

Investigations of disturbances developing in a laminar
separation bubble flow

by

Carl Häggmark

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Department of Mechanics
S-100 44 Stockholm, Sweden

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C. Häggmark 2000 Investigations of disturbances developing in a laminar separation bubble flow

Department of Mechanics, Royal Institute of Technology
S-100 44 Stockholm, Sweden

Abstract

A separation bubble flow is considered in wind tunnel experiments. An experimental set-up is utilized in which steady two-dimensional laminar boundary-layer separation occurs on a flat plate due to an adverse pressure gradient. The pressure gradient is produced by a curved ceiling in the wind tunnel test section.

In a low disturbance level environment, high frequency instability waves grow in the separated shear layer, which reattaches and transition to turbulence occurs. Detailed investigations of the disturbance development are carried out using controlled forcing of low-amplitude instability waves. Their development and growth in the separation bubble flow is investigated with hot-wire anemometry, flow visualization technique and particle image velocimetry (PIV). Conventional hot-wire measurements have been performed in the laminar boundary layer upstream of separation, in the separated shear layer and in the reattachment zone. A region with exponential disturbance growth is observed in the separated shear layer associated with a highly two-dimensional flow. A local maximum in the disturbance amplitude develops at the inflection point in the mean velocity profile, indicating an inviscid type of instability. Further downstream, in the reattachment region, a complex three-dimensional flow structure develops including reverse flow near the wall. Details of the flow field in this region have been obtained.

A hot-wire technique, sensitive to the flow direction, has been developed for measurements of reverse flow near the wall. The operation of the direction sensitive probe do not differ significantly from conventional hot-wire technique. Measurements have been carried out with the probe inside the laminar separation bubble, providing information on the reverse flow region.

Finally, measurements of the mean flow and disturbance growth have been compared with direct numerical simulations.

Descriptors: Laminar separation bubbles, instability waves, adverse pressure gradient, reverse flow, laminar-turbulent transition, boundary-layer separation, hot-wire anemometry, PIV, reattachment.

Preface

This thesis considers a laminar separation bubble flow and disturbances developing therein. It is based on the following papers:

- I HÄGGMARK, C. P., BAKCHINOV, A. A. & ALFREDSSON, P. H. 2000 Experiments on a two-dimensional laminar separation bubble. *Phil. Trans. R. Soc. Lond. A* **358**, (in press).
- II HÄGGMARK, C. P., BAKCHINOV, A. A. & ALFREDSSON, P. H. 2000 Measurements with a flow direction boundary-layer probe in a two-dimensional laminar separation bubble. *Exp. in Fluids* **28**, (in press).
- III HÄGGMARK, C. P. 2000 An experimental study of instability waves in a laminar separation bubble.
- IV HILDINGS, C., HÄGGMARK, C. P. & HENNINGSON, D. S. 2000 A numerical and experimental study of a transitional separation bubble. (submitted to *Aerosp. Sci. Technol.*).

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CHAPTER 1

Introduction

When the titanium faced head makes proper contact you perceive a particular, ‘metallic’ sound. An indeed powerful feeling rushes through your body as your ‘ammunition’ is fired off at a speed of 75 m/s. Looking up you observe a tiny object in the unclouded blue sky before it disappears out of sight on its flight to the undulating fairway.

Even if many a player put their faith in the gods of the game of golf two physical fluid flow phenomena have a great influence on the path of flight of the golf ball: *boundary layer separation* and *laminar-turbulent transition*.

The boundary-layer concept was put forward by Prandtl (1904), who recognized the importance of internal friction of a fluid flow in the region near a solid wall - the boundary layer. In the same paper Prandtl also explained how the boundary layer could be brought to break away from the surface due to an increasing pressure in the direction of the flow, a positive pressure gradient, whereby a region with reverse flow follows.

Along with the occurrence of separation on a body is often the formation of irregular fluid motion, eddies, and even large wakes which change the pressure distribution on the body and thereby both the lift and drag forces. The effect can be dramatic. Figure 1.1 illustrates the impact of separation in terms of drag. Two bodies, a cylinder with a diameter d , and an airfoil with chord length $167d$ and a thickness of $35d$, travel with the same speed, V , through the air. For a certain range of velocities the drag force on the much larger airfoil is the same as on the cylinder. For a cylinder the drag coefficient, based on the cylinder diameter $c_{D,diameter}$, is approximately equal to one in the Reynolds number range $10^4 - 10^5$. For the airfoil in figure 1.1 the Reynolds number based on the chord is approximately two orders of magnitude larger, however in that case, assuming that the boundary layers are laminar, the drag coefficient based on the chord, $c_{D,chord}$, is approximately 0.006. This seemingly preposterous result is explained by the fact that separation occurs on the cylinder, leaving a large wake behind it, which is not the case on the streamlined airfoil. Since separation alters the pressure distribution, pressure forces strongly contribute

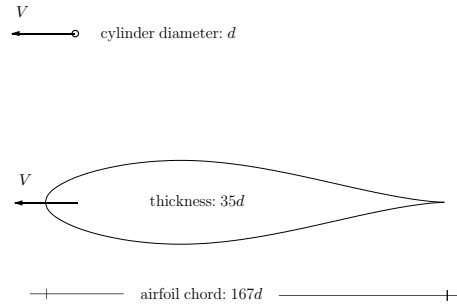


FIGURE 1.1. Circular cylinder and airfoil travelling with the same speed V , experiencing the same drag force in the case of laminar boundary layers on the airfoil.

to the drag on the cylinder besides frictional forces which are present on both bodies. On cylinders and spheres the effect of separation on the flow is large, which means that the theory for a frictionless fluid do not give a good prediction of the flow outside the boundary layer in the region where separation occurs.

The history of research on laminar-turbulent transition traces back to the classical experiments of Osborne Reynolds in 1880 on the flow of liquids in glass pipes. Reynolds (1883) determined a non-dimensional parameter, a number later given his name, which is the the most important number in fluid mechanics. Reynolds found a critical value of the Reynolds number below which the flow was stable and regular (laminar). However, at the critical value the flow suddenly changed and became unordered and irregular (turbulent). Laminar and turbulent flows have different properties. If we return to our golf player and take a closer look on the golf ball being launched in the first lines, we find that the surface of a modern golf ball is not smooth but equipped with a large number of dimples. Without dimples boundary layer separation is laminar and occurs at the windward side of the ball, almost at the ‘waist’, whereas on a dimpled ball boundary-layer transition occurs before separation due to the dimples. Since the turbulent boundary layer withstands the positive pressure gradient better than the laminar one, separation is delayed to the leeward side. The wake of the ball is hereby reduced and so is the drag force. The golf player can enjoy longer shots.

This thesis deals with a flow in which both the above illustrated phenomena, laminar boundary-layer separation and laminar-turbulent transition, occur - the laminar separation bubble flow.

1.1. Aim and method

The transition process in laminar separation bubble flows has been given moderate consideration in the literature in relation to its importance in engineering applications. As a matter of fact transition in adverse pressure gradient laminar separation bubble flows is not well understood in comparison with many other types of transitional flows. The transition process in the Blasius boundary layer has for instance attracted much attention, both of theoretical, numerical and experimental nature, which has lead to a detailed understanding of the physics of the flow, involving close descriptions of several different transition scenarios, in which agreement between theory and experiments has promoted an increased understanding. The same holds for instabilities and transition in free shear flows where a high level of detail of the interaction of wave disturbances has been established.

One aim with the current work is to experimentally study a laminar separation bubble flow at controlled conditions, in order to extend the knowledge of the development of disturbances leading to laminar-turbulent transition. Another aim with the work has been to obtain accurate and detailed experimental information on the separation bubble flow, suitable for comparisons with and evaluations of numerical computations and models. The method used is a fundamental approach not only within research on laminar-turbulent transition but within physics in general. Known disturbances, created artificially, are introduced into the flow field and by studying their development and response information on the highly complex separated flow can be extracted.

Hot-wire anemometry has been the primary tool in these investigations, in order to measure low-amplitude instability waves. A hot-wire technique has been developed by which flow reversal in the separation bubble can be detected and measured. Flow visualization and particle image velocimetry have also been used, whereby both spatial and temporal information have been obtained. Finally, the experimental set-up has been modelled in a direct numerical simulation.

