EFFECTS OF AN UPSTREAM TRIANGULAR PLATE ON THE WING-BODY
JUNCTION FLOW

by

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Abstract

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The use of a short triangular leading-edge plate at the base of a wing-body junction is experimentally evaluated as a passive control method to mitigate horseshoe vortices. The impact of the plate geometry on the efficacy of the control is assessed by considering triangular plates that vary in length and thickness. The wing model is a NACA 0020 airfoil. The Reynolds number based on the chord length is varied from $Re_c = 25,000$ to 75,000. The incoming boundary layer is laminar. Particle Image Velocimetry is utilized to characterize the temporal behavior and circulation strength of horseshoe vortices. All the triangular plates considered are found to decrease the circulation strength of the horseshoe vortices in the plane of symmetry by varying degrees compared to the uncontrolled configuration. Among the plates considered in this study, the results show that the longer and thinner the plate, the better the vortex mitigation. Overall, the proposed method provides an effective way to mitigate horseshoe vortices at wing-body junctions.

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Chapter 1

Introduction

1.1 Introduction

When a boundary layer, either laminar or turbulent, encounters an obstacle protruding from a surface, some distance upstream of the obstacle, it separates as a result of the adverse pressure gradient and rolls upon itself, creating complex vortices, known as horseshoe vortices. These vortices often have large effects on the flow properties in the junction region. They can change the local heat transfer rate, increase skin friction and produce noise. Horseshoe vortices are encountered in the junction regions of, for example, airplane wings, pin fins found within channels and nozzles, guide vanes in gas turbine engines, turbomachinery blades, bridge piers and beds, computer chips on a circuit board, and ship appendages and hulls. In the case of the bridge pier-bed junctions, the horseshoe vortices create a scour hole (a depression left behind when sediment is washed away at the juncture). This effect threatens the structural integrity of bridge piers. In the case of gas turbines and turbomachinery blades, the horseshoe vortices can significantly increase the local heat transfer rates, resulting in thermal gradients in the blades. In the case of wing-body junctures, adverse effects of horseshoe vortices are increase of local skin friction and generation of unwanted noise . With the aim of reducing such adverse

effects, several studies have investigated control methods that essentially fall into one of two categories: those that alter the geometry at the juncture and those that alter the surface conditions upstream of the obstacle. Both flow control strategies have their basis in weakening the obstacle-induced adverse pressure gradient, which is the cause of the boundary layer separation and thereby the horseshoe vortices.

In the former flow control category, Devenport et al. (1990) studied the effects of a fillet wrapped around the entire base of a wing at the junction region. They showed that this type of a fillet prevents neither the formation of horseshoe vortices nor the bimodal unsteadiness related to noise generation, instead, it increases the size and strength of the horseshoe vortex legs and their unsteadiness in the wake [1]. In their subsequent work, Devenport et al. (1992) explored the use of a leading-edge fillet at the wing junction. The results were much more promising. They found that, at zero angle of attack, this fairing eliminated the boundary layer separation upstream of the wing nose as well as the bimodal unsteadiness by reducing the magnitude and extent of the adverse pressure gradients experienced by the approach boundary layer. Consequently, it prevented the formation of horseshoe vortices in front of the leading edge [2]. They, however, reported that weak vortex legs might still form downstream of the nose region due to the skew-induced streamwise vorticity. This work proves that altering solely the leading edge of the wing-body junction can yield effective control over horseshoe vortices. Wang et al. (2009) and Huang et al. (2015) strengthened this point with their studies of the cylinder-flat plate junctures where an inclined rod and a tetrahedron, respectively, were installed at the leading edge of the cylinder [3, 4]. In the work of Wang et al. (2009), it was shown that an upstream inclined-rod, with a proper inclination angle and attack angle, can totally suppress the horseshoe vortex induced by the obstacle. However, a new but weaker horseshoe vortex forms in front of the inclined rod. Huang et al. (2015) reported that, depending on the Reynolds number and the geometric parameters of the upstream tetrahedron, one can yield a reduction in the number of horseshoe vortices

by one compared to the natural flow or completely prevent the formation of horseshoe vortices. On the other hand, Barberis et al. (1998) employed a leading-edge fillet for a wing-body junction with a turbulent boundary layer separation and showed that it decreases the spatial extent of the vortex but does not noticeably change its magnitude [5]. Wei et al. (2008) investigated the effect of the frontal bluntness of the obstacle on the horseshoe vortices. Their experiments at cylinder-plate junctions showed that as the cross-sectional shape of the cylinder changes from square to circle and to rhombus, the cylinder-induced adverse pressure gradient decreases, the location of the primary horseshoe vortex gets closer to the cylinder, and the size and strength of the primary horseshoe vortex reduces [6]. Olcmen and Simpson (2007) installed protruding fences in different shapes on various wing models exposed to a turbulent approach boundary layer. The fences were placed at various heights above the flat surface. Their work determined the fence types that are effective in reducing the wall-pressure fluctuations upstream of the wing models [7].

There also exist many studies in the second category of flow control methods that involve changing the upstream surface conditions instead of the leading-edge geometry of the object. For instance, Yen et al. (2012) tested the effects of altering the upstream floor roughness. This control method had a favorable effect as it causes an increase in the turbulence intensity and thereby a decrease in the junction vorticity [8]. Another method in the same category involves the implementation of a cavity upstream of the obstacle. The cavity weakens the adverse pressure gradient upstream of the cavity whilst increasing it in the region between the cavity and the obstacle. The upstream cavity proposed by Kang et al. (2009) was shown to decrease the strength of the horseshoe vortex [9]. Kairouz and Rahai (2005) proposed using longitudinal triangular riblets within a turbulent boundary layer upstream of a wing-body junction. Based on the velocity measurements carried out at the wing mid-chord and downstream, they found that the ribbed surface weakens the strength of the horseshoe vortices and displaces them away

from the junction [10]. Active control of the upstream boundary layer by suction or blowing has also been the subject of investigations. Philips et al. (1992) examined the role of suction applied at the upstream surface and showed that it can achieve reduction in the size and circulation of the horseshoe vortex [11]. Seal and Smith (1999) also observed weakening of horseshoe vortices at a turbulent junction flow via upstream suction [12]. Thrift and Thole (2012) investigated the upstream flow injection, focusing on its effects on the heat transfer rate at a vane-wall junction. Their findings demonstrated that high momentum injection increases the mixing, and hence, the heat transfer rate, whereas the low momentum injection is similar to the case with no injection [13]. Considering the required energy and the usability in an operating system, these active control approaches are found, however, less attractive than the passive methods.

