Stability and transition of three-dimensional boundary layers

by

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Abstract
A focus has been put on the stability characteristics of different flow types existing on air vehicles. Flow passing over wings and different junctions on an aircraft face numerous local features, ranging from different pressure gradients, to interacting boundary layers. Primarily, stability characteristics of flow over a wing subject to negative pressure gradient is studied. The current numerical study conforms to an experimental study conducted by Saric and coworkers, in their Arizona State University wind tunnel experiments. Within that framework, a passive control mechanism has been tested to delay transition of flow from laminar to turbulence. The same control approach has been studied here, in addition to underlying mechanisms playing major roles in flow transition, such as nonlinear effects and secondary instabilities.

The same flow type has been considered to study the receptivity of three-dimensional boundary layers to freestream turbulence perturbations. Similarly, the numerical configuration, follows the experiments performed in the same group by Downs (2012). The experiments entail investigation of the effect of low freestream turbulence on crossflow instability. A well-documented experiment enables the numerical studies to properly reproduce the experimental environments.

Another common three-dimensional flow feature arises as a result of streamlines passing through a junction, the so called corner-flow. For instance, this flow can be formed in the junction between the wing and fuselage on a plane. A series of direct numerical simulations using linear Navier-Stokes equations have been performed to determine the optimal initial perturbation. Optimal refers to a perturbation which can gain the maximum energy from the flow over a period of time. Power iterations between direct and adjoint Navier-Stokes equations determine the optimal initial perturbation. In other words this method seeks to determine the worst case scenario in terms of perturbation growth. Determining the optimal initial condition can help improve the design of such surfaces in addition to possible control mechanisms.

Descriptors: Receptivity, stability, optimal growth, three-dimensional boundary layers, crossflow instability, roughness control, freestream turbulence, secondary instability
Stabilitet och laminär-turbulent omslag i tredimensionella gränsskikt

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Abstrakt


En intressant typ av tredimensionell flöde uppstår när en fluid strömmar längst med hörnet av två korsande ytor. Detta flöde kan t.ex. bildas i övergången mellan vingen och flygplanskroppen. En serie av numerisk simulering har utförts för att hitta de initialstörningar som nås maximal energi under en vis tidsperiod och därmed identifiera det mest kritiska störningen.

Nyckelord: receptivitet, stabilitet, optimal tillväxt, tredimensionellt gränsskikt, crossflow, fristömssturbulens, sekundärinstabilitet.
Preface

The current study focuses on the different underlying phenomena regarding the stability characteristics of three-dimensional boundary layers. An introduction, briefing the types of boundary layers created on aircraft is given. Different methods in investigating the stability features are also discussed. In the second part the following articles are presented.

**Paper 1.** S. M. Hosseini, D. Tempelmann, A. Hanifi & D. S. Henningson,

**Paper 2.** S. M. Hosseini, A. Hanifi & D. S. Henningson,
*Effect of freestream turbulence on roughness-induced crossflow instability* Internal report (2013)

**Paper 3.** O. Schmidt, S. M. Hosseini, U. Rist, A. Hanifi & D. S. Henningson,
*Optimal initial perturbations in streamwise corner-flow* Internal report (2012)
Division of work between authors
The research project was initiated by Dr. Ardeshir Hanifi (AH) with Prof. Dan S. Henningson (DH) as the co-advisor.

**Paper 1**
The computations have been performed by Seyed M. Hosseini (SH) using the codes developed by David Tempelmann (DH) with input from AH. The paper has been written by SH with feedback from DT, AH and DH.

**Paper 2**
The computations have been performed by (SH) with input from AH. The paper has been written by SH with feedback from AH and DH.

**Paper 3**
The computations have been performed by Oliver Schmidt (OS) using the codes developed by OS, and SH. The paper has been written by OS with feedback from SH, Ulrich Rist (UR), AH and DH.
## Abstract

### Abstrakt

### Preface

## Chapter 1. Introduction

## Chapter 2. Transition in Three-Dimensional Boundary Layers

2.1. Receptivity

2.2. Instability mechanisms

2.2.1. TS-Waves

2.2.2. Görtler vortices

2.2.3. Crossflow instability

2.2.4. Attachment line instability

2.2.5. Non-linear effects and secondary instabilities

2.2.6. Transition

2.2.7. Transition control

## Chapter 3. Corner Flow

3.1. Corner flow

3.2. Optimal initial perturbations

3.2.1. Governing equations

3.2.2. Optimal perturbation

## Chapter 4. Summary of Papers

Paper 1

Paper 2

Paper 3

## Chapter 5. Conclusions & Outlook

## Chapter 6. Acknowledgements

Bibliography
Part II - Papers

Paper 1. Stabilization of a swept-wing boundary layer by distributed roughness elements 27

