefficient, LESP, and effective angle of attack results are compared to determine which parameter is more accurate and can detect the separation initiation earliest.

In Figure 5.11, comparisons of C_L , C_D , LESP, and α_{eff} results are given for Case 1A1. In the plot, horizontal dashed blue lines are the critical LESP values for the flat plate. Additionally, yellow and red bands are where instantaneous LESP is at or over the critical LESP value. If LESP is positive, band is colored as yellow and if LESP is negative, band is red. This plot is not enough to evaluate the results and decide which parameter is suitable to indicate flow separation initiation by itself. Therefore, in Figure 5.12, DPIV images of selected instants, such as borders of the bands and critical peaks, are given.

At $t^*=1.2$, LESP reaches the critical LESP, which is shown as the left border of the yellow band. In the corresponding DPIV image, formation of the leading-edge vortex on the lower surface of the flat plate is observed. Even though the size of the leading-edge is relatively small and it is still attached to the surface, this indicates the initiation of the flow separation.

At $t^*=2.2$, while C_D reaches maximum negative peak, LESP reaches maximum positive peak. When LESP indicates flow separation initiation at this instant, effective angle of attack is $\alpha_{eff} \approx -25^\circ$. In the corresponding DPIV image, the stagnation point is located at the upper surface of the flat plate and the leading-edge vortex is shed so, the flow separation is observed.

At $t^*=2.6$, LESP returns back to critical LESP as it decreasing, which is shown as the right border of the yellow band. Additionally, at this instant, C_L and α_{eff} results reach maximum negative peaks. In the corresponding DPIV image, the streamlines in front of the leading-edge are nearly parallel to the leading-edge, which explains effective angle of attack reaching $\alpha_{eff} \approx -90^\circ$.

As the time progress, the flow tries to recover, however shortly after at $t^*=2.8$, LESP reaches to critical LESP in the negative direction. In the DPIV image, the separated leading-edge vortex is enlarged and lean on the large negative vortex. The stagnation point is on the move towards the leading-edge as the effective angle of attack increases.

At $t^*=3$, DPIV image is similar to the previous instant, as C_D reaches maximum positive peak and LESP reaches maximum negative peak, whereas C_L and α_{eff} are still increasing.

Next at $t^*=3.2$, the stagnation point returns back to leading-edge in the DPIV image, while LESP reaches critical LESP during increasing. At this instant effective angle of attack is $\alpha_{eff} \approx -12.5^\circ$. There is a similarity is observed between $t^*=1.2$ and $t^*=3.2$ instants because of the formation of a small leading-edge on the lower surface and the stagnation point locating at the leading-edge.

Finally, at $t^*=5.2$, small positive and negative peaks are observed from LESP and C_D , respectively. Even though LESP does not reach the critical value, it is still close enough to evaluate. Additionally, positive peak is observed from C_L and effective angle of attack is $\alpha_{eff} \approx 5^\circ$. In the corresponding DPIV image, the vorticity level on the upper side of the flat plate near the leading-edge is seemed to be intense than the lower size as the streamlines are more curved, but no leading-edge vortex formation is observed. Therefore, LESP being close to the critical value does not indicates initiation of flow separation, it has to reach to that exact value.

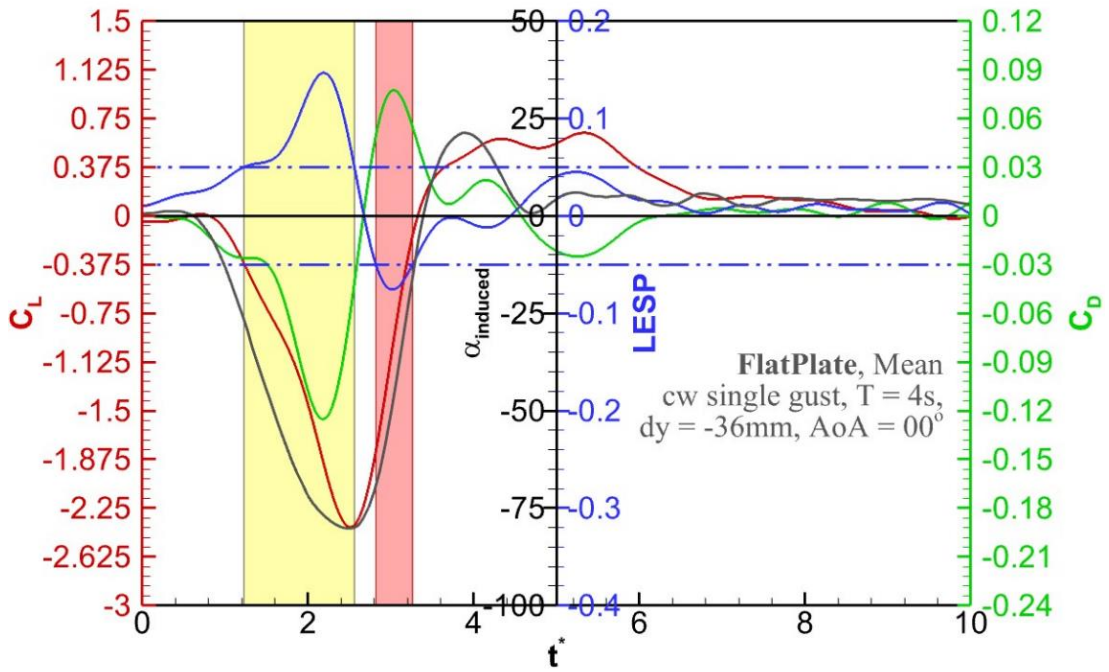


Figure 5.11 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 1A1.

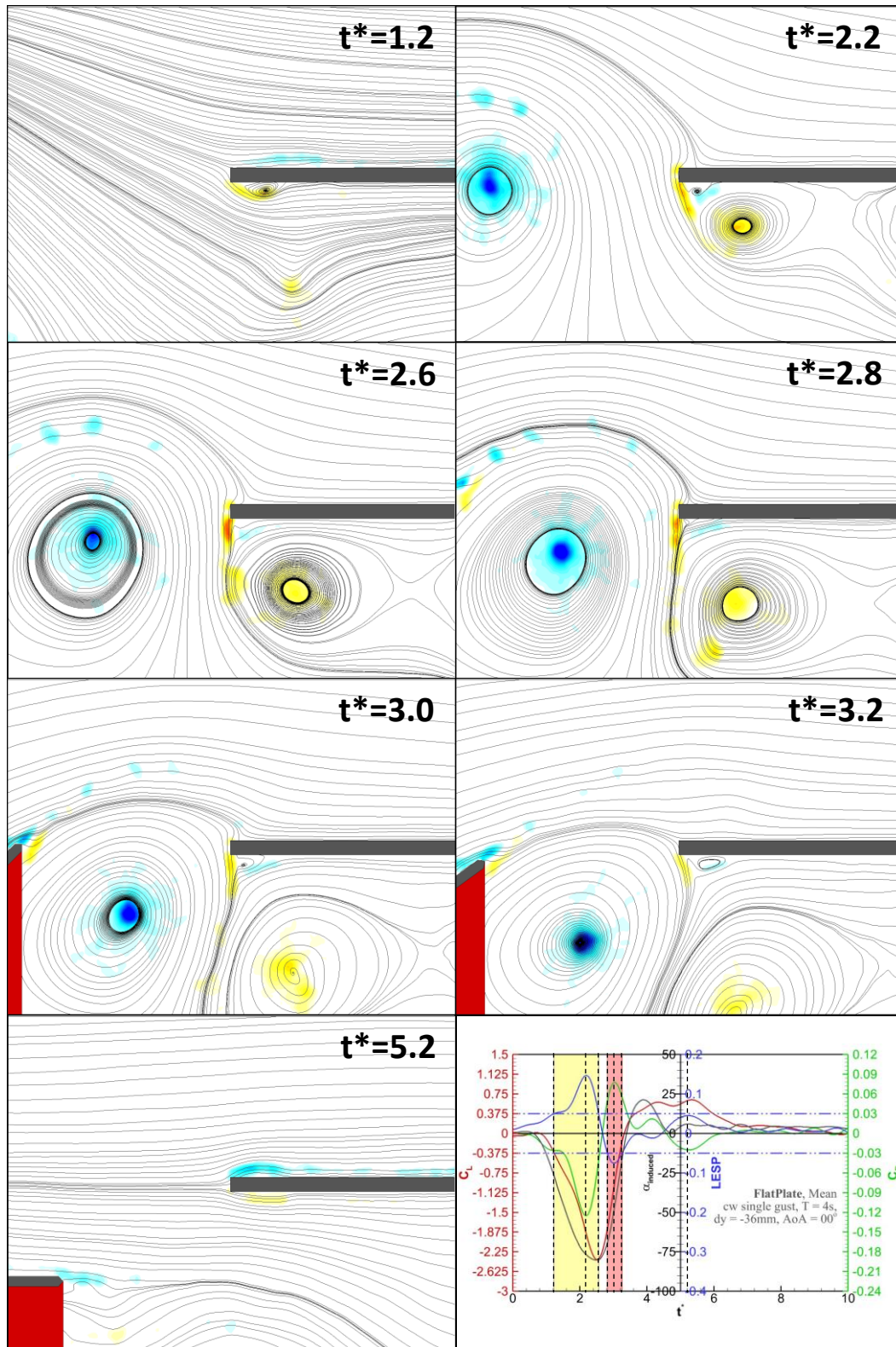


Figure 5.12 : DPIV images of selected instants for Case 1A1.

5.5.2 Case 1B1: NACA0012 $\Delta y = -36$ mm, $T = 4$ [s/($\frac{1}{2}$ rev)]

As it was explained and given in the results of Case 1A1 from flat plate, an initial investigation is also done for NACA0012 to confirm the applicability and accuracy of the measurements of total force acting on a wing for LESP calculations, instead of using sectional force. Consequently, for NACA0012 airfoil, a comparative study is conducted before focusing on flow separation initiation prediction methods.

The results of Case 1B1 considers a NACA0012 wing model with $\Delta y = -36$ mm and $T = 4$ [s/($\frac{1}{2}$ rev)] parameters, which is defined as the base case.

In Figure 5.13, mid-span and quarter-span sectional ΔC_D results from CFD, calculated by integration up to various x/c locations, along with CFD total ΔC_D for NACA0012 are given. For both mid and quarter-span plots of NACA0012, behavior of the sectional ΔC_D results is different than flat plate. The sectional ΔC_D results of NACA0012 converge towards the total ΔC_D at a higher rate, as the integration point moves from leading-edge to trailing-edge. However, there is a divergence between the sectional ΔC_D results for $x/c=1.00$ location and the total ΔC_D . Even though the converge rate is high for the initial integration locations, it slows down after the $x/c=0.30$ integration point, as the sectional results at and after that point are already similar to the total. In the literature, Narsipur et al. [7] used $x/c=0.30$ location to calculate suction from sectional force derived from pressure distributions of NACA0012. Based on this information, in this study, it is suggested that total force can be used instead of sectional force for suction calculations, considering the sufficient similarity between the sectional C_D results for $x/c=0.30$ and the total ΔC_D result. The difference in results between the flat plate and the NACA0012 comes from their distinct shapes. The flat plate, with its blunt edges and flat upper and lower surfaces, provides a clearer observation of the dominance of pressure over shear stress during the integration process. In contrast, the NACA0012 airfoil's water drop shape divides pressure and shear stress into components, causing both pressure and shear stress effecting both lift and drag at each integration point. Also, between mid and quarter span sectional results, it is observed that quarter-span sectional ΔC_D is more similar to total ΔC_D , as it was observed with the flat plate. After $t^*=5$, the mid-span sectional results do not settle and diverge from the total. But, quarter-span sectional results closely follow the total and shows similar magnitudes for the maximum

negative and positive peaks. This topic will be discussed later on in more detail by studying three-dimensionality of the flow.

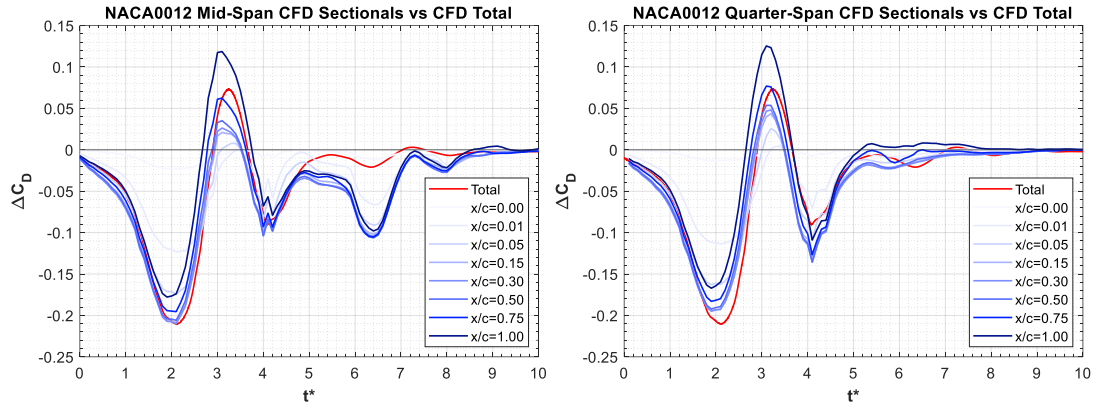


Figure 5.13 : Comparisons of CFD mid-span and quarter-span various sectional and CFD total ΔC_D results for NACA0012.

Next, a comparison between experimental and CFD results are done. In Figure 5.14, mid-span and quarter-span sectional ΔC_D results from CFD, for $x/c=0.30$, 0.50 , and 1.00 integration points, along with CFD total and experimental ΔC_D for the NACA0012 are given. Even with a small phase difference, sectional ΔC_D results from CFD for $x/c=0.30$ and 0.50 and CFD total ΔC_D are highly similar to the experimental ΔC_D . This similarity is observed especially in the maximum negative peak at $t^*=2$. The small differences in magnitude and phase can be linked to the sensor uncertainty of the experimental data. Quarter-span sectional results are defined as more reliable in the previous comparison due to their similarity to the total, and the comparison with experimental data also supports this. However, the most significant difference observed between experimental results and both mid and quarter-span sectionals, as well as the total results, is the negative peak occurrence in the CFD data between $t^*=3.8-5$. While the experimental ΔC_D settles after the maximum positive peak, none of the CFD results settle, and in fact, a secondary negative peak occurs. This is can be related to the path of the negative vortex that is generated. It is possible that during the experiments, the negative vortex moves away from the wing at a faster rate compared to the CFD analysis, so that the wing has less interaction with the vortex and the effects diminishes.

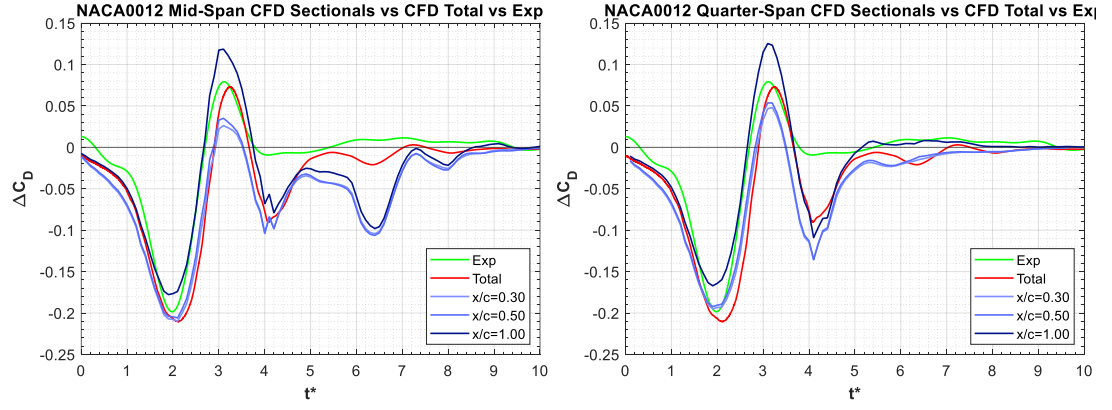


Figure 5.14 : Comparison of CFD mid-span and quarter-span sectional with CFD total and experimental ΔC_D results for NACA0012.

The similarity observed between the sectional and total ΔC_D results from CFD and experimental data satisfies the applicability of the suction calculation method, but before starting the flow separation prediction indicator investigation, the lift results are also compared. In Figure 5.15, mid-span and quarter-span sectional ΔC_L results from CFD, calculated by integration up to various x/c locations, along with CFD total ΔC_L for the NACA0012 are given. For both mid and quarter-span plots, all of the sectional ΔC_L results show similar convergence behavior towards to the total ΔC_L when compared to the flat plate results. As the integration point moves from $x/c=0.00$ to $x/c=1.00$, an evolution is observed among the sectional ΔC_L results as they ultimately converge towards the total ΔC_L result. Additionally, compared to ΔC_D results, it is evident that the sectional ΔC_L results for $x/c=1.00$ integration point display more similarity to the total, whereas $x/c=0.30$ was enough for ΔC_D results. However, drag is directly related to the calculation of the suction so it is not expected for lift to converge for $x/c=0.30$. Furthermore, between the mid and quarter span sectional results, quarter span sectional ΔC_L is more similar to total ΔC_L . This is concluded based on the biggest difference occurring after $t^*=4.4$. During this period, quarter-span sectional results are attempting to settle, whereas mid-span results are still significantly decreasing and increasing. The reason of this behavior is explained later on, with three-dimensionality of the flow.

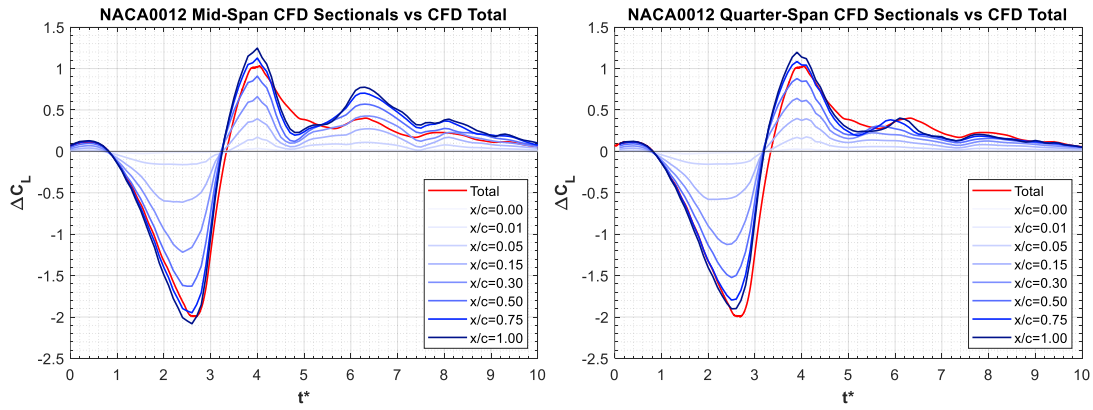


Figure 5.15 : Comparisons of CFD mid-span and quarter-span various sectional and CFD total ΔC_L results for NACA0012.

Next, some of the sectional ΔC_L results and total ΔC_L result from CFD is compared with experimental data. In Figure 5.16, mid-span and quarter-span sectional ΔC_L results from CFD, for $x/c=0.30, 0.50$, and 1.00 integration points, along with CFD total and experimental ΔC_L for the NACA0012 are given. Regardless of the presence of a phase difference, a similarity is observed between the experimental ΔC_L result and the CFD mid and quarter-span sectional ΔC_L for $x/c=1.00$, as well as CFD total ΔC_L . Given the sensor uncertainty, most of the differences between the experimental and CFD results can be associated with the sensor uncertainty. Quarter-span sectional for $x/c=1.00$ and total results are highly similar to the experimental result and the large difference observed in ΔC_D between $t^*=3.8-5$ is not observed in ΔC_L . After the maximum positive peak both CFD and experimental results are on the way to settlement.