CHAPTER 2

Aspects of laminar separation bubble flows

2.1. Laminar separation bubbles in engineering flows

Laminar separation bubbles may occur in a variety of flows in engineering applications, may it be in turbomachinery flows, on the rotor blades of a wind power plant or on hydrofoils. It is however within the field of low-Reynolds number aerodynamics that separation bubbles traditionally are to be found. Separation bubbles are indeed a controlling phenomenon in airfoil flows in terms of exerted lift and drag. Associated with the laminar separation bubble is a substantial growth of the boundary layer and fluctuations therein, which will govern the boundary layer structure and hereby the losses comprising the airfoil drag. Separation bubble flows are highly unstable and as a result of the formation of a separation bubble, transition to turbulence often occurs, strongly affecting the behaviour of the boundary layer downstream the separated region. Such a global impact on the flow has to be accounted for if accurate predictions of lift force, drag force or heat transfer are desired.

The laminar separation bubble is a characteristic feature of flows in low Reynolds number airfoil applications, where $Re_{chord} < 10^6$. In many situations it is desirable to reduce the large changes in velocity and pressure in the reattachment region of the bubble that cause a large growth in momentum thickness causing a larger drag of the airfoil. This is of primary concern within low Reynolds number airfoil design, where an ‘optimal’ shape of an airfoil under different operating conditions and constraints is sought, see Drela & Giles (1987), Drela (1988), Liebeck (1992).

A laminar separation bubble on an airfoil can be eliminated completely by enforcing transition upstream of the point of separation. In many applications this is not desirable since the turbulent boundary layer present over a larger portion of the airfoil as a result of such action gives an increased skin friction leading to even larger total drag of the airfoil. Therefore, the aim is often to control the separation bubble in the sense that it should not be removed by promoting transition upstream of separation; instead, through careful design of the airfoil shape or by placing roughness at the surface transition should occur

sufficiently close after separation. This in order to avoid a situation where the separated shear layer fails to reattach, leading to global separation and severe loss of lift. We will see that harmonic forcing of low amplitude instability waves in the boundary layer upstream of separation has favorable effects in controlling the bubble in that respect.

A key element in boundary layer computations of engineering flows with laminar separation bubbles is prediction of the point of transition. The transition point determines the size of the bubble and the development of the boundary layer. Correct information on the location of the separation point is therefore decisive in numerical computations of flows with transitional bubbles. To predict the point of transition in aeronautical flows with separation bubbles several models and engineering methods have been proposed in the literature. Several of these methods are inspected in Hildings (1997).

2.2. Classifications of separated flows

Flow separation is indeed a phenomenon which is characterized by particularity - in some sense one separated flow is not any other alike. However, some general characterizations and distinctions among separation bubble flows are given in this section to provide an overview and place the current work in its context.

Alving & Fernholz (1996) make a distinction between separation caused by sharp gradients in the surface geometry, denoted geometry-induced separation, and separation from smooth surfaces caused by adverse pressure gradients - adverse-pressure-gradient-induced separation (APG-induced separation) - and discuss in general terms differences between these two cases (see figure 2.1). The former category includes the forward- and backward-facing step geometries which have been extensively studied and which in much experimental and numerical work on separated flows serve as cornerstone test cases. One reason for this is the fact that the point of separation is fixed in space and time and that separation occurs for all Reynolds numbers (except creeping flow). This is in contrast to the latter category where both the separation and the reattachment points can move in the streamwise direction as a response to variations of the flow environment. Alving & Fernholz also distinguish between ‘strong’ and ‘mild’ separation bubbles on the basis of the height of the shear layer upstream of separation relative to the height of the separation bubble. A separation bubble is referred to as a ‘strong’ bubble when the height of the shear layer preceding separation is of the same size or smaller than the height of the bubble, whereas, conversely, in a ‘mild’ separation bubble the height of the bubble is considerable smaller than the pre-separated shear layer.



FIGURE 2.1. Two classes of separation: geometry-induced and adverse pressure gradient-induced separation

A separation bubble flow can also be classified according to the status of the boundary layer at the separation and reattachment points as being either laminar, transitional or turbulent. In a laminar separation bubble the boundary layer is laminar at both the separation and reattachment points, while in the transitional bubble the boundary layer is still laminar at separation but turbulent at reattachment. If the boundary layer is turbulent at both separation and reattachment the separation bubble is called turbulent. In older aeronautical literature the term ‘laminar separation bubble’ is used to denote a bubble where the boundary layer is laminar at separation but turbulent at reattachment, i.e. a transitional separation bubble according to the above definitions.

In the present work we will adhere to the traditional nomenclature and the term ‘laminar separation bubble’ refers to a bubble which is formed by the separation of a laminar boundary layer followed by a development of instability leading to laminar-turbulent transition, unless otherwise explicitly stated.

Another distinction is sometimes found in the literature on separation bubbles between ‘short’ and ‘long’ APG-induced transitional separation bubbles occurring on airfoils. The actual separation to reattachment length is not decisive whether a bubble should be termed long or short but rather the effect of the bubble on the static pressure distribution at the surface. A long bubble strongly alters this pressure distribution compared with the inviscid distribution and a distinct suction peak does not appear. Instead the pressure distribution at the leading edge is smeared out and it returns gradually downstream to the inviscid one. A short bubble on the other hand causes only a minor perturbation to the inviscid pressure distribution with a retained suction peak which can increase with an increasing angle of attack. The length of a short bubble, sometimes referred to as a leading edge separation bubble, is usually only a few percent of the chord length. Nevertheless, Tani (1964) gives examples of bubbles with lengths of 20 % of the chord which are termed short due to the presence of

a sharp suction peak upstream of separation. In this case the effect on the pressure distribution is considerable.

Related to the distinction between these two types of separation bubbles is the bursting phenomenon, which we will return to in section 2.4.

A sketch of a laminar separation bubble flow over a smooth, curved surface is shown in figure 2.2, in which the vertical scale is exaggerated for clarity. The figure shows the flow over a smooth, curved surface and two solid lines are drawn, marking the dividing streamline, $\Psi=0$, where Ψ is the two-dimensional stream function, and the outer edge of the separated shear layer, δ . At a certain position upstream of the bubble the pressure gradient, dP/dx , changes from being negative to becoming positive. Downstream of this minimum pressure point the laminar boundary layer separates at the separation point, S, subjected to an adverse pressure gradient, and a shear layer detaches from the surface. In a steady two-dimensional flow over a fixed wall the separation point agrees with the point of zero wall shear stress, τ_w , which is therefore often used as a definition of the point of separation. This definition is not by any means general and do not apply in other types of separated flows, such as in cases with three-dimensional separation or unsteady two-dimensional separation. At a position further downstream, R, the separated shear layer reattaches to the surface and a turbulent boundary layer develops. In this way a region with almost stagnant fluid becomes located beneath the separating and reattaching shear layer - the laminar separation bubble.

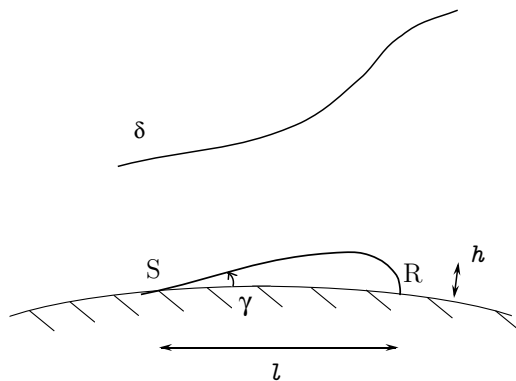


FIGURE 2.2. Basic parameters of a laminar separation bubble.

The height, h , of the bubble is usually taken as the maximum distance between the wall and either the dividing streamline or the zero velocity line. The total length of the separation bubble, i.e. the distance between the separation

and reattachment points is denoted by l in figure 2.2. A length scale, l_{tr} , equal to the distance between the separation point and a transition point, assumed to be located slightly upstream of R , is often used in empirical transition prediction methods. Another characteristic lengthscale of the separation bubble appearing in the literature is the momentum thickness at separation, θ_s . θ is found to be fairly constant in the bubble, at least upstream of the transition point where the shear stress at the wall is low. The separation streamline emanates from the wall and makes an angle, γ , with the wall. This separation angle is given by

$$\tan(\gamma) = -3\left(\frac{d\tau_w/dx}{\partial p/\partial x}\right)_{x=x_s} \quad (2.1)$$

see e.g. Lighthill (1963). The static pressure, p , is here a function of both the streamwise and wall normal coordinates.