Paper 2. Effect of freestream turbulence on roughness-induced crossflow instability 43

Paper 3. Optimal initial perturbations in streamwise corner-flow 63
Part I

Introduction
CHAPTER 1

Introduction

The design procedures in aviation industry, despite being revolutionary in the start, have gone through substantial changes over the last decades. One main aspect of such changes roots in the urge for optimising different features of air vehicles. Aerodynamic modifications have conspicuously benefited in drag reduction from such advances owing to the new findings in the field of fluid mechanics.

Wings, fuselages and their attachment points are among the top contributors to total friction drag. Evidently reducing this drag can considerably mitigate the fuel consumption and emission of pollutants. One common way to achieve this goal is to keep the flow laminar over a larger part of aerodynamic surfaces. Over the last decades laminar wing design has received growing attention from academia and front line industries. The flow viscosity induces a gradient in velocity near the wing surfaces referred to as boundary layer. This is accompanied by pressure gradient and three-dimensional effects caused by the sweep angle of the wing. On the other hand the junctions, i.e between wing and fuselage, promote a different type of three-dimensional effect. For instance at a right angle junction, the wall normal component of one boundary layer, transpires as the crossflow component of the other and vice versa. The latter is referred to as Corner-Flow. The deformation of streamlines over such surfaces creates intrinsic instabilities which due to imperfections can lead to flow breakdown and transition from laminar to turbulent flow.

Numerous so called receptivity studies are dedicated to determining the role of environmental disturbances acting on the boundary layer, namely, freestream turbulence, surface roughness, and acoustic waves. Such perturbations can be characterised in the far field or on the surface, however once they penetrate the boundary layer their characteristics change due to the filter-like acting role of the boundary layer. The receptivity studies aim to correlate the perturbations outside and inside the boundary layer. Direct numerical simulation, and adjoint based simulation of various forms of Navier-Stokes equations can serve as the receptivity tools in determining such correlations. Moreover, once the disturbance amplitudes, and scales are determined, their dominance is dictated by the boundary layer. Once susceptible to instabilities they continue to gain energy until they reach a certain amplitude that nonlinear effects begin to dominate modifying the underlying meanflow. In some cases this is accompanied by the appearance of secondary instabilities which are prompted by an inflected
meanflow. The substantial nature of secondary instabilities in those cases lies beneath their explosive growth which appears right before transition.

In this study the stability characteristics exclusive to different types of three-dimensional boundary layers present on a conventional aircraft are studied using various techniques. For instance, the receptivity characteristics of flow over a wing are computed by the means of direct numerical simulation. The effect of roughness, and freestream turbulence are investigated. Additionally a flow transition control mechanism by means of subcritical roughness elements placed near the leading edge has been investigated. Subcritical refers to excited modes that can not cause transition merely on their own. Additionally, a popular form of instability analysis via determining the worst case scenario for a perturbation is applied to the corner-flow. In other words, such an analysis seeks to pin-point a form of perturbation that can gain the maximum energy from the flow over a certain period of time. The perturbation is referred to as optimal initial condition.
CHAPTER 2

Transition in Three-Dimensional Boundary Layers

The transition mechanisms in three-dimensional boundary layers has been the subject of many studies in the past. Morkovin (1969) laid out different stages of transition and coined the term Receptivity as depicted in figure 2.1. Receptivity refers to the process in which the external disturbances penetrate into the boundary layer altering in scales, amplitude and other characteristics. In this process the boundary layer acts as a filter. Such disturbances can then seize different paths to transition or die out depending on the meanflow. In the overviews by Bippes (1999), Saric et al. (2003), the authors explain the process in which disturbances of different sorts, penetrate a boundary layer and set the initial condition. Furthermore the evolution of such perturbations and their role in breakdown of flow is studied. Our study of the three-dimensional boundary layers of a swept wing and a corner-flow is mainly focused on exponential and transient growth. The next sections present the kinds of prevalent intrinsic stabilities of three-dimensional boundary layers present on a wing or in a corner.

