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INSIGHT INTO WINGTIP VORTEX – WING WAKE FREE SHEAR LAYER INTERACTION

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ABSTRACT

The interaction between the free shear layer, the wingtip vortex and the aerodynamic efficiency was investigated behind a lift-generating wing, using Particle Image Velocimetry (PIV) in the Low-Speed Wind Tunnel at the University of Dayton (UD-LSWT). The experiments were conducted in the wake of an AR 4 flat plate with and without a spanwise boundary layer trip (BLT) placed on the upper surface at 10 percent chord from the leading edge of the wing. The interaction of the free shear layer in the process of wingtip vortex formation and the correlation of this interaction to the behavior of the aerodynamic efficiency of the wing were detailed. The streamwise, cross-stream and spanwise plane oriented PIV of the wingtip vortex indicate free shear layer interaction with the wingtip vortex at lower angles of attack. This interaction was manifested as a change in the wingtip vortex normalized azimuthal velocity profile as well. At an angle of attack less than that corresponding to the maximum lift to drag ratio (L/D), the additional momentum loss in the wake due to the BLT was reflected in the free shear layer velocity profile. At an angle of attack greater than that corresponding to the maximum (L/D), the additional momentum loss in the wake was observed in the wingtip vortex core axial velocity profile. The composite of profiles of the velocity components from multiple different planes evokes the possibility of a cross-over of momentum from the free shear layer to the wingtip vortex in the vicinity of the maximum (L/D) lift condition.

INTRODUCTION

Gunasekaran and Altman (2016) documented the effect of a spanwise boundary layer trip (BLT) on the free shear layer (FSL) and the wingtip vortex behind an AR 4 flat plate. Marasli et al (1986) showed that the properties in the FSL in the wake of an object upstream are unique to turbulent generators. Subsequently, Gunasekaran and Altman (2013) showed that not only is the FSL unique but the performance information of the wing is preserved in the FSL at relatively large distances downstream of the wing. Therefore, the inherent connection between the upstream flow over the wing and the properties seen in the wake is the motivation behind this study. Currently, most commercial airplanes do not cruise at the lift condition associated with maximum aerodynamic efficiency because it is too slow. It is hypothesized that a better understanding of the relationship between the aerodynamic efficiency, the properties in the wingtip vortex (a surrogate for induced drag) and the properties in the FSL (a surrogate for parasite drag) can be used to improve the aerodynamic efficiency at conventional cruise conditions.

Given the inherent relationship between the parasite drag and induced drag, very little is understood about the relationship between the FSL and the wingtip vortex. Devenport et al. (1996) indicated that the boundary of the wingtip vortex was dominated by the inboard wake of the wing which rolls up in a spiral. But the effect and extent of this interaction on roll up of the wingtip vortex remain unknown.

Assuming axial gradients in the wingtip vortex are smaller when compared to the radial gradients in the wingtip vortex, Batchelor (1964) used the equations of motion for the steady axisymmetric flow of an incompressible fluid to obtain the relationship between the wingtip vortex core axial velocity and the azimuthal velocity (Equation 1). From Figure 1, assuming steady, incompressible flow, the conservation of radial momentum equation can be represented as,

$$V_x\frac{\partial V_r}{\partial x}+V_r\frac{\partial V_r}{\partial r}-\frac{V_\theta^2}{r}=-\frac{1}{\rho}\frac{\partial P_{vortex}}{\partial r}+\nu\left(\frac{V_r}{r^2}-\nabla^2 V_r\right) \quad (1)$$

where ρ is density, P_{vortex} is the pressure in the wingtip vortex, V_x is the axial velocity, V_r is the radial velocity, V_θ is the wingtip vortex azimuthal velocity and r is the radius of the wingtip vortex. Using the potential flow theory (assuming inviscid, incompressible and steady flow), the tangential velocity can be represented as directly proportional to the strength of the vortex (Γ) and inversely proportional to the radius of hte vortex r. Therefore, from Equation 1 the following relationship can be derived:

