

Infrared Thermography Imaging of an Unsteady Laminar Separation Bubble on a NACA 0018 Pitching Airfoil

Alex Zanotti*, Matteo Poletti and Luca Riccobene

Department of Aerospace Science and Technology, Politecnico di Milano, Italy

*Corresponding author: alex.zanotti@polimi.it

Keywords: Infrared Thermography, Laminar Separation Bubble, Airfoil, Unsteady Aerodynamics, Imaging.

ABSTRACT

This study investigates the dynamics of a Laminar Separation Bubble (LSB) on a NACA 0018 airfoil at low Reynolds numbers, comparing steady-state conditions with sinusoidal pitching motions to enhance aerodynamic performance characterization. By employing Infrared Thermography (IRT) and its unsteady extension, Differential Infrared Thermography (DIT), the research identifies the critical separation, transition, and reattachment points that define the LSB structure. Wind tunnel tests were conducted at Politecnico di Milano utilizing a 3D-printed model and a high-sensitivity FLIR A6781 SLS camera to capture time-resolved thermal footprints under varying reduced frequencies, oscillation amplitudes, and Reynolds numbers. The analysis, processed through custom mapping and dewarping algorithms, reveals a significant hysteresis in the bubble's position during the pitching cycle, where the lag between upstroke and downstroke phases increases linearly with pitch rate and amplitude. While steady-state IRT remains a benchmark for validation, this work highlights that DIT is a robust, non-intrusive diagnostic tool capable of tracking the transient behavior of transition and reattachment points, providing an essential framework for validating numerical tools and understanding complex boundary layer phenomena in unsteady aerodynamic applications.

1. Introduction

The transition from laminar to turbulent boundary layer (BL) is of critical importance regarding aerodynamic performance of an airfoil. Indeed, a laminar flow which extends for as much chord length as possible enables to reduce viscous drag and therefore reduce fuel or power consumption. The determination of boundary layer transition is particularly challenging in low-speed wind tunnel experiments, as for airfoils operating at low Reynolds numbers and characterized by large thickness, transition takes place over a Laminar Separation Bubble (LSB) (Cole & Mueller, 1990)). A LSB is a three-dimensional aerodynamic feature consisting in a pocket of stagnant, recirculating flow. In a two-dimensional slice, as represented in Fig. 1, the LSB begins at the *laminar separation point* due to an adverse pressure gradient, then a laminar shear layer is created. Due to instability

and disturbance growth, the laminar shear layer transitions into a turbulent one at the *transition point*. Eventually the turbulent shear layer reattaches to the surface at the *reattachment point* and an attached boundary layer is developed.

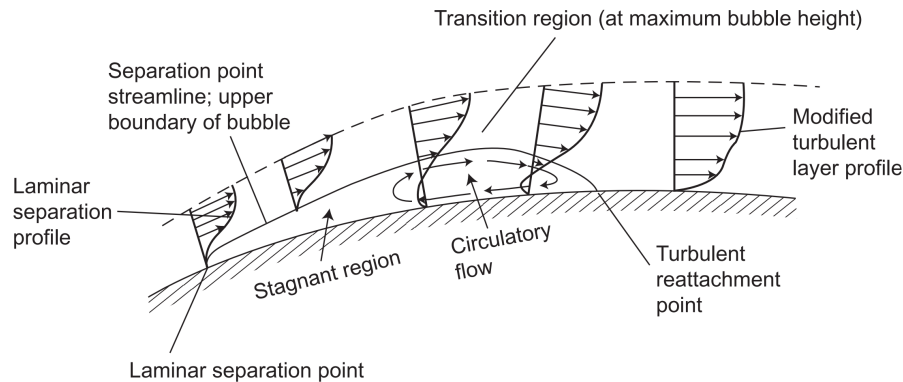


Figure 1. Representation of a laminar separation bubble (LSB), from Houghton et al. (2017).

Transition to turbulence occurs in the separated shear layer, thus it is essential to correctly identify the points of separation and reattachment of the flow of the suction side of the airfoil. For these reasons, an accurate experimental evaluation of the characteristic transition points positions related to the occurrence of a LSB represents an essential aspects for the characterization of the airfoil performance, as well as for validating and calibrating numerical prediction tools.

Infrared thermography (IRT) (Astarita & Carlomagno, 2012) is an imaging non-intrusive technique that has been reliably used to detect laminar-to-turbulent BL transition in stationary flow conditions (Wolf et al., 2020). Recent studies by Wynnchuk & Yarusevych (2020) and Grille Guerra et al. (2023) investigated systematically the position of the three LSB key characteristics points on an stationary airfoil by combining the use of IRT with Particle Image Velocimetry (PIV). Differential Infrared Thermography (DIT) technique (Raffel & Merz, 2014) enabled to extend successfully the application of IRT to unsteady flow conditions (Richter & Schulein, 2014). DIT represents an extension of the classical IRT approach and is based on the subtraction of two thermal images captured at two different angle of attack of the airfoil.

The present work is aimed at extending to unsteady periodical flow conditions the investigation by Wynnchuk & Yarusevych (2020) of the LSB occurrence on a NACA 0018 airfoil by means of Differential Infrared Thermography (DIT).

2. Experimental setup

A dedicated pitching airfoil test rig was designed and installed at the Green Wind Tunnel of the Aerodynamics Laboratory of the Department of Aerospace Science and Technology of Politecnico di Milano. The wind tunnel test section measures 1000 mm (length) $\times$ 300 mm (width) $\times$ 450 mm

(height) and the maximum flow velocity achievable is 36.5 m s^{-1} with turbulence level below 0.35%. The complete setup of the IRT experiments on the pitching airfoil test rig is shown in Fig. 2.