2.1. Receptivity

Goldstein (1983, 1985), classified the receptivity process into two main categories. The first category includes the receptivity near a body leading edge, due to the boundary layer thickness which is small, and subject to a large pressure gradient. The second category, covers a region further downstream where for instance, surface imperfections can generate initial perturbations, often referred to as localised receptivity. A number of methods have been developed to evaluate the nature of initial perturbation penetrating the boundary layer. Different examples can be found in literature, such as asymptotic methods in Goldstein & Hultgren (1989), finite Reynolds-number models discussed by Crouch (1992) and Choudhari & Streett (1992), and Hill (1995) of the adjoint model.

One frequently reported observation in three-dimensional boundary layers is associated with the receptivity to surface roughness with different levels of freestream turbulence. In reviews by Bippes (1999) and Saric et al. (2003) it was noted that stationary crossflow disturbances are prone to dominance in low levels of freestream turbulence. Later numerical simulation by Schrader et al. (2009) confirmed such observations. Tempelmann et al. (2012a) numerically investigated worst case scenarios in the receptivity of a boundary layer to surface roughness and freestream vorticity. They show that the optimal surface roughness has a wavy shape in the streamwise direction, while the optimal
freestream disturbance takes a localized streak-type structure. Additionally the authors compared the receptivity amplitudes of the boundary layer to surface non-uniformity and freestream perturbation content. The former showed to have a receptivity amplitude of one order of magnitude higher than the latter.

2.2. Instability mechanisms

Figure 2.2 depicts different regions on a wing where the flow faces different local features, such as curvature, and pressure gradient. Each region can act as stabilising for one type of instability while destabilising the other type simultaneously. In this section the common types of instability prone to occur on a swept wing are discussed.

2.2.1. TS-Waves
This viscous type of instability was first theoretically shown by Tollmien (1929) and Schlichting (1933). They refer to travelling waves within the boundary layer. Inherently negative pressure gradients stabilises such travelling waves while the positive pressure gradient has a destabilising effect.
2.2. INSTABILITY MECHANISMS

2.2.1. TS & Crossflow instability

2.2.2. Görtler instability

The passage of flow over a concave surface gives way to destabilising centrifugal forces which can create instabilities in the form of counter-rotating vortices, so called Görtler vortices. This region is marked in figure 2.2 near the lower side of the trailing edge. For a recent work on Görtler vortices refer to Schrader et al. (2011).

2.2.3. Crossflow instability

This type of instability is an exclusive signature of three-dimensional boundary layers. The wing sweep causes the boundary layer to acquire an inflection point. This inflection point boosts the centrifugal forces, which are in turn balanced by pressure adjustment of the flow outside the boundary layer. On the other hand, inside the boundary layer the pressure remains constant while, velocity reaches zero on the wall. The imbalanced forces are then transpired in the form of vortices, termed as crossflow vortices. A negative pressure gradient is a destabilising factor leading to their dominance on the upper side of the wing at a negative angles of attack. The current study mainly focuses on this particular kind. The interaction between surface imperfections, freestream perturbations and their effects on crossflow instability are further analyzed.

2.2.4. Attachment line instability

Also known as the leading-edge contamination is normally brought about by the propagation of waves along the attachment line of the wing, illustrated in figure 2.2. Such waves can be generated form the wing root. This was first observed in the experiments by Gray (1952). He noticed that by increasing the sweep angle the transition location moves towards the attachment line. Poll (1979) for
2. TRANSITION IN THREE-DIMENSIONAL BOUNDARY LAYERS

the first time distinguished between transition induced by crossflow instability and leading edge instability. Mack et al. (2008) have recently performed a study on the global instability around a parabolic body while considering the interactions between crossflow and attachment line instability.

2.2.5. Non-linear effects and secondary instabilities

Bippes (1999) pointed out that, in contrast to transition due to Tollmien-Schlichting instability, no efficient transition criterion is conceivable in a crossflow dominated case if the nonlinear effects are neglected. In flow cases where the meanflow is modified due to nonlinearities the stability characteristics are significantly modified. It can be deduced from the presence of modes generated through nonlinear interactions of various primary perturbations. Figure 2.3a depicts the modal amplitude of stationary crossflow vortices generated by placing an array of roughness elements near the leading edge of an infinite swept wing. The roughness element has a spanwise periodicity of $\beta$ and consequently generates the super-harmonics. A comparison is given with parabolised stability equations (PSE) analysis. This allows for determining the present nonlinear effects. For more on the application of PSE and nonlinear PSE on a boundary layer with roughness element refer to Herbert (1993, 1997), and Tempelmann et al. (2012b). It can be clearly observed from the linear and nonlinear computations that the nonlinear interactions significantly influence the amplitudes of the stationary crossflow modes. This enables the transfer of energy between different modes where linear stability analysis fails, resulting in over prediction of amplitudes of fundamental stationary crossflow modes.