As considerable amount of work has been done in the literature to understand the horseshoe vortex dynamics at junctures. For a certain obstacle geometry (such as wing, cylinder, etc), the behavior of the horseshoe vortices is dependent on the flow parameters (the boundary-layer characteristics, free stream velocity, free-stream turbulence level, and the fluid viscosity and density) as well as the characteristic dimensions of the obstacle (such as width, diameter, etc.). Many studies put forth efforts to categorize junction flows into distinct flow regimes for different obstacle geometries. Schwind (1962) and Baker (1989) are the first to present such classifications for laminar juncture flows [14, 15]. The subsequent study of Greco (1990), however, gives the most complete categorization for circular cylinder-flat plate junctures with laminar approach flow [16]. Based on the work of Greco, with increasing Reynolds number for a fixed junction configuration, these flow regimes appear in the following order: steady, oscillating, amalgamating, breakaway, and transitional. Although switching from one state to the adjacent state was observed to occur intermittently, this ordered sequence represents the general progression of horseshoe vortex regimes [15, 16]. Note that these vortex regimes were defined for circular cylinder-plate junctions by Greco (1990), however, nearly comparable classifications were

also observed for other types of junction geometries, such as for horseshoe vortices in 60° wedge-wall junctions, rectangular cylinder-plate junctions, square cylinder-plate junctions and orthogonal plate-plate junctions in the works of Schwind (1962), Seal (1993), Lin et al. (2008), and Lin et al. (2002) [12, 14, 17, 18], respectively. The steady regime consists of one, two or three steady horseshoe vortices with the same rotational sense as the approach boundary-layer vorticity. Next to these horseshoe vortices, there exist also an equal number of smaller and weaker counter-rotating vortices ejecting from the surface fluid. Within this regime, the number of horseshoe vortices increases as the Reynolds number and/or the ratio of the obstacle diameter to the boundary-layer thickness increase [15]. The oscillating vortex regime involves periodic to-and-fro movement of horseshoe vortices. The horseshoe vortices in this regime first move toward each other until a minimum separation distance, and then move away from each other to a maximum distance. The vortices do not coalesce with each other at any point in this cycle. The frequency and amplitude of oscillations in this regime increases as the Reynolds number increases. The amalgamating vortex regime involves a cyclic behavior involving coalescence of two vortices with one another. The cycle in this regime starts with the downstream movement of the vortex that is closest to the obstacle. This vortex is stretched as it approaches the nose of the obstacle. Once it reaches its nearest point to the obstacle, it reverses direction, moves upstream and amalgamates with the oncoming horseshoe vortex near the horseshoe vortex formation region, forming a new vortex for the next cycle. The frequency of amalgamation, once again, increases as the Reynolds number increases. The amalgamating regime gives way to the breakaway regime at higher Reynolds numbers. In the breakaway regime, the cycle starts with the development of a horseshoe vortex just downstream of the separation line. This vortex breaks away from the formation region, moves downstream towards the body and coalesces with the vortex closest to the cylinder. The main difference between the amalgamating regime and the breakaway regime is that the coalescence in the breakaway regime occurs near the

obstacle rather than near the vortex formation region. The frequency of the breakaway process increases with increasing Reynolds number. Horseshoe vortices in the oscillating, amalgamating and breakaway regimes are all periodic systems. Once in the transitional regime, they behave highly irregularly, and the entire horseshoe vortex system depicts a non-symmetric, incoherent, and turbulent like behavior.

Schwind (1962) and Greco (1990) attempted to explain the existence of the above-mentioned horseshoe flow regimes and their progression considering the conservation of vorticity concept [14, 16]. They argued that as the free-stream velocity increases, different regimes appear in order to diffuse the increased amount of vorticity convected into the junction region from the upstream boundary layer. Greco (1990) shows that other than the adverse pressure gradient generated by the obstacle, there exists a local region of adverse pressure gradient beneath the main horseshoe vortices. The effect of the adverse pressure gradient generated by both the obstacle and the main horseshoe vortices is to create, at the plate surface, the opposite-sign vorticity which cross-cancels the vorticity convected into the junction region. According to Greco (1990), the flow simply adjusts itself into a flow regime to maintain this balance.

Baker (1979) and Thomas (1986) altered the Karman vortex shedding in the wake of a circular cylinder mounted on a base plate by placing a splitter plate behind the cylinder and saw no variations in the periodic horseshoe vortex behavior. They concluded that the periodic unsteady behavior in horseshoe vortices has no dependency on the wake shedding process [15, 19].

Several researchers investigated the influence of the obstacle height on the strength of the horseshoe vortices and/or their behavior. Height variations were found to matter only for short obstacles with a small aspect ratio. Gregory and Walker (1951), Sedney and Kitchens (1975), and Rodriguez y Dominguez et al. (2006) showed that horseshoe vortices are weaker for short cylinders and an increase in height leads to an increase in both the strength and the number of vortices. Once the cylinder is sufficiently tall, the

horseshoe vortex system becomes independent of height variations [20, 21, 22]. Leading edge shape of the obstacle was shown to matter for the size and strength of the horseshoe vortices. Mehta (1984) and Rood (1984) showed that a less blunt leading-edge geometry results in a somewhat smaller and weaker vortex [23, 24].

The abovementioned flow regimes were determined for junctures in laminar boundary layers. A number of investigations also focused on junction flows with a turbulent approach boundary layer. The vortical flow field in such turbulent junction flows was shown to be highly unsteady by Kim et al. (1991). Their visualizations of a wing-body junction flow revealed a sequence of flow events although the process was never periodic. They detected stretching of the horseshoe vortex nearest the wing nose while newer multiple vortices formed upstream and grew with time. They observed leapfrogging of these vortices and eventual merging with the vortex nearest the nose [25]. Devenport and Simpson (1990) are the first published work to report the presence of bimodal (double-peaked) velocity histograms over a certain region in turbulent wing body junction flows. This bimodal region encompassed most of the mean horseshoe vortex. They attributed this bimodality to aperiodic switching of the flow between two flow modes [1]. Olcmen and Simpson (1994) detected bimodality also in wall-pressure fluctuations and showed that the shape of the wing is a dominant factor that determines whether the bimodal behavior exists or not [26]. In applications, bimodality is important as such chaotic, low-frequency bistable behavior leads to large velocity and surface pressure fluctuations, increases the local heat transfer rate and generates undesirable low-frequency noise. A fuller review of the related previous work on fully turbulent junction flows can be found in the review paper of Simpson (2001) [27].

1.2 Objectives

The research presented herein is an experimental investigation into the efficacy of using a short triangular leading-edge plate at the base of a wing-body junction, as a passive control method to mitigate horseshoe vortices. A short review of the flow topology for laminar and turbulent horseshoe vortices, and different flow control proposals, aiming to reduce their negative impacts, are given from the published literature in Section 1.1. The approach boundary layer is laminar. Particle Image Velocimetry (PIV) measurements are conducted upstream of the wing on the symmetry plane in a water tunnel. Triangular leading-edge plates of different thickness and upstream extent are assessed at Reynolds numbers of 25,000, 50,000 and 75,000 (based on the chord length) by cross-comparing the induced horseshoe vortex regimes and the circulation strength of the horseshoe vortices. The investigated Reynolds number range in this work is most pertinent to the cooling flow past computer chips on a circuit board [12]. Although the bluntness of the leading-edge shape has been the subject of previous research, as far as the author is aware, no previous published work has demonstrated the effect of the extend of upstream prominence for a control device. Also, taking into consideration all the investigations described in the forgoing, it can be seen that, neither the temporal tracking nor the size of the horseshoe vortices were calculated, in earlier studies, using a robust vortex identification method. Whereas, while evaluating a control method, such an approach would be very instrumental. Thence, the λ_2 criterion is employed in the present work for the identification of the horseshoe vortices.