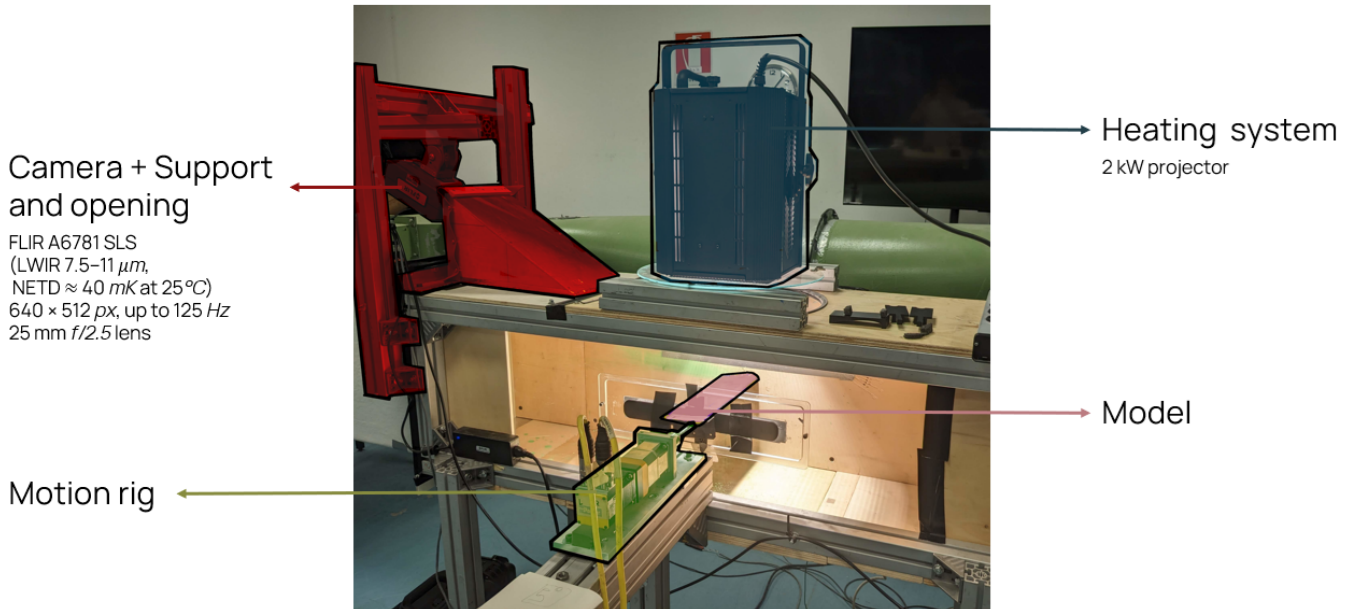


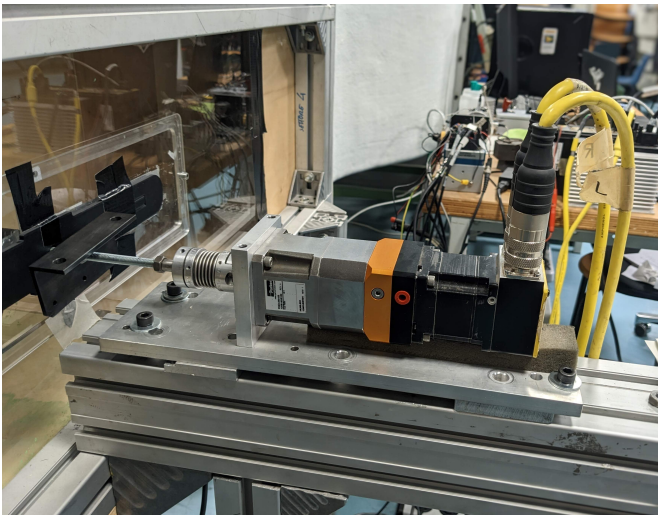
Figure 2. IRT experimental set-up on pitching airfoil test rig.

The airfoil model consists of a straight rectangular wing featuring a NACA 0018 airfoil, with chord $c = 100 \text{ mm}$ and span $b = 300 \text{ mm}$. It is manufactured with 3D printing using Acrylonitrile Styrene Acrylate (ASA) filament. In order to minimize reflections during the experiments, the model has been coated with a black matte paint. The airfoil surface includes 8 equally spaced fiducial markers of diameter $d = 5 \text{ mm}$ made with aluminium tape (see Fig. 3). A dedicated motion system was specifically designed and employed for these tests to perform sinusoidally pitching cycles of the airfoil around its quarter chord. The motion system was mainly composed by a servomotor coupled with a 40:1 gearbox (see Fig 4a). A pitching motion control routine based on angular feedback of the airfoil coming from the encoder built within the servomotor was implemented in *LabVIEW*.

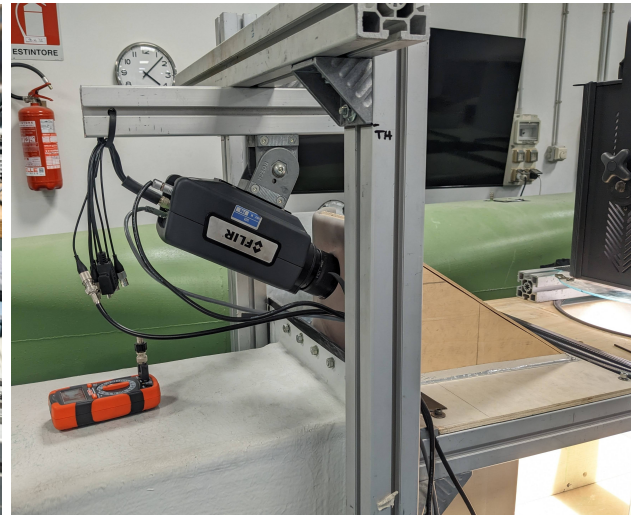
A 2 kW Fresnel projector was used to guarantee a constant heat flux through the tempered glass on the ceiling of the test section. The projector was placed with its internal lamp at 490 mm height above the airfoil model and provided a chordwise constant temperature increase of the model surface of 8–10 K. Image acquisition was performed using a FLIR A6781 SLS long-wave infrared camera (LWIR) that feature a cooled strained-layer superlattice detector that operates in the 7.5–11 μm spectral range. The thermal sensitivity is limited by a noise-equivalent temperature difference of 40 mK at 25°. The device has a maximum resolution of 640 $\times$ 512 px with a frame rate of up to 125 Hz at full resolution. The camera was installed externally at the end of the test section and was held by a support system composed by a modular structure consisting of four aluminium frames



Figure 3. NACA 0018 airfoil model with fiducial markers and support.



(a) Servomotor coupled with gear-box



(b) LWIR Infrared Camera

Figure 4. Particulars of the motion and imaging systems.

and an adjustable mount (see Fig 4b). This design allows adjustment of the height, horizontal position and viewing angle in order to achieve the desired Field of view (FOV) that covered the area over the airfoil upper surface of the model.