$$\left(\frac{\Gamma}{2\pi}\right)^2=\frac{2r^2(P_0-P_{vortex})}{\rho} \quad (2)$$

where P_0 is the pressure at infinity. From Equation 2, assuming the circulation of the wingtip vortex and the density remains constant as a function of downstream distance, if the core diameter (r)increases with downstream distance, the pressure in the core (P_{vortex}) increases leading to axial deceleration (wake-like profile). If the core diameter decreases with the distance downstream, the pressure in the core decreases leading to axial acceleration (jet-like profile). Batchelor hypothesized that the transition from wake-like to jet-like profile might be influenced by the balance between the induced and parasite drag of the wing. Brown (1973) took Batchelor's model further and hypothesized that the parasite drag of the wing is rolled up in the wingtip vortex which changes the nature of the wingtip vortex core axial velocity.

Experimental evidence of this particular type of wingtip vortex-FSL interaction was observed in an experiment conducted in the Horizontal Free Surface Water Tunnel (HFWT) at the Air Force Research Labs (AFRL) on an AR 4 flat plate (Gunasekaran and Altman (2012)). The Reynolds stress contours of the FSL across different spanwise stations in the wake of an AR 4 flat plate at a 2° angle of the attack showed that the wingtip vortex under these conditions is sandwiched between the shear layers at the wingtip spanwise station 10 chord lengths downstream (Figure 3). It is strange that despite the complex dynamics and comparatively violent mixing associated with the wingtip vortex roll-up process, the shear dominated wake remains neatly stratified. The extent of this type of interaction between the wingtip vortex and the FSL has not previously been identified in the literature.

EXPERIMENTAL SETUP

The depth of the interaction between the FSL and the wingtip vortex was studied in detail through experimental investigations documented in Gunasekaran and Altman (2016). A brief summary of the experimental setup is repeated here for clarity. The PIV experiments were conducted in the Low-Speed Wind Tunnel at the University of Dayton at an approximate Reynolds number of 150,000. The on-body boundary layer, mid-semi span free shear layer and the evolution of the wingtip vortex of an AR 4 flat plate were examined using Particle Image Velocimetry (PIV) at 2, 3, 4, and 5 chord lengths downstream of the trailing edge of the wing. The evolution of the wingtip vortex was interrogated in three different planes oriented along the three axes (Streamwise, Cross-stream, and Spanwise) (Figure 2). Then a spanwise BLT with a thickness to chord ratio of 0.6% was introduced to change the character of the boundary layer and the nature of its associated turbulence over the upper surface of the flat plate.

INTERACTION BETWEEN THE FSL AXIAL VELOCITY AND THE WINGTIP VORTEX AXIAL VELOCITY

The FSL axial streamwise velocity and the wingtip vortex core axial velocity demonstrated interesting interaction (Figure 4). At 1° angle of attack, the wingtip vortex is nascent and the wake is shear layer dominated since minimal lift is being produced by the flat plate at this angle of attack. The wingtip vortex and the shear layer are indistinguishable at this angle of attack. At a 2° angle of attack, the flat plate generates sufficient lift for both the shear layer and the wingtip vortex to be easily observed. At this angle of attack, bifurcation of the wingtip vortex and the shear layer begins but they are still difficult to discern independently. At a 3° angle of attack, a clear bifurcation of the wingtip vortex and shear layer can be extracted from the contours. As the angle of attack is increased to 4°, the shear layer convects downwards from the wingtip vortex and distinguishable shear layer and wingtip vortex wake signatures are clearly observed. Although perhaps simply coincidental, it is nevertheless fascinating that the wingtip vortex divides from the shear layer in the vicinity of the maximum (L/D) angle of attack of the flat plate (~3° angle of attack).

It was also found that the presence of the BLT increased the peak azimuthal velocity at lower angles of attack. The freestream normalized azimuthal velocity profile (Figure 5a) clearly indicates differences in the velocity magnitude between the trip and the no-trip case at 1° and 2° angles of attack. However, the wingtip vortex axial velocity profile (Figure 5b) shows no corresponding variation between the trip and the no-trip case at these angles of attack.