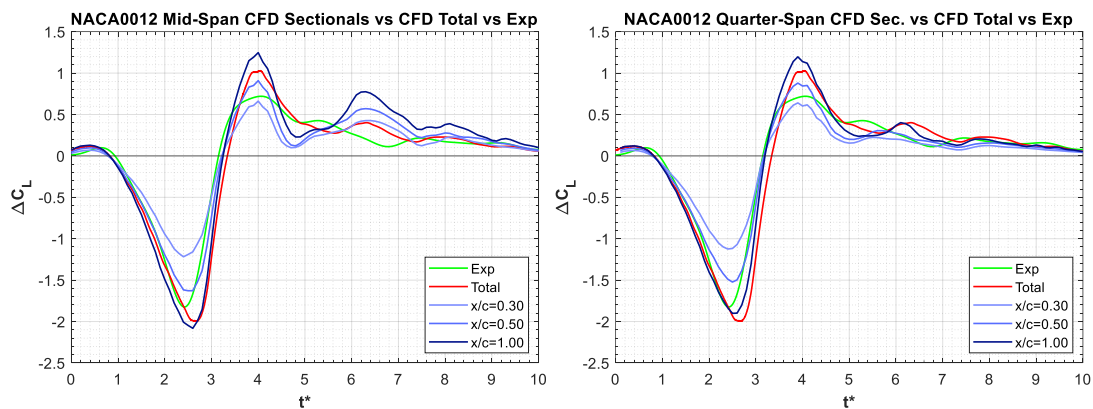


Figure 5.16 : Comparison of CFD mid-span and quarter-span sectional with CFD total and experimental ΔC_L results for NACA0012.

In the previous ΔC_L and ΔC_D comparisons, some differences were found between the mid-span and quarter-span CFD sectional results, especially at the steadying period, and it was mentioned that this could be a result of the three-dimensionality effects of the flow. Hence, 3-D flow images from CFD are examined.

In Figure 5.17, velocity colored snapshots of Q criterion isosurfaces from CFD for NACA0012 are given with comparisons of ΔC_L and ΔC_D results from CFD mid-span sectional, CFD quarter-span sectional, and CFD total. On the ΔC_L and ΔC_D comparison plots, given instants of the 3-D images are marked.

At $t^*=1.0$, in both of the ΔC_L and ΔC_D graphs, both sectional and total results are overlapping. The 3-D image at that instant demonstrates this extreme similarity from the symmetrical vortical structures. For instance, the leading-edge vortex is uniform throughout the entire wing span, there is no vortical structure on the surface near the trailing-edge, and the small vortical structures formed in the wake region are also similar. As time progresses, both ΔC_L and ΔC_D sectional and total results gradually begin to diverge. But, this divergence is most significantly observed in ΔC_D results between total and sectional results.

At $t=2.6$, the maximum negative peak of ΔC_L is reached, while the maximum negative peak of ΔC_D has already occurred. At this instant, ΔC_L results display a slight magnitude and phase difference between each other. However, for ΔC_D , the total result shows a greater magnitude and phase difference compared to the sectionals, which are once again overlapping. In the corresponding 3-D image, the leading-edge vortex seems to expand uniformly across the span towards the trailing-edge. This uniform and symmetrical expansion can be linked to the similarity observed in the sectional results. Nevertheless, the difference of the total ΔC_D result can be a result of the long starting vortex connected to the tip vortices of the gust generator, that occurs at the wake region of the NACA0012.

Then, at $t^*=3.4$, the ΔC_D results start to converge again following the maximum positive peak, while the ΔC_L sectional results slightly diverge from the total. But, both quarter and mid-span sectional ΔC_L and ΔC_D results mostly overlap. Even though the leading-edge vortex experiences slight fluctuations, it does not significantly affect the results as they continue to become similar. Next, at $t^*=3.8$, both of the mid and quarter-span ΔC_L results perfectly overlap, while the total ΔC_L has a magnitude difference as

it approaches the maximum positive peak. On the other hand, quarter-span sectional and total ΔC_D results perfectly overlap, while mid-span has a magnitude difference. After this instant, the quarter-span sectional and total ΔC_D progress very similarly. In the corresponding 3D image, a uniform leading-edge vortex is still visible, but the vortical structures at the trailing-edge show slight asymmetric behavior. Still, the vortical structures maintain an overall symmetrical pattern, which is observed in the ΔC_L and ΔC_D plots. After this moment, at $t^*=5.2$, while ΔC_L results temporarily converge, ΔC_D results diverge intensely. Later on, at $t^*=6.4$, mid-span sectional ΔC_D result diverge extensively even more, accompanied by large divergence in the mid-span sectional ΔC_L result. This behavior of the forces can be observed from the corresponding 3-D images.

At $t^*=5.2$, the horseshoe vortex breakdowns and there are a lot of formations of complex vortical structures. The previously dominant leading-edge vortex, which had a symmetric and uniform structure, begins to shrink and lose its uniformity. Additionally, the vortical structures near the trailing-edge start to fluctuate as they detach from the surface.

Moreover, at $t^*=6.4$, the leading-edge vortex becomes significantly diminished and displays clear asymmetry. All of the vortical structures show very complex and turbulent behavior. Overall, prior to $t^*=3.8$, the three-dimensionality of the flow has minimal effect and can be considered negligible, as the sectional results indicate high similarity. But, after that moment, the vortical structures become more complex and start to mix up, which indicates a significant influence of the three-dimensionality of the flow. The differences in the mid-span sectional, quarter-span sectional, and total CFD results of ΔC_L and ΔC_D are previously explained by the 3-D images, particularly after $t^*=3.8$, when the results diverge the most and the vortical structures become complex and asymmetric. In addition, 2-D vorticity and streamline images from DPIV and CFD are examined to explain the differences between the experimental and CFD total ΔC_L and ΔC_D results better.

In Figure 5.18, DPIV and CFD vorticity and streamline comparisons with C_f distributions over the NACA0012 are shown. C_f distributions are obtained from the CFD simulations, where the red line represents the upper surface friction distribution, and the blue line represents lower surface friction distribution. The peaks in the C_f

plots occur where the vortices are located. The given six instances are critical instants, where the total C_L and ΔC_D results from experimental and CFD diverge the most.

At $t^*=1.0$, there is a magnitude difference observed between the experimental and CFD total ΔC_D results (Figure 5.14), while the lift is very close to zero. In the corresponding images of DPIV and CFD, the streamlines are highly similar and weak vortical structures formed near the trailing-edge appear symmetrical, which explains zero lift. Consequently, the magnitude difference in ΔC_D results can be explained as an intensity difference. The following results display similarities to those of the flat plate.

At $t^*=2.0$, the maximum negative peak is observed in the experimental ΔC_D result, while the CFD total result is very close to it (Figure 5.14). Then, at $t^*=2.2$, both the CFD total ΔC_D result (Figure 5.14) and the experimental ΔC_L result (Figure 5.16) reach their negative peaks. In both of the moments, the DPIV and CFD images show a high degree of similarity, and the experimental vortices align with the C_f plots, where peaks correspond to the vortex locations. The only significant difference is that in the CFD images, the leading-edge vortex on the bottom surface is larger than the experimental vortices, which explains the difference in magnitude observed in the force plots.

After that, at $t^*=3.0$, the experimental ΔC_D result nearly reaches its maximum positive peak, while CFD total result is still approaching it (Figure 5.14). In the corresponding images, the vortices and streamlines are highly similar. However, there is a minor difference in the locations of the large negative vortex and large positive vortex under the NACA0012, which can be linked to the slight phase difference observed in the force results. Also, the peaks in the C_f plots align with experimental image too.

At $t^*=3.8$, significant differences between the experimental and CFD for both total ΔC_L and ΔC_D results are observed (Figure 5.14 and Figure 5.16). This particular moment is important because while experimental ΔC_D result instantly settles, a second negative peak occurs in the CFD total results, which is highly different from the flat plate results. Significant differences are detected between the corresponding DPIV and CFD images. On the lower surface of the NACA0012, the flow is a lot more disturbed in CFD images, as it is evident from the streamlines, and the large negative vortex is pushed against the leading-edge of the NACA0012. These probably increase drag in the negative direction in the CFD total ΔC_D result. In contrast, in the DPIV image, the streamlines around the NACA0012 are relatively steadier, even though the streamlines

below the NACA0012 are slightly fluctuating, and the large negative vortex moves downward.

Finally, at $t^*=6.4$, experimental ΔC_L and ΔC_D results reach a nearly steady state, while CFD total ΔC_L is showing a second small positive peak and a third small negative peak is observed in CFD total ΔC_D result (Figure 5.14 and Figure 5.16). During this moment, there is an extreme difference in the trailing-edge of the gust generator, which effects the flow around the NACA0012 in the CFD image. Despite the gust generator having stopped rotating 2.4 seconds earlier, two medium vortices form at the trailing-edge. In the DPIV image, the streamlines are even closer to the steady state compared to the previous instant, which is evident in the force plots. However, in the CFD image, the location of the stagnation point is not at the tip point but at the lower surface of the leading-edge, which prevents the results from settling. Additionally, at that moment, the flow is under the influence of the 3-D effects, so the results are expected to be complicated.

In Case 1A1 and the current case (1B1), experimental and CFD total ΔC_L and ΔC_D results are studied for flat plate and NACA0012. Additionally, before beginning LESP analysis for NACA0012, comparisons are conducted between flat plate and NACA0012, considering the experimental and CFD total ΔC_L and ΔC_D results. Previously, during the discussion of the NACA0012 results, some of the differences from the flat plate results were highlighted. However, presenting them together in the same plots will provide a clear understanding of the differences.

In Figure 5.19, comparisons of flat plate and NACA0012 experimental ΔC_L and ΔC_D results are given. For both ΔC_L and ΔC_D experimental results, between flat plate and NACA0012, visible magnitude and slight phase differences is observed. Most of these differences are in the range of sensor uncertainty, especially in ΔC_D results where the sensor uncertainty is significantly high compared to the low drag values. The maximum negative peak is highest for the flat plate in ΔC_L , while for NACA0012, it is highest in ΔC_D . Moreover, the two consecutive positive peaks are detected in the flat plate ΔC_L result, which do not exist in NACA0012 results. The settling time is similar for ΔC_L results, but in ΔC_D results, NACA0012 settles faster. These findings suggest that the shape of the wing model is important, as the effect of the gust can vary for both lift and drag.

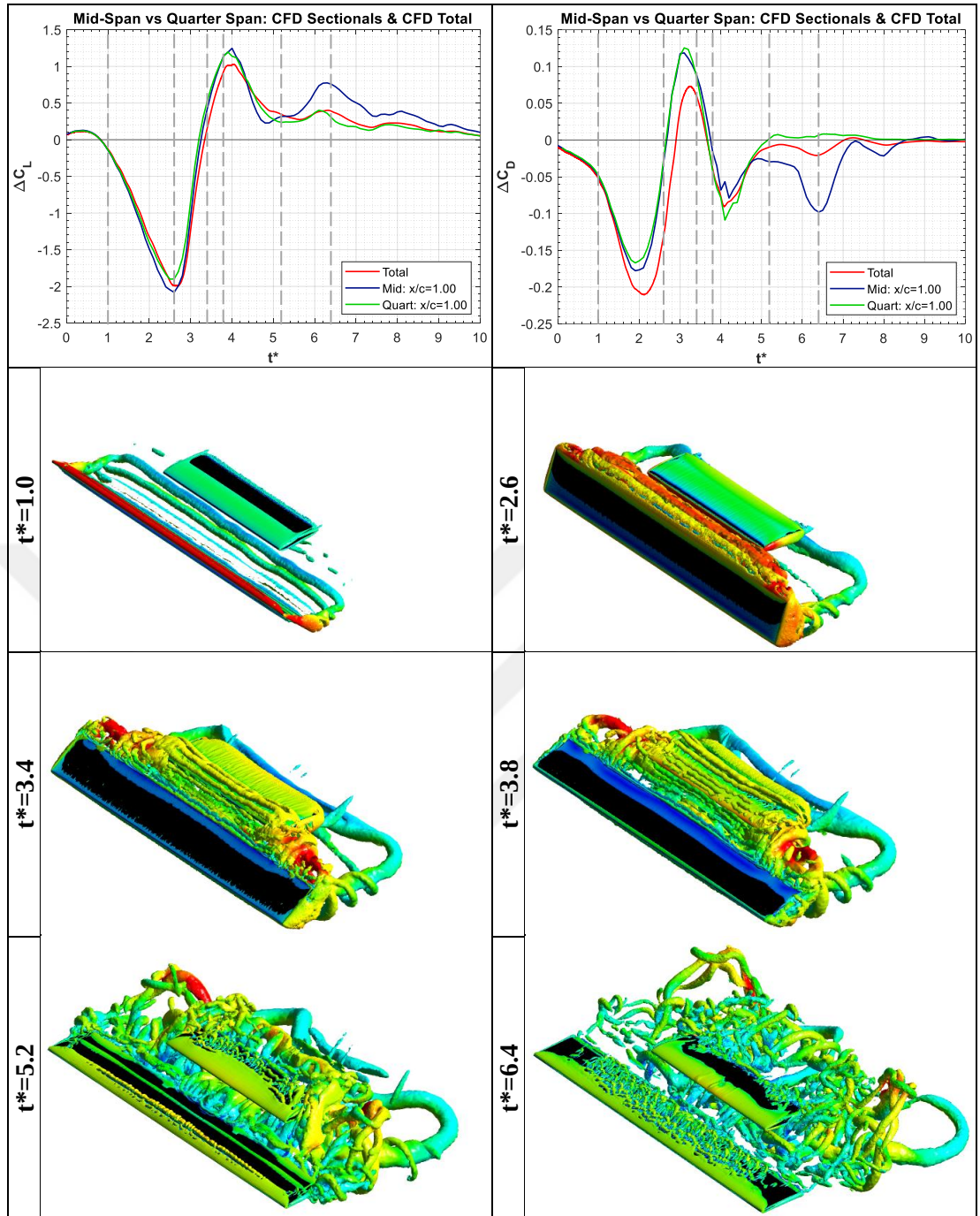


Figure 5.17 : Comparison of ΔC_L and ΔC_D from CFD mid-span sectional, CFD quarter-span sectional, and CFD total, with velocity colored snapshots of Q criterion isosurfaces from CFD for NACA0012.

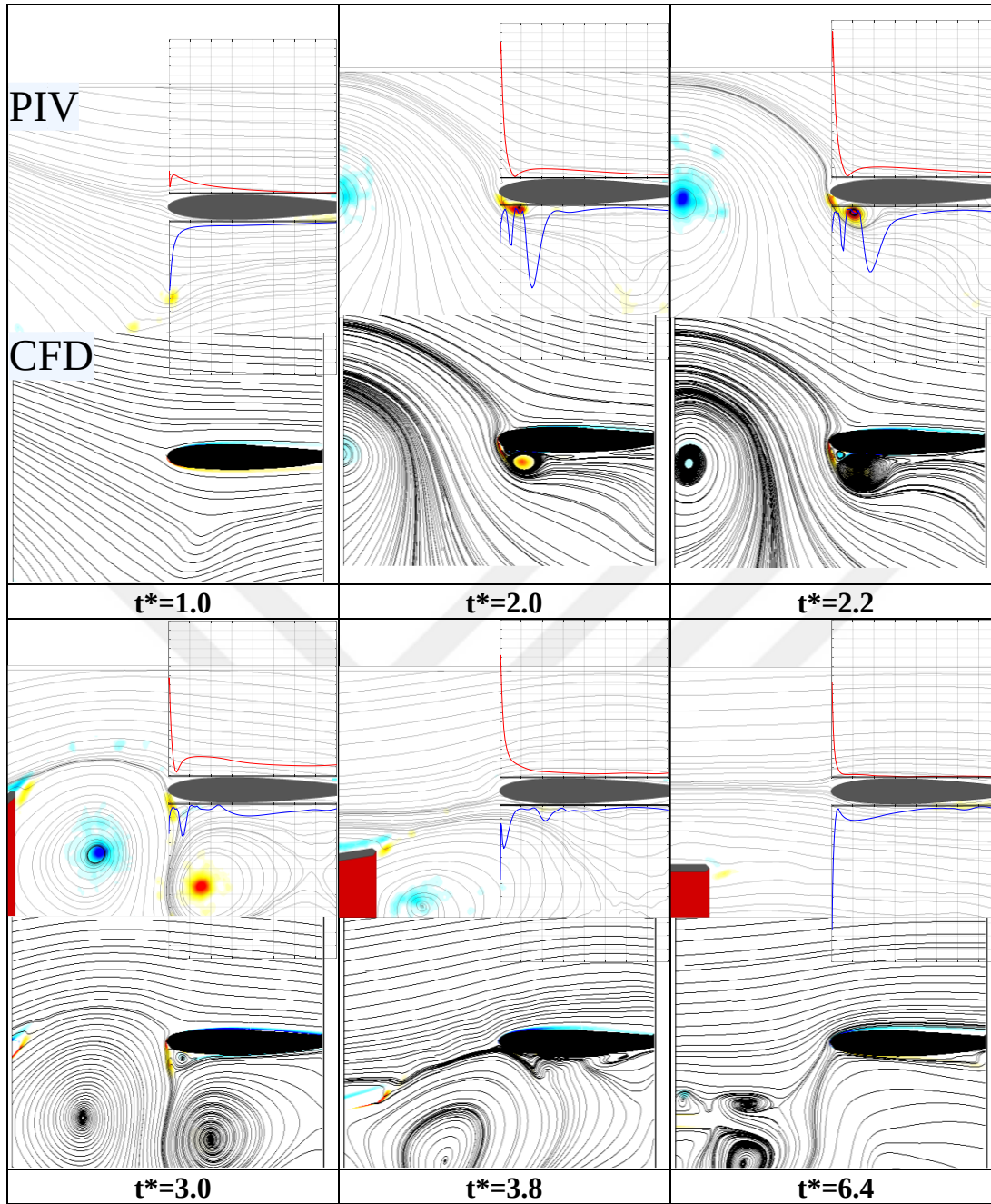


Figure 5.18 : DPIV and CFD vorticity and streamline comparisons with C_f distributions over the NACA0012 airfoil.

In Figure 5.20, comparisons of experimental and CFD total ΔC_L and ΔC_D results for flat plate and NACA0012 are given. Basically, total CFD results for both flat plate and NACA0012 are included to the plots in Figure 5.19 as dashed lines. In the ΔC_L plot, flat plate and NACA0012 results are extremely similar between the CFD results. However, in the ΔC_D plot, the CFD results show greater similarity to their experimental counterparts, with the NACA0012 experimental results are most similar to its CFD counterpart, and vice versa for the flat plate. Even then, magnitude and phase differences are observed. Another important difference is that NACA0012 CFD result

have a considerably large second negative peak, while the other results are settling. Something similar occurs only in the experimental flat plate result, but that peak is smaller and observed at a later point in time. Overall, the CFD results are similar to experimental results, which is positive indication for the validation process.

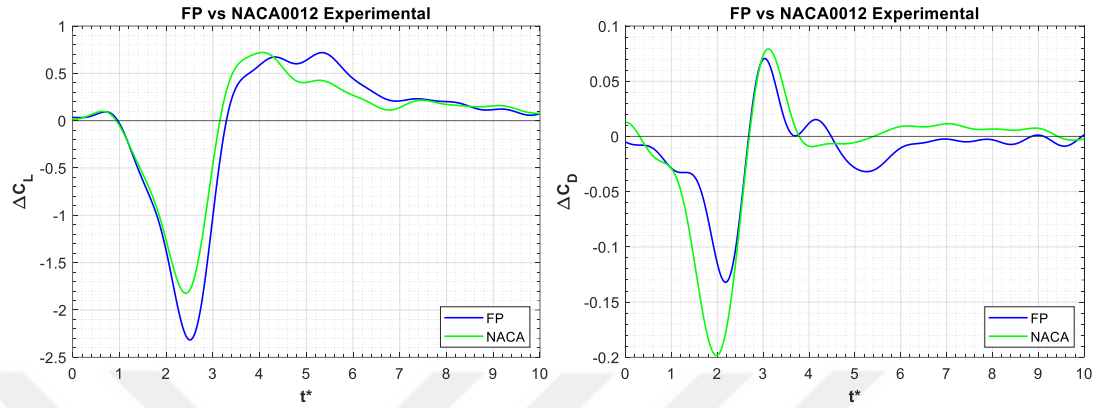


Figure 5.19 : Comparisons of flat plate and NACA0012 experimental ΔC_L and ΔC_D results.