3. IRT Image Analysis

The thermal images were analyzed by an in-house MATLAB code implementing DIT technique developed by Tomasello (2024) and improved by Poletti (2025). The code enabled to map the images onto a three-dimensional grid by automatically detecting the fiducial markers (see Fig. 5a) and to dewarp the viewed upper model into a 2D surface (see Fig. 5b). Then, a region of interest (ROI) was selected from the dewarped thermal image to exclude tridimensional aerodynamic

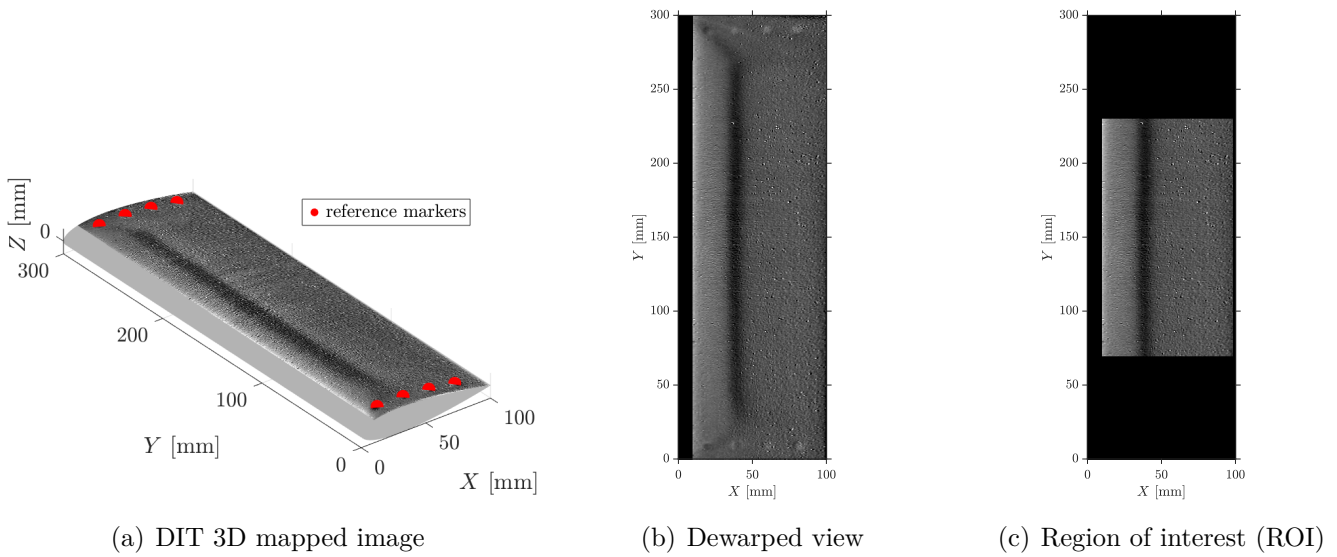


Figure 5. Sample DIT thermal image post-processing.

feature or local non uniformities that could compromise the reliability of the results (see Fig. 5c).

The distributions of the chord-wise temperature variation intensity ΔT extracted along the ROI surface span were averaged and smoothed to obtain a single chord-wise intensity profile. The LSB characteristic points location can be evaluated from the DIT ΔT intensity profile as suggested by Grille Guerra et al. (2023). In particular, for steady state airfoil conditions, the separation point can be identified in correspondence of the maximum peak of ΔT profile, the transition point at the minimum peak ΔT , while the reattachment point is found where ΔT changes sign (see Fig. 6a).

On the other hand, the DIT chord-wise ΔT intensity profiles obtained for unsteady pitching motion conditions show the maximum peak at the airfoil trailing edge coordinate, as shown by the sample profile evaluated by the present measurements depicted in Fig. 6b. This outcome is in accordance with the results obtained by Wolf et al. (2019), thus suggesting that the method for identifying the LSB separation point from DIT in steady state conditions could be inadequate. Therefore, the goal of the present DIT measurements was to evaluate the effect of pitching motion amplitude and reduced frequency on the position of the LSB transition and reattachment points. In particular, the investigation of the LSB reattachment point behavior under pitching airfoil conditions represents a novelty of the present work with respect to literature.

The experimental test matrix included preliminary steady state measurements using classical IRT technique to validate the set-up against results from the literature (Wynnychuk & Yarusevych, 2020) and to evaluate the reference positions along airfoil chord of the LSB characteristic points (separation, transition, reattachment) for comparison with unsteady DIT measurements. Unsteady pitching conditions considered Reynolds numbers of 80,000 and 120,000 with a mean angle of attack $\bar{\alpha}$ equal to 5° and oscillation amplitude $\hat{\alpha}$ between 2° and 5° . The complete test matrix of the

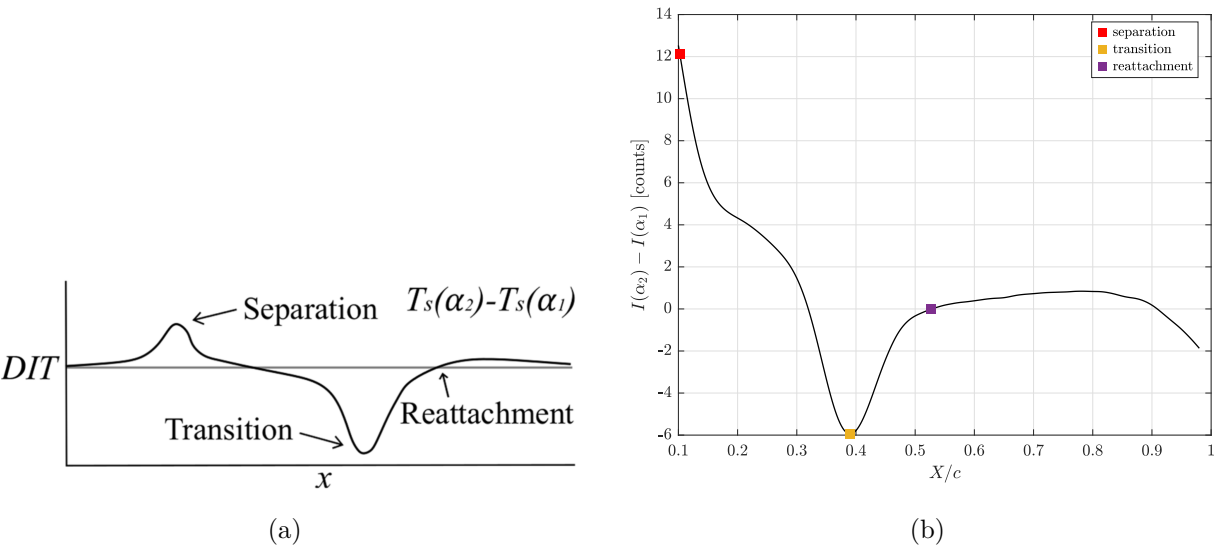


Figure 6. (a) Sketch of the identification of LSB characteristic points from DIT intensity profile, from Grille Guerra et al. (2023); (b) Sample DIT chord-wise intensity profile from present measurements

experimental campaign is reported in Tab. 1.