The circulation of the wingtip vortex with and without a boundary layer trip was found to be invariant. Therefore, for the tripped case and the no-trip case, the 1° and 2° angles of attack seem to violate the underlying assumptions behind Batchelor's model which states that any changes in azimuthal velocity of the wingtip vortex should result in a change in axial velocity. It is hypothesized that the presence of wingtip vortex-FSL interaction at lower angles of attack induces viscous effects which inhibit applicability of Batchelor's model at lower angles of attack.

INTERACTION BETWEEN THE FSL AND THE WINGTIP VORTEX AZIMUTHAL VELOCITY

In both the trip and the no-trip cases, the normalized azimuthal velocity profiles in the wingtip vortex inner core region show good correlation with Batchelor's model at all angles of attack. However, the deviation from Batchelor's model can be observed at the wingtip vortex core boundary (Figure 6a) at lower angles of attack for the tripped case.

The disturbances observed in the azimuthal velocity profile and the deviation from the behavior of Batchelor's model at lower angles of attack is hypothesized to be due to the enhanced interaction between the FSL and the wingtip vortex resulting from the BLT. This hypothesis was substantiated by analyzing the wingtip vortex PIV results in the spanwise plane. At 1° angle of attack, the FSL and the wingtip vortex are in the same plane and in sufficient proximity to have a significant interaction (Figure 6b). This is especially true in the near-wake. As the angle of attack increases, the FSL departs below the plane of the wingtip vortex. At a 2° angle of attack, the FSL is only distinguishable 2 chord lengths downstream. At 3° angle of attack, the FSL moves out of the plane of the wingtip vortex entirely. As the distance between the wingtip vortex and the shear layer increases, the interaction between them decreases. This bifurcation of the wingtip vortex and the FSL was shown earlier in Figure 2. It is interesting to note that this occurs in the vicinity of the maximum (L/D) lift condition.

The instantaneous streamlines of the wingtip vortex (Figure 7) shows that the wingtip vortex is not fully formed at 1° and 2° angles of attack and is at a close proximity to the free shear layer. At 3° and 4° angle of attack, the wingtip vortex is more pronounced due to less interaction with the free shear layer.

CROSS-OVER OF MOMENTUM BETWEEN THE FSL AND THE WINGTIP VORTEX

In the freestream normalized mid semi-span FSL velocity profiles, the differences between the trip and no trip case begin to decrease with increase in angle of attack (Figure 8a). The differences between the trip and no trip case increase with an increase in angle of attack for the wingtip vortex axial velocity profiles (Figure 8b). The comparison of the momentum deficit in the mid semi-span FSL velocity profile and wingtip vortex core axial velocity profile show a cross-over of the momentum between 2° and 3° angles of attack (Figure 9). Between these angles of attack, the FSL bifurcates from the wingtip vortex as observed in the streamwise axial velocity contour of the wingtip vortex shown in Figure 4. It is hypothesized that the transfer of loss of momentum due to the BLT occurs in the near wake due to the pressure imbalance imposed by the tip vortex. The correlation of this variation with the location of maximum (L/D) lift condition is noteworthy and is found at all downstream distances tested. This behavior and the consequent interaction between the wingtip vortex and shear layer could potentially lead to serious implications with respect to increasing aerodynamic efficiency.

CONCLUSIONS

This study provided clear evidence of the interaction between the FSL and the wingtip vortex and their collective relationship to the aerodynamic efficiency.