Figure 2.3 shows a photograph of a smoke visualization of an APG-induced separation bubble on a flat plate in a wind tunnel. The smoke enters the boundary layer upstream of the separation point through a narrow slit in the plate, perpendicular to the free stream. A sideview of the flow over the plate is captured in the photograph. A layer of smoke detaching from the surface is clearly visible, as is its mirror image reflected from the polished aluminum surface of the plate. The smoke sheet, located in the separated shear layer, is fairly intact up to the point of maximum deflection from the surface. However, the laminar separation bubble flow is unstable, and disturbances, growing in the separated shear layer, cause the thin, homogeneous, smoke sheet to rapidly disperse into an irregular flow downstream of reattachment.

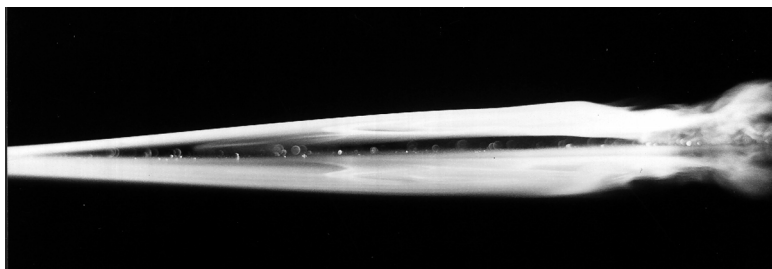


FIGURE 2.3. Flow visualization by Häggmark (1995) of a laminar separation bubble flow over a flat plate (unpublished work).

2.3. Experimental considerations

Laminar separation bubbles present experimental obstacles originating from the properties of the physics of the flow field as well as difficulties with measurement techniques which can provide accurate experimental data. In this section some general features of separation bubbles is pointed out which deserve attention from an experimental point of view.

Laminar separation bubbles occur in general on curved surfaces and their physical size is small, circumstances which makes traversing of a measurement probe in the bubble difficult and delicate since the measurement probe can disturb the flow. The fact that, generally, the growth rates of disturbances are much higher in laminar separation bubbles compared to transitional boundary layer flows raise the requirements on the accuracy of measured flow quantities since the flow develops and changes in a shorter streamwise distance.

At the same time, the presence of reverse flow in the separated region close to the wall, especially in the reattachment region, puts a restriction on the applicability of the single hot-wire technique. In the separated flow region back-flow is present which implies that a single hot-wire probe cannot in that case correctly measure the flow velocity, since the technique is based on the physical principle of measuring the convection of heat. It cannot separate forward moving fluid from fluid moving in the upstream direction. For example, in a harmonically oscillating flow in a pipe, figure 2.4, where the mean flow is zero, the measured mean velocity from the anemometer will yield a nonzero positive value, whereas the r.m.s. velocity will be underestimated.

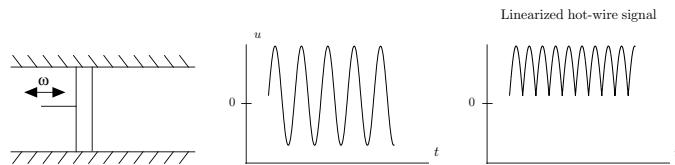


FIGURE 2.4. Oscillating pipe flow. Comparison between actual velocity and a possible result of a measured output velocity signal from a single hot-wire.

Dovgal *et al.* (1995) estimated the error in measured amplitude of a harmonic disturbance in an axisymmetric geometry-induced separation bubble flow with a small amount of back-flow (1.3 %) and conclude that close to the location where the mean flow is zero, large errors occur in the measured amplitude of the forced frequency component, an error which increases with increasing disturbance amplitude. Still, these errors were by far too low to explain the discrepancies between measured amplitude profiles and eigenfunctions obtained from the Orr-Sommerfeld equation (see chapter 3 for theoretical details).

Laminar separation bubbles show a natural unsteadiness and high sensitivity to external disturbances in the flow, originating for instance from different parts of the wind tunnel. Pressure gradient fluctuations can without notice alter the position of separation, in the streamwise or spanwise direction, or even change the entire flow field. The unstable nature of the flow makes it therefore difficult to accurately determine basic parameters of the bubble, figure 2.2, such as the point of separation and reattachment, and integral parameters at these locations.

2.4. Bubble bursting

A phenomenon associated with the unsteady features of laminar separation bubbles, and which has been a matter of controversy in the literature, is the bursting of a short separation bubble. Bursting in this context denotes a process in which the separation bubble experience a rapid change in length and expands in the streamwise direction as a response to changing flow conditions, usually changes in the angle of attack or free stream velocity. On an airfoil this causes a drastic change in pressure distribution and hence in lift. Therefore, it has been of large interest to predict and understand the bursting phenomenon.

Prediction of bubble bursting involved questions such as: Under what conditions do bursting occur in a given flow situation? Which parameters control bubble bursting and which are their critical values? Can a general criterion for bursting be found?

Owen & Klanfer (1953) distinguished between short and long separation bubbles in terms of their length, l , in displacement thicknesses at the position of separation. For short and long bubbles $l/\delta_s^* \sim \mathcal{O}(10^2)$ and $\mathcal{O}(10^4)$, respectively. They suggested a value of a critical Reynolds number, $Re_{\delta_s^*}$, for bursting in the range 400-500.

Horton (1969) suggested a method to predict bursting based on a pressure gradient criterion and a correlation between the separation to transition length and the momentum-thickness Reynolds number at separation. Roberts (1980) proposed a similar method in which the free-stream turbulence was included.

In the analysis of Gaster (1966) two parameters, the momentum-thickness Reynolds number at separation, Re_{θ_s} , and a nondimensional pressure gradient parameter P , where $P = (\theta_s^2/\nu)\Delta U/\Delta x$, govern the bursting process and Gaster proposed a unique relation between them at bursting conditions - a bursting line. ΔU is the velocity difference over the bubble length, Δx , of the inviscid flow distribution, present in the absence of separation. Gaster used an airfoil to induce an adverse pressure gradient on a flat plate and measured the inviscid pressure distribution by tripping the laminar boundary layer, thereby creating an attached turbulent boundary layer along the plate. By varying the free stream velocity, angle of attack of the airfoil and its streamwise and wall-normal position relative to the plate, separation bubbles in which P and Re_{θ_s} varied over a broad range could be studied in a $(P-Re_{\theta_s})$ -plane. Gaster observed a correlation between these parameters from different bubbles and different experiments, however the relation was not unique. Gaster concluded that additional effects should be important in the bursting process of separation bubbles.

Pauley, Moin & Reynolds (1990) investigated numerically the unsteady features of 2D separation by studying the response of a laminar boundary layer on one of two walls in a channel, to a suddenly imposed adverse pressure gradient, applied by suction through a slot in the opposite wall of the channel. When a weak pressure gradient was applied a steady separation resulted but at higher strengths of the adverse pressure gradient the separated shear layer started to shed vortices. Pauley *et al.* proposed a criterion for the onset of vortex shedding based on a non-dimensional pressure gradient, $P_{max} = \frac{\theta_s^2}{\nu}(\frac{dU}{dx})_{max} \approx -0.24$ at the onset of vortex shedding. The non-dimensional pressure gradient used by Pauley *et al.* differed from that used by Gaster (1966) only in the choice of evaluation of the inviscid velocity gradient where Pauley *et al.* used the maximum negative gradient whereas Gaster used an averaged value. They compared Gaster's data with this criterion and suggested that the 'bursting' phenomenon observed by Gaster corresponded to the demise of vortex shedding. In other words the 'short' bubble corresponded to a bubble exhibiting vortex shedding while the 'long' bubble corresponded to a steady separation bubble.

Pauley *et al.* (1990) found a Strouhal number, defined as $St_\theta = \frac{f\theta_s}{(U_e)_s}$, where f is the shedding frequency, θ_s the momentum thickness at separation and $(U_e)_s$ the local edge velocity at separation, to be constant in the computations independent of Reynolds number, $St_\theta = 6.86 \times 10^{-3}$. In a later paper, Ripley & Pauley (1993), modelled the experiment by Gaster (1966) in a numerical study by tailoring the boundary conditions at the upper boundary to produce the inviscid pressure distributions in Gaster's experiment. The Strouhal number

was again found to be constant for the cases computed, $St_\theta=5.5-5.7\times 10^{-3}$, independent of Reynolds number, but differed from the value found in Pauley *et al.* (1990). Ripley & Pauley concluded that the Strouhal number is a function of the pressure distribution.

Watmuff (1999) evaluated Gasters modified pressure gradient parameter, P , and found that the bubble studied was, in Gasters terminology, a short bubble, far from the conditions at bubble bursting. The same holds for the separation bubble studied in the present investigation. We will come back to the experimental work by Watmuff in chapter 4.3 when reviewing work on the development of three-dimensional flow structures in laminar separation bubbles.