	Steady	Unsteady
Infrared technique	IRT	DIT
Mean angle $\bar{\alpha}$, [deg]	[0, 2, 4, 6, 8, 10]	5
Pitch amplitude $\hat{\alpha}$, [deg]	-	$\pm[2, 3, 4, 5]$
Reynolds number Re	80,000, 120,000	80,000, 120,000
Pitch freq. f , [Hz]	-	[1, 2, 3, 4, 6]
Red. freq. $k = \pi f c / U_\infty$	-	[0.0172 - 0.1047]
No. of infrared images	800	3300
Acquisition frequency [Hz]	40	100

Table 1. Test Matrix of the experimental campaign.

4. Results and discussion

The transition point locations identified via DIT for pitching cases at $\bar{\alpha} = 5^\circ$, with amplitudes $\hat{\alpha}$ ranging from 2° to 5° , are compared in Fig. 7. This comparison illustrates the sensitivity of these locations to the reduced frequency of the oscillation cycle.

The results clearly indicate that transition locations under unsteady conditions do not align with steady-state measurements. Instead, a distinct hysteresis loop forms around the static curve. Specifically, the hysteresis reveals that LSB transition points occur at the same chordwise X/c

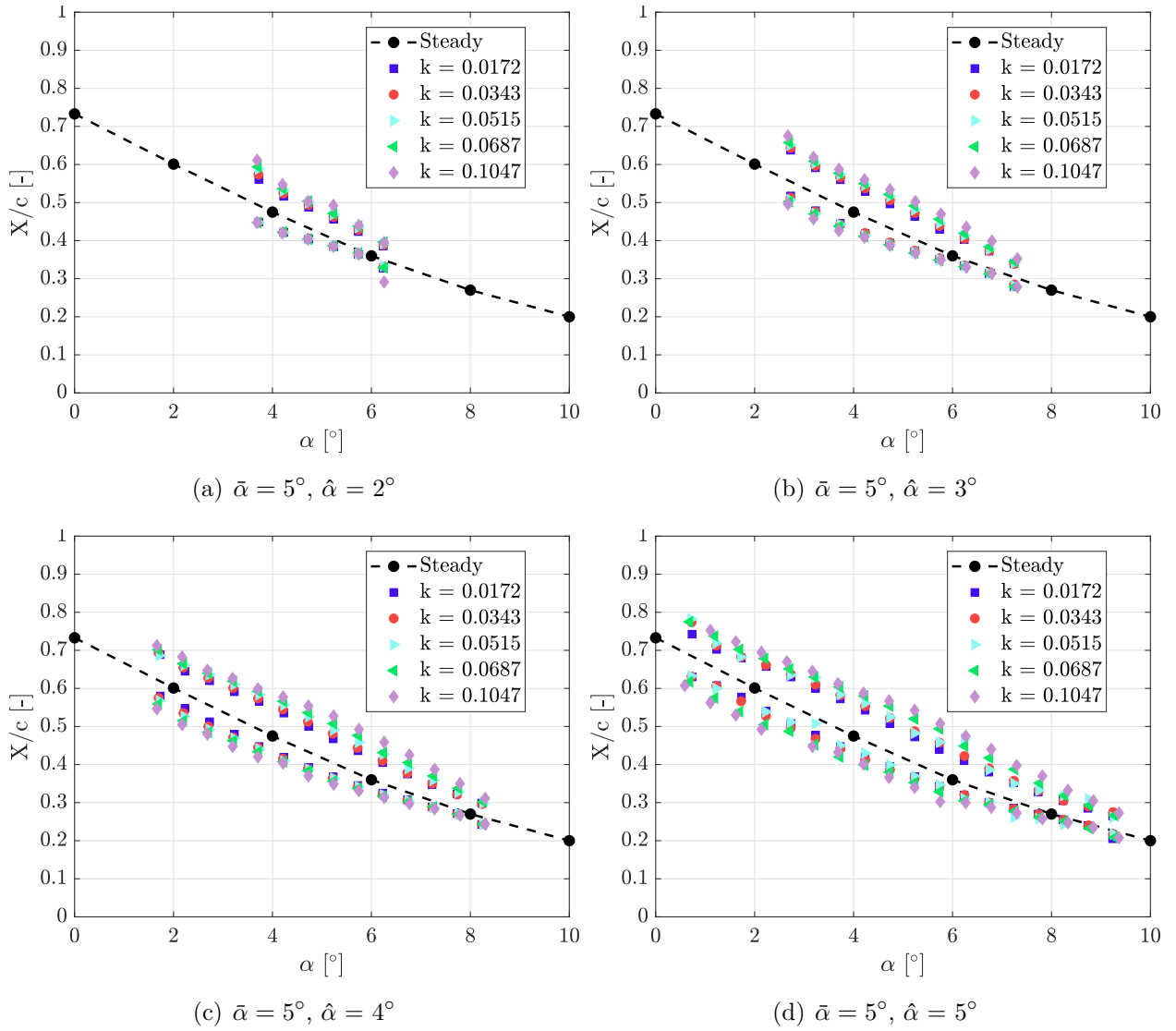


Figure 7. Comparison of the LSB transition point locations evaluated by DIT by varying reduced frequency k , $\bar{\alpha} = 5^\circ$, $Re = 120,000$.

station at higher instantaneous angles of attack during the upstroke than during the downstroke. Quantifying the hysteresis magnitude as the discrepancy between unsteady and static locations, a more pronounced effect is observed during the upstroke, which intensifies as the reduced frequency k increases. On the other hand, the downstroke transition points closely follow the static path, exhibiting only minor sensitivity to frequency. This trend is consistent across all investigated pitching amplitudes $\hat{\alpha}$. To further elucidate this behavior, Fig. 8 contrasts sample DIT images captured at a constant angle of attack $\alpha = 4.75^\circ$ during both upstroke and downstroke phases.