- At lower angles of attack, the wingtip vortex core boundary deviates from Batchelor's azimuthal velocity model. This shows that Batchelor's model is less applicable at lower angles of attack where an interaction between the FSL and the wingtip vortex are more pronounced.
- The FSL deviates from the wingtip vortex in the vicinity of maximum (L/D) resulting in an easily distinguishable wingtip vortex and reduced FSL interaction with the wingtip vortex. Therefore, in the cross-stream direction at angles of attack lower than maximum (L/D), the FSL interaction with the wingtip vortex is significant. At angles of attack higher than those corresponding to maximum (L/D), the interaction attenuates.
- At angles of attack higher than maximum (L/D), the peak axial core velocity shows a greater deficit in the tripped case when compared to the peak axial core velocity at lower angles of attack. This increase in the "drag" of the wingtip vortex is due to the transfer of momentum from the FSL to the wingtip vortex. This conclusion was derived by determining the differences between the trip and the no-trip case in the wingtip vortex axial velocity and in the mid semi-span FSL.
- At lower angles of attack, the additional loss of momentum due to the BLT is manifested in the FSL. At higher angles of attack, the additional loss of momentum due to the boundary layer trip is contained within by the wingtip vortex. This cross-over of momentum happens in the vicinity of maximum (L/D).

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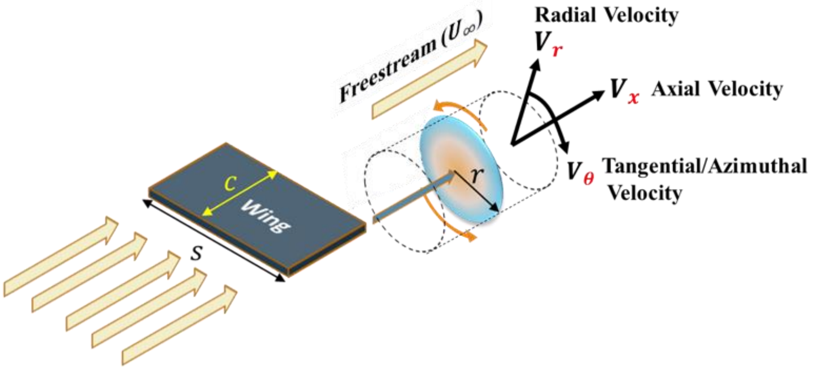

Figure 1 Wing-Wingtip vortex schematic with the coordinate axis definition (One tip vortex is shown for clarity). A cylindrical coordinate system is used for analysis with the control volume enveloping the wingtip vortex.

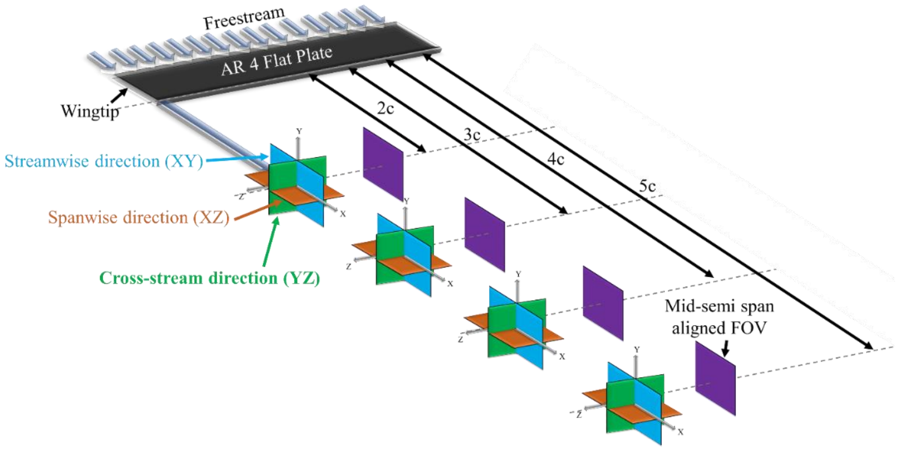

Figure 2 3D schematic of PIV Planes (Mid semispan, Streamwise (XZ), Cross-stream (YZ) and Spanwise (XY)) with respect to the flat plate.