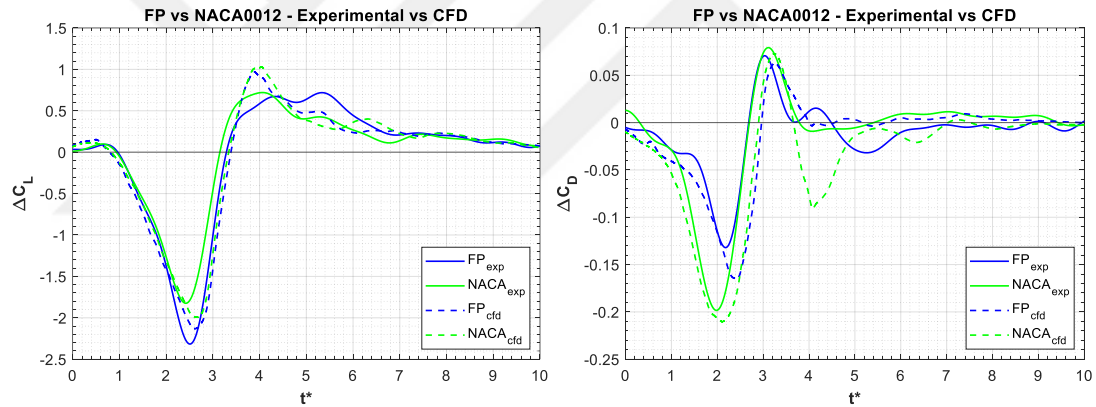


Figure 5.20 : Comparisons of experimental and CFD total ΔC_L and ΔC_D results for flat plate and NACA0012.

Parallel to the findings from Case 1A1, from the experimental and CFD comparisons, necessary similarity is observed between the direct measurements of the total forces acting on the wing and sectional forces calculated from integration of pressure and shear stress distribution. Thus, for NACA0012 cases, direct force measurements can be used to calculate suction force, hence LESP. Moreover, lift coefficient, drag coefficient, LESP, and effective angle of attack results are compared as a part of the investigation of determining the ideal flow separation initiation indicator parameter.

In Figure 5.21, comparisons of C_L , C_D , LESP, and α_{eff} results are given for Case 1B1. In the plot, horizontal dashed blue lines are the critical LESP values for the flat plate. Additionally, yellow band is the region where instantaneous LESP is at or over the

positive critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.22.

At $t^*=1.6$, instantaneous LESP is very close to the critical LESP but it is not equal. As LESP does not reach to the critical value, no separation initiation such as leading-edge vortex formation is observed in the corresponding DPIV image. In the image, while the flow is fully attached, the stagnation point is observed to be moving to the upper side of the airfoil. The movement of the stagnation point is directly linked to the effective angle of attack, as $\alpha_{eff} \approx -50^\circ$.

Next, at $t^*=2.0$, instantaneous LESP is extremely close to the critical value compared to the previous instant, however the yellow band's border does not start at that instant possibly because of the digits. Additionally, C_D reaches maximum negative peak, whereas C_L and α_{eff} continues to decrease. In the corresponding DPIV image, formation of a leading-edge vortex is clearly observed, which indicates the initiation of flow separation.

At $t^*=2.13$, LESP fully reaches the critical value and in the corresponding DPIV image, the leading-edge vortex is bigger than the previous instant. Also, the stagnation point still progresses away from the leading-edge.

At $t^*=2.4$, C_L reach maximum negative peak, while LESP already passed the critical value and currently decreasing. Leading-edge vortex is very large and it seems to be attached to the airfoil but, it is very close to detaching, in the corresponding image.

At $t^*=3.0$, maximum negative peak is observed from LESP, while from C_D maximum positive peak is observed. Even with the maximum peak, instantaneous LESP is far away from the critical. In the corresponding DPIV image, previous leading-edge vortex is already shed and moving away from the airfoil so, the flow is on the road of recovering. There is no formation of new leading-edge vortices, which explains no indication of a new separation. Moreover, the stagnation point is recovering as it moves towards the leading-edge, which is linked to the increase in effective angle of attack as it is $\alpha_{eff} \approx -45^\circ$.

Next, at $t^*=3.2$, C_D is decreasing, while LESP, C_L , and α_{eff} are increasing. Now effective angle of attack is $\alpha_{eff} \approx -25^\circ$ and in the corresponding DPIV image, the

stagnation point is very close to the leading-edge. Slight vortical structures under the airfoil are now clearly disappeared and the flow is recovering as the large negative vortex and the shed leading-edge vortex are moving away from the airfoil.

Finally, at $t^*=4.2$, C_L reaches maximum positive peak and the effective angle of attack is $\alpha_{eff} \approx 20^\circ$. Additionally, LESP and C_D are close to zero. In the DPIV image, the stagnation point is shifted slightly under the leading-edge mid-point therefore positive angle is observed. Other than that, flow is nearly recovered as the vortical structures disappeared and their after affects are decreasing.

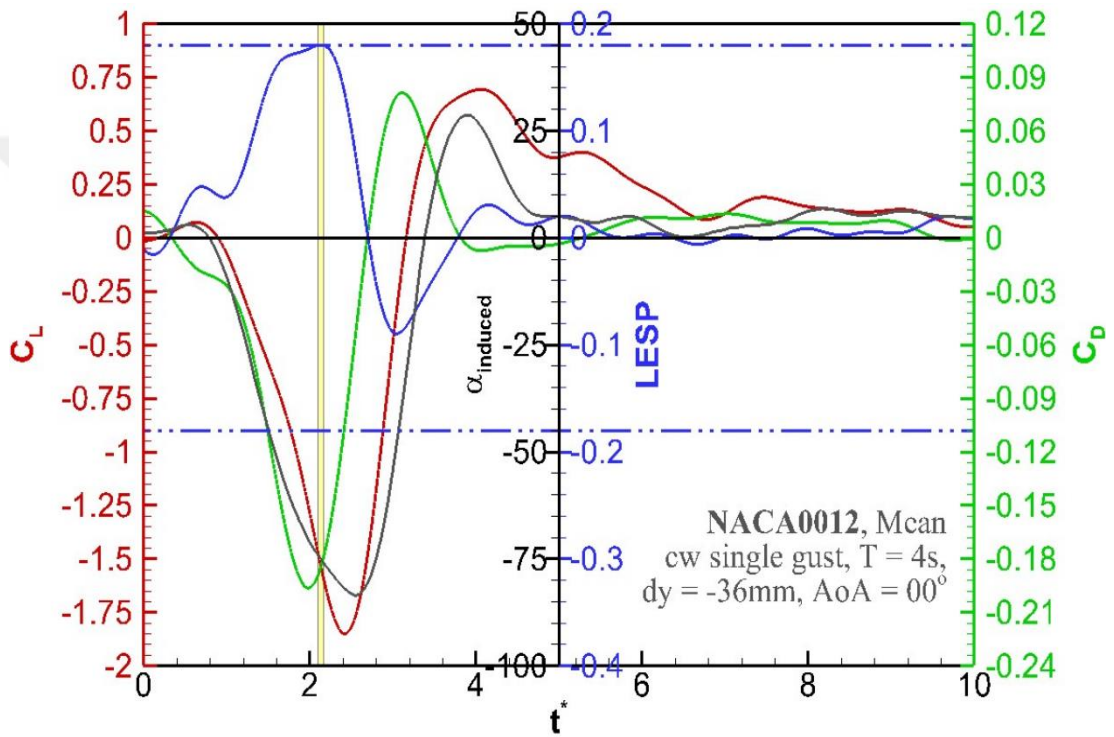


Figure 5.21 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 1B1.

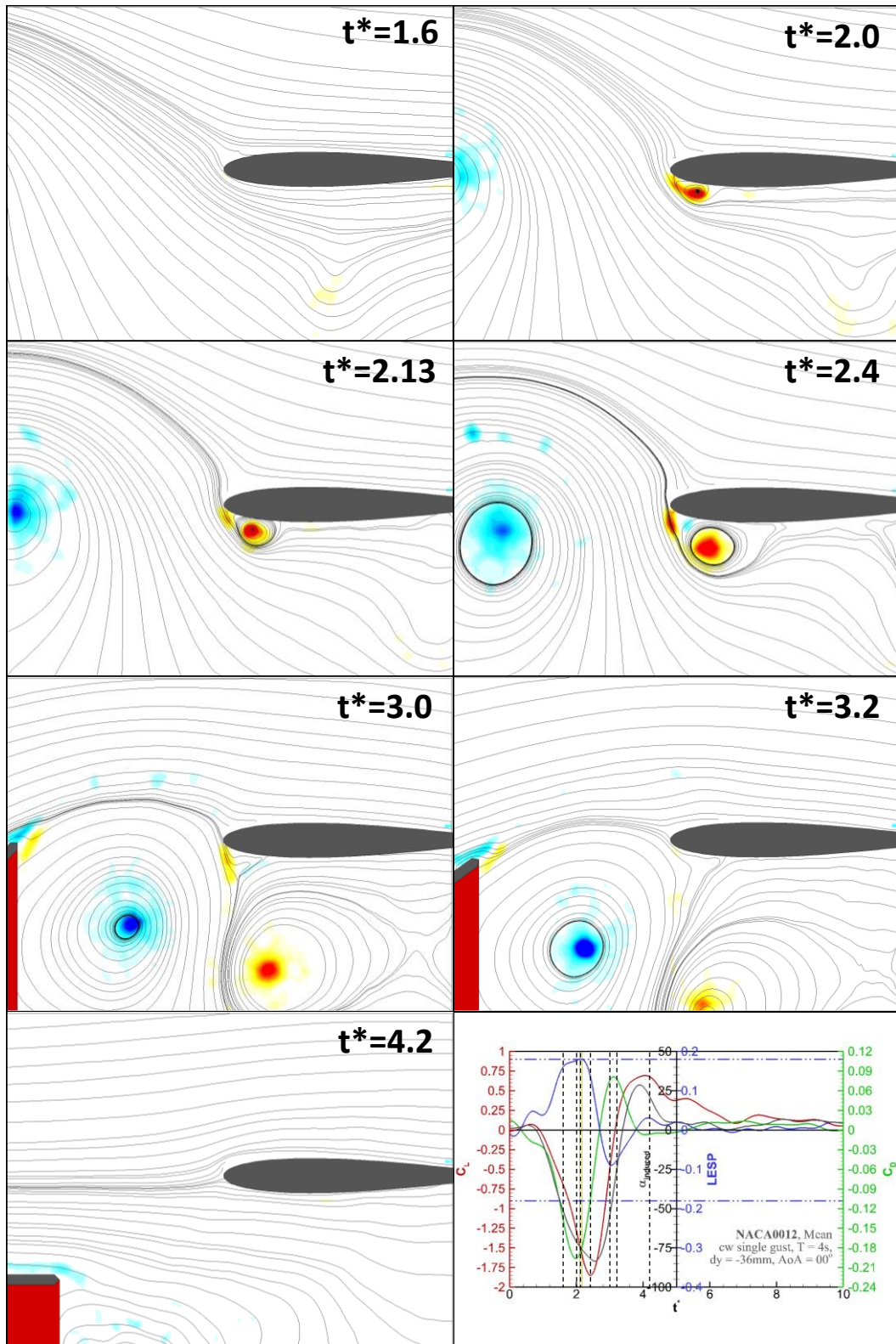


Figure 5.22 : DPIV images of selected instants for Case 1B1.

5.5.3 Case 2A1: Flat Plate $\Delta y = -36$ mm, $T = 3$ [s/(1/2rev)]

In Figure 5.23, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 2A1. The horizontal dashed blue lines in the plot are the critical LESP values for the flat plate. Also, yellow and red bands are the region instantaneous LESP is at or over the critical LESP value. If LESP is positive, band is colored as yellow and if LESP is negative, band is red. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.24.

At $t^* = 0.53$, instantaneous LESP reaches to critical LESP, which is marked as the left border of the yellow band. At this instant, C_L and α_{eff} reach to small positive peaks. In the corresponding DPIV image, unlike Case 1A1, the formation of the leading-edge vortex is not as clear, however, the flow around the leading-edge is not as smooth as a steady flow. Additionally, the stagnation point is at the leading-edge, which is linked to the very small positive value at that instant.

Next, at $t^* = 1.8$, LESP reaches maximum positive peak and α_{eff} reaches maximum negative peak, while C_L and α_{eff} are still decreasing towards maximum negative peaks. In the DPIV image, the flow is clearly separated, as leading-edge vortex is already formed and it is very close to detaching. Moreover, the stagnation point is positioned at the upper surface of the flat plate, which corresponds to the decrease in the α_{eff} and C_L .

At $t^* = 2.13$, LESP is decreasing, as it is at the critical value, and C_D is increasing, while C_L and α_{eff} are at maximum negative peaks. The stagnation point in the DPIV images are still located at the upper surface and the streamlines in front of the leading-edge are very close to being parallel to the edge surface. Also, while the detached leading-edge vortex is progressing away from the flat plate, a new formation of a very small leading-edge vortex is observed.

Next at $t^* = 2.33$, LESP reaches negative critical LESP value. This corresponds with the small leading-edge vortex formation at the corresponding DPIV image. Additionally, the stagnation point is moving towards the leading-edge, which is linked to the increase in the α_{eff} and C_L . At $t^* = 2.53$, LESP reaches maximum negative peak and C_D reaches maximum positive peak, whereas C_L and α_{eff} are still increasing. In the DPIV image, the flow is still separated and the small leading-edge vortex is still

observed. Moreover, the stagnation point is at the corner of the leading-edge, which corresponds to the increase in the α_{eff} and C_L .

At $t^*=2.93$, LESP reaches the critical value again as it is increasing. Effective angle of attack is $\alpha_{eff} \approx 5^\circ$ and C_L is very close to zero. In the DPIV image, the stagnation point is at the leading-edge but just a little under the mid-point. Moreover, the flow is still turbulent under the flat plate and due to the sharp corners of the flat plate, small vortical structures are observed at the upper and lower surfaces, near the leading-edge.

Finally, at $t^*=4.2$, C_D reaches to second negative peak, while LESP reaches to third positive peak. However, this peak of LESP does not reach to critical value. In the corresponding DPIV image, the stagnation point is at the lower corner of the leading-edge, which corresponds to the $\alpha_{eff} \approx 15^\circ$. Additionally, even though a leading-edge vortex is formed at the upper surface, the flow is in the recovering period as the large negative vortex is nearly out of the picture. Therefore, separation will not occur, which is observed from the LESP as it does not reach to the critical value and all of the results settle shortly after this instant.

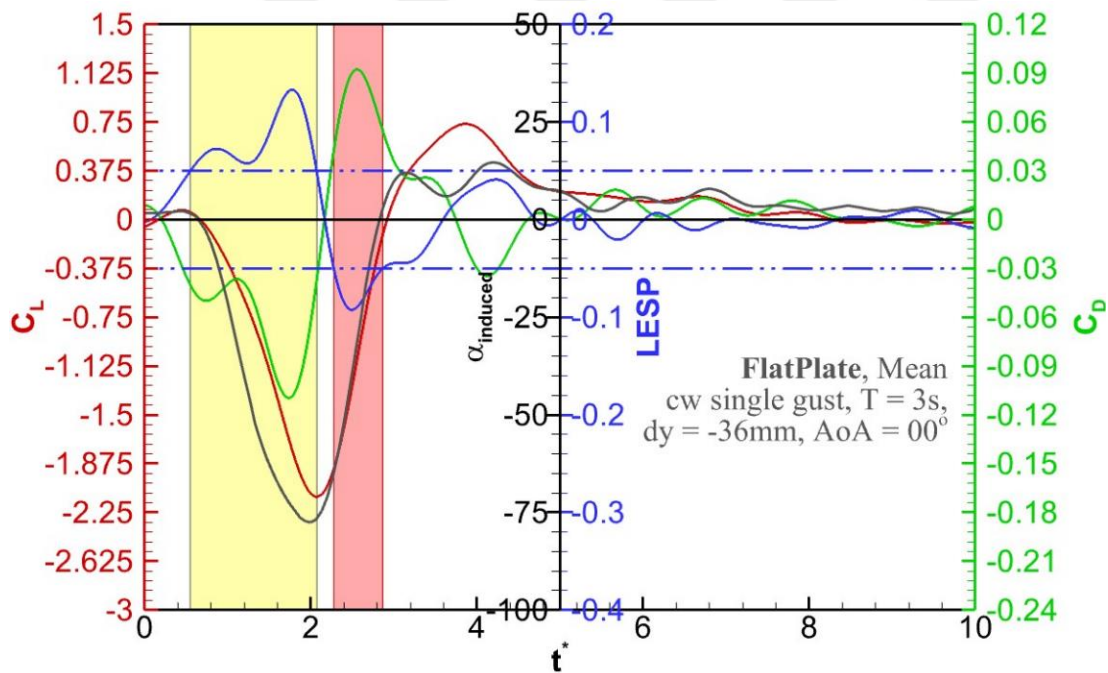


Figure 5.23 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 2A1.

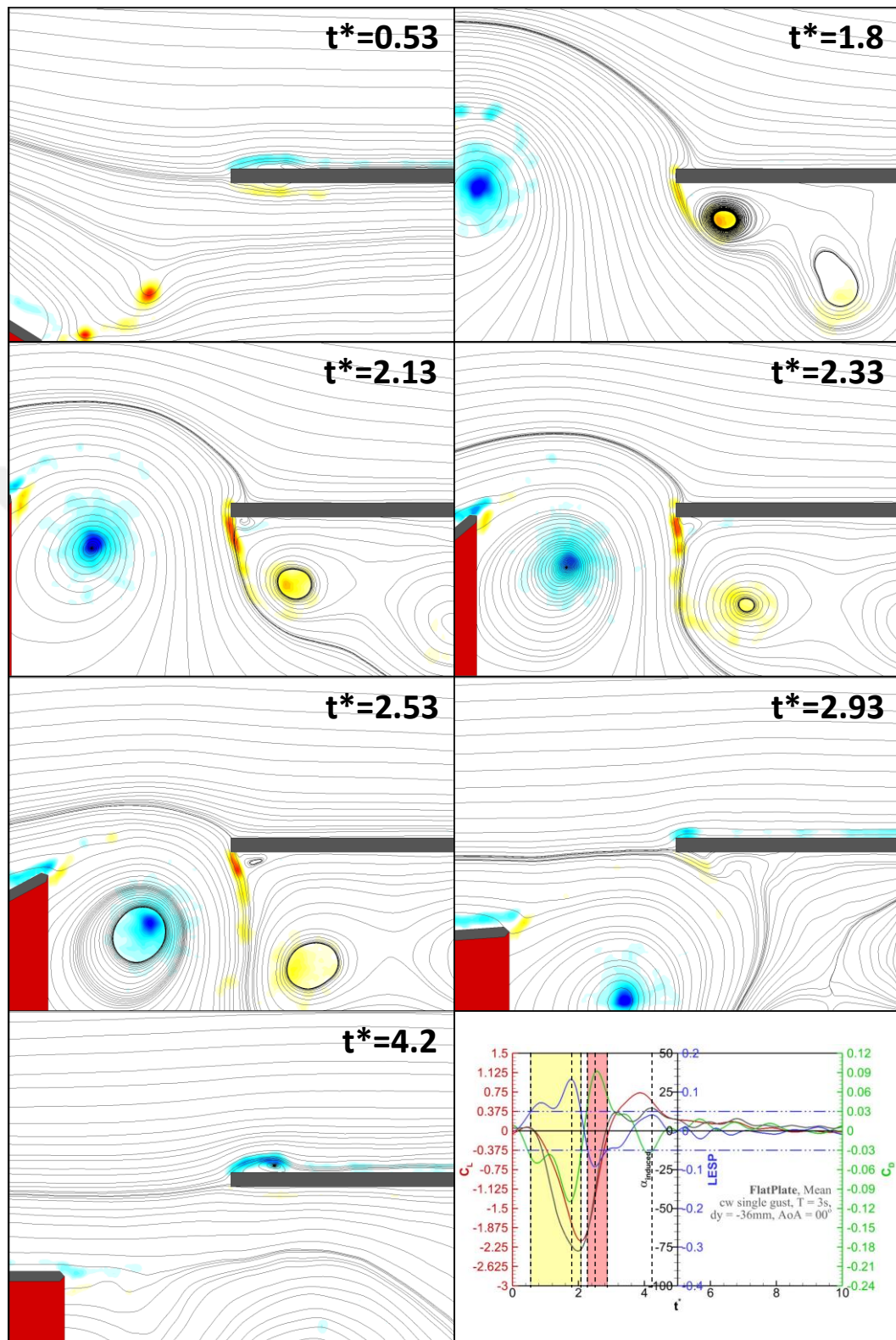


Figure 5.24 : DPIV images of selected instants for Case 2A1.