Chapter 2

Details of Experimental Set-up and Methodology

2.1 Flow facility

Experiments were conducted in a recirculating-type water tunnel, located at the University of Toronto Institute for Aerospace Studies as shown in Fig. 2.1. The main test section of this tunnel has an area of $610mm \times 685mm$ and a length of $5,000mm$. The test section walls are made of plexiglas material to allow visual access to the flow. Prior to the test-section inlet, the flow passes through a settling chamber, composed of a set of screens and a honeycomb screen, and is accelerated along a 6:1 contraction section. Underneath the water channel is a linear traverse that spans the entire length of the test section (in the streamwise direction). There also exists a secondary traverse spanning the spanwise direction. These traverses enable the accurate positioning of diagnostic tools, such as the laser or camera. During the course of experiments, the tunnel top was covered to avoid propagation of disturbances from the free surface. However, these covers were removable whenever a temporary physical access was needed (such as during the mounting of the experimental rig).

Figure 2.1: Recirculating water channel at the University of Toronto Institute for Aerospace Studies

The calibration of the channel speed was conducted across its working range using the particle image velocimetry (PIV) technique, to be discussed in Section 2.3. Using this technique, also the flow uniformity was tested across the working section of the channel. The results demonstrated a flow uniformity better than 0.3% [28]. At the Reynolds numbers considered in this study, the free-stream turbulence intensity of the tunnel was found to be less than 0.7% using Constant Temperature Anemometry (CTA)[29].

2.2 Test models

The junction flow was produced by a NACA 0020 airfoil and the channel wall. This airfoil model had a maximum thickness T of $50.8mm$ and a wing span of $584mm$. It was 3D-printed from stereolithography (SLA) material due to the manufacturing ease, low cost, low water absorption and durability. To reduce costs, the model is hollow and enclosed. Fig. 2.2 provides a sketch of the airfoil along with its dimensions. As shown in this figure, ribs were placed inside the airfoil at a spacing of $76.2mm$ to provide structural rigidity, and the tip of the model at both ends contained slots to enable insertion of different splitter plates. The channel blockage ratio of the complete experimental setup was 7.2%.

The smooth outer finish of the model was obtained by sanding and priming the 3D-printed model prior to the final coat. This consisted of using 300, 600 and 1000 grit wet sand papers, while intermittently applying a thin coating of primer. When applying the

Figure 2.2: NACA0020 test model. The dimensions of the model are indicated in terms of the maximum thickness T of the airfoil, which has a value of $50.8mm$: (a) CAD Drawing (b) Engineering schematic model

Figure 2.3: Experimental model while undergoing smoothing, priming and final coating stages: (a) after the initial primer coating (b) after the matt black coating

primer, the model was placed on a vertical stand to enable ease of rotation. The model after the application of the primer can be seen in Fig. 2.3 (a). Once priming and sanding stages were completed, a matt black coating was applied to the model, as shown in Fig. 2.3 (b). Matt black was chosen to prevent reflections of the PIV laser from the model surface. After the final coating was applied, a final sanding, using a 1000-grit sand paper, was performed.

Four different triangular-shaped plates were tested in the present study. Fig. 2.4 designates the geometric parameters (height, length and width) of the plates and Table 2.1 presents the value of these parameters for each plate used in the present study in non-dimensional form (in terms of the maximum thickness T of the airfoil). All four plates had the same height. Three of them had the same width while their upstream length varied. The fourth plate had twice the width of the others, while its length was

Figure 2.4: Splitter plate model parameters

Splitter Plate	Width (W/T)	Length (L/T)	Height (H/T)
L1-W1	0.1	1	1.5
L2-W1	0.1	2	1.5
L3-W1	0.1	3	1.5
L2-W2	0.2	2	1.5

Table 2.1: Nomenclature and non-dimensional parameters for splitter plate models

the same as one of the plates. This way, the effect of variations in the thickness and the upstream extent of the control plate can be assessed.

2.3 Experimental method

High-image-density Particle Image Velocimetry (PIV) was employed to measure the velocity field in the plane of symmetry of the junction flow region. The flow was seeded with neutrally buoyant, hollow glass spheres, having a mean diameter of $10\mu m$. A double cavity Nd:YAG laser, operating at a maximum energy output of 200 mJ/pulse and a wavelength of 532 nm, was used along with a series of spherical and cylindrical lenses to produce a laser sheet for the illumination of the seeding particles in the planar flow region of interest. A 2 MP CCD camera was employed to record the particle images. As

illustrated in Fig. 2.5 , the laser system directed the light sheet vertically from beneath the water tunnel floor to the plane of symmetry in the junction region, and the camera faced this laser-illuminated area at a right angle. A sequence of 1,000 image pairs at a rate of 14.5 frame pairs per second was recorded. This corresponded to approximately 69 seconds of continuous data acquisition. The technique of digital PIV determines the local in-plane velocity vectors by dividing the PIV data into small subareas, known as interrogation areas [30]. The particles within each interrogation area are determined by assuming a Gaussian intensity profile, with a kernel density estimation value set by the user according to the conditions of the flow and the seeding density. Images of the detected tracer particles from the first and second illumination are correlated to determine a displacement vector for each interrogation area [30]. This is done statistically by performing a discrete cross-correlation, as given by the following equation:

$$R(x, y) = \sum_{i=1}^M \sum_{j=1}^N I(i, j) I(i + \Delta x, j + \Delta y) \quad (2.1)$$

where I is the intensity value, M and N are the number of pixels within the grid cell, and Δx and Δy are shifts of the image position. The image is shifted around the grid cell and the cross-correlation is performed for each possible shift direction [28]. In the present study, during the cross-correlation of the particle image patterns, the use of a 16 pixels x 16 pixels interrogation window with a 50% overlap yielded a total of 26,082 velocity vectors with a spatial resolution of $0.229mm$ over the grid region of 189×138 . All data processing was carried out using the INSIGHT 4G software, supplied by TSI Inc. To further increase the accuracy of vector measurements in the separated boundary layer region, the feature known as image deformation was used, which is a built-in feature in INSIGHT4G [31, 32]. This technique was found to increase the number of good vectors found within the vortex structures near the channel floor.

Once the raw velocity vectors have been extracted from the PIV images, the data

is then post-processed, which involves vector validation, removal and replacement of spurious vectors, and data smoothing. Spurious vectors are generally caused due to noise or reflections from the channel floor. For post-processing, the software called CleanVec was used. This software allows the user to look at all the images and set maximum and minimum tolerances for the vectors to distinguish any spurious vectors. The software also allows the user to specify a similarity parameter, which assesses the vectors by comparing them to their neighboring vectors. All the vectors which were identified as spurious are removed from the data field. After this process another software, built in-house, is used to fill the removed velocity vectors with artificially created vectors by analyzing the surrounding vectors.