In a paper by Hammond & Redekopp (1998) a model separation bubble flow is theoretically and numerically studied with respect to local and global instabilities using the Orr-Sommerfeld equation. Velocity profiles consisting of Falkner-Skan profiles with reverse flow (Stewartson 1954) with an additional term containing two perturbation parameters, enabling a larger and independent variation in the amount and extent of the reverse flow in comparison with the pure Stewartson family, are analyzed. The amount of maximum reverse flow is found to be decisive whether an inflection point instability mode turns absolute unstable or not and a level of maximum back-flow of the order of 30 % is required. Hammond & Redekopp suggest a possible connection with the onset of large-scale vortex shedding observed in Pauley *et al.* (1990) when the strength of the applied adverse pressure gradient was increased in their simulations.

CHAPTER 3

Stability considerations

As has been shown previously adverse pressure gradient flow is sensitive to wave disturbances which in general are amplified in the adverse pressure gradient region and in particular in the separation bubble. In the bubble they reach large amplitudes, but despite this it is possible to use linear stability theory to describe several of the wave characteristics. A good review of the use of linear stability theory for separated flows is given by Dovgal *et al.* (1994). In the following stability equations are derived and some results are given which are pertinent for the flows studied here.

3.1. Basic flow equations

The continuity equation for an incompressible flow is in vector notation

$$\nabla \cdot \bar{\mathbf{u}} = 0 \quad (3.2)$$

whereas the Navier-Stokes equations can be written

$$\frac{\partial}{\partial t} \bar{\mathbf{u}} + (\bar{\mathbf{u}} \cdot \nabla) \bar{\mathbf{u}} = -\rho^{-1} \nabla p + \nu \nabla^2 \bar{\mathbf{u}} \quad (3.3)$$

We now assume that the velocity and pressure can be written as a steady field ($U(y)\bar{\mathbf{e}}_x$ and $P(x)$) with small time dependent fluctuations ((u', v', w') and p'). The basic flow field is here assumed to be in the x -direction with a variation normal to the surface (in the y -direction).¹ If this is introduced into the continuity and NS-equations, the non-linear terms are dropped (as well as the primes for the fluctuating components) and we make the equations non-dimensional in a suitable manner, we obtain,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \quad (3.4)$$

¹With this assumption for the basic velocity field we assume that the flow is parallel, however this may be a questionable assumption for separated flows.

$$\frac{\partial u}{\partial t} + U \frac{\partial u}{\partial x} + vU' = -\frac{\partial p}{\partial x} + \frac{1}{Re} \nabla^2 u \quad (3.5)$$

$$\frac{\partial v}{\partial t} + U \frac{\partial v}{\partial x} = -\frac{\partial p}{\partial y} + \frac{1}{Re} \nabla^2 v \quad (3.6)$$

$$\frac{\partial w}{\partial t} + U \frac{\partial w}{\partial x} = -\frac{\partial p}{\partial z} + \frac{1}{Re} \nabla^2 w \quad (3.7)$$

where Re is the Reynolds number. In these equations and in the following a prime (') denotes a y -derivative. By taking the divergence of eqs. (3.5)-(3.7) and using the continuity eq. (3.4) we obtain

$$\nabla^2 p = -2U' \frac{\partial v}{\partial x}. \quad (3.8)$$

This may be used together with eq. (3.6) to eliminate p , resulting in an equation for the normal velocity, v :

$$\left[\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) \nabla^2 - U'' \frac{\partial}{\partial x} - \frac{1}{Re} \nabla^4 \right] v = 0. \quad (3.9)$$

For a boundary layer flow the boundary conditions are

$$v = v' = 0 \quad \text{at} \quad y = 0 \quad (3.10)$$

$$v, v' \rightarrow 0 \quad \text{at} \quad y \rightarrow \infty \quad (3.11)$$

A normal-mode ansatz is introduced, i.e. wave disturbances of the type

$$v(x, y, z, t) = \hat{v}(y) e^{i(\alpha x + \beta z - \alpha c t)} \quad (3.12)$$

where α and β are the streamwise and spanwise wave numbers respectively and $c = c_r + ic_i$ is the complex phase speed. An unstable disturbance is obtained if $c_i > 0$. Introducing (3.12) into (3.9) yields

$$\left[i\alpha(U - c)(D^2 - k^2) - i\alpha U'' - \frac{1}{Re}(D^2 - k^2)^2 \right] \hat{v} = 0, \quad (3.13)$$

where $k^2 = \alpha^2 + \beta^2$. This equation is the so called Orr-Sommerfeld equation.

In the above derivation the wave instability was seen as a temporal problem, i.e. the wave disturbance was assumed to grow (or decay) with time. However, many flows have a spatial rather than a temporal development (e.g. boundary layer flows) and it is more correct to consider disturbances which grow (or

decay) in space. For this case the disturbance may be described with a real frequency and a complex streamwise wave number. Such a disturbance can be expressed as

$$v = \hat{v}(y)e^{i(\alpha x + \beta z - \omega t)}$$

where $\alpha = \alpha_r + i\alpha_i$.

3.2. Inviscid linear stability theory - the Rayleigh equation

The inviscid part of equation (3.13) is usually called the Rayleigh equation and can be written as

$$(D^2 - k^2)\hat{v} - \frac{U''\hat{v}}{U - c} = 0 \quad (3.14)$$

By multiplying eq. (3.14) with the complex conjugate of the solution and integrating over the flow interval it is possible to give a statement of the stability of inviscid flows. The imaginary part of the resulting expression becomes

$$c_i \int_0^\delta \frac{U''}{|U - c|^2} |\hat{v}|^2 dy = 0 \quad (3.15)$$

from which it follows that a necessary condition for instability, $c_i > 0$, is that the mean velocity has an inflection point ($U'' = 0$). This condition is known as Rayleigh's inflection point criterion (Rayleigh 1880). Fjørtoft (1950) considered the real part of the expression and showed in addition that the shear has to have a maximum at the inflection point in order for the profile to be unstable. These results are of special interest in the context of adverse pressure gradient boundary layers, since such flows have an inflectional point of the kind giving instability according to these criteria.

3.3. Pressure gradients and separation

Falkner-Skan profiles are similarity solutions to the boundary layer equations when the boundary layer edge velocity varies as $U_e \sim x^m$. For a favourable pressure gradient, i.e. a flow with an increasing boundary layer edge velocity, $m > 0$, whereas for an adverse pressure gradient with a decreasing edge velocity, $m < 0$. Neutral curves for several values of m were calculated by Obremski *et al.* (1969) (see Landahl & Mollo-Christensen 1987). A negative pressure gradient give a higher critical Re (i.e. the Reynolds number for which wave disturbances first become amplified increases), whereas for a positive pressure gradient the critical Re decreases. It can be noted that flows with $m > 0$ are stable in the inviscid limit, i.e. for $Re \rightarrow \infty$, since such profiles do not exhibit an inflection point.

Once the adverse pressure gradient becomes large enough, flow separation occurs. For such a case the assumption of parallel flow is less accurate. However, direct numerical simulations by Rist & Maucher (1994), have shown that growth rates for wave disturbances obtained with linear parallel theory, agree well with the non-parallel computations if the basic flow field is taken from the steady laminar bubble.

Dovgal *et al.* (1994) showed, for a model profile, typical behaviour of the instability developing on an inflectional profile and on profiles with backflow at the wall. The following characteristics may be noted

- The phase velocity of the waves are, for not too long wave lengths, approximately equal to the mean velocity at the inflection point.
- The amplitude distribution of the streamwise disturbance velocity show three maxima, the middle one is found approximately at the inflection point.
- The differences in both growth rate and amplitude distribution are fairly small between the viscous and inviscid case, showing the importance of the inflection point.

3.4. Secondary instability of wave disturbances

In the Blasius boundary layer flow, the development of wave disturbances of small amplitude agree fairly well with linear theory (so called Tollmien-Schlichting (TS) waves). However, the experiments of Klebanoff *et al.* (1962) showed that such waves become three dimensional when the amplitude increases. This is usually called a K-type secondary instability and the three dimensional pattern is described as peak and valley regions. The peak regions have instantaneous inflectional velocity profiles in the normal direction and large amplitude; short duration events which were called “spikes” were observed there in the streamwise velocity signal.

This process may be explained by interaction between the 2D TS-waves and three-dimensional waves. Secondary instability has been found to occur when the amplitude, i.e. the amplitude of the maximum of the TS wave reaches approximately 1% of the free stream velocity. Several flow visualization studies show that during this process the instability takes the form of Λ -shaped structures which are aligned in the streamwise direction. In this case the frequency of the secondary instability is the same as that of the primary wave. This transition scenario is called K-type secondary instability.