5.5.4 Case 3A1: Flat Plate $\Delta y = -36$ mm, $T = 6$ [s/(1/2rev)]

In Figure 5.25, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 3A1. The horizontal dashed blue lines in the plot are the critical LESP values for the flat plate. Also, yellow and red bands are the region instantaneous LESP is at or over the critical LESP value. If LESP is positive, band is colored as yellow and if LESP is negative, band is red. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.26.

Firstly, at $t^* = 1.6$, instantaneous LESP reaches critical LESP value. This is expected to indicate initiation of the flow separation. In the corresponding DPIV image, formation of a leading-edge vortex is observed on the lower surface of the flat plate, which indicated the initiation of the flow separation that will follow. Additionally, the stagnation point is located at the upper corner of the leading-edge, which corresponds to the decrease on the C_L and α_{eff} .

Next, at $t^* = 2.8$, instantaneous LESP reaches to maximum positive peak and C_D reaches maximum negative peak, while C_L and α_{eff} are still decreasing. However, maximum negative peak of α_{eff} is very close. In the corresponding DPIV image, the flow is clearly separated and the leading-edge vortex is enlarged and detached. Also, a small second leading-edge vortex formation is observed. Moreover, the stagnation point is now positioned at the upper surface of the flat plate, which is linked to the decrease in the C_L and α_{eff} . Effective angle of attack is $\alpha_{eff} \approx -85^\circ$, which is observed from the streamlines in front of the leading-edge as they are nearly parallel to the surface of the edge.

At $t^* = 3.4$, LESP reaches critical value as it is decreasing, while C_D , C_L , and α_{eff} are increasing. In the DPIV image, detached leading-edge vortex is even more enlarged. However, the flow around the flat plate is trying to recover as the stagnation point moves towards the leading-edge.

At $t^* = 4.33$, LESP reaches to the critical value again. At this instant C_L and α_{eff} are nearly zero. In the corresponding image, $\alpha_{eff} \approx 0^\circ$ is observed from the stagnation point being positioned at the mid-point of the leading-edge perpendicularly. Additionally, formation of a small leading-edge vortex is detected which is linked to

the LESP value reaching to the critical value. Therefore, flow separation is expected to be observed as its initiation is indicated by the LESP.

Consistently, at $t^*=4.8$, the flow is already separated in the DPIV image. Additionally, new formation of a leading-edge vortex at the upper surface is observed. This new vortex is also another pointer for the flow separation, which is provided by the instantaneous LESP reaching to the critical value for the third time at $t^*=5.93$. Clearly, the flow is separated from the upper surface due to the detaching of the newly formed leading-edge vortex. Furthermore, the flow under the flat plate is still very complex as the large negative vortex and initially formed leading-edge vortex are repress each other.

Finally, at $t^*=6.53$, LESP reaches to the critical value final time as it is decreasing and all the parameters are trying to settle. The starting of the recovery period of the flow is observed in the corresponding image. The formation of a leading-edge vortex is normal as LESP is at the critical value but, this vortex will diminish without separation as the flow recovers.

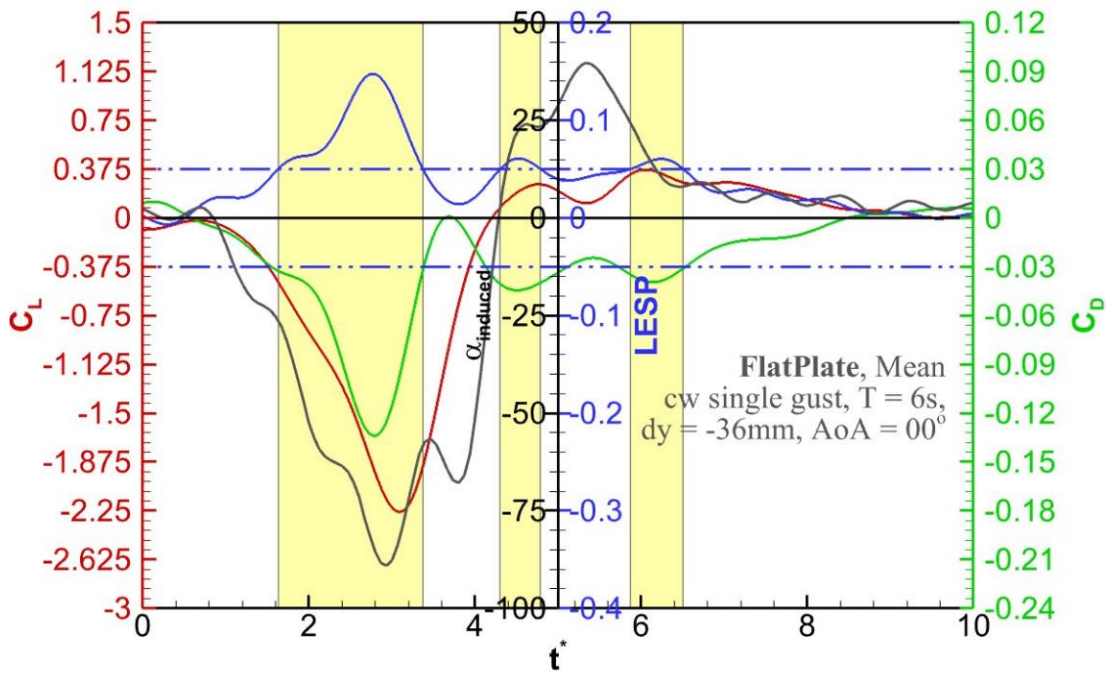


Figure 5.25 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 3A1.

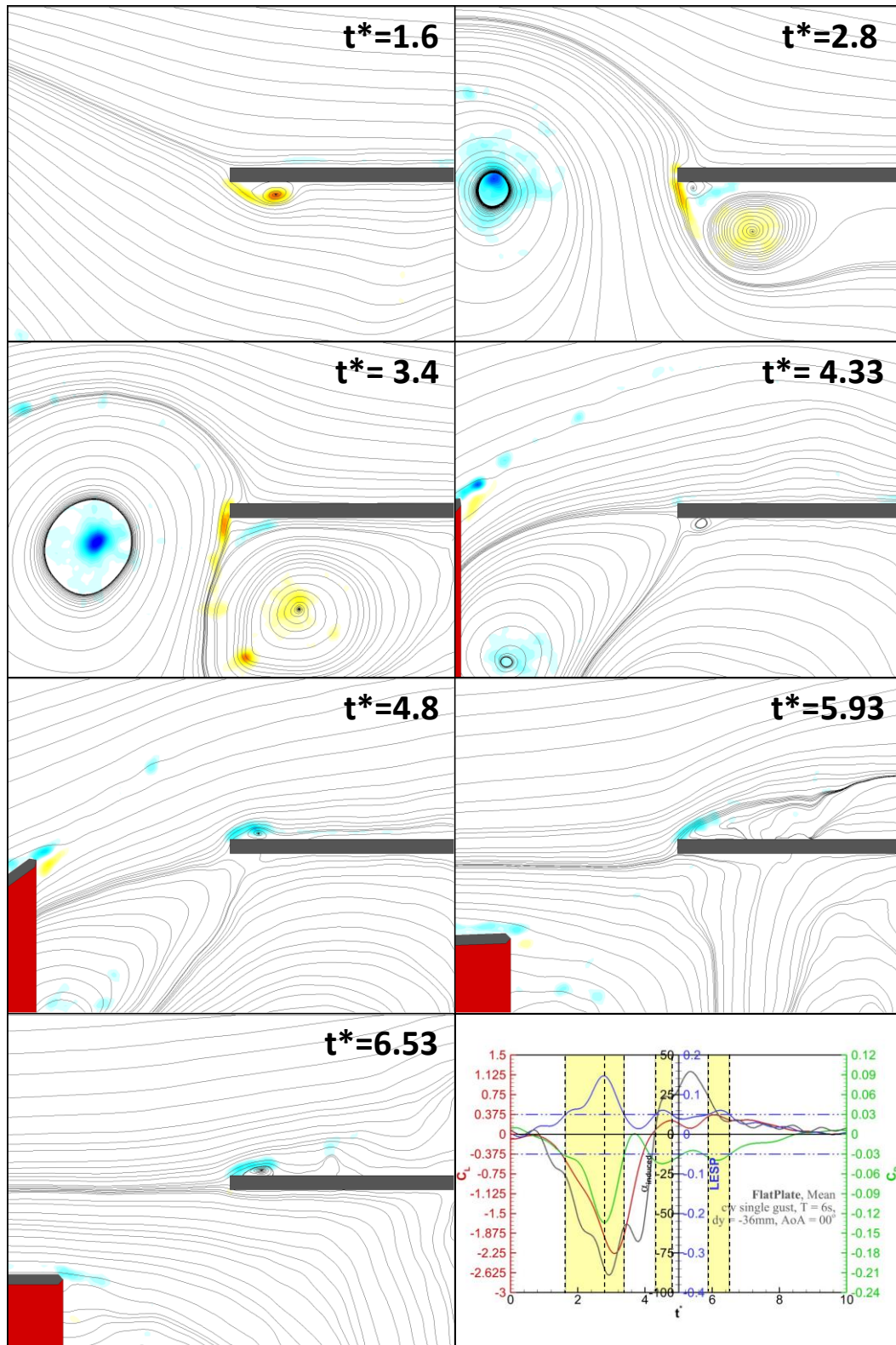


Figure 5.26 : DPIV images of selected instants for Case 3A1.

5.5.5 Case 1A2: Flat Plate $\Delta y = -111$ mm, $T = 4$ [s/(1/2rev)]

In Figure 5.27, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 1A2. The horizontal dashed blue lines in the plot are the critical LESP values for the flat plate. Also, red band is the region instantaneous LESP is at or over the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.28.

Initially, at $t^* = 1.0$, a small positive peak is observed for LESP, but it is under the critical value. In the corresponding DPIV image, even though LESP is far away from the critical, formation of a small leading-edge vortex is observed on the lower surface of the flat plate. After that instant, LESP starts to decrease as C_D increases.

Then, at $t^* = 2.0$, α_{eff} reaches to maximum negative peak, $\alpha_{eff} \approx -30^\circ$, while LESP is still decreasing and under the critical value. At that instant in the DPIV image, the stagnation point is positioned at the upper corner of the leading-edge, which corresponds to the negative effective angle of attack and C_L . While lift and α_{eff} are consistent with the previous cases (1A1, 2A1, and 3A1), LESP is not because it does not indicate the initiation of the separation as accurate as the other cases. At this instant, LESP is far away from the critical but, at the corresponding image, leading-edge vortex is very large, which should indicate the initiation.

Next, at $t^* = 2.6$, LESP reaches to the critical value at last. Additionally, C_L reaches maximum negative peak while α_{eff} is increasing. In the DPIV image for this instant, leading-edge vortex is detached and the flow is clearly separated at the leading-edge.

At $t^* = 3.0$, LESP reaches maximum negative peak, while C_L reaches maximum positive peak. In front of the detached leading-edge vortex, another vortex is also observed. The second vortex started to form at the previous instant, due to detached leading-edge vortex encountering the large negative vortex, and it got enlarged in this instant.

Next, at $t^* = 3.6$, LESP reaches critical value as it is increasing. C_L and α_{eff} are also increasing, whereas C_D is decreasing. In the DPIV image, detached leading-edge vortex is nearly diminished. This is due to negative vortex gust being generated far below from the flat plate in this case, so that it progresses under the flat plate and directly effects the leading-edge vortex. When they encounter, large negative vortex

disturbed leading-edge vortex's vortical structure. Additionally, even though the stagnation point is still at the leading-edge, the flow angle is tilted in the positive direction, which corresponds to positive the C_L and α_{eff} results. As a result of the positive effective angle of attack, another leading-edge vortex is formed at the upper surface.

Next, at $t^*=4.4$, C_L reaches maximum positive peak but LESP and C_D are close to zero. In the corresponding image, while the flow under the flat plate is highly recovered, the newly formed leading-edge vortex is enlarged. However, LESP results do not display any indication towards separation.

Finally, at $t^*=5.4$, LESP reaches to a small positive peak, which is close but under the critical value. In the DPIV image, the leading-edge vortex is very large but it is not fully detached. Therefore, while the flow separates at the leading-edge, it reattaches again over the surface of the flat plate in a later location. After that the flow is in recovery period as all of the results settle.

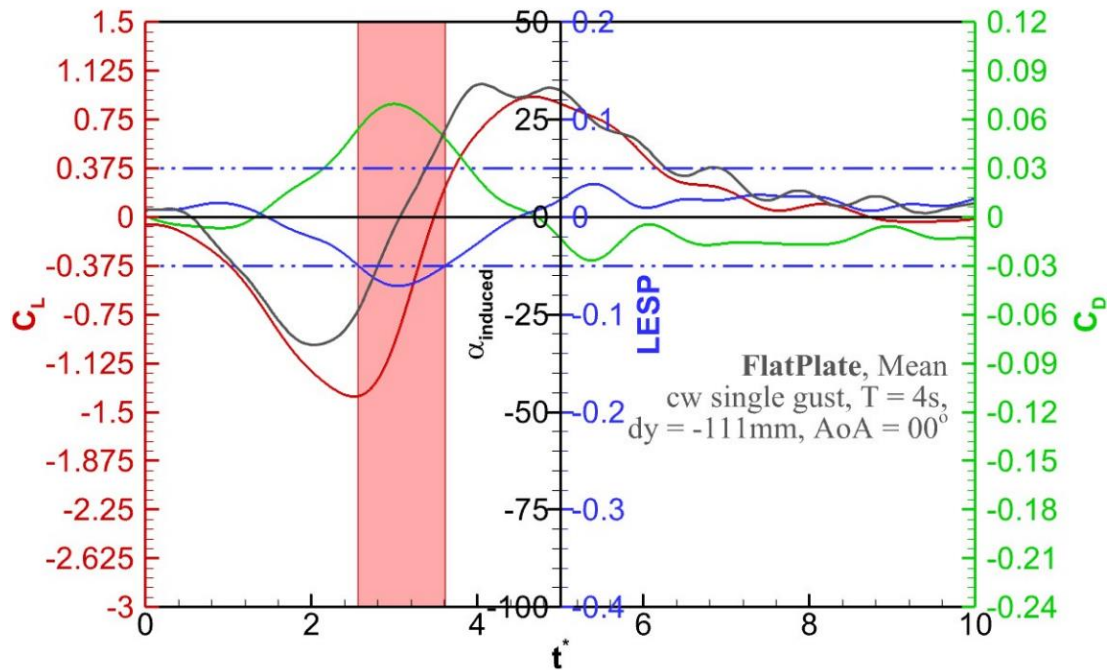


Figure 5.27 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 1A2.

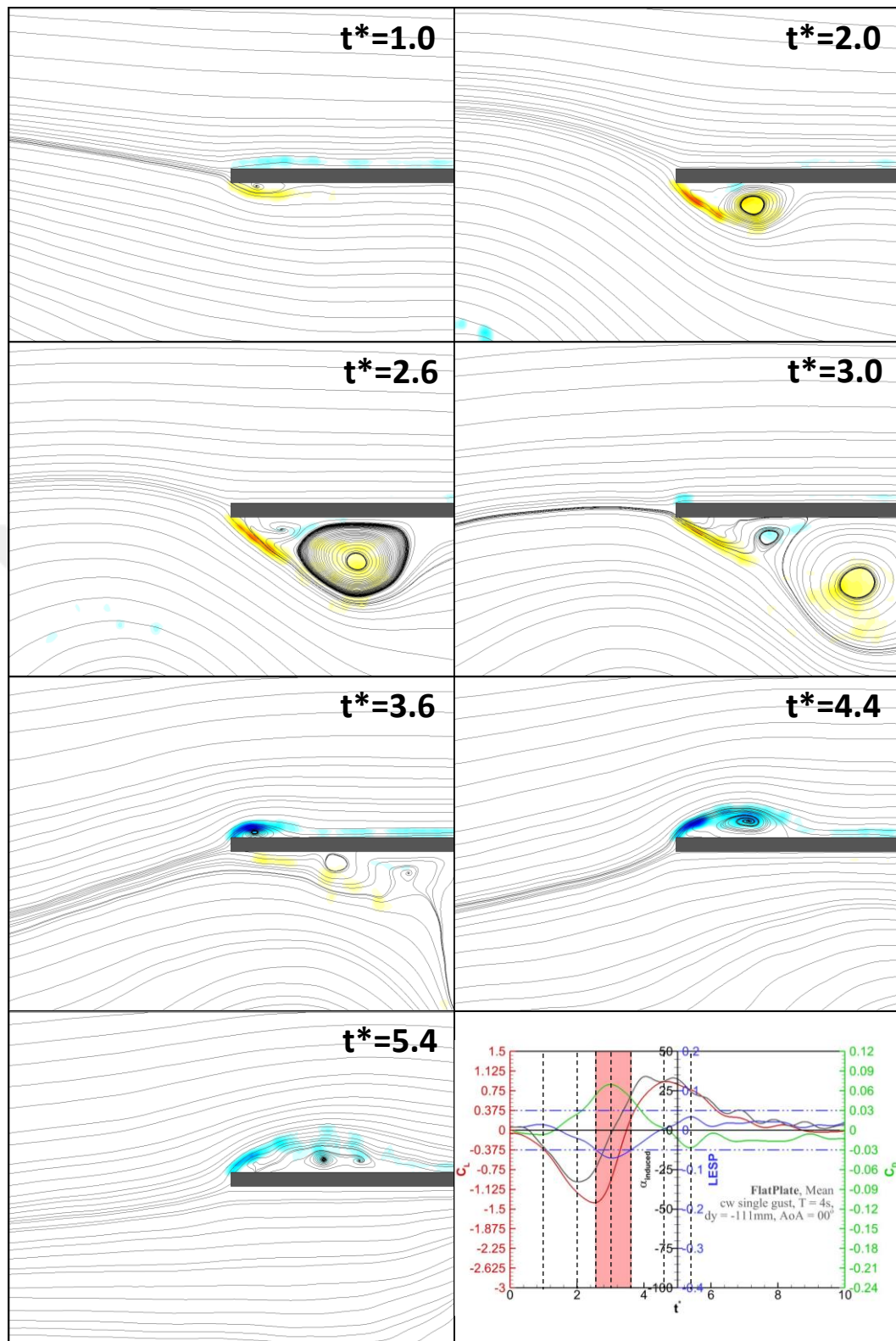


Figure 5.28 : DPIV images of selected instants for Case 1A2.

5.5.6 Case 2A2: Flat Plate $\Delta y = -111$ mm, $T = 3$ [s/($\frac{1}{2}$ rev)]

In Figure 5.29, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 2A2. The horizontal dashed blue lines in the plot are the critical LESP values for the flat plate. Also, red band is the region instantaneous LESP is at or over the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.30.

Firstly, at $t^* = 0.6$, a small positive peak is observed from LESP, but it is far away from the critical LESP. In the corresponding DPIV image, there is no formation of leading-edge vortex. This is more consistent compared to the initial peak in Case 1A2, where leading-edge vortex is observed even though LESP is far under the critical.