The parameters that influence the PIV measurement error include the particle image diameter, the particle image density, the particle image contrast, the out-of-plane displacement and the in-plane image deformation association with the velocity gradient [32]. These parameters were taken into consideration during post-processing. The Gaussian peak was reduced to 1.45, to capture more vectors, this did increase the number of bad vectors, but these were removed during the post-processing, resulting in an overall greater accuracy for the coherent vortex structures found in the junction flow. The specifications for the PIV equipment used for the current research are summarized in Table 2.2 and Fig. 2.5 presents the respective equipment shown in the experimental setup for PIV.

2.4 The coordinate system

The coordinate system used in this study is defined in Fig. 2.5. The x , y and z coordinates denote the streamwise, spanwise and transverse directions, respectively. Note that the origin of the coordinate system is located at the crossing point of the most upstream point of the model and the midspan of the channel floor. This most upstream point is the leading edge of the wing in absence of the splitter plate, while it is the nose of the

Component	Detailed Information
Seeding particles	Hollow glass spheres, mean diameter of 10 μm
Illumination source	New wave double cavity Nd:Yag laser with maximum energy output of 200mJ/pulse with a wavelength of 532nm and a maximum operating speed of 14.5Hz
Digital camera	Powerview Plus 2MP CCD camera with pixel array size of 1600x1200 pixels
Synchronizer	Model 610335 synchronizer
Software	TSI 4G Insight (64-bit) loaded onto a PC with 64Gb of RAM. Hart correlation and image deformation used. Grid correlation 64x64 to 16x16. Per test case 1,000 PIV image pairs were recorded.

Table 2.2: Particle Image Velocimetry (PIV) equipment used in the current research

Figure 2.5: Experimental model and setup: (a) wing model dimensions (b) experimental setup

splitter plate in presence of the splitter plate.

2.5 Boundary layer characteristics

PIV measurements conducted in the absence of the airfoil showed the development of a laminar boundary layer over the channel wall in agreement with the Blasius boundary layer solution. The boundary layer thicknesses at the leading edge location of the airfoil when the airfoil and the splitter plate are absent were found to be $\delta = 17.6mm, 12.5mm$ and $10.3mm$ for $Re_c = 25,000, 50,000$ and $75,000$, respectively. The change in the boundary-layer thickness between the leading edge location of the airfoil and the leading edge location of the plates when they are not present was at most $1.4mm$.

2.6 Vortex identification methodology

The well-known λ_2 criterion, developed by Jeong and Hussain (1995), was used to identify the horseshoe vortices from the velocity field data in the plane of symmetry. This method is based on the observation that a local pressure minimum is neither a sufficient nor a necessary condition to detect a vortex core under strong unsteady and viscous effects. This is because the unsteady straining can create a pressure minimum through flow expansion without involving rotation or swirling motion, and the viscous effects can eliminate the pressure minimum within a vortex. Neglecting the unsteady and viscous effects, the symmetric part of the gradient of the incompressible Navier-Stokes equation becomes:

$$S^2 + \Omega^2 = -\frac{1}{\rho} \nabla(\nabla p) \quad (2.2)$$

where S and Ω are respectively the symmetric and anti-symmetric components of the velocity gradient tensor ∇V defined as:

$$S = \frac{1}{2}[\nabla V + (\nabla V)^T] \quad (2.3)$$

$$\Omega = \frac{1}{2}[\nabla V - (\nabla V)^T] \quad (2.4)$$

and $\nabla(\nabla p)$ is the Hessian of the pressure when unsteady straining and viscous effects are neglected. A local pressure minimum (i.e., a vortex core) exists in a plane if this pressure Hessian has two positive eigenvalues. From equation 2.2, this condition is equivalent to requiring the $S^2 + \Omega^2$ tensor to have two negative eigenvalues. If λ_1 , λ_2 and λ_3 are the eigenvalues of $S^2 + \Omega^2$ such that $\lambda_1 \geq \lambda_2 \geq \lambda_3$, points with $\lambda_2 < 0$ would automatically have $\lambda_3 < 0$, and hence, belong to a vortex core. Thus, the λ_2 criterion defines a vortex core in an incompressible flow as a connected region where $\lambda_2 < 0$.

As stated by Mullners et al. (2012), because the λ_2 criterion is based on the local analysis of the velocity gradient tensor, the measurement noise in instantaneous velocity fields can contaminate the derivatives [33], yielding extra weak levels of negative λ_2 . Such noisy vortex identification can be seen in Fig. 2.6 (a), where the contours of the absolute value of the negative λ_2 (i.e., $|\lambda_2| < 0$) are plotted for a representative data acquired using PIV. To capture the vortical organization while eliminating noise, a cut off threshold for the absolute value of negative λ_2 contours was applied in this study. Fig. 2.6 (b) depicts the effectiveness of noise elimination in vortex detection using a threshold value on the representative data. Further to the threshold criterion, a secondary criterion was implemented to eliminate small-scale vortices. This criterion is similar to what Gao (2007) used for PIV experimental data where they required a minimum core area of 5 points to define a vortex. In this study, a minimum core of 4 points was used as the secondary criterion in identification of vortices [34].

Figure 2.6: Absolute value of $\lambda_2 < 0$ contours for instantaneous representative data acquired using PIV: (a) when no threshold is applied to $|\lambda_2 < 0|$ levels, (b) when the threshold for $|\lambda_2 < 0|$ levels is equal to 10% of the maximum $|\lambda_2 < 0|$ value. Flow is from left to right.

2.7 Circulation Strength

To quantify the strength of individual vortices, the circulation was calculated for every instant in the PIV sequence using the integral

$$\Gamma = \iint_A \omega dA \quad (2.5)$$

This integration was performed over the vortical area identified by the λ_2 method after eliminating the noise through the above-mentioned λ_2 threshold.

2.8 Estimation of the probability density functions from Kernel distributions

During the course of investigation, for every junction configuration in question, horse-shoe vortices were assessed in the symmetry plane in terms of two key quantities: the circulation strength (Γ) and the streamwise position of the vortex upstream of the airfoil (i.e., the x location of the vortex core). To this end, the probability density function of a bivariate distribution, involving circulation and streamwise position of vortices, was sought. The PIV measurements provided a sequence of 1,000 instantaneous image pairs per experiment. To account for the limited data sampling size, Kernel density estimates were used in lieu of the probability density functions throughout this study. The Kernel

density estimate of the data was calculated using

$$f_h(x) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{x - x_i}{h}\right) \quad (2.6)$$

where $K(\cdot)$ is the Kernel smoothing function, N is the sampling size and h is the bandwidth (also known as the smoothing parameter). Gaussian Kernel smoothing function was utilized with optimal bandwidths determined using

$$h_i = \left\{ \frac{4}{(p+2)N} \right\}^{1/(p+4)} \sigma_i \quad (2.7)$$

where, p denotes the number of dimensions (for the present bivariate case the number of dimensions is $p = 2$), h_i denotes the optimal bandwidth and σ_i the standard deviation of the samples in the i^{th} dimension. In order to accommodate for the possible outliers from the Gaussian distribution, the median absolute deviation estimator defined by

$$\tilde{\sigma} = median \{ |y_i - \tilde{\mu}| \} / 0.6745 \quad (2.8)$$

was used in equation 2.7 as the robust estimate of the standard deviation in accord with Bowman and Azzalini (1997). Here, μ denotes the median of the sample [35].