A subharmonic instability which occurs at lower amplitudes of the primary TS-wave than the K-type has also been observed.² Since this instability occurs at lower amplitudes one may assume that it is this instability that would first be observed for natural disturbances. Similar Λ -shaped structures as during K-type instability have been observed through flow visualization, but these are here in a staggered pattern. When observed with a fixed hot wire the frequency will be half of the frequency of the primary instability, i.e. a subharmonic frequency.

²This type is usually called subharmonic, H-type (after Herbert) or N-type (after Novosibirsk).

CHAPTER 4

Studies on laminar separation bubbles

In this chapter a brief survey of work related to instability and transition in laminar separation bubbles is given, with main focus on experimental results. We will however begin by looking back at a small selection of the early investigations of laminar separation bubbles besides those already mentioned previously.

4.1. Early work

The first study where we have found the term “bubble” was that of Jones (1934), who performed experiments in a wind tunnel on the stalling phenomenon of airfoils. Jones used a force balance, pressure measurements and a small tuft attached to the tip of a needle which could be positioned in the flow. Preceding stall on an airfoil Jones discovered the presence of a “kind of shallow bubble”, in which the pressure was uniform. Jones considered the presence of the bubble as a warning that airfoil stall was approaching, but did not consider it to be crucial in the practical problem of stall.

von Doenhoff (1938) made experiments on a separating laminar boundary layer on a flat plate. Separation was caused by an adverse pressure gradient obtained by placing the plate in a divergent channel. von Doenhoff suggested that the distance from the separation point to the transition point could be determined from the Reynolds number based on the edge velocity at the point of separation and that this Reynolds number was ~ 50000 . He also discussed the applicability of the flat plate separation results to the situation at the leading edge of an airfoil. von Doenhoff argued that separation occurred with a tangential path to the curved surface at the separation point and that transition occurred a distance downstream given by the above criterion. A turbulent region spread from here on at a constant angle of 15° , thereby forming a triangular bubble region. Whether or not reattachment of the shear layer occurred could by this method be geometrically determined.

McCullough & Gault (1951) investigated different airfoils with respect to their stalling characteristics and made a classification into three different types.

They could observe laminar separation bubbles from pressure measurements and liquid film technique prior to stall and realized the importance of the stability of a separated laminar shear layer in the process of stall.

The review by Ward (1963) summarizes results on laminar separation bubbles and their connection to airfoil stall. Ward also discusses and reviews some work on the process of transition in the separated shear layer, which was assumed to occur from either amplification of Tollmien-Schlichting waves or from a process with turbulent spots. Further experimental results on separation bubbles can be found in Tani (1964), including results for circular cylinders.

4.2. Instability and transition

Modern work of relevance to the present investigation has been carried out at the Institute of Theoretical and Applied Mechanics in the State University of Novosibirsk, where fundamental theoretical, numerical and experimental work on instability and transition in laminar separation bubbles has been ongoing since the 1980's. Results from this research has been reported in English mainly in proceedings from several IUTAM symposia, focusing both on laminar-turbulent transition and on boundary-layer separation, but also in the review article by Dovgal *et al.* (1994). A brief summary of the experimental results is given below.

4.2.1. Experimental studies

Kozlov (1985) reports from several experiments dealing with instability of separation bubbles in different experimental configurations using hot-wire anemometry in a low turbulence free stream environment. In one experiment with separation on an airfoil, a separation bubble caused by an adverse pressure gradient on a smooth surface is studied. The growth of artificial disturbances at a certain frequency, generated both by means of a vibrating ribbon and with a loudspeaker placed in the wind tunnel diffusor downstream the test section, are investigated and both means of excitation are found to produce disturbances with approximately the same growth rate. 3D-disturbances are also considered by studying the evolution of a wave packet generated from a point source upstream of separation. An influence on the mean velocity profiles resulting from the disturbance forcing is observed both for 2D and 3D artificial forcing, leading to fuller velocity profiles. An effect on the mean flow when forcing a wave packet is observed even at spanwise positions outside the region of propagation of the wave packet.

The effect of acoustic waves on a symmetrical Joukowski airfoil at 11° angle of attack and at $Re_c \approx 95\,000$ is also reported in Kozlov (1985). At

these conditions the separated shear layer formed on the suction side of the airfoil do not reattach to the surface. When applying monochromatic acoustic waves in a certain frequency range from a loudspeaker mounted in the diffuser disturbance waves of the same frequency appears in the boundary layer and separation is completely suppressed. Kozlov notes an interesting hysteresis effect which manifests itself in the dependence of the range of frequencies which causes elimination of the separated region on the history of excitation. This range of frequencies spans from 200 Hz up to 1125 Hz when monotonically increasing the frequency of the acoustic waves. However, if the frequency is decreased the effective frequency range for separation control is 600 Hz down to 200 Hz.

In a later study by Kozlov *et al.* (1991) of a globally separated flow over an airfoil at a different flow condition ($Re_c \approx 500\,000$) it was noted that suppression of separation, once initiated by high intensity sound, can be sustained after switching off the sound excitation.

The same sort of impact on the mean flow in a separation bubble as mentioned above is found in still another experiment reported from Kozlov (1985) considering a flow over a fractured wall composed by two joint flat plates inclined away from each other, fixing the point of separation at the joint. In this setup artificial disturbances are also generated by sound from the diffuser. The intensity of the sound level generated by the loudspeaker is 88 dB. The growth rate of the forced disturbances are found to be independent of their initial amplitude at the investigated frequency.

Dovgal (1985) considers a transitional separation bubble in a similar fractured wall configuration, where the two plates are inclined towards each other, forming a dent. Artificial forcing with the vibrating ribbon technique is performed and the behaviour of small amplitude disturbances in the flow is studied. Amplification curves show that the growth rate of the forced disturbances are independent of the initial amplitude for amplitudes less than approximately 1 % of the free stream velocity. Hereby spatial amplification rates could be calculated for a range of frequencies. A difference in growth rate is observed for the boundary layer upstream of separation compared to the separated region, which is attributed to the difference in stability characteristics of the two flows. Wall normal r.m.s. profiles of the disturbance waves show a two-peak structure upstream of separation and a three-peak structure in the separation bubble. A strong effect on the mean flow profile in the separation bubble was further found as a response to low-amplitude disturbance forcing, implying a reduction in the height of the bubble. This influence by the excited wave on the mean flow was found to increase with the wave amplitude of the forced wave.

The mean flow influence was also seen from a substantial change in the wall pressure distribution. The change in pressure distribution that took place when applying forced disturbances compared to the natural flow case was much stronger than the effect of varying the amplitude of the forced waves between the linear and nonlinear region. Without artificial forcing the wall pressure distribution is independent of the streamwise position beginning upstream of the separation point extending downstream to reattachment, whereas a maximum in the pressure distribution existed between the separation and reattachment points at all forcing conditions (the amplitude of the forced disturbances varied between 0.34 to 2.34 %).

In Dovgal *et al.* (1987) further experiments on instability and transition in separation bubbles are reviewed including 3D-separation. Separation of the boundary layer on an axisymmetric body is also discussed.

Experiments with separated regions occurring at surface roughnesses such as steps and humps are described in Dovgal & Kozlov (1990). Low-amplitude 2D-disturbance waves are introduced with a vibrating ribbon in a Blasius boundary layer upstream of a 1.65 mm high rectangular hump with a streamwise length of 10 mm ($h/\delta = 0.35$, where δ is the boundary layer thickness). Profiles of the disturbances in the separation bubble formed downstream of the hump displayed three local maxima and the corresponding phase profiles showed two shifts, similar to what was found by Dovgal (1985). After reattachment, which in this experiment was laminar, the amplitude profile regained the shape it had in the Blasius boundary layer.

In this separation bubble the same type of mean flow influence as in Dovgal (1985) and Kozlov (1985) resulted from the artificial forcing with an increase in mean flow distortion with increasing amplitude of the forced disturbances, although in this case transition was not initiated by the separation bubble and reattachment was laminar.

Further investigations on the development of instability waves in separation bubbles behind humps have been carried out by Boiko *et al.* (1991). Two experimental configurations are used, one being the same as in Dovgal & Kozlov (1990). In the second configuration a rounded hump is mounted on the flat plate ($h = 1$ mm, $h/\delta = 0.40$). In both configurations the separation bubbles are completely laminar, i.e. transition occurs far downstream of reattachment. The aspect ratios (bubble length to height) of the separation bubbles in the two configurations at the experimental flow conditions are approximately 50 and 100, respectively.