At $t^* = 1.73$, LESP reaches to critical value, while both C_L and α_{eff} reach maximum negative peaks. In the DPIV image, leading-edge vortex formation is observed. Moreover, the stagnation point is at the upper corner of the leading-edge, which corresponds to the maximum negative α_{eff} .

Next, at $t^* = 2.13$, C_D is already passed the maximum positive peak and starts to decrease, as LESP value reaches critical value while increasing. The leading-edge vortex is nearly detached and the flow is separated at the leading-edge.

At $t^* = 2.4$, the critical LESP is still very close to the critical value. In the DPIV image, the initial leading-edge vortex is enlarged and formation of another small leading-edge vortex is detected.

Right after that, LESP again reaches to the critical value at $t^* = 2.6$. the large leading-edge vortex is near the surface of the flat plate, even though it progresses along the chord and the flow is still separated.

At $t^* = 3.0$, LESP is increasing as it again reaches the critical value one last time. Additionally, C_L and α_{eff} are also increasing, while C_D is decreasing. In the DPIV image, the leading-edge vortex is nearly out of the picture but, the flow under the flat plate is still away from recovery as there are small disturbances at the leading-edge. Also, although the stagnation point is at the leading-edge, it is starting to tilting in the positive direction, which corresponds to the increase in α_{eff} . Therefore, the flow around the upper corner of the leading-edge starts to get curvier as small vortical structures increases.

Finally, at $t^*=3.8$, LESP and C_D are close to settling, while C_L and α_{eff} reach maximum positive peaks. In the DPIV images, the flow under the flat plate is nearly recovered, while a leading-edge vortex is clearly formed at the upper side. This is linked to the maximum value of α_{eff} . However, this leading-edge vortex does not detach, as all the parameters settle after this instant. During this case (2A2) and 1A2, α_{eff} did not reach extremely high values because the stagnation point is never positioned on the upper or lower surfaces of the flat plate.

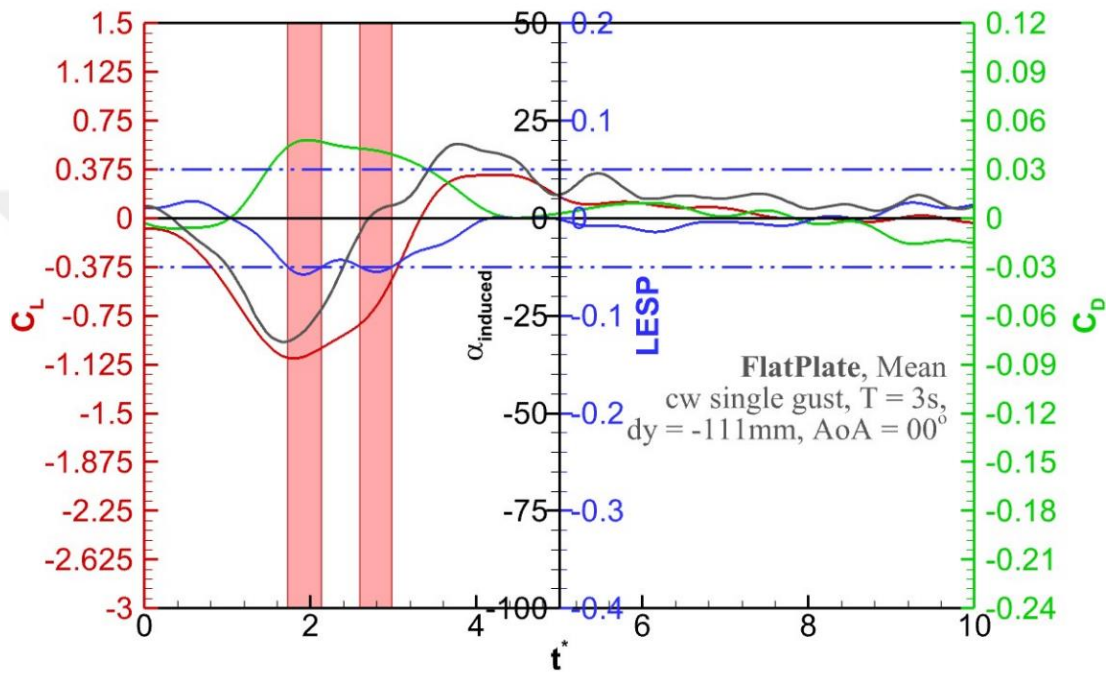


Figure 5.29 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 2A2.

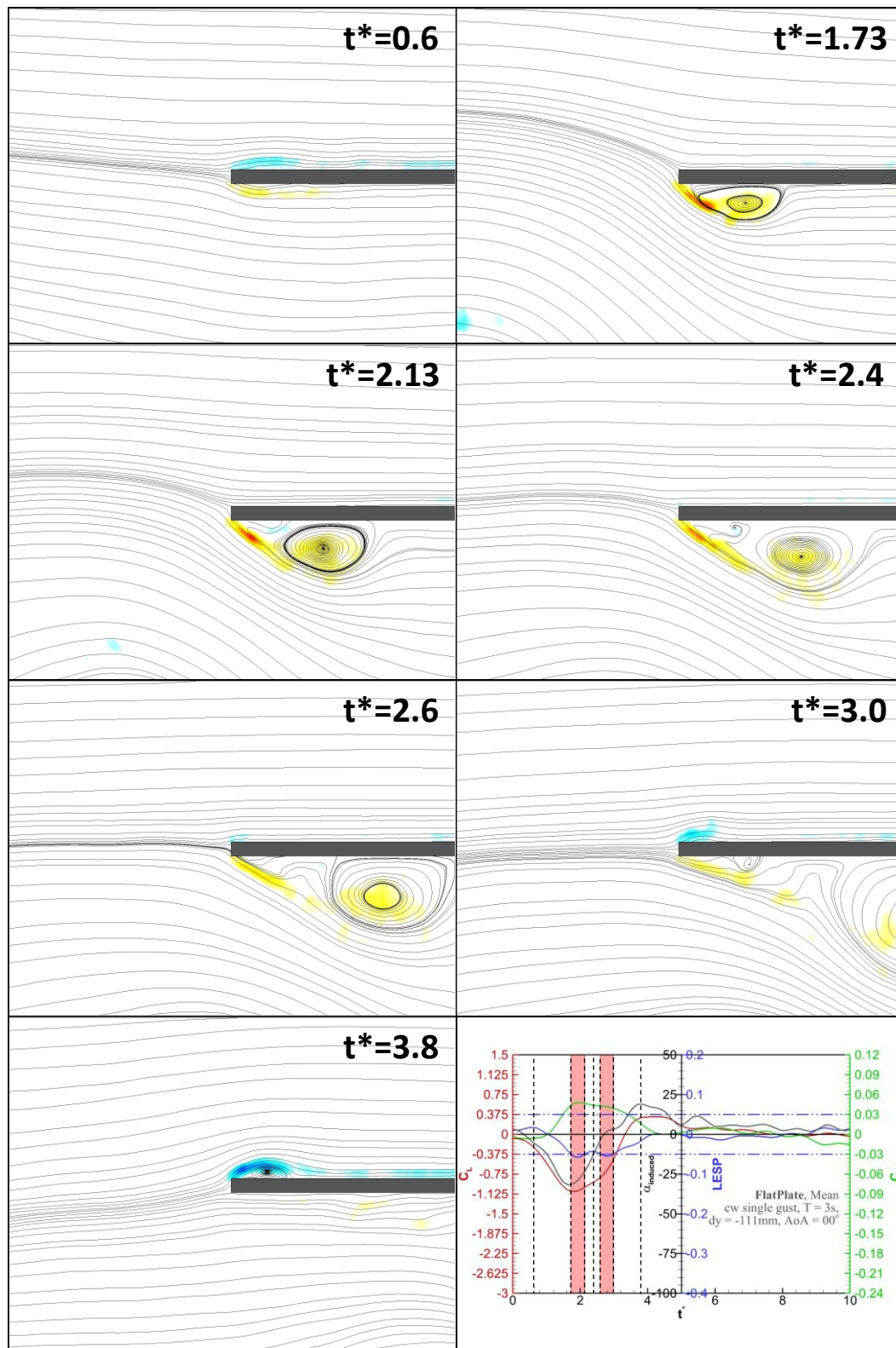


Figure 5.30 : DPIV images of selected instants for Case 2A2.

5.5.7 Case 3A2: Flat Plate $\Delta y = -111 \text{ mm}$, $T = 6 \text{ [s/(1/2 rev)]}$

In Figure 5.31, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 3A2. The horizontal dashed blue lines in the plot are the critical LESP values for the flat plate. Also, yellow and red bands are the region instantaneous LESP is at or over the critical LESP value. If LESP is positive, band is colored as yellow and if LESP is negative, band is red. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.32.

Initially, at $t^* = 0.53$, C_D reaches to a small positive peak, whereas the other parameters are close to zero. In the corresponding DPIV image, the flow seems to be steady however, very minor fluctuations in the streamlines probably increase C_D . Also, due to the sharp corners of the flat plate, at the leading-edge vortical structures are observed. However, these are not any indicator for actual flow separation.

At $t^* = 2.73$, LESP reaches to critical value and α_{eff} reaches maximum negative peak. In the DPIV image, leading-edge vortex is clearly formed on the lower surface of the flat plate, which is an indicator, corresponding to LESP, for the flow separation. Effective angle of attack is $\alpha_{eff} \approx -33^\circ$, as the stagnation point is located at the upper corner of the leading-edge.

Next, at $t^* = 3.6$, LESP reaches maximum negative peak, while C_D reaches maximum positive peak. At this instant, both C_L and α_{eff} are increasing. The previously formed leading-edge vortex is fully detached and the flow is fully separated, in the DPIV image. Moreover, second leading-edge vortex is forming, while a third vortex is formed between the detached and newly formed vortices.

After that, at $t^* = 4.73$, LESP reaches critical value as it increases. In the corresponding DPIV image, the flow under the flat plate is recovered as the flow is reattached to the surface again. However, with the increase and positive value of α_{eff} , a new leading-edge vortex is formed on the upper surface of the flat plate.

At $t^* = 5.4$, LESP reaches to the critical value again. In the DPIV image, recently formed leading-edge vortex is enlarged and it indicates the flow will separate, corresponding to the indication of LESP. The flow is separating at the leading-edge but, reattaching after the leading-edge vortex. On the other hand, the flow is fully separated at $t^* = 6.0$, as the leading-edge vortex is detached and extremely large. At this

instant, LESP reaches to the maximum positive peak, while C_D reaches maximum negative peak. Also, C_L and α_{eff} just passed the maximum positive peak. The stagnation point is located at the lower surface of the flat plate, which caused leading-edge vortex to get enlarged even more.

Finally, at $t^*=6.0$, LESP reaches to critical value as it is decreasing and all the parameters are on the way to settling. In the DPIV image, the large leading-edge vortex is nearly out of the picture, however, small vortices are formed in front of it near the leading-edge. Therefore, the flow is still fully separated. With the incoming steady flow, the flow at the leading-edge will reattach as the parameter settle.

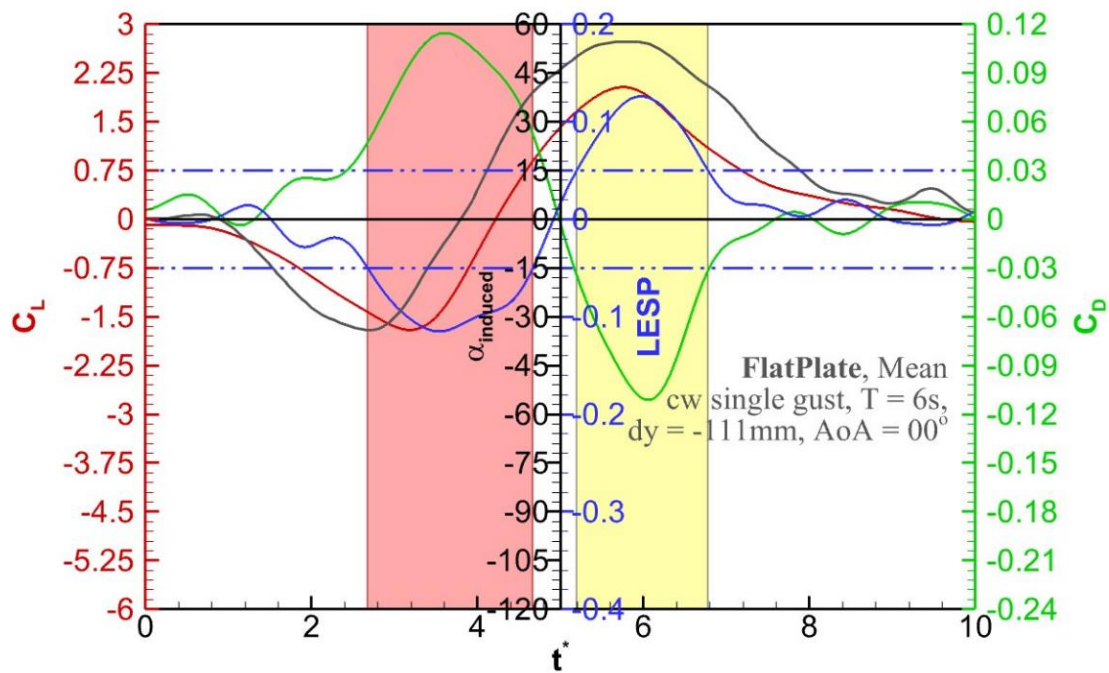


Figure 5.31 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 3A2.

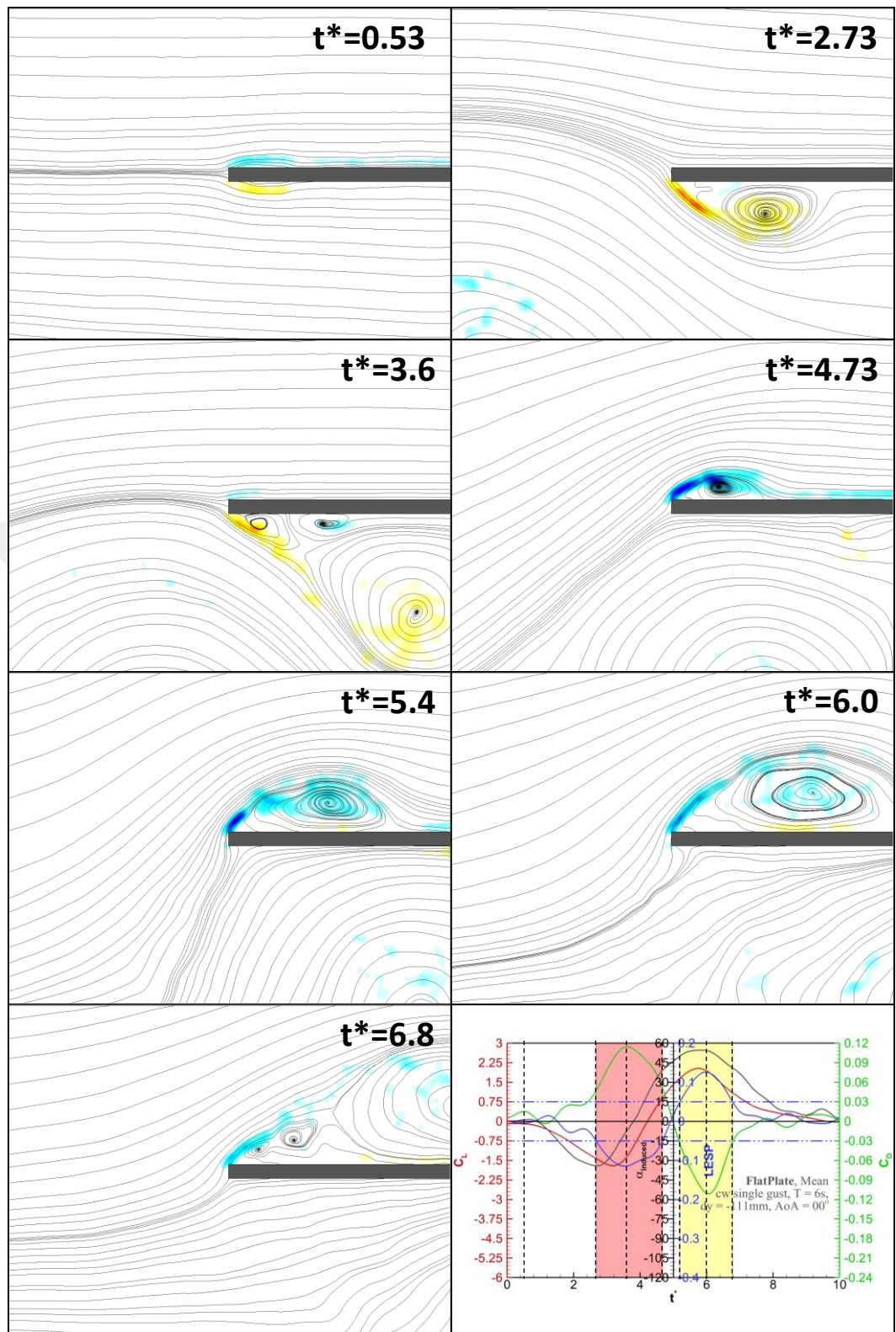


Figure 5.32 : DPIV images of selected instants for Case 3A2.

5.5.8 Case 2B1: NACA0012 $\Delta y = -36$ mm, $T = 3$ [s/($\frac{1}{2}$ rev)]

In Figure 5.33, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 2B1. The horizontal dashed blue lines in the plot are the critical LESP values for the NACA0012 airfoil. Yellow band is the region where LESP is at or over the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.34.

At $t^* = 0.6$, C_L and α_{eff} reach to a small positive peak, whereas LESP is increasing and C_D is decreasing. At this instant, instantaneous LESP is far away from the critical LESP value. As expected from the low LESP results, a leading-edge vortex is not detected in the corresponding DPIV image.

Next, at $t^* = 1.6$, LESP reaches to the critical LESP, while other parameters are decreasing. In the corresponding image, a leading-edge vortex is starting to form, as the stagnation point is moved to the upper surface of the airfoil. The leading-edge vortex is highly small at this instant therefore, the next instant will prove if LESP really indicated the initiation of flow separation.

At $t^* = 1.8$, shortly after the first crossing, LESP reaches to the critical value again, as it is decreasing. In the DPIV image, the previously formed leading-edge vortex is undoubtedly expanding, which will cause leading-edge separation, as predicted by LESP.

At $t^* = 2.2$, LESP and C_D intersect precisely at zero, while C_L and α_{eff} are increasing after reaching their maximum negative peaks. In the corresponding image, the leading-edge vortex is even larger, which causes separation at the leading-edge. After this instant, the stagnation point is moving back to the leading-edge, with the increase in α_{eff} .

At $t^* = 2.6$, LESP reaches maximum negative peak, while C_D reaches maximum positive peak. In the image, leading-edge vortex is now fully detached and the flow is still fully separated. However, the stagnation point is actually recovering with the consistent increase in α_{eff} .

Next, at $t^* = 3.2$, LESP is decreasing to settle, while C_L and α_{eff} reach to their maximum positive peaks. The leading-edge vortex is now out of the picture in the figure, as the large negative vortex dominates the flow. The stagnation point is

positioned under the mid-point of the leading-edge with a slight angle, which corresponds to $\alpha_{eff} \approx 15^\circ$.

Finally, at $t^*=4.0$, LESP and C_D are settling, whereas C_L and α_{eff} decreasing to settle. In the DPIV image, the flow is nearly recovered, as the upper and lower surface of the flat plate is nearly back to symmetrical flow.