The dark regions in the DIT images, which qualitatively mark the local thermal minimum associated with transition, shift position between the two phases at the same α . Using the thermal footprints of the markers as spatial references, Fig. 8(a) shows the dark region located between

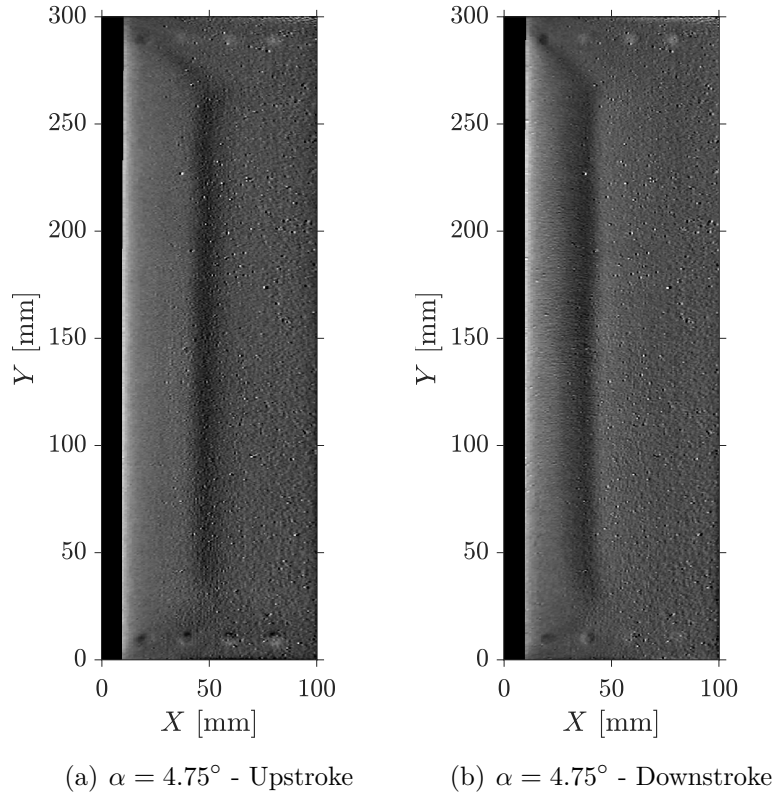


Figure 8. Comparison of DIT images at same angle of attack $\alpha = 4.75^\circ$ in upstroke and downstroke motion, $\bar{\alpha} = 5^\circ$, $\hat{\alpha} = 4^\circ$, $k = 0.0515$, $Re = 120,000$.

the second and third markers during the upstroke, while it aligns with the second marker during the downstroke (Fig. 8(b)). This confirms the underlying flow physics, i.e. transition hysteresis is directly coupled to the pitching phase and is augmented by increasing frequency. Regarding transition, the widening of the hysteresis loop with k results from the unsteady pressure gradient's failure to equilibrate with viscous forces within the boundary layer; as frequency increases, the reduced adaptation time leads to a larger spatial lag (Richter et al., 2016; Gardner et al., 2019).

The reattachment point locations, compared in Fig. 9, exhibit a similar hysteresis, though more pronounced during the upstroke phase than the transition point itself. During the downstroke, reattachment points remain near steady-state positions, mirroring the low-hysteresis behavior observed in transition. However, as the angle of attack increases during the upstroke, the divergence from static values becomes more significant. Notably, for pitching cycles with oscillation amplitudes $\hat{\alpha}$ of 4° and 5° at the lowest reduced frequencies ($k = 0.0172$ and $k = 0.0343$), the reattachment point position shows a divergent trend toward the airfoil trailing edge at high angles of attack. A closer analysis of this divergence at low reduced frequencies is provided by examining DIT images and differential thermal intensity distributions at $\alpha = 6.75^\circ$ (see Fig. 10).

While reattachment is qualitatively linked to the downstream edge of the dark DIT region, at the

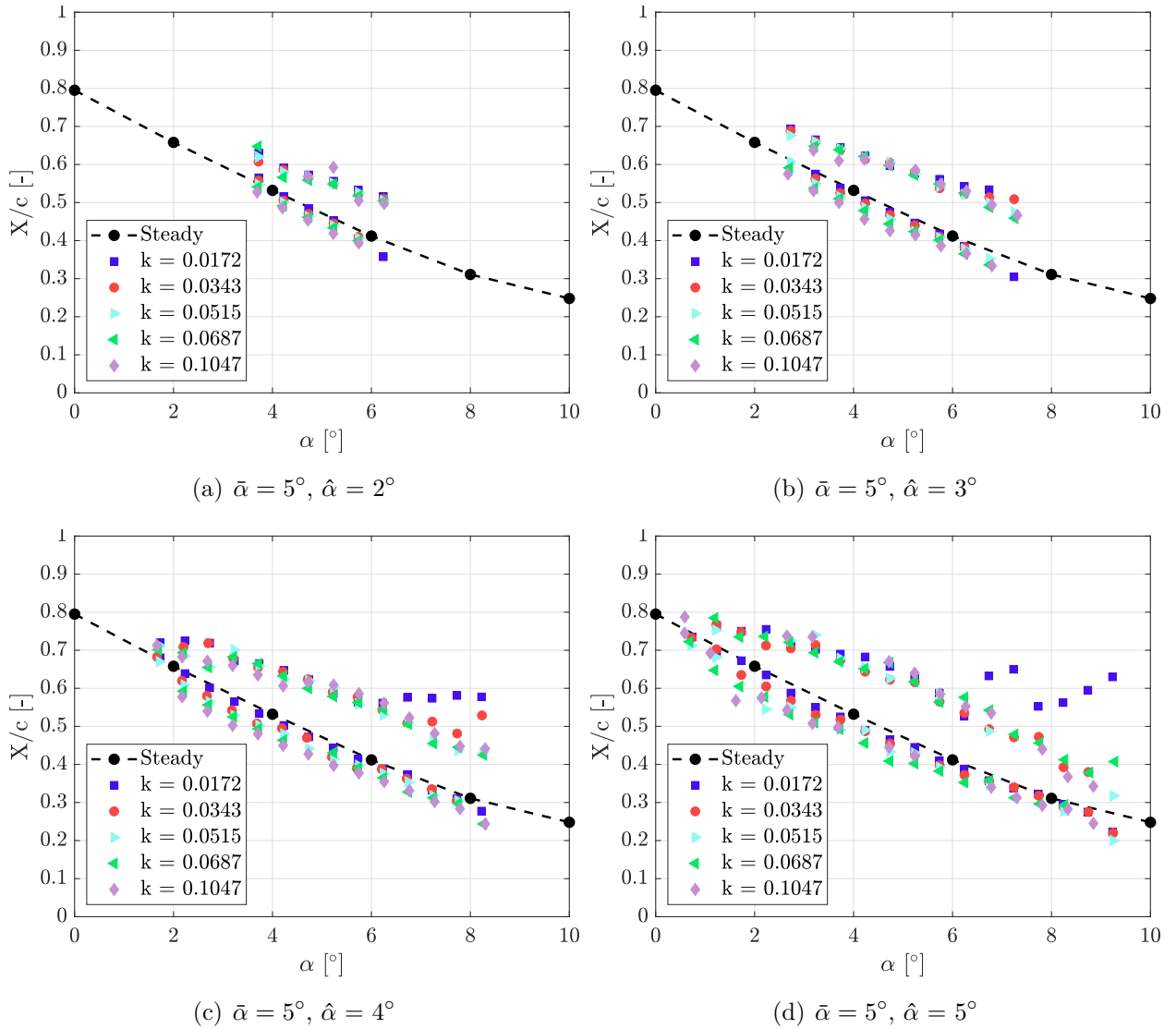
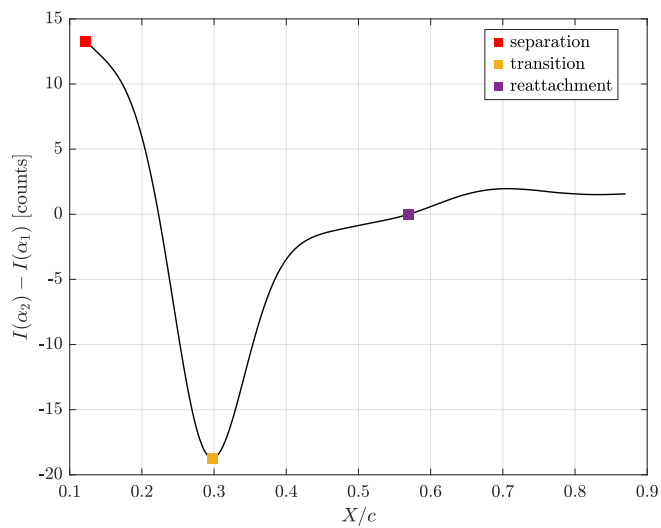