Chapter 3

Results and Discussion

The use of a triangular splitter plate at the nose of an airfoil is evaluated as a passive control method to mitigate the horseshoe vortices at the airfoil-wall juncture. Particularly, the impact of the thickness and the upstream extent of the splitter plate on the efficacy of the control achieved for different Reynolds numbers is assessed. During the analyses, for each junction configuration in question, the λ_2 definition of vortices and the time-sequence of vorticity fields will be utilized to reveal the temporal behavior of horseshoe vortices in the symmetry plane, and the circulation will be determined to quantify the changes in the strength of vortices. This section will start with the presentation of the results for the uncontrolled junction configuration (which has no control plate) for three Reynolds numbers, and then, will continue with the evaluation of the controlled configurations with upstream triangular plates of different length and thickness.

3.1 Temporal behavior of horseshoe vortices

3.1.1 The uncontrolled junction configuration (the baseline case)

Fig. 3.1 compares the spatiotemporal evolution of the vortical structures, identified using the λ_2 definition, between all three Reynolds numbers under consideration when no

Figure 3.1: For the uncontrolled (baseline) junction configuration, the left-hand side shows the variation in the streamwise location (x-coordinate) of the vortex cores, identified using the λ_2 criterion, with time, and the right hand shows the absolute value of the negative λ_2 contours ($\lambda_2 < 0$) overlaid over the corresponding instantaneous velocity vectors at three sequential instants selected from a cycle. Results presented in (a-d) corresponds to $Re_c = 25,000$, (e-h) corresponds to $Re_c = 50,000$ and (i-l) corresponds to $Re_c = 75,000$

Figure 3.2: For the uncontrolled (baseline) case, time sequence of the instantaneous vorticity contours. Each column presents patterns corresponding to a different Reynolds number with a minimum and incremental values of vorticity from left to right as follow: $|\omega_{min}| = 15s^{-1}$ and $|\Delta\omega| = 5s^{-1}$ for $Re_c = 25,000$, $|\omega_{min}| = 20s^{-1}$ and $|\Delta\omega| = 20s^{-1}$ for $Re_c = 50,000$ and $|\omega_{min}| = 50s^{-1}$ and $|\Delta\omega| = 25s^{-1}$ for $Re_c = 75,000$

control plate is employed. The right-hand side of this figure presents, for each Reynolds number, the absolute value of the negative λ_2 contours (i.e., $|\lambda_2 < 0|$ contours) superimposed over the corresponding instantaneous velocity vectors at three selected instants in time and the left-hand side depicts the streamwise coordinate (x) of the identified vortex cores as a function of time (t). For visual clarity, the x - t traces of vortex cores are presented in this figure only over a time period of 5 seconds, rather than the full 69 seconds of data acquisition time. These x - t traces exhibit an unsteady and cyclically repetitive nature for all three Reynolds numbers. With increasing Reynolds number, the frequency of the cycle increases. At any given instant in time, these traces show two discrete horseshoe vortices detected via the λ_2 criterion within the PIV field of view. One apparent trend in these traces is that the vortex closer to the airfoil reaches further downstream locations as the Reynolds number increases. The $|\lambda_2 < 0|$ contour plots for each Reynolds number (given on the right-hand side of Fig. 3.1 depict the two vortices at three sequential instants selected from a full cycle. These vortices have a clockwise rotational sense as apparent from the velocity vectors. The horseshoe vortex closer to the airfoil (hereafter referred to as the primary vortex) is labeled as V1 and the one further upstream (referred to as the secondary vortex) is labeled as V2. The sequences of $|\lambda_2 < 0|$ contour plots, given in Fig. 3.1, demonstrate the following consecutive states for all three Reynolds numbers under consideration: (1) in the first snapshot, the two-vortex system, consisting of V1 and V2, is detected for each Reynolds number (in Figs. 3.1 (b), (f) and (j), respectively). (2) In the second snapshot, while these vortices are advected downstream, V2 is developed further in size and V1 is stretched and got smaller (as seen in Figs. 3.1 (c), (g) and (k)). Concurrent consideration of the x - t traces of these vortices, given on the left, show that during the downstream progression of the secondary vortex (V2), the primary vortex (V1) first advects downstream, stagnates and then moves slightly upstream. The slight upstream movement of V1 is seen most obviously for $Re_c = 25,000$, whereas it appears only in some cycles of $Re_c = 50,000$ and is

not even visible for $Re_c = 75,000$. The latter is presumably attributable to the decrease in the number of the tracked vortices per cycle with increasing Reynolds number as a result of the use of the same PIV data acquisition rate for each Reynolds number. (3) In the third snapshot of $|\lambda_2 < 0|$ contours, V1 and V2 are replaced with a new primary vortex (labeled as new-V1), while a new secondary vortex (labeled as new-V2) is developed in the upstream. The new primary vortex (new-V1) is a result of the coalescence of the two vortices V1 and V2, as can be seen from an inspection of Fig. 3.2, where time sequences of instantaneous vorticity contours are provided for each Reynolds number. The dashed lines, therein and all the vorticity contour plots to be discussed hereafter, are used to indicate the negative vorticity (corresponding to clockwise rotation) and the solid lines are used to indicate the positive vorticity (counterclockwise direction). As a common characteristic to all three Reynolds numbers under consideration, it can be concluded that the horseshoe vortex systems present in the uncontrolled case are within the breakaway regime. Moreover, the above observed increase in the frequency of the periodic vortex motion with increasing Reynolds number is in total agreement with the previous findings in the literature pertinent to the breakaway regime [16].

3.1.2 Effect of an upstream triangular splitter plate on horseshoe vortices (the controlled case)

Now that the details of the uncontrolled junction flow have been revealed in the preceding section, the control achieved by plates of different length and thickness can be explored. All the splitter plates evaluated in this section have the same height of $1.5T$, while their upstream length and thickness varies. Three lengths and two thicknesses were considered to produce four distinct triangular plates to be evaluated as a control measure. Refer to Table 2.1 for the dimensions of these plates and their abbreviated names.