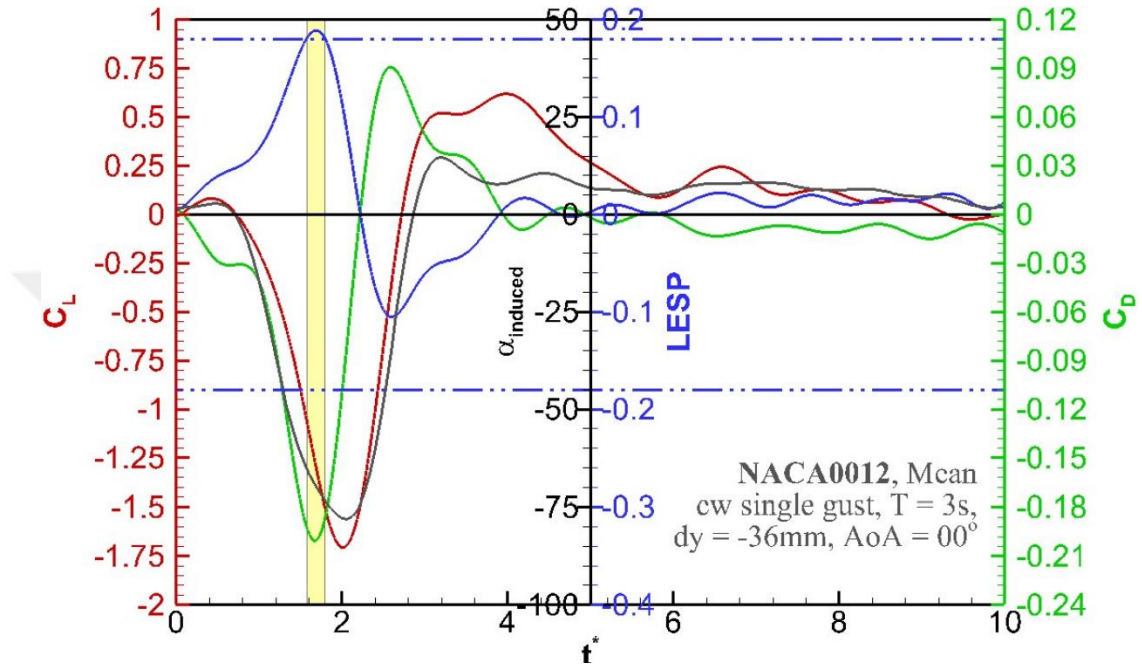


Figure 5.33 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 2B1.

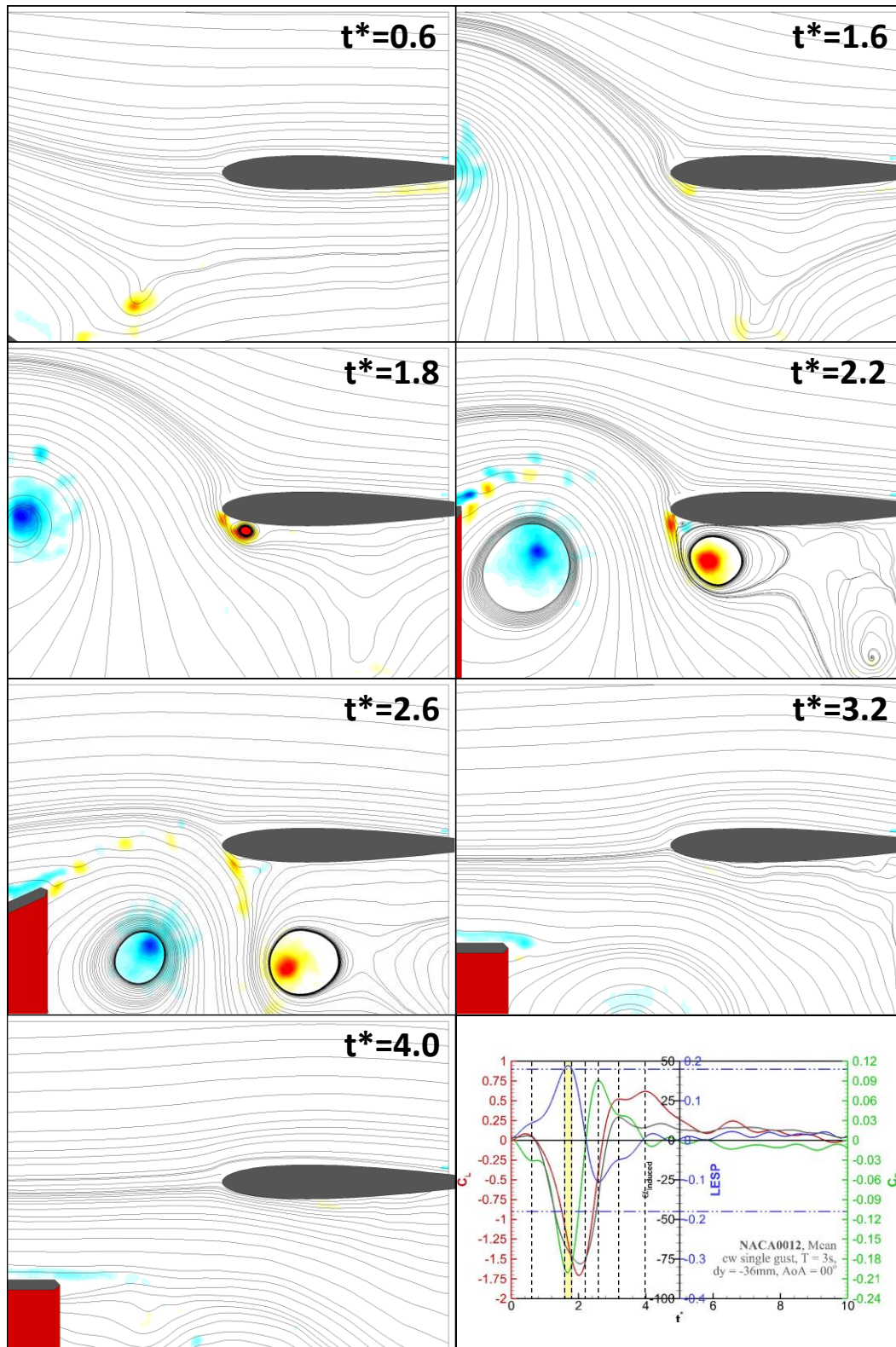


Figure 5.34 : DPIV images of selected instants for Case 2B1.

5.5.9 Case 3B1: NACA0012 $\Delta y = -36$ mm, $T = 6$ [s/(1/2rev)]

In Figure 5.35, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 3B1. The horizontal dashed blue lines in the plot are the critical LESP values for the NACA0012 airfoil. Neither yellow or red bands are produced in this plot, which specifies that LESP does not pass or even reach to the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.36.

Firstly, at $t^*=2.2$, LESP is close to the critical value. In the corresponding DPIV image, formation of a small leading-edge vortex is detected and the stagnation point is positioned over the upper surface of the airfoil. However, this does not mean separation occur as the leading-edge vortex is very initial.

Next, at $t^*=2.4$, C_D reaches to maximum negative peak, while LESP is even closer to the critical value. Now, in the corresponding image, the leading-edge vortex is more visible, as the stagnation point moves even further away from the leading-edge on the upper surface.

At $t^*=2.73$, LESP is observed to be nearly touching to the critical value. This behavior of the LESP data is also observed in the Case 1B1, where LESP is extremely close to the critical value. However, due to the difference in digits, yellow band that indicates the initiation of separation does not appear. Moreover, in the DPIV image, the leading-edge vortex is even enlarged, as the stagnation point is still moving away from the leading-edge. With the size of this leading-edge vortex, separation is expected to occur in a later instant due to the course of the parameters.

Next, at $t^*=3.0$, leading-edge is still expanding and as expected, the flow started to separate at the leading-edge. At this instant, LESP is decreasing, while C_L reaches to maximum negative peak. However, α_{eff} is still decreasing towards the maximum negative peak.

After that, at $t^*=3.53$, α_{eff} ultimately reaches to the maximum negative peak, as $\alpha_{eff} \approx -85^\circ$. In the DPIV image, large negative vortex and detached leading-edge vortex are leaning to each other. At this instant, the flow is still fully separated.

Next, at $t^*=3.8$, LESP is decreased, while other parameters are increasing. In the DPIV image, the stagnation point is starting to move back to the leading-edge, while large

negative vortex and detached leading-edge vortex are progressing away from the airfoil.

Finally, at $t^*=5.4$, α_{eff} reaches to a maximum positive peak, while other parameters are trying to settle. In the corresponding DPIV image, the stagnation point is now located on the lower surface of the airfoil, as $\alpha_{eff} \approx 45^\circ$. Large negative vortex and detached leading-edge vortex are nearly out of the picture as the flow is in the recovery period.

In this case (3B1) and Case 1B1, the plot did not display yellow or red bands as the instantaneous LESP got extremely close to the critical LESP value. In contrast, leading-edge separation did occur and the plots did not indicate any initiation of separation. Therefore, an error band should be included for an alert system as the indication for the initiation can be faulty due to difference in small digits.

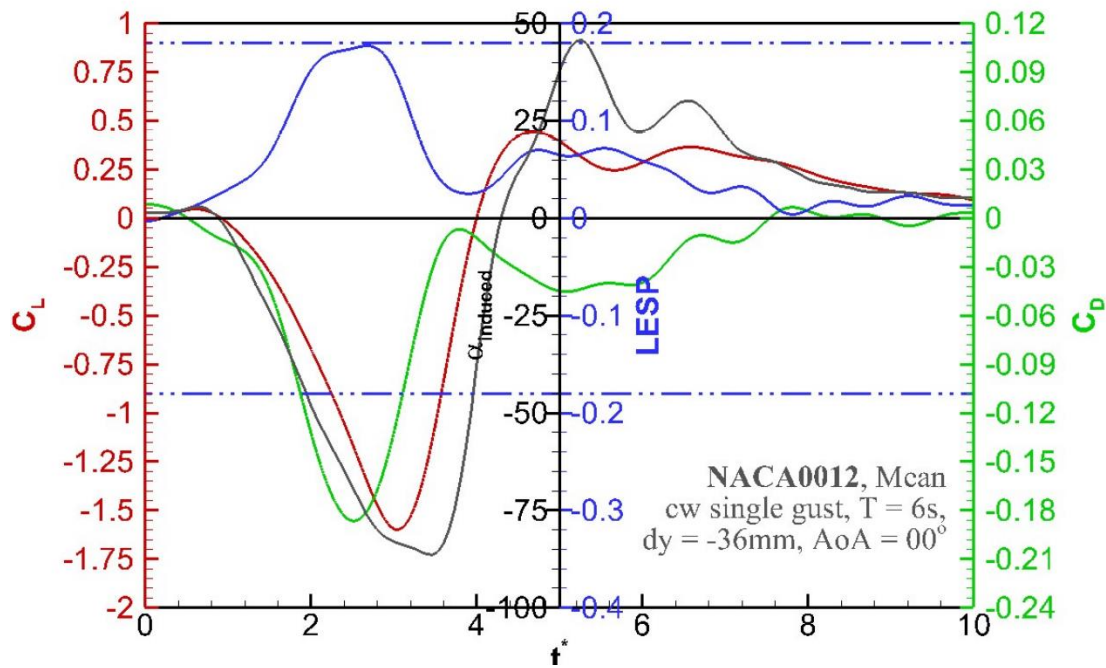


Figure 5.35 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 3B1.

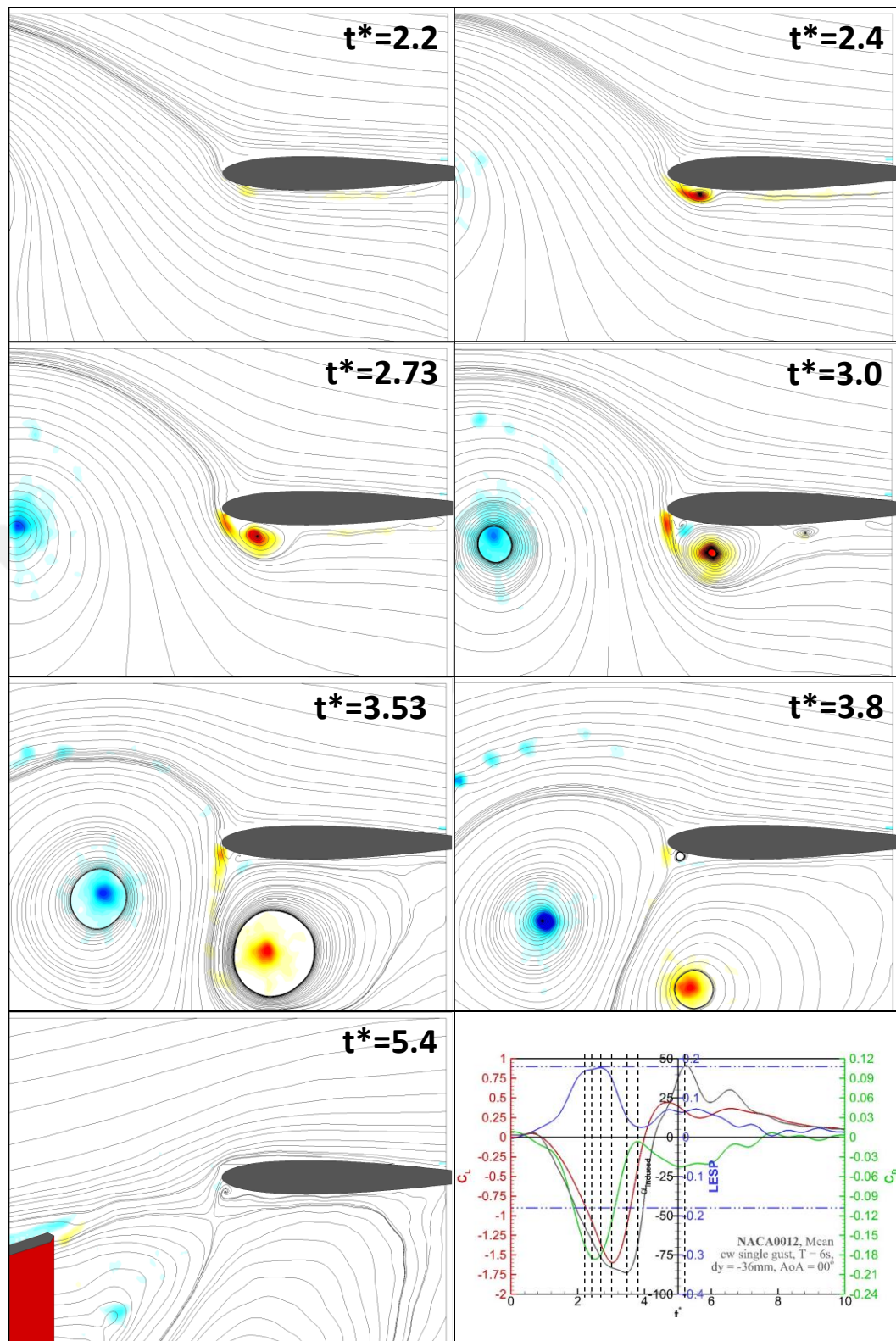


Figure 5.36 : DPIV images of selected instants for Case 3B1.

5.5.10 Case 1B2: NACA0012 $\Delta y = -111$ mm, $T = 4$ [s/($\frac{1}{2}$ rev)]

In Figure 5.37, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 1B2. The horizontal dashed blue lines in the plot are the critical LESP values for the NACA0012 airfoil. Neither yellow or red bands are produced in this plot, which specifies that LESP does not pass or even reach to the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.38. Throughout this case, LESP does not come closer to the critical value, even at the positive and negative maximum peaks. Therefore, no flow separation at the leading-edge is expected.

At $t^*=1.6$, in the corresponding DPIV image, the stagnation point is moving on the upper surface of the airfoil, away from the leading-edge, which corresponds to the decrease in the α_{eff} . Also, while LESP is increasing, no formation of leading-edge vortex is detected.

Next, at $t^*=2.0$, LESP reaches maximum positive peak, while C_D reaches maximum negative peak. Even with the maximum value, LESP is not far-off from the critical value. As expected, in the corresponding DPIV image, still no initiation of leading-edge vortex, hence, there is no indicator for a later on separation.

At $t^*=2.4$, LESP is decreasing, while C_L reaches maximum negative peak. In the DPIV image, the stagnation point is moving towards to leading-edge as α_{eff} is starting to increase after reaching to maximum negative peak at $\alpha_{eff} \approx -35^\circ$. At this instant, vorticity is slightly increased on the lower surface of the airfoil. However, the development of this vortex is not located at the leading-edge.

Then, at $t^*=3.0$, LESP and C_D intersects at zero, whereas C_L and α_{eff} are increasing. In the DPIV image, previously detected vortex is clearly formed, however, it is located approximately at the maximum thickness location of the airfoil. Therefore, no leading-edge separation is expected, with the course of the flow in this case.

At $t^*=3.53$, LESP reaches to the maximum negative peak and it even more away from the critical value than the maximum positive peak. In the DPIV image, the vortex is detached and the flow is separated near the trailing-edge. This type of separation is not crucial, as it will not cause dynamic stall with the course of the flow in this case. Thus, it is not deemed important.

Next, at $t^*=3.93$, LESP and C_D intersects at zero again, while C_L and α_{eff} are still increasing. In the DPIV image, the stagnation point is now moved under the leading-edge mid-point, which corresponds to the increase in α_{eff} . The flow that had separated near the trailing-edge is now nearly fully attached to the surface.

Finally, at $t^*=4.8$, LESP reaches to a second positive peak and in the DPIV image, no vortex formation is observed. Also, at this instant, C_L and α_{eff} reaches to their maximum positive peaks, as $\alpha_{eff} \approx 40^\circ$. After this instant, the stagnation point will move back to the leading-edge, as the flow fully recovers and the parameters will settle.

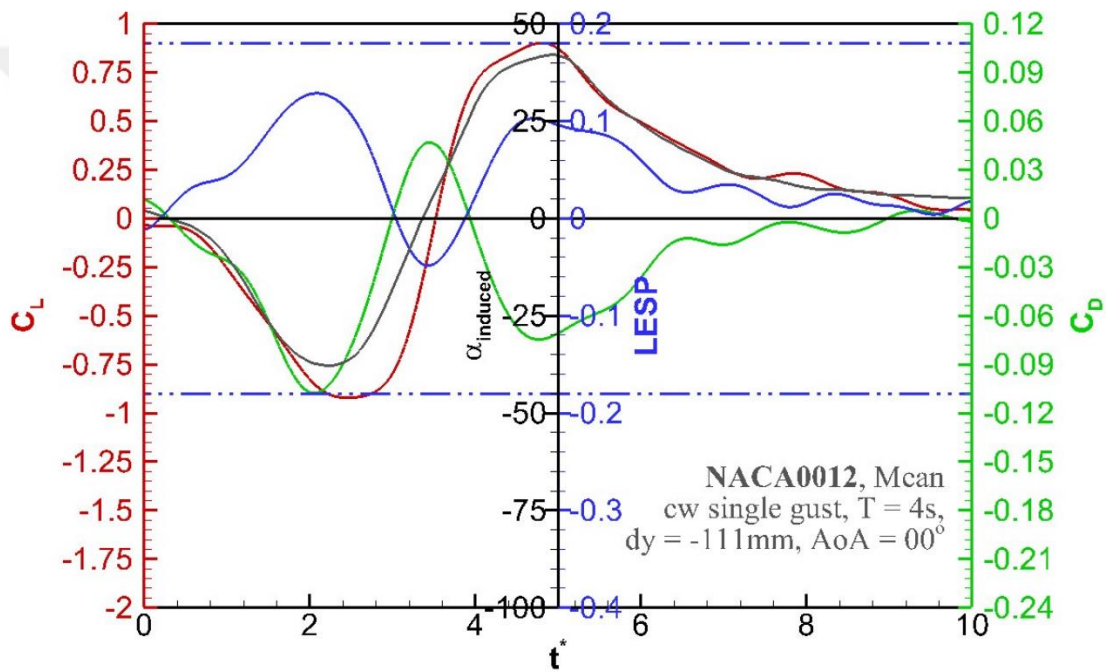


Figure 5.37 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 1B2.