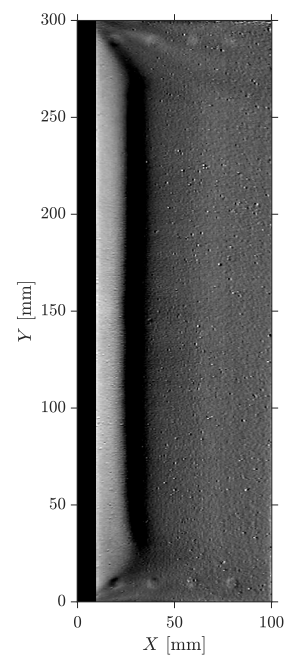
Figure 9. Comparison of the LSB reattachment point locations evaluated by DIT by varying reduced frequency k , $\bar{\alpha} = 5^\circ$, $Re = 120,000$.

lowest frequency, the differential intensity distribution changes sign further downstream than suggested by the thermal image (see Fig. 10(b)). The distribution curve approaches the X/c axis with a shallow slope, intercepting it closer to the trailing edge. At the highest frequency ($k = 0.1047$), the curve intercepts the axis with a steeper slope further upstream (see Fig. 10(d)), which is consistent with the absence of intermediate gray shades in the thermal image.

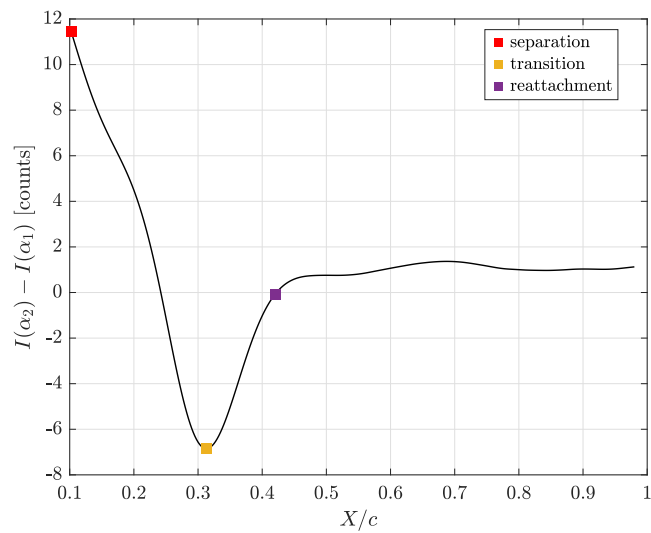
While the observed divergence might be correlated with shear layer instabilities or incipient stall caused by high adverse pressure gradients, the lack of complementary data from techniques like PIV or PSP limits a definitive physical interpretation. Furthermore, methodological factors such as optical noise or the limited applicability of the DIT sign-change criterion under these specific conditions may also influence reattachment identification. Generally, the data show that increasing



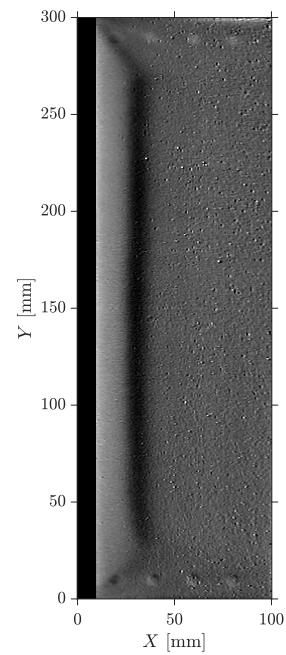
(a) $k = 0.0172$



(b) $k = 0.0172$



(c) $k = 0.1047$



(d) $k = 0.1047$

Figure 10. Comparison of differential intensity distribution and DIT images at $\alpha = 6.75^\circ$ in upstroke, $\bar{\alpha} = 5^\circ$, $\hat{\alpha} = 4^\circ$, $Re = 120,000$.

reduced frequency strengthens the hysteresis loop, particularly in the upstroke. This confirms and extends the findings of Wolf et al. (2019) and Grille Guerra et al. (2023) to the reattachment point.

The influence of pitch amplitude $\hat{\alpha}$ is highlighted by comparing cycles at fixed reduced frequencies (see Figs. 11 and 12).