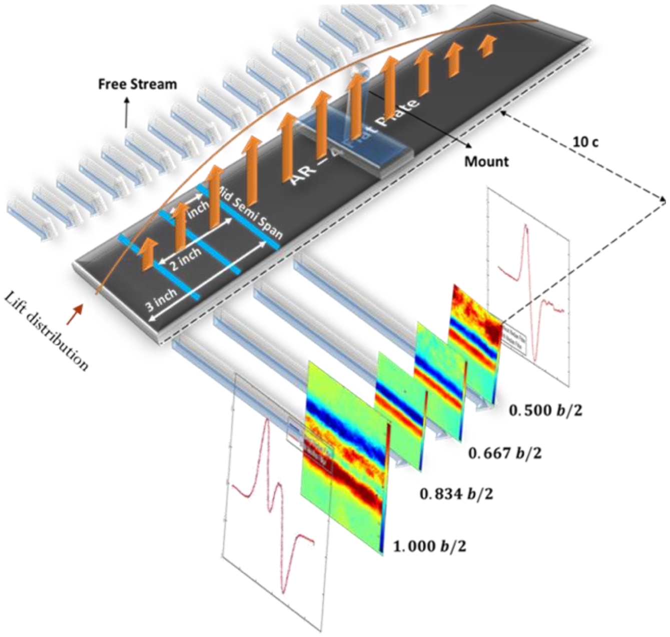

Figure 3 Variation of Reynolds stress at different spanwise stations (0.5 b/2, 0.667 b/2, 0.834 b/2 and 1.000 b/2 (Wingtip)). The wingtip vortex is essentially preserved 10 chord lengths downstream sandwiched between nearly identical inboard Reynolds stress distributions

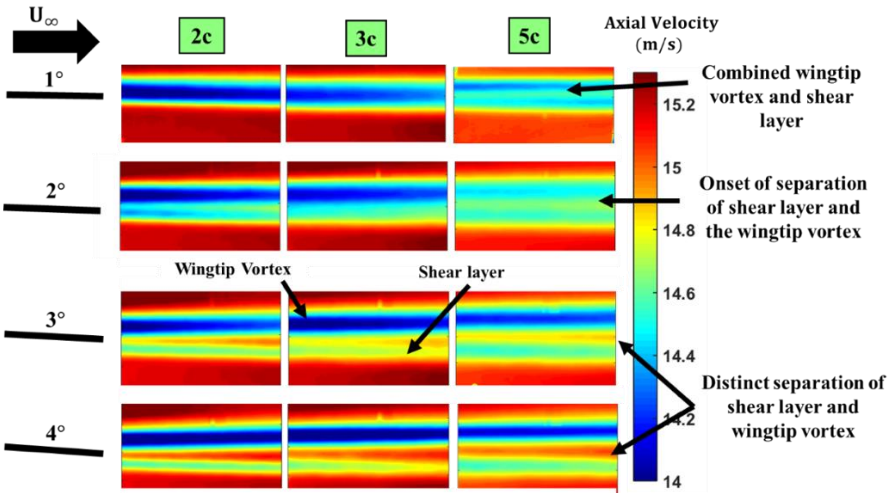

Figure 4. The interaction of the axial free shear layer and the wingtip vortex axial velocity can be clearly seen at lower angles of attack. The shear layer separates from the wingtip vortex at the vicinity of maximum (L/D) lift condition.