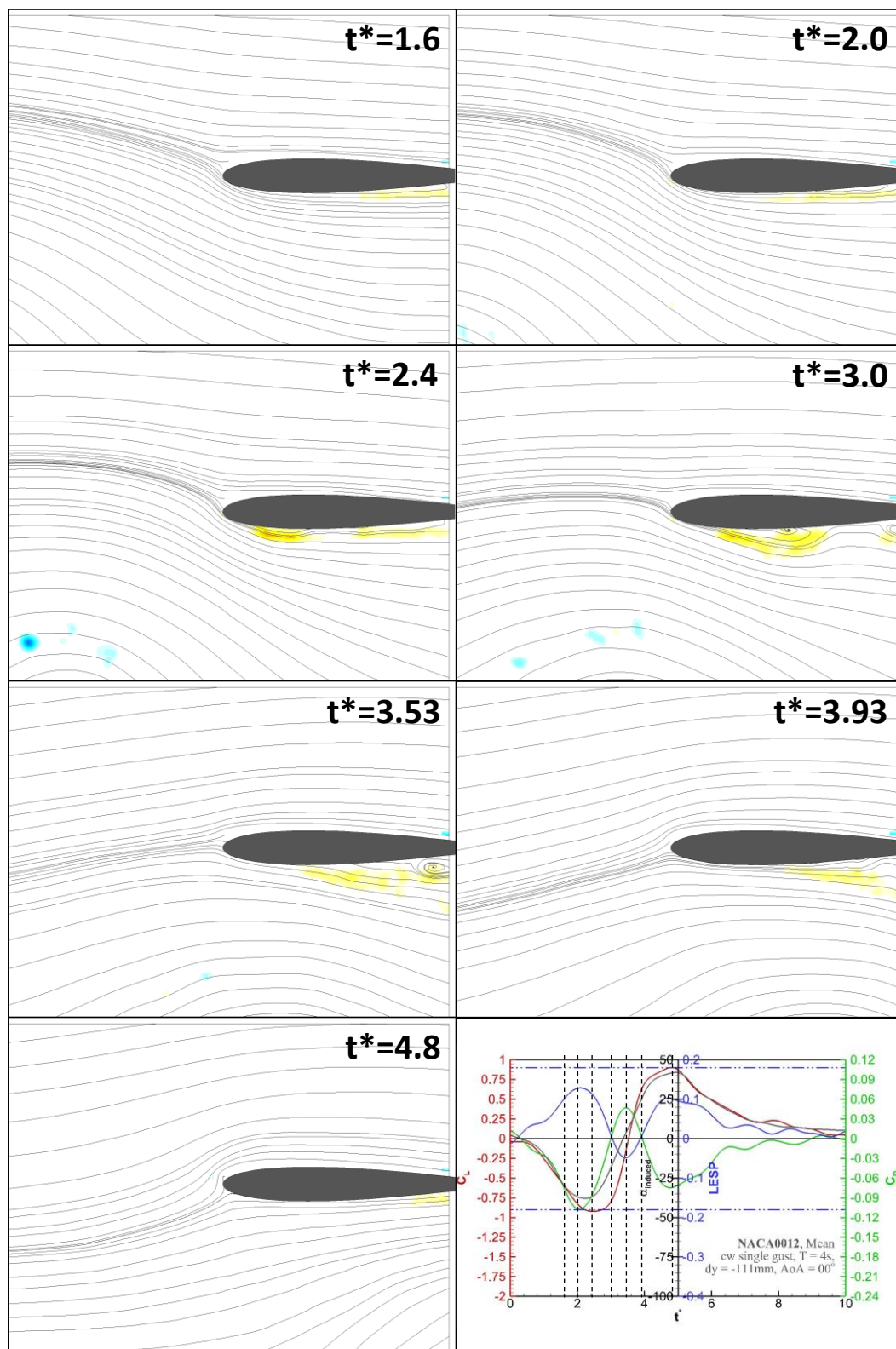


Figure 5.38 : DPIV images of selected instants for Case 1B2.

5.5.11 Case 2B2: NACA0012 $\Delta y = -111$ mm, $T = 3$ [s/(1/2rev)]

In Figure 5.39, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 2B2. The horizontal dashed blue lines in the plot are the critical LESP values for the NACA0012 airfoil. Neither yellow or red bands are produced in this plot, which specifies that LESP does not pass or even reach to the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.40. Similar to Case 1B2, during this case, LESP does not come closer to the critical value, even at the positive and negative maximum peaks. Therefore, no flow separation at the leading-edge is expected.

At $t^* = 1.6, 1.8$, and 2.0 , LESP is near the maximum positive peak, while C_L , α_{eff} , and C_D are near their maximum negative peaks. For their corresponding DPIV images, no leading-edge vortex is detected at any of these three instants. Even though LESP is at its highest, it is still far away from the critical value, which is why no leading-edge vortex is formed. Therefore, the flow is not expected to separate at the leading-edge. The only difference between the images are the increased vorticity on the lower surface of the airfoil. However, these vorticity levels are not enough to develop separation at the leading-edge. Additionally, the stagnation point is located at the upper surface of the airfoil, which corresponds to the maximum negative value of effective angle of attack, $\alpha_{eff} \approx -35^\circ$.

Next, at $t^* = 2.8$, LESP and C_D intersects at zero, while they are respectively decreasing and increasing. In the DPIV image, vorticity levels after approximately maximum thickness location of the airfoil is more intense compared to the previous instant. However, even than the only effect is slight disturbances, as there is no formation of a full vortex. Also, the stagnation point is progressing towards the leading-edge, as α_{eff} and C_L are increasing.

At $t^* = 3.2$, LESP reaches to maximum negative peak, however, it is even more away from the critical value than the maximum positive peak. In the DPIV image, the flow is still slightly fluctuation near the trailing-edges but there is no full separation detected. In Case 1B2, the disturbances near the trailing-edge had caused clear vortices and separation, however, even that is not considered important as it is not at the leading-edge. Therefore, in this case, these small disturbances on the flow are insignificant.

Next, at $t^*=3.6$, from the DPIV image it is observed that the flow is recovering around the airfoil as the stagnation point positioned nearly at the leading-edge mid-point. The α_{eff} increases at this instant, as the flow is slightly tilted. Additionally, LESP is increasing after the maximum negative peak.

Finally, at $t^*=4.2$, LESP and C_D are settled, whereas α_{eff} and C_L are on the way to settling. In the corresponding image, the flow is nearly symmetrical around the airfoil, which shows the recovery. Only the stagnation point is slightly shifted under the mid-point of the leading-edge, which explains the positive α_{eff} .

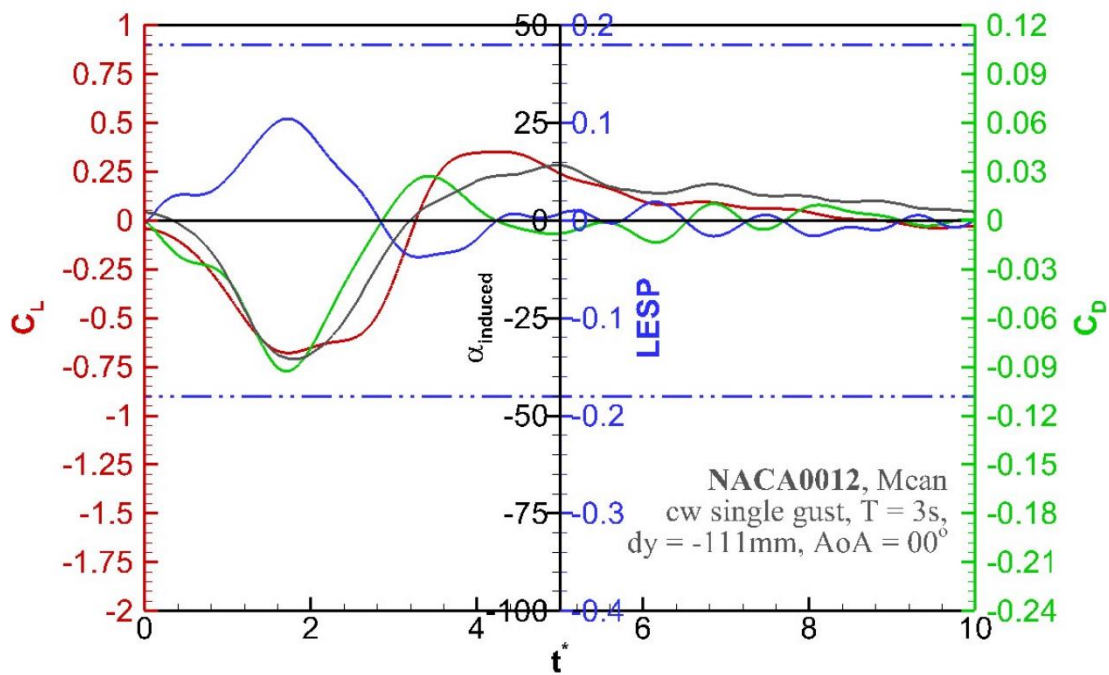


Figure 5.39 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 2B2.

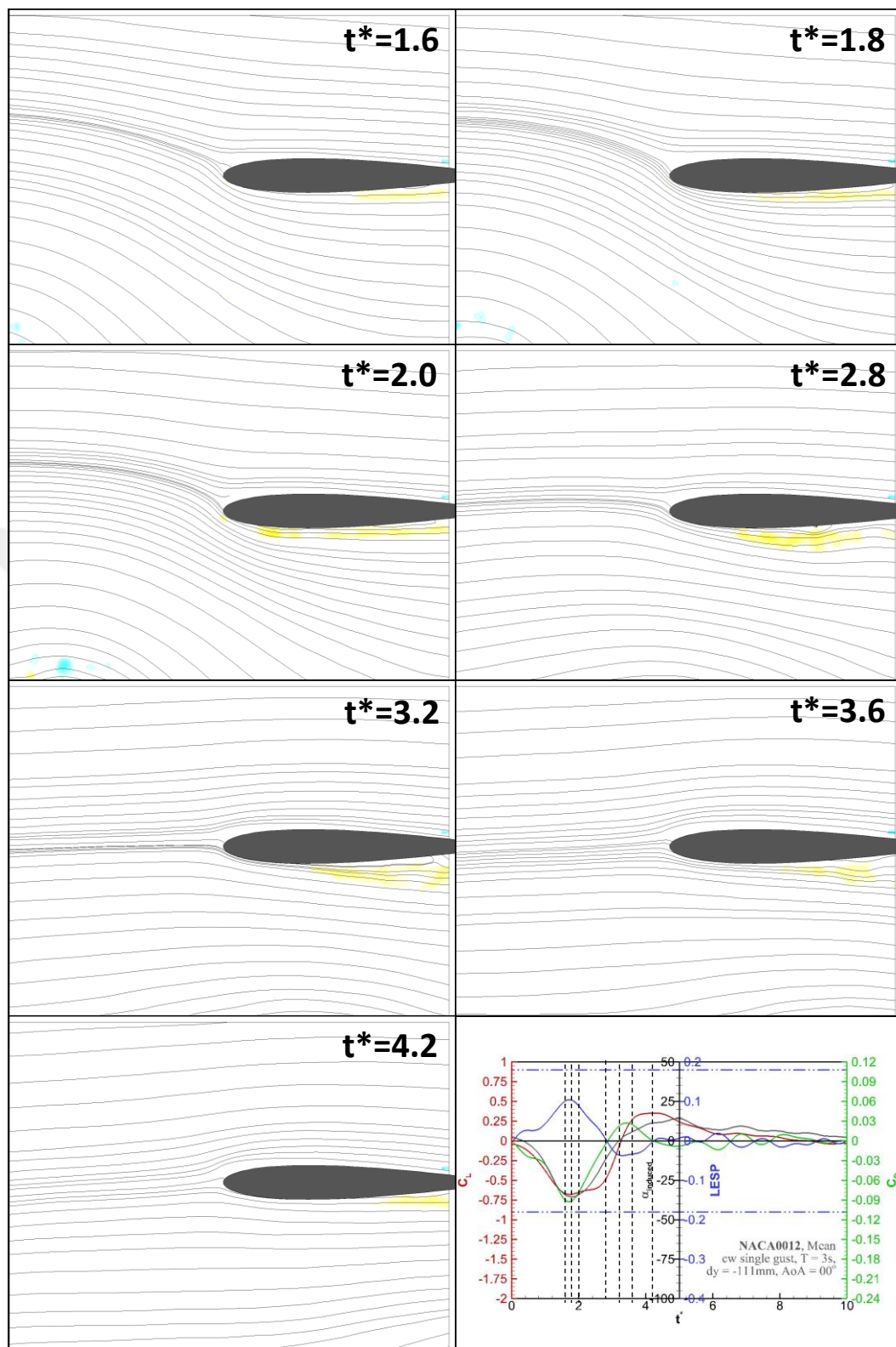


Figure 5.40 : DPIV images of selected instants for Case 2B2.

5.5.12 Case 3B2: NACA0012 $\Delta y = -111$ mm, $T = 6$ [s/($\frac{1}{2}$ rev)]

In Figure 5.41, comparisons of C_L , C_D , LESP, and α_{eff} are given for Case 3B2. The horizontal dashed blue lines in the plot are the critical LESP values for the NACA0012 airfoil. Yellow band is the region where LESP is at or over the critical LESP value. Significant instants are determined from the plot to compare the results with the corresponding DPIV images, which are given in Figure 5.42.

Firstly, at $t^* = 2.6$, LESP reaches maximum positive peak but, it is away from the critical LESP. In the corresponding DPIV image, formation of a leading-edge vortex is slightly observed from the vorticity levels, even though streamlines are not twisting. By looking at this instant, flow separation is not expected as the instantaneous LESP does not reach to the critical and it is not even considered close.

However, at $t^* = 3.4$, in the DPIV image, there is a very clear formation of a vortex. The reason of LESP not indicating initiation of separation can be due to the location of the formed vortex. Compared to the other formed vortices in previous cases, the leading-edge vortex is a lot closer to the leading-edge, and in this case this vortex is positioned behind the maximum thickness of the airfoil.

At $t^* = 4.0$, LESP reaches to maximum negative point, but similar to the previous maximum peak, it is away from the critical value. In the DPIV image, there is no formation of a new vortex and the former vortex is detached. Even though LESP still does not indicate separation, the flow is separated. However, compared to the other cases, the separation starts on the lower surface of the airfoil and slightly away from the leading-edge. In the previous images, the stagnation point started locating on the over surface of the airfoil, however, after α_{eff} passed the maximum negative peak, the stagnation point moved back to the leading-edge.

Now, at $t^* = 5.33$, the flow is fully reattached as the stagnation point is now located on the lower surface of the airfoil. Additionally, at this instant, LESP reaches to the critical value which indicates the initiation of flow separation at the leading-edge. In the corresponding image, formation of a leading-edge vortex is observed as the streamlines are pushed against each other with a curvature.

Next, at $t^* = 5.53$, the leading-edge vortex is more detectable from the vorticity levels. At this instant, LESP and C_L reach to maximum positive peaks, while C_D reaches to maximum negative peak. α_{eff} is also approaching to its maximum positive peak and

the stagnation point is farther away from the leading-edge as it is located on the lower surface of the airfoil.

At $t^*=5.8$, LESP reaches to critical value one last time as it is decreasing. In the DPIV image, leading-edge vortex is nearly detached and the flow is nearly separated, even though it reattaches just after the vortex.

Finally, at $t^*=6.2$, effective angle of attack reaches to maximum positive peak, $\alpha_{eff} \approx 72^\circ$, whereas the other parameters are progressing to settle. In the DPIV image, the leading-edge vortex is detached and the flow is even more separated as it reattaches after the mid-point of the chord. After this instant, the stagnation point will move back to the leading-edge as the flow recovers.

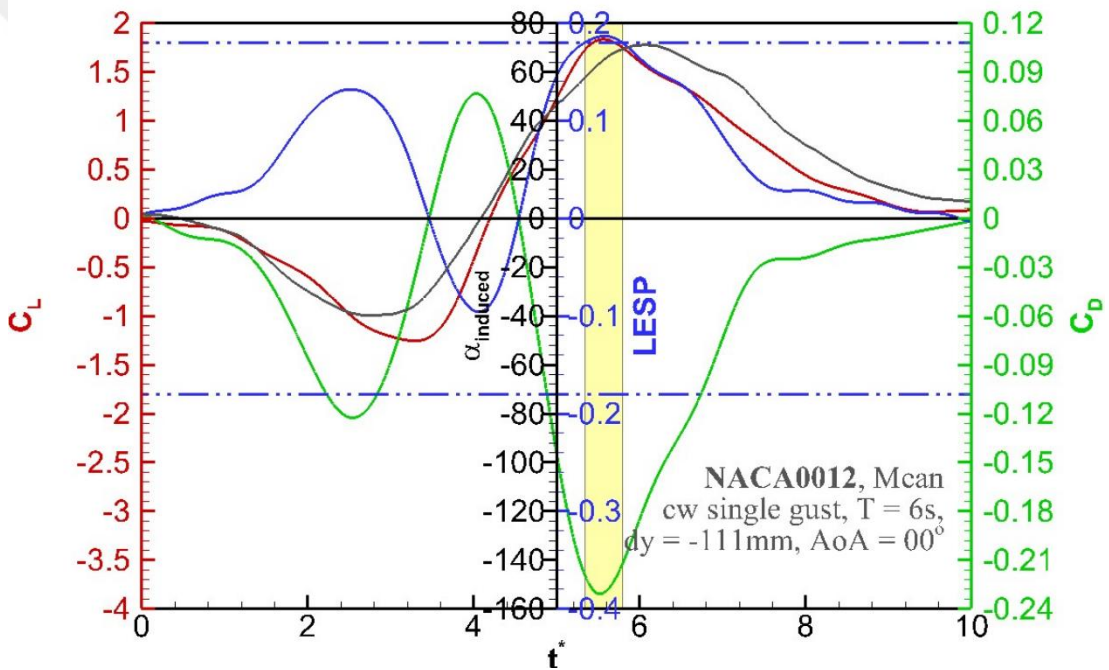


Figure 5.41 : Comparison of C_L , C_D , LESP, and α_{eff} for Case 3B2.

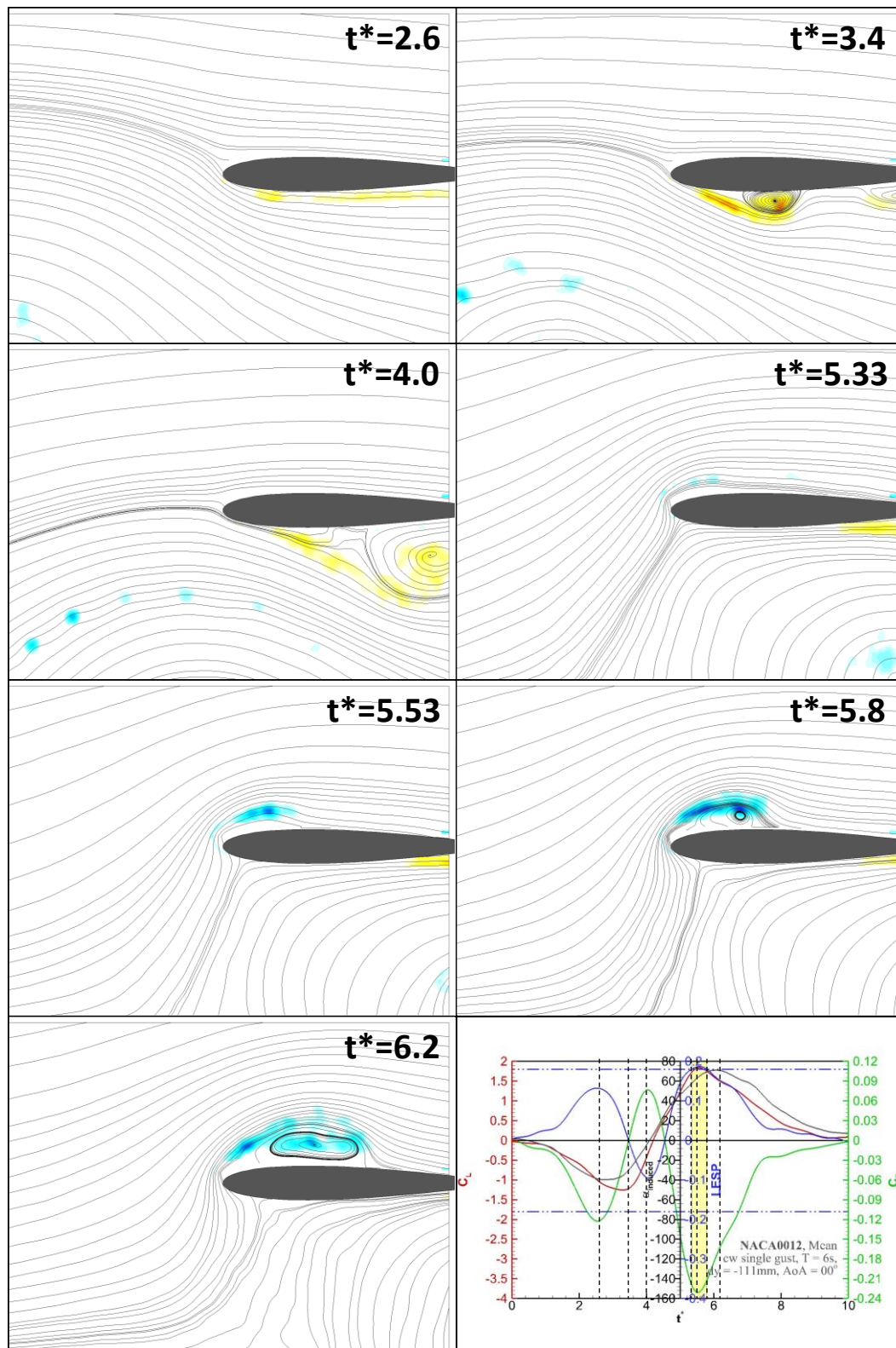


Figure 5.42 : DPIV images of selected instants for Case 3B2.