Another extremely important factor lies in the modifications of the mean-flow which can have a substantial influence on the stability characteristics. The so called secondary instabilities have generally a high frequency signature, accompanied by an explosive growth. Malik et al. (1994), Wassermann & Kloker (2002), and Wassermann & Kloker (2003) investigated the role of secondary instability caused by meanflow modifications. The authors find that secondary instabilities are prone to occur on a modified meanflow carrying an inflection point. One exclusive signature of this kind of instability as is pointed out in Klebanoff et al. (1962) is the explosive growth of high frequency modes. Figure 2.3b illustrates the amplitudes of steady and unsteady crossflow modes obtained via a Fourier decomposition. Amplitudes of the steady disturbances are obtained by subtracting the meanflow, from the zero-frequency mode. The explosive growth of high frequency mode can clearly be seen prior to transition.

2.2.6. Transition

As was discussed in the previous sections perturbations can take numerous paths to flow breakdown and eventual transition. Kachanov (1994) provides a thorough overview of boundary-layer transition mechanisms. Figure 2.4 demonstrates the transition caused by stationary and travelling crossflow modes on
2.2. INSTABILITY MECHANISMS

a wing at a negative angle of attack. In this example stationary and travelling crossflow vortices are generated as a result of interactions between surface roughness and a complex background noise. The background noise is introduced as a random wall-normal volume forcing, imposing a range of frequencies onto the flow. Turbulent spots appear intermittently prior to a complete breakdown of the flow as is illustrated in figure 2.4a. Further analysis of this flow demonstrates the role nonlinearities and secondary instabilities play in the process of flow breakdown to turbulence.

2.2.7. Transition control

Countless methods and approaches have been tested in order to delay the transition. Two major related campaigns are those of experiments in Göttingen and Saric and coworkers. In the latter set of experiments, a new technique in which excitation of a subcritical perturbations, has been used to modify the meanflow to damp the most unstable crossflow modes. Subcritical refers to a mode which can not cause transition merely on its own. Saric et al. (1998) perform control experiments using the Swept NLF(2)-415 wing. Roughness elements are distributed near the leading edge with a spanwise periodicity equal to the chosen subcritical mode. In absence of any roughness element, transition occurs around the pressure minimum location $x/c = 71\%$. Application of the subcritical roughness elements moved the transition location all the way down to $x/c = 80\%$. In our study the same approach for transition control is examined. One additional consideration has also been taken into account regarding the level of background noise. In some of the wind tunnels in Europe similar experiments showed none or very small positive effect. This has been associated to the higher level of freestream turbulence or acoustic perturbations in the wind tunnels in Europe in comparison to Arizona State University wind tunnel. In our study a higher level of background noise has been chosen

Figure 2.3. (a) Amplitude of stationary crossflow vortices with $\beta = n\beta_0$. (b) Amplitude evolution of steady and unsteady disturbances. The gray lines represent unsteady disturbances plotted at a constant frequency step size (190Hz).
in order to examine the robustness of such a transition control. Figure 2.4b depicts the isosurfaces of the instantaneous velocity of the controlled case. It is apparent that the control mechanism effectively delays the transition location.
CHAPTER 3

Corner-Flow

The second part of this thesis is dedicated to studying the type of flows formed near the junction of two connecting surfaces. Examples of such flows are commonly found near the attachment line of a wing and a fuselage on an aircraft. Baseflow characteristics of such flows in addition to some relevant stability characteristics are discussed in the following sections.