In the first configuration the development of a low-amplitude wave packet in the separation bubble is studied. The wave packet is introduced upstream of separation by localized excitation. It is found that the dispersion of the wave packet in the separated region is much smaller than is the case for the Blasius boundary layer obtained when removing the hump.

In the other configuration an investigation is undertaken of the interaction between a 2D fundamental instability wave and an oblique subharmonic wave. Two vibrating ribbons are used to generate the disturbances. The oblique wave is generated by turning one of the ribbons in the xz -plane at an angle to the direction of the leading edge of the plate. In the middle of the separation bubble the amplitude of the subharmonic wave varies periodically in the spanwise direction due to resonance between the fundamental and subharmonic wave. Amplification curves of the subharmonic disturbance along spanwise resonance points show little difference for three different wave angles, $\psi = 0^\circ, 20^\circ$ and 37° ($\psi = \arctan(\lambda_x/\lambda_z)$).

Boiko *et al.* (1991) further observed a suppression of low-frequency velocity fluctuations in the region close to the separation point, which was connected to artificial forcing of a low-amplitude fundamental 2D-wave. The amplitude of the 2D-wave at this location was 0.22 %. The same effect was found when the wave was forced both by a vibrating ribbon and by external acoustic waves.

4.2.2. Numerical studies

Direct numerical simulations of laminar separation bubbles under the forcing of various artificial disturbances have been carried out in Germany by Rist and co-workers. Some results of their work with relevance to the present study are presented here and in the next section.

In Rist & Maucher (1994) computations of a laminar separation bubble on a flat plate are performed, and the development of different 2D- and 3D-wave disturbances is considered. The separation bubble flow is obtained by prescribing a streamwise decreasing free stream velocity. The separation bubble appears as a local ‘perturbation’ on the laminar flow and the Blasius boundary layer upstream of separation is re-developing downstream of reattachment. Two-dimensional instability waves are found to experience the highest growth in the flow. Comparisons of growth rates between linear stability calculations performed on velocity profiles taken from the laminar base flow with results from direct numerical simulations, DNS, suggest that non-parallel effects were small.

In another DNS-study of separation bubbles on airfoils, Maucher *et al.* (1994), the boundary condition in the free stream was prescribed according

to an experimental velocity distribution taken from the midchord region of an FX66-S-196 airfoil at an angle of attack of 9° and $Re_c=1.5\times 10^6$. When prescribing the streamwise velocity component low frequency oscillations of the separation bubble appeared, oscillations which could be damped using a viscous-inviscid interaction method. Maucher *et al.* conclude that the linear development of 2D-instability waves could be captured with the numerical method but that three-dimensional simulations are needed in order to capture further details of transition in laminar separation bubble flows.

Pauley and co-workers have numerically studied two-dimensional separation in a series of papers (Pauley *et al.* 1990; Ripley & Pauley 1993; Lin & Pauley 1996), focusing among other things on the unsteady features of separation bubbles, including the complex problems associated with bubble bursting (section 2.4). One conclusion of their work is that two-dimensional vortex shedding plays a strongly dominant role, in comparison with small-scale turbulence, leading to reattachment of the separated shear layer, and thereby controlling the size of the bubble. The vortex shedding is found to be the result of an inviscid, inflectional instability mechanism of Kelvin-Helmholtz type.

4.3. Development of three-dimensional disturbances

The development of three-dimensional flow structures in nominally two-dimensional separated flows is a puzzling issue in studies of laminar separation bubbles.

Rist & Maucher (1994) investigated by DNS the development of different combinations of 2D- and 3D-instability waves by suction and blowing at the wall, upstream of the separation bubble, and found a strong influence on the mean flow in the reattachment region when large amplitude disturbances were introduced. They found that the introduction of a pair of oblique waves resulted in mean flow profiles in better agreement with experimental observations compared to a disturbance case where a large amplitude 2D-wave together with a pair of low-amplitude oblique waves were introduced.

In a study by Maucher *et al.* (1997) the development of 3D-disturbances in a two-dimensional separation bubble flow on an airfoil is investigated by prescribing an ‘inviscid’ experimental edge velocity distribution at the upper boundary of the computational domain. The inviscid free stream velocity distribution was obtained in the experiment by ‘tripping’ the laminar boundary layer, thereby preventing separation, a technique previously used by Gaster (1966). In the separation bubble secondary temporal amplification of low-amplitude 3D-waves is observed originating from the reattachment region when the 3D-waves are

generated together with a large-amplitude 2D-wave. The 3D-waves give rise to longitudinal vortices which dominate the flow in the reattachment region.

Recent simulations (Maucher, Rist & Wagner 1999; Maucher, Rist, Kloker & Wagner 2000) have provided more information on this instability mechanism which seems to set in at higher Reynolds numbers in the reattachment region of laminar separation bubbles.

Wilson & Pauley (1998) studied the experiment of Gaster (1966) using two- and three-dimensional large eddy simulations. They investigated the formation and development of Görtler vortices, which had been predicted by Inger (1987) to occur in separated shear layers at operating conditions of low Reynolds number airfoil flows, and which had previously been investigated in the direct numerical simulations by Pauley (1994). When a steady low-amplitude spanwise harmonic velocity perturbation was generated at the inlet of the computational box better agreement with the separation bubble data of Gaster (1966) was obtained.

Recent experimental studies on the development of three-dimensional disturbances involves Ablaev *et al.* (1998) and Watmuff (1999). Ablaev *et al.* investigated the development of a pair of oblique, travelling waves in a separation bubble behind a small, sharp edged bump. The waves were generated by suction and blowing from two slits in the flat plate, inclined 45° to the direction of the incoming stream, and located upstream of separation. They conclude that the transition process in the separation bubble shows similarities with the oblique transition scenario studied previously by other authors in boundary-layer and channel flow.

In Watmuff (1999) a detailed experimental study of a two-dimensional separation bubble is reported. The experimental set-up consists of a curved test section ceiling, producing an adverse pressure gradient on the floor of the test section. A laminar separation bubble flow, with a highly two-dimensional separation line, forms on the floor and the flow field is studied with flying hot-wire anemometry and X-wire technique. Flow visualization of the bubble is carried out using the naphthalene sublimation technique. Watmuff introduces a low-amplitude wave packet at the minimum pressure point, (cf. Gaster & Grant 1975), upstream of separation by activating an electromagnetic shaker connected to a diaphragm and a 0.6 mm hole in the test section floor. The development and growth of the wave packet is investigated from the position at the point source, throughout the separated region and far downstream of reattachment. The phase averaged spanwise vorticity in an x - y -plane shows the appearance of a Kelvin-Helmholtz cat's eye pattern supporting the idea that the growth of the wave disturbance is due to an inviscid instability mechanism.

Wall normal r.m.s. velocity fluctuations in a y - z -plane above the bubble show a spanwise regular structure, both with and without forcing of the wave packet, and with local maxima right downstream of reattachment. In detailed measurements of the reattachment region, involving 31 365 measurement points being measured two times with an X-wire probe, all three velocity components were measured. Contour maps of the phase averaged vorticity magnitude show the formation of three-dimensional vortex loops in the reattachment region. Initially, the vorticity is oriented in the spanwise direction, but further downstream a deformation occurs and large vortex loops evolve, which are still found to exist far downstream in the turbulent boundary layer.

Alam & Sandham (2000) studied laminar separation bubbles on a flat plate by fully three-dimensional direct numerical simulations, prescribing a positive wall normal velocity distribution at the upper boundary of the computational domain. This approach was used by Hildings (1997) in a 2D-simulation study on laminar separation bubbles. Two- and three-dimensional instability waves were generated upstream of separation. Staggered Λ -vortices are observed in the flow prior to breakdown. Comparisons between two-dimensional and three-dimensional simulations show large differences in the mean structure of the separation bubble flow.

In another 3D direct numerical simulation of a laminar separation bubble flow by Spalart & Strelets (2000), also prescribing the wall-normal velocity at the upper boundary of the computational domain, no artificial forcing of instability waves upstream of separation is considered. A separation bubble in a channel is studied, similar to the study by Pauley *et al.* (1990).

A rapid three-dimensional development of the separated shear layer is found in the computations. Spalart & Strelets (2000) conclude that the transition process is different from a Görtler instability or a secondary instability related to high amplitude TS-waves. They find no presence of Λ -vortices in the computations.