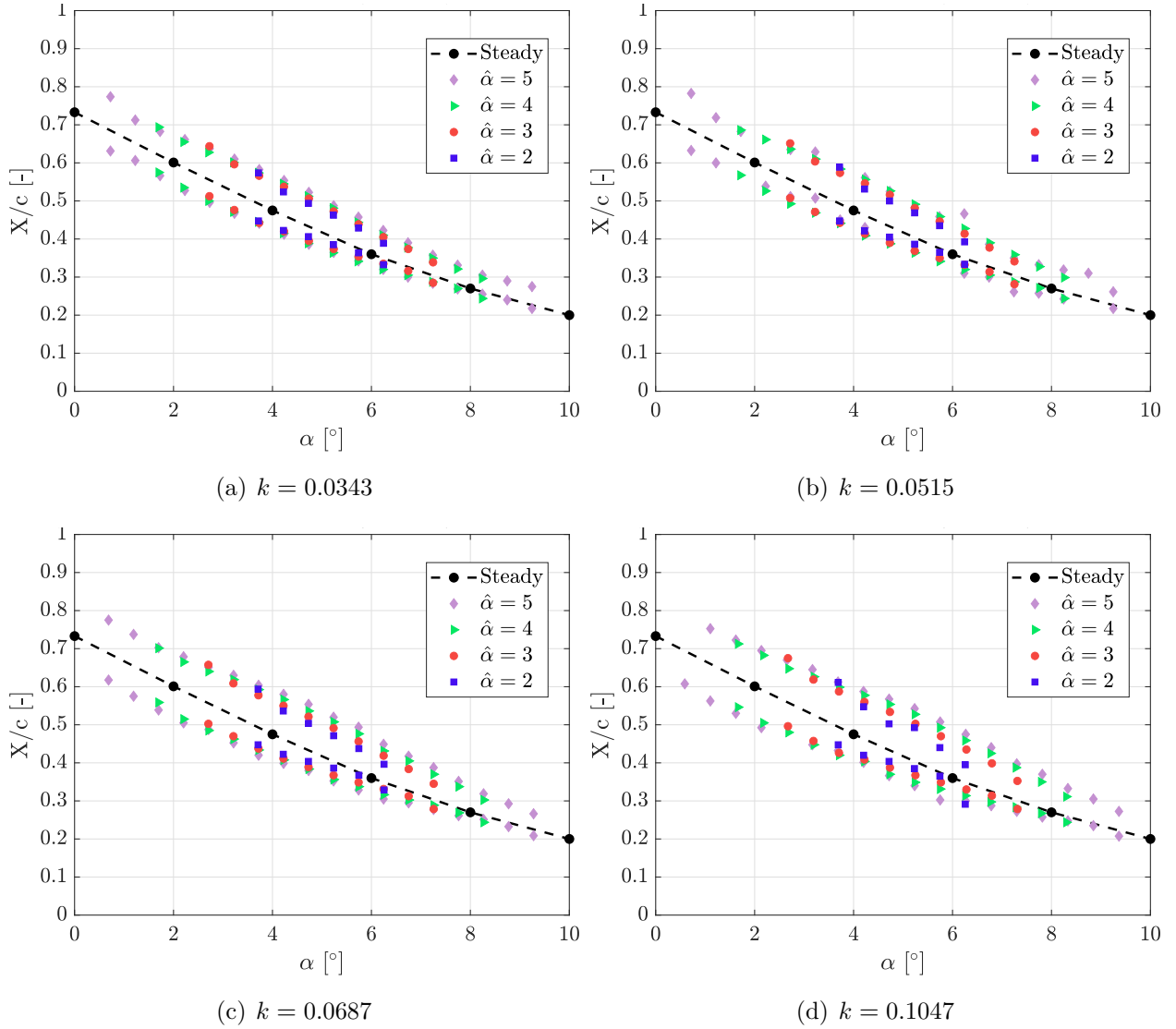


Figure 11. Comparison of the LSB transition point locations evaluated by DIT by varying pitching cycle amplitude $\hat{\alpha}$, $Re = 120,000$.

For transition, amplitude has a negligible effect on hysteresis at low frequencies, but a slight increase is observed at higher frequencies during the upstroke. Reattachment shows a similar trend, with the hysteresis loop widening as amplitude increases. The divergent trend at high α during the upstroke is particularly evident at low frequencies for large amplitudes, though this divergence tends to diminish if reduced frequency is increased.