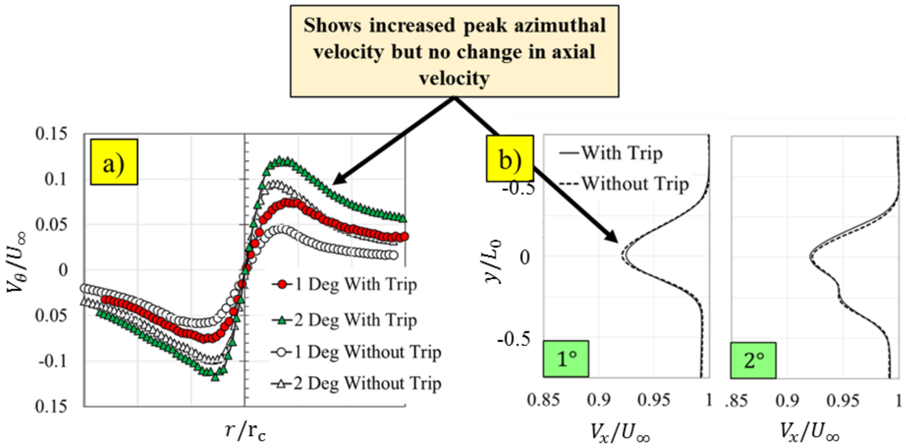

Figure 5 a) The BLT increased the peak azimuthal velocity when compared to the no-trip case. b) But no changes are observed in the axial/streamwise velocity in the tripped case at lower angles of attack. Hence in this case Batchelor's model does not conserve momentum.

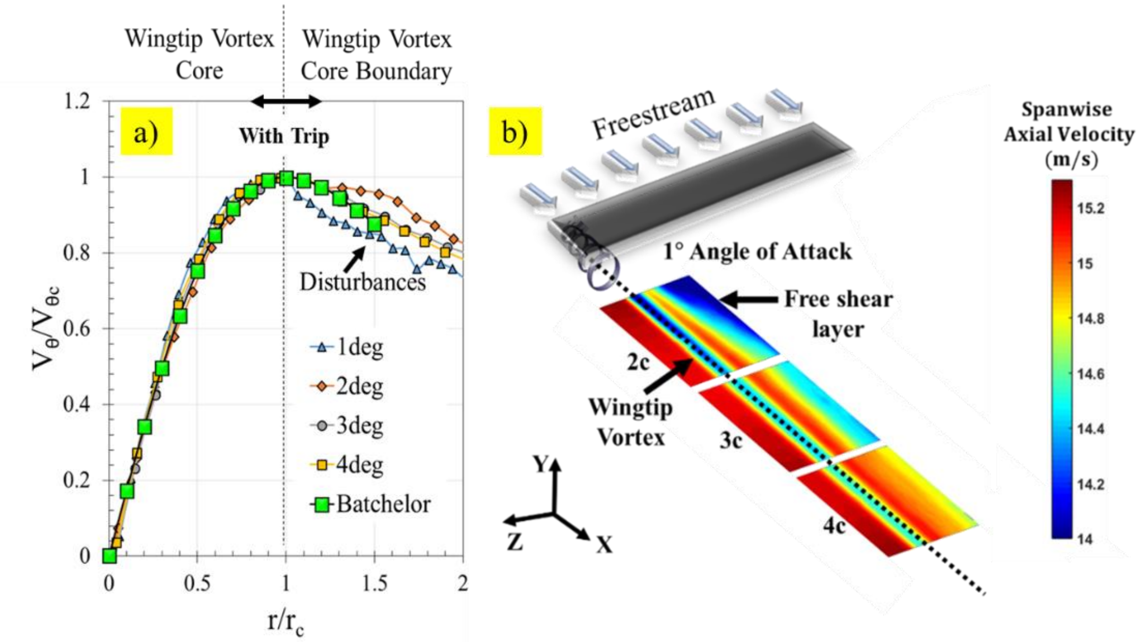

Figure 6. The tripped case shows deviation from the Batchelor's model in the wingtip vortex core boundary at lower angles of attack due to enhanced interaction between the FSL and the wingtip vortex.