3.1. Corner-flow

Stability analysis of corner-flow has been the focus of studies such as, Dhanak (1993) who used a locally parallel flow approximation. Balachandar & Malik (1993) addressed the two dimensional stability problem and found an inviscid instability (corner mode) which has a higher growth rate than the conventional Tollmien-Schlichting instability (viscous mode). This explained the earlier transition to turbulence in the corner-flow compared to the Blasius boundary layer. Parker & Balachandar (1999) studied the effect of pressure gradient in a viscous framework and found that even a small adverse streamwise pressure gradient gives dominance to the inviscid mode. They found the viscous modes to be more active away from the corner. Alizard et al. (2009) further looked into the linear stability features using a local linear stability theory for computing temporal growth and the parabolised stability equations for spatial growth. They discovered that the corner mode is on the edge between the stable and unstable region, and did not find an unstable inviscid mode in the local framework. However in their non-parallel analysis they found the same previously stable corner modes to be unstable. Non-parallel effects seemed to be insignificant with respect to the viscous modes. Their results showed slight disagreement with Parker & Balachandar (1999) which was explained by the difference in the baseflows. Ridha (2003) also reported a high sensitivity of such characteristics to the baseflow. Alizard et al. (2010) performed sensitivity analysis of small baseflow variation on the linear stability results. They confirmed profound influence of baseflow modification regarding the stability of the corner mode. The study showed that a small deviation of $\approx 1\%$ can trigger the inviscid mechanism which allows a lower critical Reynolds number. This can somewhat explain the discrepancy in transitional Reynolds number between experiments and simulations. This also confirmed the results previously reported by Zamir (1981) which emphasised the difference in transitional Reynolds numbers between simulations and experiments.
3. CORNER-FLOW

3.1. Isosurfaces of the wall-normal velocity $V$. The direction of the flow is from left to right. The gray surfaces represent the corner walls.

3.2. Optimal initial perturbations

The initial perturbations that can gain the maximum energy from a flow over a certain period of time is often referred to as optimal initial condition. In the current study, linear optimal initial perturbations are computed for the first time in a global framework, in order to pin-point the worst case scenarios in terms of perturbation characteristics. We use a self-similar and a modified baseflow. The latter resembles the baseflow often observed in experiments. Figure 3.1 shows the isosurfaces of the wall normal velocity component of the baseflow with the self similar solution. The current baseflow has been obtained by solving the parabolised Navier-Stokes equations (cf. Schmidt & Rist 2011).

An optimisation technique has been used which employs Lagrange multipliers. The objective function to be optimized is set as the kinetic energy of the perturbations (cf. Monokrousos et al. 2011) as will be explained in the next chapter.

3.2.1. Governing equations

The initial optimal perturbations are computed within a linear framework using the linearised Navier-Stokes equations. The instantaneous velocity and pressure field is decomposed into $u = U + u'$ and $p = P + p'$, where $U$, $P$ denote the mean values and $u'$ and $p'$ represent the perturbations. By inserting the
3.2. OPTIMAL INITIAL PERTURBATIONS

decomposition into the Navier-Stokes equations and subtracting the equation of the mean values one can reach at the linearised Navier-Stokes equation 3.1

\[
\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{u}' + (\mathbf{u}' \cdot \nabla) \mathbf{U} = -\nabla p' + \frac{1}{Re} \nabla^2 \mathbf{u}' \tag{3.1a}
\]
\[
\nabla \cdot \mathbf{u}' = 0. \tag{3.1b}
\]

Here we are interested in the initial condition which over a preset period of time can obtain the maximum energy from the flow, therefore the energy of the perturbation at time \( \tau \) is monitored:

\[
E(\tau) = \frac{\langle \mathbf{u}'(\tau), \mathbf{u}'(\tau) \rangle}{\langle \mathbf{u}'(0), \mathbf{u}'(0) \rangle}, \tag{3.2}
\]

where the inner product is given by

\[
\langle \mathbf{u}', \mathbf{u}' \rangle = \int_{\Omega} \mathbf{u}' \cdot \mathbf{u}' dv. \tag{3.3}
\]

herein, \( G(\tau) \) is defined as the maximum energy growth over all the possible initial conditions. Computing this value can be considered to be equivalent to calculating the maximum eigenvalue of an auxiliary problem (cf. Trefethen et al. (1993), Reddy & Henningson (1993), and Blackburn et al. (2008)). Forming the eigenvalue problem includes the definition of a linear operator which maps the velocity forward in time such that

\[
\mathbf{u}'(\tau) = \mathcal{A}(\tau)\mathbf{u}'(0),
\]

leading to

\[
G(\tau) = \max_{\mathbf{u}'(0)} \frac{\langle \mathbf{u}'(\tau), \mathbf{u}'(\tau) \rangle}{\langle \mathbf{u}'(0), \mathbf{u}'(0) \rangle} = \max_{\mathbf{u}'(0)} \frac{\langle \mathcal{A}(\tau)\mathbf{u}'(0), \mathcal{A}(\tau)\mathbf{u}'(0) \rangle}{\langle \mathbf{u}'(0), \mathbf{u}'(0) \rangle}. \tag{3.4}
\]