In Fig. 3.3, contour patterns of $|\lambda_2 < 0|$ at selected instants in time and spatiotemporal traces of vortex cores are given for junctions controlled by plates of $1T$, $2T$ and $3T$

Figure 3.4: For junctions controlled by plates of 1T, 2T and 3T length and 0.1T thickness (named as L1-W1, L2-W1 and L3-W1, respectively), representative contour patterns of instantaneous vorticity at the Reynolds number of $Re_c = 25,000$. Minimum and incremental values of vorticity are $|\omega_{min}| = 18s^{-1}$ and $|\Delta\omega| = 4s^{-1}$

length, and 0.1T thickness at the Reynolds number of $Re_c = 25,000$. These plates are labeled in the figure respectively as L1-W1, L2-W1 and L3-W1 in accord with the naming convention introduced earlier in this work. These results depict a single vortex in steady state for all three plates. Recall that the breakaway flow regime involving a two-vortex system was detected for the uncontrolled junction flow at this same Reynolds number. Here, it is seen that, all three plates with varying upstream extends effectively achieve a regression of the flow regime to the steady vortex regime with one single horseshoe vortex. Note that the detected displacements with time in vortex core traces are insignificant and therefore negligible for these cases. 2T- and 3T-long plates (L2-W1 and L3-W1) result in a vortex closer to the tip of the plate compared to the 1T-long plate (L1-W1). Moreover, as the upstream reach of the control plate increases, the vortical organization detected by the λ_2 method appears to get poorer. A striking parallel observation comes from the instantaneous contour patterns of vorticity, given in Fig. 3.4, that is, an increase in the plate length yields a vortex with weaker vorticity levels and a smaller size. Since, in the cases discussed here, a steady vortex regime is detected, the vorticity contour pattern from a single instant in time is sufficient to represent the general flow behavior.

Fig. 3.5 presents a comparison of the spatiotemporal features, identified using the λ_2 method, induced by the same size plates as in the above case (having a length of 1T, 2T and 3T, and a thickness of 0.1T) but at a higher Reynolds number of 50,000. The plate that has a length of 1T (i.e., L1-W1) yields two steady vortices as apparent from the

Figure 3.5: For junctions controlled by plates of 1T, 2T and 3T length and 0.1T thickness (named as L1-W1, L2-W1 and L3-W1, respectively) at the Reynolds number of $Re_c = 50,000$, the left-hand side shows the streamwise location (x-coordinate) of the vortex cores as a function of time, and the right-hand side shows the absolute value of the negative λ_2 contours ($|\lambda_2| < 0$) at selected instants in time overlaid over the corresponding instantaneous velocity vectors. Results presented in (a-d) correspond to the shortest plate (L1-W1), (e-h) correspond to the medium-length plate (L2-W1) and (i-l) correspond to the longest plate (L3-W1).

Figure 3.6: For junctions controlled by plates of 1T, 2T and 3T length and 0.1T thickness (named as L1-W1, L2-W1 and L3-W1, respectively), representative contour patterns of instantaneous vorticity at the Reynolds number of $Re_c = 50,000$. Minimum and incremental values of vorticity are $|\omega_{min}| = 50s^{-1}$ and $|\Delta\omega| = 5s^{-1}$

snapshots of $|\lambda_2 < 0|$ contours and the x-t traces of vortices. Increasing the length of the plate to 2T and 3T (i.e. L2-W1 and L3-W1, respectively) results in a single vortex in the steady regime. Hence, once again, the breakaway regime observed in the uncontrolled junction flow regresses to the steady vortex regime with the use of the control plates at this Reynolds number. Compared to the uncontrolled case, the number of vortices observed at an instant in time stays the same for the plate with a length of 1T (L1-W1), while it decreases to a single vortex for the plates with lengths of 2T and 3T (L2-W1 and L3-W1). As the upstream reach of the plates increases from 1T to 2T and then to 3T, the vortical organization detected in $|\lambda_2 < 0|$ contour plots appears to gradually get inferior. The representative contour plots of instantaneous vorticity, given in Fig. 3.6, also show a gradual mitigation in the levels and the spatial extend of vorticity for increasing plate length. Furthermore, the closest vortex to the corner of the junction appears closer to the tip of the plate as the length of the plate increases.

In Fig 3.7, a similar comparison as above is made for the same plates at a higher Reynolds number of 75,000. Both the vortex core traces given in Fig. 3.7 (a) and the $|\lambda_2 < 0|$ contour plots given in Figs. 3.7 (b) to (d) show that the plate with a length of 1T (L1-W1) exhibits the breakaway regime as in the case of the uncontrolled junction flow at this Reynolds number. The sequence of the instantaneous vorticity contours, given in Fig 3.8, also confirms this observation. Hence, this plate does not induce much improvement over the uncontrolled baseline configuration. On the other hand, as evident

Figure 3.7: For junctions controlled by plates of 1T, 2T and 3T length and 0.1T thickness (named as L1-W1, L2-W1 and L3-W1, respectively) at the Reynolds number of $Re_c = 75,000$, the left-hand side shows the streamwise location (x-coordinate) of the vortex cores as a function of time, and the right-hand side shows the absolute value of the negative λ_2 contours ($|\lambda_2 < 0|$) at selected instants in time overlaid over the corresponding instantaneous velocity vectors. Results presented in (a-d) correspond to the shortest plate (L1-W1), (e-h) correspond to the medium-length plate (L2-W1) and (i-l) correspond to the longest plate (L3-W1).

Figure 3.8: For the junction configuration controlled by the plate that has a length of $1T$ and a thickness of $0.1T$ (named as L1-W1), time sequence of the instantaneous vorticity contours at the Reynolds number of $Re_c = 75,000$. Minimum and incremental values of vorticity are $|\omega_{min}| = 90s^{-1}$ and $|\Delta\omega| = 10s^{-1}$

Figure 3.9: For junctions controlled by plates of $2T$ and $3T$ length and $0.1T$ thickness (L2-W1 and L3-W1, respectively), representative contour patterns of instantaneous vorticity at the Reynolds number of $Re_c = 75,000$. Minimum and incremental values of vorticity are $|\omega_{min}| = 90s^{-1}$ and $|\Delta\omega| = 10s^{-1}$

from Figs. 3.7 (e) to (l), the longer plates with a length of $2T$ and $3T$ (L2-W1 and L3-W1) effectively achieve the steady vortex regime and reduce the number of vortices to one. The corresponding instantaneous contour plots of vorticity, given in Fig. 3.9, depict clearly these one vortex systems for both $2T$ - and $3T$ -long plates as well. An overall comparison of vorticity contours at this Reynolds number reveals that the spatial extent and magnitude of vorticity decrease as the upstream length of the plate increases (from $1T$ to $3T$).

Effect of the plate thickness on the horseshoe vortex system is evaluated by testing two plates, one with a thickness of $0.1T$ and the other with a thickness of $0.2T$. These plates have the same length of $2T$, and are named respectively as L2-W1 and L2-W2 in short. Fig. 3.10 shows the results obtained using the λ_2 criterion for the thicker plate that has a thickness of $0.2T$ (i.e., L2-W2) at three different Reynolds numbers. At $Re_c = 25,000$, Figs. 3.10 (a) - (d) depict that this plate induces a steady vortex regime with a single identifiable vortex. Similarly, the thinner plate L2-W1, presented earlier, was also seen to induce a steady one-vortex system at this Reynolds number. However, the vortical organization in $|\lambda_2 < 0|$ contours appears to be greater for the thicker plate. Moreover, for the thicker plate (L2-W2), the instantaneous vorticity levels, given in Fig. 3.11, is slightly amplified in magnitude than that of the thinner plate (L2-W1) shown in Fig. 3.4. For a higher Reynolds number of $Re_c = 50,000$, the thicker plate (L2-W2) induces a steady two-vortex regime, as can be seen in Figs. 3.10 (e)-(h) and Fig. 3.11. The thinner plate, however, was shown earlier to induce a single steady vortex. Once again, for the thicker plate (L2-W2), the vortical organization in $|\lambda_2 < 0|$ contours is higher than that of the thinner one at the same Reynolds number. Vorticity levels are also higher for the thicker plate. At a Reynolds number of $75,000$, the thicker plate (L2-W2) yields a three-vortex system in the oscillating vortex regime as can be seen from the zigzagging motion in vortex core traces in Fig. 3.10 (i) and the back and forth motion of $|\lambda_2 < 0|$ concentrations in Fig. 3.10 (j) - (l). The instantaneous vorticity