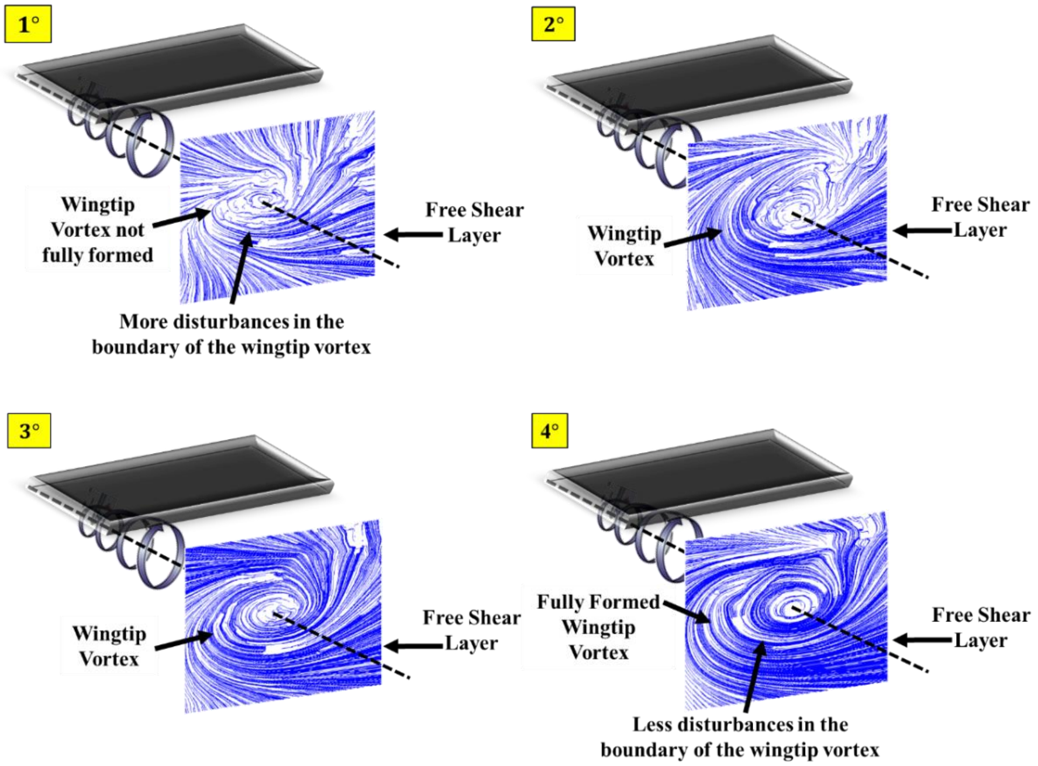

Figure 7 Instantaneous streamlines of the wingtip vortex taken 2 chord lengths downstream at several angles of attack. At a lower angle of attack, the wingtip vortex is not fully formed with greater perturbations seen in the wingtip vortex outer core boundary. At higher angles of attack, the roll-up of the wingtip vortex is less orderly in the wingtip vortex outer core boundary. This change in the nature of the azimuthal velocity distribution is reflected in the normalized profiles seen in Figure 6a.