The view taken in Spalart & Strelets (2000) on transition in a laminar separation bubble flow is somewhat different compared to the approach in which the development of incoming artificially generated disturbances is studied. Incoming disturbances are considered to be of minor importance. Spalart & Strelets argue that the flow is completely governed and specified by three parameters: the fraction of mass-flow removed from the upper boundary, and two Reynolds numbers based on the channel height and streamwise distance between the virtual origin of the inlet Blasius boundary layer and the center of the suction slot, respectively.

CHAPTER 5

Separation control

Related to the separation bubble is the issue of separation control, which is of great technological importance. With separation control is generally understood means by which separation can be prevented or postponed. In certain applications provoking separation may also be desirable. The subject of separation control is considered by Chang (1970) and Gad-el Hak & Bushnell (1991). There are several methods to accomplish such control, both passive and active ones, e.g. shaping of surface geometry, fluid suction/injection or wall heating/cooling. Here one method related to the instability of separated shear layers is considered - excitation of the flow by sound.

The possibility to substantially reduce the separated region over airfoils at large angle of attack and at subsonic speeds by excitation of acoustic waves from a loudspeaker mounted inside the wind tunnel has been shown in several experimental studies. Sound waves as an effective way to control separation on an NACA 0018 airfoil was investigated by Häggmark (1995). The dramatic effect on the flow field is illustrated in figure 5.1, in which the flow is visualized by four wool-tufts, attached onto the suction side of the airfoil. The two-dimensional airfoil spans the width of the test section.

In the top picture of figure 5.1 no acoustic control is applied and the flow is almost completely separated, from the leading edge and onwards, and the three rearmost tufts are pointing in the upstream flow direction, while the foremost tuft is elevated from the surface. When sound is excited by a loudspeaker mounted at the test section roof above the airfoil at a frequency of 1.39 kHz, separation is prevented and the tufts become aligned with the outer flow.

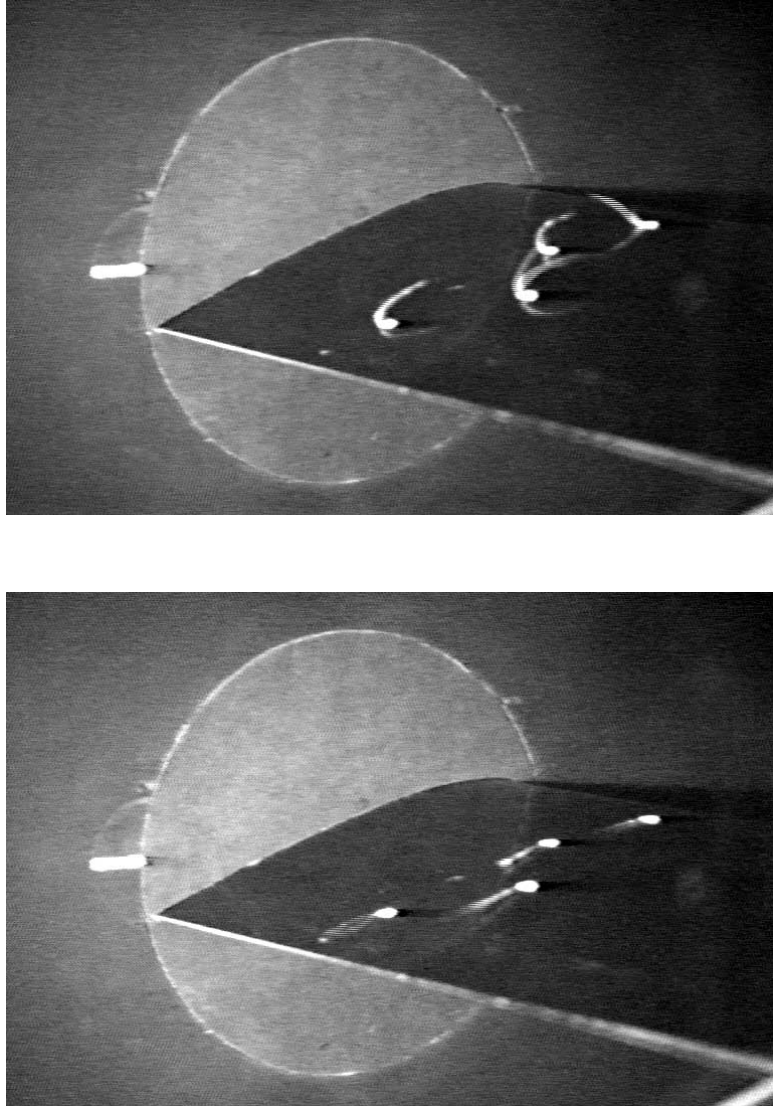


FIGURE 5.1. Visualization of the flow over an NACA 0018 airfoil by tufts. Flow direction from right to left. $Re_c=1.2\times 10^5$ and $\alpha \approx 16^\circ$. Upper photograph, no control, lower photograph, with control, $f=1.39$ kHz.

Figure 5.2, top, shows mean velocity profiles on the suction side, downstream of the leading edge, for the same airfoil in the cases without and with control. At the chord positions shown, the flow remains attached when the forcing is on. Without control forcing a detached shear layer develops and at $x/c=0.37$ the low-velocity separated region extends more than 10 mm from the surface. An increase in the edge velocity is observed due to the drag reduction from the control. The u_{rms} profiles in the no-control case shows a maximum in the separated shear layer which is deflected further out from the surface with increasing x . With control applied this maximum remains close to the wall.

Similar results were obtained by Collins & Zelenevitz (1975) who investigated the effect of sound on the flow over a wing and found that lift and stall angle enhancement, as well as drag decrease, were possible. Effects of acoustic waves on separated flows have been studied by Dovgal, Kozlov and co-workers, see section 4.2 for some of their results.

In a series of experimental studies Zaman and co-workers have investigated the effects of the external acoustic technique on airfoils.

Zaman *et al.* (1987) found that at low angles of attack low level acoustic forcing could suppress laminar separation on the suction side of the airfoil, whereas significant levels of forcing were required beyond stall in order to observe an effect. They also identified the importance of acoustic resonance in form of standing waves inside the wind tunnel for additional improvement of lift from acoustic excitation. In this respect wall normal velocity fluctuations induced by cross resonance standing waves in the test section, proved beneficial, especially at high levels of excitation.

Zaman (1992) notes that the excitation Strouhal number based on the optimum excitation frequency, i.e. the frequency which produces the largest lift increase, varied considerably between different experiments at high angles of attack, although the conditions were similar. Furthermore, in experiments applying external excitation the Strouhal number was consistently higher, although with exceptions, with a value of typically 10, compared with studies using ‘internal’ excitation, which showed values of an optimal Strouhal number of the order of 1. Internal excitation refers to methods directly producing velocity perturbations in the boundary layer, e.g. sound waves excited through holes or slots in the airfoil surface, or the usage of vibrating ribbons or wires.

Further studies on the external acoustic control technique involves Nishioka *et al.* (1990), who studied a flat-plate airfoil and found that external acoustic