In order to further simplify the problem one can employ some characteristics of the adjoint equations such as which are obtained by performing an integration by parts using the inner product definition of equation 3.3.

\[
\langle \mathbf{u}'(\tau), \mathbf{u}^*(\tau) \rangle = \langle \mathbf{u}'(0), \mathbf{u}^*(0) \rangle, \tag{3.5}
\]

and similarly,

\[
\langle \mathbf{u}'(\tau), \mathbf{u}^*(\tau) \rangle = \langle \mathcal{A}(\tau)\mathbf{u}'(0), \mathbf{u}^*(0) \rangle, \tag{3.6}
\]

which by using the inner product of equation 3.3 the following relations are obtained

\[
\langle \mathbf{u}'(\tau), \mathbf{u}^*(\tau) \rangle = \langle \mathcal{A}(\tau)\mathbf{u}'(0), \mathbf{u}^*(\tau) \rangle \tag{3.7}
\]
\[
\langle \mathbf{u}'(0), \mathbf{u}^*(0) \rangle = \langle \mathbf{u}^*(0), \mathcal{A}^*(\tau)\mathbf{u}'(\tau) \rangle \tag{3.8}
\]

simplifying equation 3.4 to

\[
G(\tau) = \max_{\mathbf{u}'(0)} \frac{\langle \mathbf{u}'(0), \mathcal{A}(\tau)\mathcal{A}(\tau)\mathbf{u}'(0) \rangle}{\langle \mathbf{u}'(0), \mathbf{u}'(0) \rangle}. \tag{3.9}
\]
Hence, the maximum initial perturbation over all the initial conditions is obtained by computing the maximum eigenvalue of operator $A^*(\tau)A(\tau)$. The so called power iteration method comprising of the following steps has been used.

- Integrate the Navier-Stokes equations forward in time to obtain $u(\tau)$.
- Integrate the adjoint Navier-Stokes equations backward in time using the initial condition $u^*(\tau) = u'(\tau)$ to obtain $u^*(0)$.
- Determine a new initial guess after localising $u^*(\tau)$ and projecting it to a divergence free space, followed by a normalization such that the resulting perturbation such has a unit norm.
- Check for convergence of the perturbation $|u^{n+1}(0) - u^n(0)|$, if not met go to the first step.

### 3.2.2. optimal perturbation

The resulting optimal initial perturbation is a wave-packet localised near the corner region of inviscid nature and symmetric to the bisector, figure 3.2. The perturbations growth is initially governed by the Orr mechanism giving rise to a transient growth and later a steady exponential growth takes over. The growth rate of the initial perturbations appears to increase with a modified baseflow corroborating the results found by Alizard et al. (2010). To the knowledge of this author, so far the study of optimal initial perturbations in corner-flows is constrained to a linear framework, however regarding the high sensitivity of stability characteristics to the baseflow, inclusion of nonlinear interactions seems to be consequential, as repeatedly reported by Ridha (2003), Alizard et al. (2010).

The presented results in paper 3 are given within the critical regime. Additional subcritical regime simulations are also performed. Subcritical in the sense that regarding the linear stability theory the perturbations are expected
3.2. OPTIMAL INITIAL PERTURBATIONS

Figure 3.3. Streamwise perturbation velocity isosurfaces of the localised optimal initial conditions. Isosurfaces are drawn for $\pm 0.1 \| u' \|_\infty$.

...to be damped while travelling in the streamwise direction. This also enables the study of possible transient growth mechanisms in that regime. Figure 3.3 depicts the optimal response of the subcritical corner-flow to the obtained optimal initial perturbations. The presence of interacting streaky structures and corner mode can be deduced. The Reynolds number based on the boundary layer displacement thickness at the inflow is ($Re_\delta = 272$).
CHAPTER 4

Summary of Papers

Paper 1

*Stabilization of a swept-wing boundary layer by distributed roughness elements.*