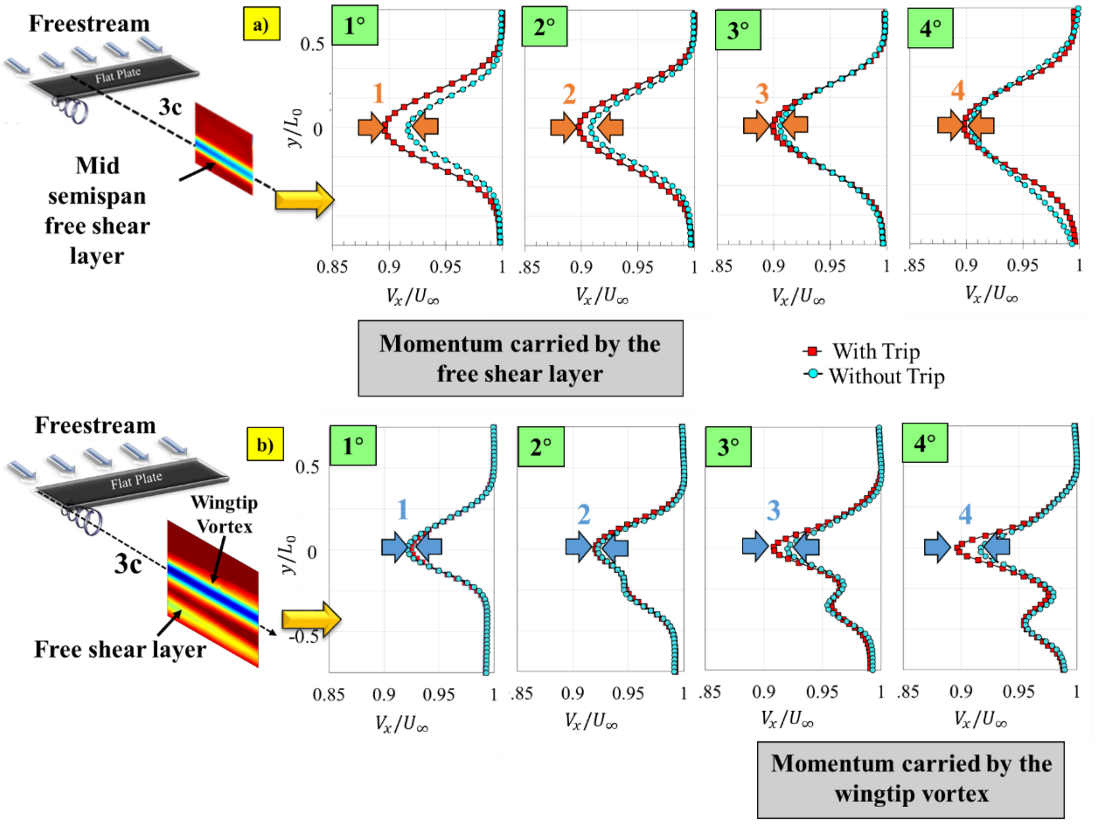

Figure 8 At lower angles of attack the momentum is carried by the FSL (a). At higher angles of attack the momentum is carried by the wingtip vortex (b). Similar results are observed at all distances downstream tested.

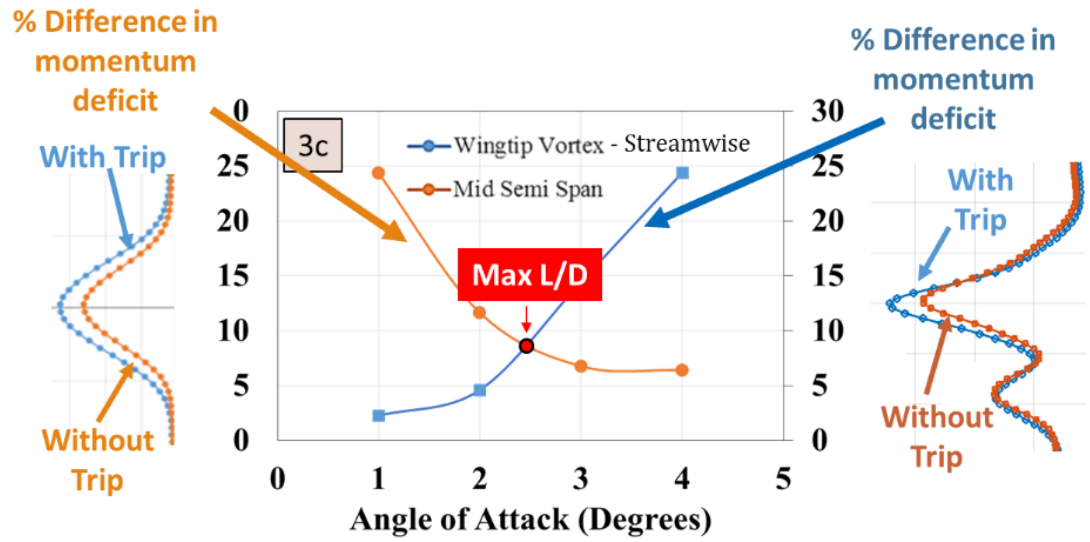

Figure 9. The cross-over of the momentum loss in the wake due to BLT between the FSL and the wingtip vortex occurs in the vicinity of the maximum (L/D) lift condition.