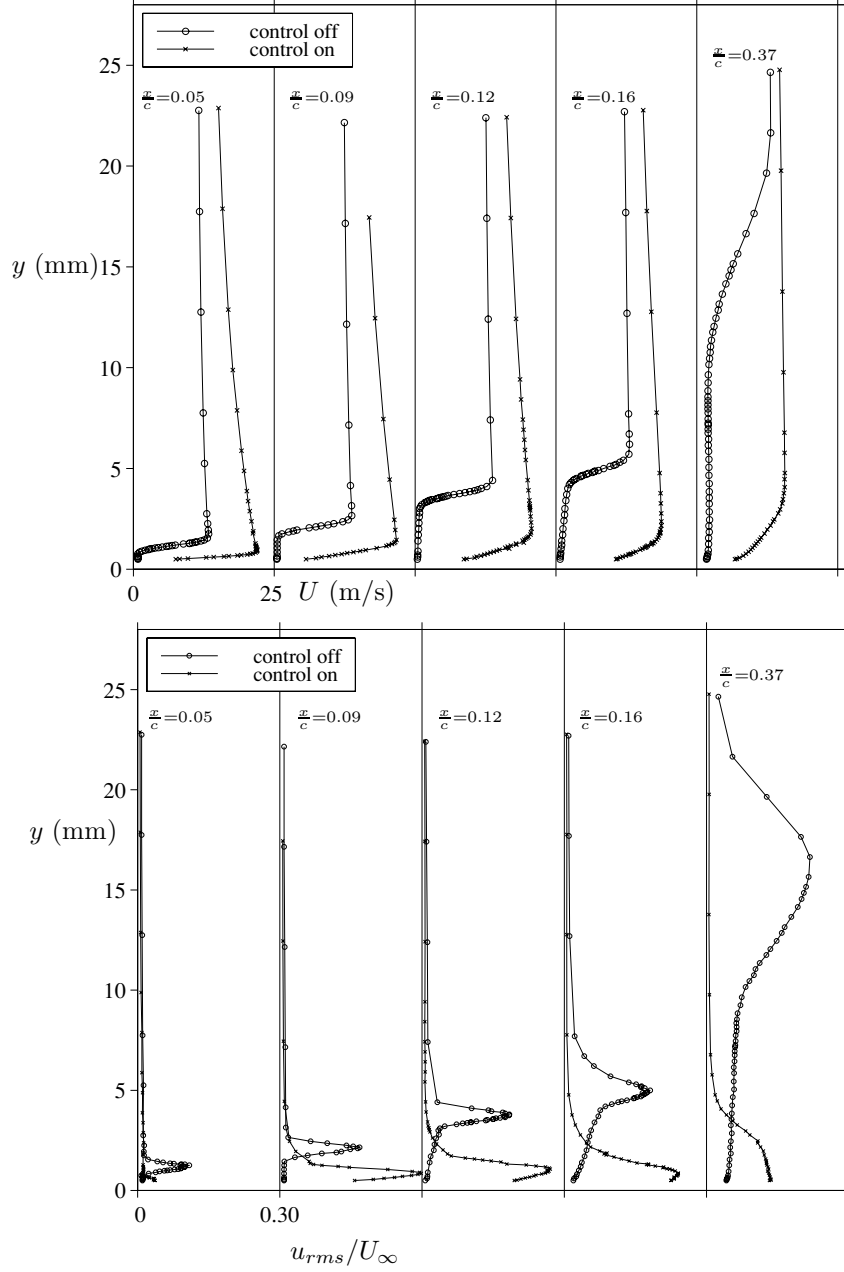


FIGURE 5.2. Mean (top) and r.m.s. fluctuating velocity profiles (bottom) on an NACA 0018 airfoil at different chordwise positions with and without acoustic control. $Re_c = 1.2 \times 10^5$, $\alpha = 16^\circ$ and $f_e = 1.39$ kHz. The y -coordinate direction is perpendicular to the incoming stream. Consecutive profiles in x are shifted 25 m/s in U and 0.3 units in u_{rms}/U_∞ .

excitation could decrease the size of a leading edge separation bubble. A reduction of the reverse flow region was detected by using two closely spaced single hot-wires.

Bar-Sever (1989) used an oscillating wire positioned shortly upstream of the leading edge of an airfoil to control the separated flow at high angles of attack. A wide band of forcing frequencies was effective but an optimum forcing frequency was found at a Strouhal number of approximately 1.5.

Hsiao *et al.* (1990) studied the internal acoustic excitation method by transmitting sound through surface slots in an airfoil and circular cylinder. Forcing at frequencies close to the frequency of the unexcited shear layer over the airfoil and at a position close to the separation point proved to be the most effective in achieving lift increase. For both the cylinder and airfoil model the most effective excitation frequency was in the Strouhal number range 1 - 3 for the Reynolds numbers investigated.

At even higher angles of attack, $\alpha > 24^\circ$, the internal forcing technique can be effective provided the forcing frequency is appropriately chosen, Hsiao (1994). In this case the effective Strouhal number was less than 1, corresponding to the bluff-body vortex shedding frequency.

The mechanism of control at high angles of attack is not well understood. Dovgal *et al.* (1994) point out that promotion of the linear instability of low amplitude wave disturbances due to the acoustic forcing, provoking laminar-turbulent transition cannot explain the results obtained with internal acoustic forcing. Zaman (1992) state that "The instability mechanism responsible for the effect in this case must be complex due to nonlinearity associated with high amplitudes, as well as due to the presence of the wall."

Zaman *et al.* (1987) made an observation regarding the unsteady properties of the separating boundary layer on an airfoil, which was pursued in Zaman *et al.* (1989). He found an unusually low frequency range of the natural velocity fluctuations in the flow, but could not identify its origin.

Looking from an engineering point of view external excitation can be applied in devices with confined flow e.g. diffusers. However larger interest for technological applications is the internal excitation technique which could be applied in a wider range of applications. Internal forcing is also attractive from the perspective that lower sound pressure levels are required compared to the external technique.

CHAPTER 6

Summary of Papers

Paper I

This paper considers a two-dimensional laminar separation bubble on a flat plate caused by an adverse pressure gradient. The adverse pressure gradient is obtained by a curved wall insert installed in the ceiling of the wind tunnel test section. Suction applied at a section of the leeward side of the curved wall allows for control of the adverse pressure gradient on the plate. The size and location of the bubble are hereby fixed in the experiment. In flow conditions with a low free stream turbulence level, referred to as natural conditions, high frequency instability waves are identified in the separated shear layer, which are not present in the attached boundary layer upstream of separation. Hot-wire spectra from measurements in the separated shear layer reveal two high frequency peaks in addition to a low frequency band, the latter being characteristic for separated flows in general. Hot-wire anemometry and flow visualization are used to study the development of these waves both at natural conditions and when they are forced artificially. The instability waves develop amplitude profiles in the separation bubble, with three local maxima, where the location of the middle maxima corresponds to the inflection point of the mean velocity profile. This is the case for both natural and forced disturbances. The instability waves grow exponentially in the separated shear layer and increase three orders of magnitude throughout the separation bubble region, which leads to a rapid transition process. Flow visualization reveals three-dimensional flow structures in the reattachment region of the separation bubble.

Paper II

A hot-wire technique is presented which measures the instantaneous flow velocity in the same way as a conventional single hot-wire and which also detects the instantaneous flow direction in highly parallel flows, such as in the vicinity of a solid wall. The probe has three in-plane and parallel wires. The centre wire is operated as a conventional single hot-wire in CTA mode whereas the two outer wires act as sensors and are operated as resistance wires. A calibration of the

probe in the forward and reverse flow direction, performed in a turnable wind tunnel calibration rig, shows that the probe is highly sensitive to changes in the direction of the flow. Measurements are performed inside a laminar separation bubble and regions of reverse flow is detected. It is found that regions with reverse-flow are mainly found in the reattachment region. The response of the probe is sufficient for measuring natural, high frequency disturbances occurring in the flow field.

Paper III

This paper is the main paper in the thesis and is focussed on controlled disturbances (in contrast to natural disturbances which were studied in paper I). Controlled forcing of two-dimensional waves was made in the boundary layer upstream of separation by suction and blowing through a slit in the flat plate. Hot-wire anemometry, smoke-visualizations and particle image velocimetry (PIV) are used in the investigation of the flow. The study was focussed on the disturbance development and growth upstream of and in the separation bubble, but also the complex flow in the reattachment region was explored. An exponential growth of two-dimensional wave disturbances is found in the separated shear layer. These waves remain two-dimensional in the linear amplification region whereas further downstream, approaching reattachment, a three-dimensionality of the waves is observed. The forced instability waves have an influence on the mean flow of the separation bubble which contracts both in the streamwise and wall normal direction. The main effect is found at the reattachment region whereas the region in vicinity of separation is less affected. A technique was proposed where PIV data can be used to find the average reattachment position. Also some measurements with free stream turbulence are presented. It seems that the transition process for this case is different and does not depend on the development of 2D-waves.

Paper IV

A numerical and experimental study of a transitional separation bubble has been carried out. The separation bubble in the experiments is reproduced in direct numerical simulations by prescribing the wall normal velocity distribution at the boundary of the computational domain, which cannot be achieved when prescribing free stream boundary conditions in the streamwise velocity. The development of two-dimensional instability waves is studied by artificial forcing upstream of separation. The rapid growth of these disturbances in the separated shear layer leads to transition in the flow. Good agreement between experimental results and simulations is obtained in this respect.

Division of work between authors

Häggmark (CH) developed, constructed and tested the experimental set-up which is used in all papers. In paper I CH and Bakchinov made the measurements; almost all evaluation of data in paper I was made by CH and most of the writing. Alfredsson contributed to the original idea and during the writing of the paper. In paper II CH developed the three wire probe and the associated electronics. CH and Bakchinov carried out the measurements. CH analyzed the data and wrote the main part of the paper. Alfredsson contributed the idea of the three wire probe and commented on the manuscript. Paper IV is based on Hildings licentiate thesis. Hildings made all the calculations, whereas CH contributed all measurement data. The rewriting of this work into paper IV was the responsibility of CH where Henningson and Hildings made contributions.

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