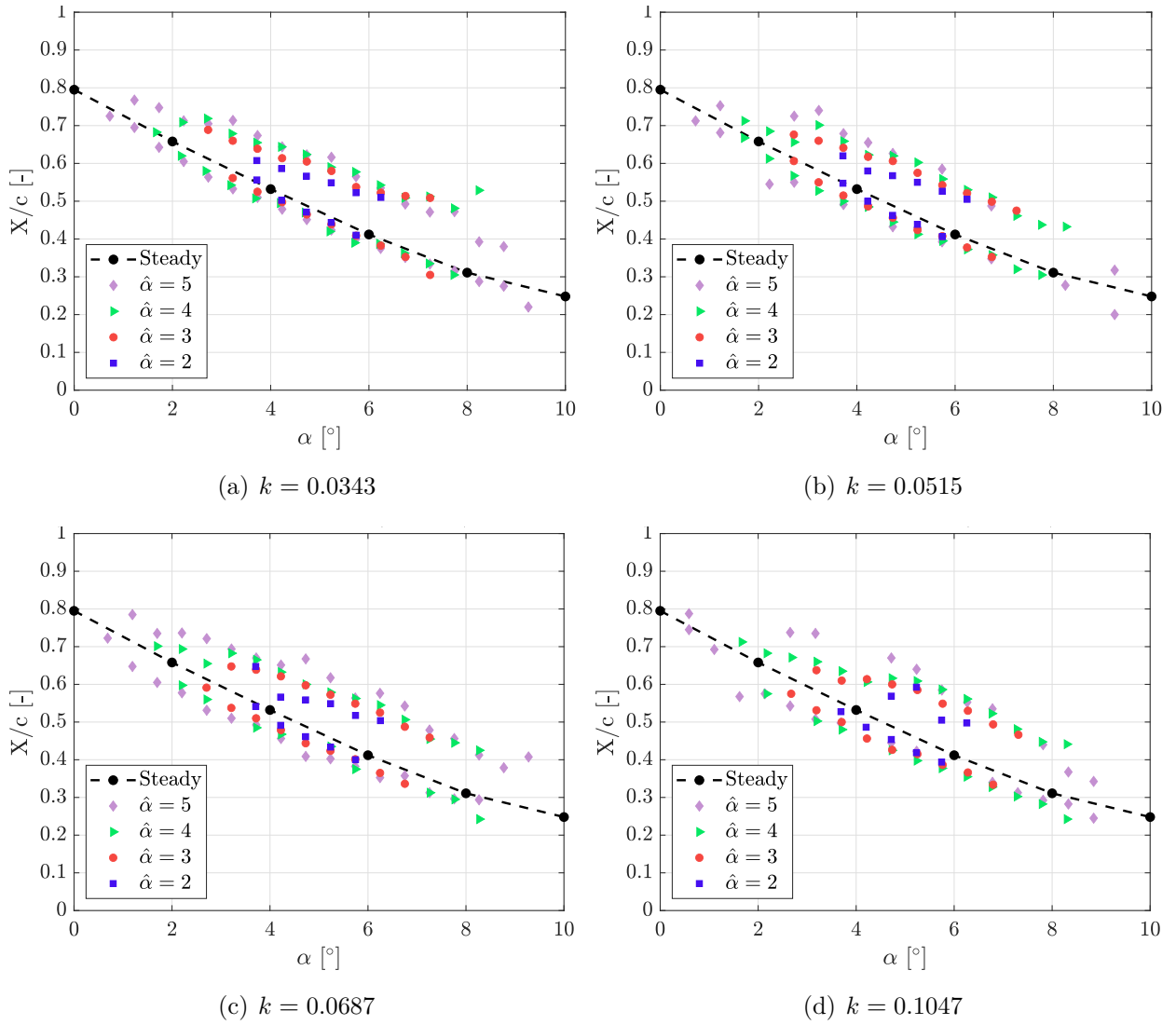


Figure 12. Comparison of the LSB reattachment point locations evaluated by DIT by varying pitching cycle amplitude $\hat{\alpha}$, $Re = 120,000$.

5. Conclusions

This study investigated the unsteady behavior of the Laminar Separation Bubble (LSB) on a pitching NACA 0018 airfoil at low Reynolds numbers using Differential Infrared Thermography. By analyzing the chord-wise temperature variation intensity profiles, the research focused on how pitching frequency and oscillation amplitude influence the transition and reattachment points of the flow. The main findings of this work are summarized in the following.

Both transition and reattachment points exhibit a marked hysteresis relative to static conditions. For a given instantaneous angle of attack, the characteristic LSB points are located further downstream during the upstroke phase than during the downstroke. The magnitude of this hysteresis is

strongly coupled with the reduced frequency. While the downstroke behavior remains relatively close to steady-state values, the upstroke phase shows a significant spatial lag that intensifies as frequency increases. This highlights the inability of the boundary layer to equilibrate with the unsteady pressure gradient at higher oscillation speeds.

A major novelty of this work was the systematic evaluation of the reattachment point in unsteady conditions. Results indicate that the reattachment point is more sensitive to pitching frequency than the transition point. Furthermore, at low reduced frequencies and high amplitudes, the reattachment point exhibited a divergent trend toward the trailing edge, suggesting the presence of complex shear layer instabilities or incipient stall. Moreover, while pitching amplitude has a marginal effect on the transition point at low frequencies, it significantly widens the reattachment hysteresis loop. The divergence observed at high angles of attack during the upstroke is most prominent at larger amplitudes and lower frequencies.

The study confirms that while DIT is highly effective for tracking transition and reattachment in periodic flows, as standard steady-state identification methods for the separation point are inadequate for unsteady pitching motion. In conclusion, this research provides valuable experimental insights into the unsteady aerodynamic performance of thick airfoils. The datasets generated serve as an essential reference for the validation and calibration of numerical prediction tools in the field of low-Reynolds-number aerodynamics. Future investigations could benefit from simultaneous PIV or PSP measurements to provide a more definitive physical interpretation of the reattachment divergence observed at high angles of attack.

Nomenclature

c	chord length [m]
f	pitching frequency [Hz]
k	reduced frequency
Re	Reynolds number
U_∞	free-stream velocity [m/s]
X/c	non-dimensionalized chordwise coordinate
I	thermal intensity [counts]
α	angle of attack [deg]
$\bar{\alpha}$	mean angle of attack [deg]
$\hat{\alpha}$	pitching amplitude [deg]

References

- Astarita, T., & Carlomagno, G. M. (2012). *Infrared thermography for thermo-fluid-dynamics*. Springer Berlin Heidelberg.
- Cole, G. M., & Mueller, T. J. (1990). *Experimental measurements of the laminar separation bubble on an eppler 387 airfoil at low reynolds numbers* (Contractor Report). NASA.
- Gardner, A. D., Merz, C. B., & Wolf, C. C. (2019). Effect of sweep on a pitching finite wing. *Journal of the American Helicopter Society*, 63(3), 1–13.
- Grille Guerra, A., Mertens, C., Little, J., & van Oudheusden, B. (2023, January). Experimental characterization of an unsteady laminar separation bubble on a pitching wing. *Experiments in Fluids*, 64(1), 1–19.
- Houghton, E. L., Carpenter, P. W., Collicott, S. H., & Valentine, D. T. (2017). *Aerodynamics for engineering students (seventh edition)*. Butterworth-Heinemann.
- Poletti, M. (2025). *Experimental characterization of an unsteady laminar separation bubble on a pitching airfoil by infrared thermography* (Unpublished master's thesis). Politecnico di Milano.
- Raffel, M., & Merz, C. B. (2014, September). Differential infrared thermography for unsteady boundary-layer transition measurements. *AIAA Journal*, 52(9), 2090–2093.
- Richter, K., & Schulein, E. (2014, May). Boundary layer transition measurements on hovering helicopter rotors by infrared thermography. In *Proceedings of the vertical flight society 70th annual forum*.
- Richter, K., Wolf, C. C., Gardner, A. D., & Merz, C. B. (2016). Detection of unsteady boundary layer transition using three experimental methods. *54th AIAA Aerospace Sciences Meeting*.
- Tomasello, R. (2024). *Infrared thermography investigation of boundary layer transition on an airfoil model* (Unpublished master's thesis). Politecnico di Milano.
- Wolf, C. C., Gardner, A. D., & Raffel, M. (2020, September). Infrared thermography for boundary layer transition measurements. *Measurement Science and Technology*, 31(11), 112002. Retrieved from <http://dx.doi.org/10.1088/1361-6501/aba070> doi: 10.1088/1361-6501/aba070
- Wolf, C. C., Mertens, C., Gardner, A. D., Dollinger, C., & Fischer, A. (2019, January). Optimization of differential infrared thermography for unsteady boundary layer transition measurement. *Experiments in Fluids*, 60(1), 1–13.
- Wynnychuk, D. W., & Yarusevych, S. (2020, July). Characterization of laminar separation bubbles using infrared thermography. *AIAA Journal*, 58(7), 2831–2843.