In this paper the robustness of a passive control mechanism in stabilising transitional three-dimensional flows is examines. The control method has been introduced by Reibert et al. A number of cylindrical roughness elements are placed close to the leading edge exciting subcritical crossflow modes. These modes can not lead to transition individually, while their excitation has shown to modify the meanflow such as to favourably influence the stability characteristics. Direct numerical simulation has been conducted conforming to the experimental set up. In contrast to the experiment a more complex perturbation is introduced in order to induce transition, namely stationary and travelling crossflow modes coexist and play a part in eventual transition of the flow to turbulence. Complementary secondary instability analysis have also been provided using the Fourier decomposition of the unsteady flow field. The control mechanism effectively delays transition, suppressing secondary instabilities. Interestingly at the location of transition the most unstable mode has comparable amplitude to the controlled case emphasizing the suppression of the secondary instability due to meanflow modifications.

Paper 2

*Effect of freestream turbulence on roughness-induced crossflow instability.*

Direct numerical simulations (DNS) have been performed in order to investigate the role of freestream perturbations at a very low turbulence level on crossflow instability. The studied cases follow the experiments conducted by Downs et al. in Texas A&M University. In their experiment the authors document the freestream perturbations to a great detail, reporting freestream turbulence length scales, intensity, spectrum, etc. This enables the numerical studies to fully reproduce the freestream perturbations in such analysis. The experiment used ASU(67)-0315 wing geometry designed to promote crossflow instability. In our study we approach the reported values in generating the low intensity freestream turbulence. A DNS code (nek5000) has been used in order to generate the perturbation field. Furthermore, a third order Lagrange interpolant is used in order to inject the velocity perturbations into the DNS domain of the meshed wing. Note that only part of the wing is meshed where crossflow receptivity coefficients to freestream perturbations are expected to be high.
Paper 3

*Optimal initial perturbations in streamwise corner-flow.*

Optimal initial perturbations are computed in a streamwise corner-flow. An optimisation procedure using power iterations within a linear framework has been applied. Two different meanflows are considered, a self-similar base-flow, followed by a modified meanflow. The latter resembles the meanflow usually observed in experiments. The resulting optimal perturbation takes the shape of a wave-packet initially gaining energy through the Orr-mechanism and progresses towards algebraic growth. One of the main features of this optimal underlies in its localisation near the corner region, further asserting the dominance of an inviscid mode near the corner region. Moreover, the meanflow modification has a rather destabilising effect increasing the exponential growth rate of the optimal.
Conclusions & Outlook

Direct numerical simulations have been performed in order to study transitional flows over wings in addition to three-dimensional stability characteristics of a so called *corner-flow*. In the first part, two sets of experiments have been selected in which effects of different environmental disturbances have been studied on crossflow instability dominated flows over a wing. The first experiment investigates the efficiency of a passive control mechanism in delaying flow transition from laminar to turbulent. In the numerical setup the crossflow instability is generated using distributed roughness elements similar to the experiment. This is accompanied by a complex background noise prompting generation of both stationary and non-stationary crossflow vortices. The application of the control roughness has two major effects. First, it partially damps out the most unstable crossflow mode, and second, it modifies the meanflow. These effects appear to successfully delay transition by damping out secondary instabilities.

In the second part an extensive experiment is considered which was conducted in TAMU wind tunnel by Downs (2012). This well documented experiment entails a study on the effect of low freestream turbulence on crossflow dominated flows. In our study so far two levels of free stream turbulence are selected and numerically reproduced using direct numerical simulations. The generated fields are then inserted into the mesh created for the upper side of the wing where the experimental measurements have taken place. The crossflow vortices on the wing are generated using roughness elements similar to the experimental set up. It is observed that the initial amplitude of the stationary crossflow vortices remains unchanged, despite a lower growth rate as compared to the case where no freestream turbulence is introduced into the domain. In this respect, a higher freestream turbulence intensity level seems to further damp the most unstable crossflow mode.

In the last part of the current work, a different flow type known as *corner-flow* has been selected to study the worst case scenarios in terms of initial perturbation growth. A simple power iteration method has been applied between direct and adjoint linear Navier-Stokes equations using direct numerical simulations. The simulations are performed using two separate baseflows, a self-similar baseflow followed by a modified one where the latter is usually
found in experiments. It was found that the worst case scenario is characterised as a localised mode near the corner region and of inviscid type. The growth rate shows significant sensitivity to the used baseflow. In the case of the modified baseflow a higher growth rate was observed. The growth mechanism starts with an algebraic growth, through Orr-mechanism, and continues to grow algebraically.
CHAPTER 6

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