Figure 3.11: For the junction configuration controlled by the plate that has a length of $2T$ and a thickness of $0.2T$ (referred to as L2-W2), representative contour patterns of instantaneous vorticity. Minimum and incremental values of vorticity are $|\omega_{min}| = 18s^{-1}$ and $|\Delta\omega| = 4s^{-1}$ at $Re_c = 25,000$ and at $Re_c = 50,000$ are $|\omega_{min}| = 50s^{-1}$ and $|\Delta\omega| = 5s^{-1}$.

Figure 3.12: For the junction configuration controlled by the plate that has a length of $2T$ and a thickness of $0.2T$ (referred to as L2-W2), time sequence of the instantaneous vorticity contours at the Reynolds number of $Re_c = 75,000$. Minimum and incremental values of vorticity are $|\omega_{min}| = 90s^{-1}$ and $|\Delta\omega| = 10s^{-1}$.

plate name	the vortex regime and the number of vortices		
	$Re_c = 25,000$	$Re_c = 50,000$	$Re_c = 75,000$
no plate	breakaway regime 2 vortices	breakaway regime 2 vortices	breakaway regime 2 vortices
L1-W1	steady regime 1 vortex	steady regime 2 vortices	breakaway regime 2 vortices
L2-W1	steady regime 1 vortex	steady regime 1 vortex	steady regime 1 vortex
L3-W1	steady regime 1 vortex	steady regime 1 vortex	steady regime 1 vortex

Table 3.1: Comparison of the vortex regimes and the number of horseshoe vortices for the uncontrolled case (with no plate) and the controlled cases with upstream triangular plates of different length: L1-W1, L2-W1 and L3-W1 show plates of 1T, 2T and 3T length, respectively. All plates have the same thickness of 0.1T, where T is the maximum thickness of the airfoil.

contours in Fig. 3.12 also illustrates such oscillatory motion in vortices. The thinner plate (L2-W1), on the other hand, was shown to induce a single horseshoe vortex in the steady regime, with weaker vortical organization and smaller vorticity magnitude at the same Reynolds number (as shown previously in Figs. 3.7 and 3.9). Overall, it can be concluded that increasing the thickness of the plate yields undesirable effects on horseshoe vortices. Up to this point, it has been seen that the uncontrolled junction configuration exhibits a two-vortex system within the unsteady breakaway regime for all three Reynolds numbers under consideration. Table 3.1 compares the vortex regimes and the number of horseshoe vortices observed for the uncontrolled (no plate) case and for the controlled cases with triangular upstream plates of different length at three different Reynolds number. Compared to the uncontrolled case, at the smallest Reynolds number of $Re_c = 25,000$, all three plate lengths in question successfully regress the flow regime to the steady vortex regime and decrease the number of horseshoe vortices by one. At a higher Reynolds number of $Re_c = 50,000$, although the shortest plate (L1-W1) induces the steady vortex regime, it is not able to change the number of vortices in comparison to the uncontrolled case. Longer plates (L2-W1 and L3-W1), however, effectively achieve steady vortex regime and reduce the number of vortices to one. At the highest considered Reynolds number of $Re_c = 75,000$, the shortest plate (L1-W1) affects neither the regime

nor the number of horseshoe vortices, while longer plates (L2-W1 and L3-W1) successfully regress the regime to steady vortex regime and eliminate one of the vortices. It can be concluded that although all three plates achieve favorable control over the horseshoe vortices at the lowest considered Reynolds number ($Re_c = 25,000$), the shortest plate is not very effective at higher Reynolds numbers. Therefore, longer plates are needed to achieve regression of vortex regimes and reduction of vortices by one as the Reynolds number increases. Moreover, at any given Reynolds number, the vortical organization and vorticity levels both get inferior with increasing plate length. Hence, based on the findings so far, in a general sense, among the control plates considered in this study, the longer the upstream reach of the plate, the more the mitigation achieved on horseshoe vortices at a given Reynolds number. It should be noted that, for any given Reynolds number, the variation in the boundary layer thickness was less than about $1.4mm$ between the most upstream point of any of the plates considered and the most upstream point of the airfoil (when no plate or airfoil is present). Therefore, when considering the upstream reach of the plates, the boundary layer thickness variations are trivial.

Table 3.2 provides a summary of the regimes and the number of vortices observed at three Reynolds numbers for the no-plate case and for the plate-controlled cases with plates of different thickness. Although the thicker plate (L2-W2) attains, at the Reynolds number of $Re_c = 25,000$, a single vortex in steady vortex regime similar to the thinner plate (L2-W1), as the Reynolds number increases, the thicker plate results in an unsteady vortex regime and/or larger number of vortices. Moreover, the vortical organization and vorticity magnitude are found to amplify for the thicker plate. Hence, an increase in the thickness of the plate causes undesirable effects. This observation is aligned with the findings of previous studies about the effect of the bluntness of the obstacle on horseshoe vortices.

plate name	the vortex regime and the number of vortices		
	$Re_c = 25,000$	$Re_c = 50,000$	$Re_c = 75,000$
no plate	breakaway regime 2 vortices	breakaway regime 2 vortices	breakaway regime 2 vortices
L2-W1	steady regime 1 vortex	steady regime 1 vortex	steady regime 1 vortex
L2-W2	steady regime 1 vortex	steady regime 2 vortices	oscillating regime 3 vortices

Table 3.2: Comparison of the vortex regimes and the number of horseshoe vortices for the uncontrolled case (with no plate) and the controlled cases with upstream triangular plates of different thickness: L2-W1 and L2-W2 show plates having a thickness of $0.1T$ and $0.2T$ thickness, respectively. Both plates have the same streamwise length of $2T$, where T is the maximum thickness of the airfoil.

3.2 Circulation strength of horseshoe vortices

To further elaborate on the performance of the triangular plates as a control measure, the circulation strength of horseshoe vortices was assessed for each junction configuration under consideration. As explained in section 2.7, circulation was established by taking the integral, given by equation 2.5, over the vortex area identified using the λ_2 criterion. This way, the instantaneous circulation strength (Γ) was determined for every identified horseshoe vortex along with the streamwise location (x -coordinate) of the vortex core at each instant in the PIV sequence. Then the probability density function (pdf) of the two variables (circulation Γ and x location of vortices) was built using bivariate Kernel density estimation, as detailed in section 2.8. In Fig. 3.13, these pdfs are presented at three different Reynolds numbers for both the uncontrolled and controlled configurations in question.