5.6 $C_L - \alpha_{eff}$ Correlation & Time Shift

In Section 5.4, the calculation of the effective angle of attack is given and in Section 5.5, effective angle of attack results are compared with lift coefficient, drag coefficient, and LESP results. However, there is a phase difference in time between the effective angle of attack results and aerodynamic coefficients. This difference arises because the effective angle of attack is calculated at pre-determined area located 10 mm in front of the leading-edge, before the flow reaches the wing models. In contrast, the aerodynamic coefficients are obtained from sensors mounted on the leading-edge of the wing. Therefore, the effective angle of attack results had to be shifted according to this distance and the gust propagation speed. In Section 5.4, it is explained that the calculation region is determined based on the $C_L - \alpha$ correlation. In this section, new results are obtained by including the time shift in the $C_L - \alpha$ correlation analysis. The best correlation is achieved for a gust propagation speed of 0.05 m/s. Considering the 10 mm distance between the center of the calculation area and leading-edge, the effective angle of results are shifted by 0.2 seconds (200 ms).

In Figure 5.43 and Figure 5.44, comparisons of shifted α_{eff} results with C_L results are given for all flat plate and NACA0012 cases, respectively. In all NACA0012 cases, the effective angle of results now display a better match with C_L results, as the time phase is decreased, significantly from the initiation of the initial positive peak until the maximum negative peak. Achieving matching results between the first initial increase and decrease periods is crucial for gust mitigation. Case 1B1, has the best correlation rate and compared to the other NACA0012 cases the convergence between effective angle of attack and C_L is highest. On the other hand, in all flat plate cases, the results are observed to not be as well-converged great as in the NACA0012 cases. Between the first initial increase and decrease periods, the effective angle of attack results shift towards the C_L results, similar to the NACA0012 cases. However, despite having high correlation rates, the same level of convergence is not observed. Moreover, the fluctuations in the effective angle of attack results from case 3A1 are very different from the C_L results, even though the correlation rate is high. This difference is also evident in the non-shifted results, but it became more significant in this section due to the high convergence rate.

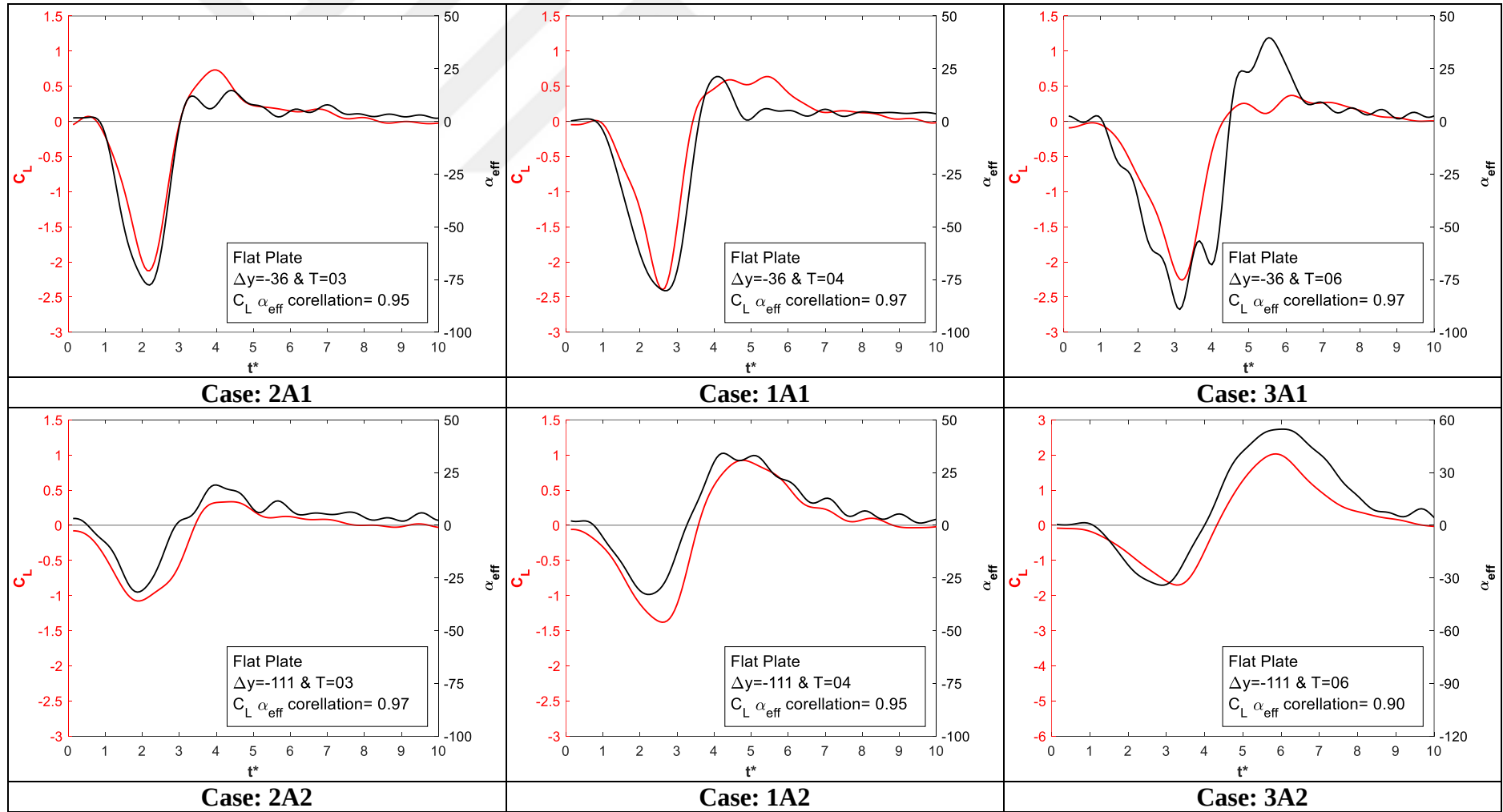


Figure 5.43 : Comparisons of shifted α_{eff} results with C_L results for all flat plate cases.

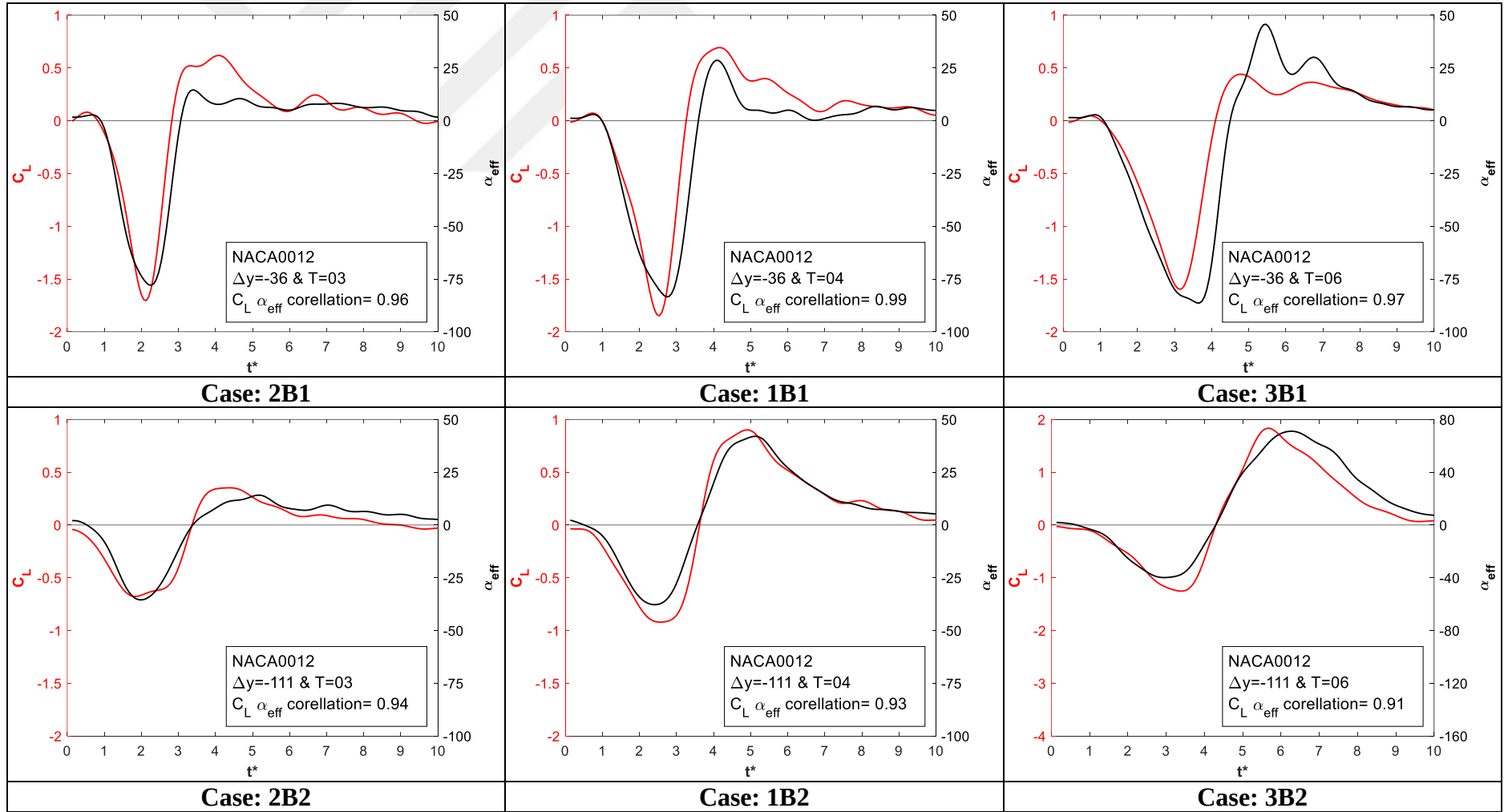


Figure 5.44 : Comparisons of shifted α_{eff} results with C_L results for all NACA0012 cases.



6. CONCLUSIONS

In this study, lift force, drag force, LESP, and effective angle of attack parameters are analyzed to investigate and to determine the most accurate and practical indicator for the initiation of flow separation at the leading-edge, during vortex gust encounters. Primarily, experimental method is used for this investigation, which includes measuring forces acting on wing models and using DPIV technique for flow visualization and vector field analysis. Additionally, computational method is used to prove applicability and accuracy of the total force measurements from experimental method conducted in this study. From CFD analysis, pressure and shear stress distributions around mid-span and quarter-span cross sections of the wing models are obtained, along with total lift and drag forces acting on the wing models. Sectional lift and drag forces are calculated from the sectional pressure and shear stress distributions. To validate applicability of total force measurements, sectional lift and drag forces from CFD are compared with total forces obtained from both Computational Fluid Dynamic (CFD) and experimental studies. This initial analysis is conducted only for base cases of flat plate and NACA0012 wing models. According to the outcome, the main analysis on prediction of the flow separation initiation is conducted for both flat plate and NACA0012 wing models under various gust encounter cases with the variations of half rotation period of the vortex gust and cross-flow distance between the vortex gust and wing model.

Most important findings of the initial analysis about the comparison of sectional and measured forces are given as follows :

- For the CFD mid-span and quarter-span sectional lift and drag results of flat plate, sectional results for $x/c=1.00$ integration point, among various integration points, showed the highest similarity with the total lift and drag acting on the flat plate from CFD analysis.
- For the CFD mid-span and quarter-span sectional drag results of NACA0012, sectional results for $x/c=0.30$ integration point (maximum thickness location),

among various integration points, showed similarity with the total drag acting on the NACA0012 from CFD analysis.

- In the comparison of CFD sectional, CFD total, and experimental total lift and drag results of both flat plate and NACA0012, a notable degree of similarity between all of them is detected. The magnitude differences between the experimental and CFD results are observed to be in the sensor uncertainty range.
- Between the CFD mid-span and quarter-span sectional lift and drag results of both flat plate and NACA0012, quarter-span sectional results are observed to be the most converged with the total experimental and CFD results.
- In the CFD sectional drag results of flat plate, the results do not converge until the trailing-edge is included to the integration. On the other hand, in the CFD sectional lift results of flat plate, an evolution is observed as the integration point progress towards the trailing-edge and the results nearly converge even without including the trailing-edge. This is explained with pressure being dominant to shear stress in this study. Moreover, for NACA0012, due to the geometric shape of the airfoil, in both sectional lift and drag results, evolution is observed as the integration point progress towards the trailing-edge.
- Three-dimensionality effect of the flow is observed approximately four seconds after the gust generator starts rotating, which corresponds to the significant differences between the mid-span and quarter-span sectional results.
- C_f results from CFD mostly matched with the experimental flow structures, as the peaks from the upper and lower surface C_f results coincide with the vortices over the wing models. The formation of a leading-edge vortex can be detected from the peaks from the C_f data.

In conclusion, the results of this initial analysis showed a strong correlation between sectional results calculated from pressure and shear stress distribution, and the forces acting on the wing. This outcome supports the proposal of utilizing direct measurements of forces acting on the wing rather than pressure data, to calculate LESP. Based on these results, a comprehensive research on the prediction of flow separation using indicators including LESP is conducted by using direct measurements of forces.

Major findings of the main analysis on prediction of the flow separation initiation are given as follows:

- The stagnation point is directly related to the effective angle of attack, therefore C_L , as it is proportional to the effective angle of attack.
- Effective angle of attack and C_L results behave similarly. Phase difference between the results is removed between the initiation of the initial positive and maximum negative peak periods by shifting the effective angle results 200 ms based on the $C_L-\alpha_{eff}$ correlation.
- When the stagnation point is positioned on the upper surface of the wing model, both the effective angle of attack and C_L are negative values. Furthermore, the leading-edge vortex forms over the lower surface of the wing. In contrast, when the stagnation point is positioned on the lower surface of the wing model, both the effective angle of attack and C_L are positive values, while the leading-edge vortex forms over the upper surface of the wing.
- LESP and C_D results are mostly symmetrical, as the LESP value is calculated from the measured axial force, which is equivalent to negative direction of the drag force.
- The development of the leading-edge separation can be described as follows: Initially, the stagnation point moves away from the leading-edge. Subsequently, a leading-edge vortex begins to form, which is located at the opposite surface from the stagnation point. As the leading-edge vortex expands, it eventually detaches or gets large enough that the flow separation occurs at the leading-edge.

The following conclusions about flow separation prediction using LESP are summarized in Table 6.1, which includes all cases.

- In most of the cases LESP accurately detected the initiation of the flow separation at the leading-edge, when the instantaneous LESP reached to the critical LESP value for both wing models.
- In one case (3B1), the initiation of flow separation could not be accurately indicated by the LESP method. This occurred when the instantaneous LESP came very close to the critical value but due to the differences in the numerical precision,

it is not displayed on the plots. However, from the PIV images, leading-edge flow separation is observed.

- In addition to the lack of detection of separation initiation, there is a case (1B1) where LESP displayed late detection as the leading-edge vortex is already formed, which is considered as an indication of the flow separation initiation.
- In four of the cases (3A1, 2A2, 1A2, & 3A2), after the formation of leading-edge vortex over the lower surface of and flow separation at the leading-edge, instead of recovering, another leading-edge vortex forms over the upper surface, which lead to another separation at the leading-edge in two of the cases (3A1 & 3A2).
- In two of the cases from NACA0012 (2B2 & 1B2), no separation is detected from LESP and leading-edge flow separation did not actually occur as the leading-edge vortex is never formed, while the stagnation point moved away from the leading-edge. Therefore, the location of the stagnation point not always corresponds to the flow separation at the leading-edge.
- The variations with approaching location and strength of the vortex gust effects the formation of the leading-edge vortices and possibility of the leading-edge separation. With the increase of the half rotation period (T), the time when the flow separation initiation, leading-edge vortex formation, is observed increases. Furthermore, with the increase of the cross-flow distance ($|\Delta y|$), upper leading-edge vortex formation is observed.
- During the flat plate cases, flow separation always occurred, whereas in two of the NACA0012 cases (2B2 & 1B2), not even leading-edge vortex is formed.

In conclusion, out of every parameter that is investigated, LESP is the most accurate one to indicate the initiation of flow separation at the leading-edge, even though some exceptions are observed. Since measuring axial force is practical in real-life and it is proved that LESP can be calculated using axial force, this method can be applied to air vehicles to detect initiation of flow separation at the leading-edge.

In the future work, this study can be continued and improved with additional different gust conditions and variations of geometric angle of attack for the wing model. Furthermore, it is important to establishing an error band or tracking the rate of LESP to prevent instances where LESP displayed late detection or failed to detect the separation initiation altogether due to differences in numerical precision. Pressure data

from specific locations on or close to the leading-edge with respect to time can be investigated as another flow separation prediction parameter. Since the pressure and shear distributions along the surfaces of the wing models matches with vortex formations, pressure and shear distributions with time for fix points have a chance to indicate formation of vortices and therefore initiation of flow separation. Lastly, error band for drag coefficient has to be determined considering the averaging of five runs during the post process, since the sensor uncertainty is extremely high for drag coefficient in this type of gust encounter research.



Table 6.1 : Summary of flow separation prediction results based on LESP for all cases.

	Flat Plate						NACA0012					
Δy	-36			-111			-36			-111		
T	03	04	06	03	04	06	03	04	06	03	04	06
Case Name	2A1	1A1	3A1	2A2	1A2	3A2	2B1	1B1	3B1	2B2	1B2	3B2
LESP Alert ($LESP(t) \geq LESP_{crit}$)	x2	x2	x3	x2 (very close)	x1 (late)	x2	x1	x1 (late)	NO (nearly)	NO	NO	x1
Stagnation point	up	up	up & low	up & low	up & low	up & low	up	up	up	up	up & low	up & low
LEV initiation	x2 low nd (2 nd small)	x2 low nd (2 nd small)	x2 low & x1 up (2 nd small)	x1 low & x1 up	x1 low & x1 up	x1 low & x1 up	x1 low	x1 low	x1 low	-	-	x1 up
Separation at LE	x1 low	x1 low	x1 low & x1 up	x1 low (no full detach)	x1 low (no full detach)	x1 low & x1 up	x1 low	x1 low	x1 low	- (near TE)	- (near TE)	x1 up

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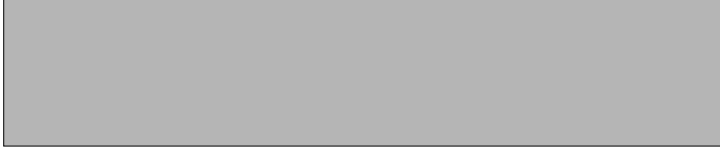
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OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

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