The pdf contours of the baseline configuration, given in Figs. 3.13 (a) - (c), show a significant increase in the most probable highest circulation levels with increasing Reynolds number. These contours also point out certain common features for all three Reynolds numbers. A parallel inspection of the time sequences of vorticity contours, given in Fig. 3.2, is also helpful for the understanding of these features. It can be seen that the most probable location of the peak circulation occurs just prior to the location of vortex coales-

cence for all three Reynolds numbers. From the formation region up until this location, vortices convect downstream as their circulation increases. Downstream of the point of coalescence, the time-sequence of vorticity contours (in Fig. 3.2) show that the new vortex, that is formed from the coalescence of two vortices, advects further downstream toward the airfoil, stagnates for a while and then moves slightly upstream right before amalgamating with another vortex. During this phase, the vortex undergoes stretching and its vorticity gets considerably smaller. In parallel to this observation, downstream of the point of vortex coalescence, the pdf contours for all three Reynolds numbers show a decrease in the circulation of vortices. High probability in pdf distributions appears at around the region where vortices stagnate with a very low circulation.

First and foremost, for all plate-controlled configurations, the most probable peak circulation appears considerably lower than the uncontrolled case at a given Reynolds number. This suggests that any of the plate-controlled cases considered in this study are better than the baseline.

At the Reynolds number of $Re_c = 25,000$, all plate-controlled configurations in question are known to have a single horseshoe vortex in the steady regime. As a result, the pdfs corresponding to these cases exhibit a high probability of circulation at and in close vicinity of the location where this vortex is detected. As the upstream length of the plate is increased at this Reynolds number from 1T to 2T and then to 3T (L1-W1, L2-W1, L3-W1, respectively), the most probable circulation level for vortices mitigates drastically, implying an improvement in flow control. Comparison of the pdf results for L2-W1 and L2-W2 at $Re_c = 25,000$, however, shows that an increase in the plate thickness while keeping the plate length unchanged causes a significant amount of increase in the most probable levels of circulation.

At $Re_c = 50,000$, the shortest plate (L1-W1) was seen in the preceding section to produce a two-vortex system in the steady regime. Consequently, the corresponding pdf contours appear in two distinct concentrations, related to these vortices. Although

the primary vortex has higher circulation values than the secondary one, they are both smaller in comparison to the most probable circulation levels seen in the uncontrolled configuration. As the plate length increases to $2T$ and then to $3T$ (L2-W1 and L3-W1, respectively), only one pdf concentration corresponding to the single steady vortex arises. The most probable circulation, once again, decreases with increasing plate length. On the other hand, an increase in thickness amplifies the most-probable circulation levels as apparent from a comparison of the L2-W1 and L2-W2 at this Reynolds number.

At $Re_c = 75,000$, being within the breakaway regime, the shortest plate (L1-W1) once again shows pdf characteristics similar to the baseline case. That is, the most probable location of high circulation levels appear just prior to the location of vortex coalescence; after coalescence, the circulation of the resulting vortex decreases as it moves downstream and stagnates; and a local maximum in pdf contours occurs at the stagnation region of this vortex. Compared to the baseline, however, the vortex formation, advection and stagnation region shortens considerably in length. Also, high probability levels of circulation are much smaller than those of the uncontrolled case at this Reynolds number. As the plate length increases (from L1-W1 to L2-W2 and to L3-W3), the most probable circulation levels decrease. However, with an increase in thickness (from L2-W1 to L2-W2), the oscillatory regime with three vortices sets in, and much higher levels of circulation become highly probable compared to the thinner plate.

Figure 3.13: Contour patterns of the probability density function of the circulation (Γ) and the streamwise (x) location of vortices. From top row to the bottom, the patterns correspond to the uncontrolled (baseline) configuration, and the configurations fitted with the plates referred to as L1-W1, L2-W1, L3-W1 and L2-W2, respectively. $Re_c = 25,000, 50,000$ and $75,000$ from left column to the right.

Chapter 4

Conclusion

In the present study, installing a triangular-shaped plate at the upstream corner of a wing-body junction is experimentally assessed as a passive control technique to suppress and/or mitigate the horseshoe vortices. The effects of plate length and thickness upon the regime and strength of horseshoe vortices are discussed for Reynolds numbers ranging from $Re_c = 25,000$ to $75,000$ (based on the chord length). Experiments are performed in a recirculating water tunnel. The incoming boundary layer is laminar. For any given Reynolds number, the change in the thickness of the boundary layer between the most upstream point of the wing and the most upstream point of each control plate considered was negligibly small. Therefore, under the same Reynolds number condition, all cases studied here were exposed to the same boundary layer thickness at their upstream point. The following conclusions are drawn from the analyses of the PIV results:

1. The uncontrolled (natural) wing-body junction demonstrates a two-vortex system in periodic breakaway regime for all three Reynolds numbers investigated in this study.
2. The horseshoe vortices forming in all plate-controlled junctions investigated in this work have lower circulation strength than the uncontrolled case. Therefore, any one of the triangular plate-controlled cases is better than the baseline.

3. For the control plates considered in this work, increasing the upstream reach of the triangular plate at a given Reynolds number mitigates the vortical organization, vorticity, size and circulation strength of horseshoe vortices further. Moreover, although all plate lengths being discussed successfully regress the junction flow to steady vortex regime and eliminate one of the horseshoe vortices at the lowest considered Reynolds number of $Re_c = 25,000$, the shortest plate at higher Reynolds numbers is not able to achieve such control over the flow. Therefore, longer plates are needed at higher Reynolds numbers to achieve steady vortex regime and to reduce the number of horseshoe vortices. As a general rule, it has been proven that the longer the plate, the better the mitigation in horseshoe vortices.

4. As the plate thickness increases, the vortical organization, vorticity, size and circulation strength of vortices amplify significantly. In addition, increasing plate thickness results in extra horseshoe vortices and/or transforms the flow to an unsteady vortex regime. With increasing Reynolds number, the thicker plate performs even poorer as a control measure. Therefore, an increase in the thickness of the plate deteriorates the desired control. As a general rule, it can be stated that the thinner the plate, the better the mitigation in horseshoe vortices.

Overall, the installation of a triangular splitter plate at the base of a wing-body junction is found to be a promising passive control measure for the mitigation of horseshoe vortices.

Chapter 5

Future Work

Using a short triangular leading-edge plate at the base of a wing-body junction has been assessed as a passive control method at Reynolds numbers of 25,000, 50,000 and 75,000 (based on the chord length). The plate geometries considered had a length of $1T$, $2T$ and $3T$, a width of $0.1T$ and $0.2T$, and a height of $1.5T$, where T is the maximum thickness of the wing. The wing model was a NACA 0020 airfoil. The approach boundary layer was laminar. The work can be expanded in the future to investigate the following points:

- The assessment of this method for a turbulent approach boundary layer.
- The efficacy of the control method at varying angles of attack.
- Implementing this method for a swept-wing-body junction.
- Exploring additional plate geometries in order to determine the optimal configuration.

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