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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF INCOMPRESSIBLE LAMINAR BOUNDARY LAYERS WITH AND WITHOUT SUCTION

Ph.D THESIS

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This PDF-file contains chapter 1:

Introduction and outline of thesis

1. Introduction and outline of thesis.

1.1. Introduction.

During the development of the airplane to its present form a continuous reduction of aerodynamic drag has been achieved. This drag reduction was made possible by the practical application of wing theory beginning around 1918 and the introduction of streamlined shapes beginning after 1929. The year 1929 is marked by Mellvil Jones' well-known paper "The streamline aeroplane" [6] in which he indicated the improvements in performance to be obtained from streamlining.

Streamlining has been realised by the introduction of the cantilever monoplane, the retractable undercarriage, improved flow around the engines, better construction methods leading to a smoother surface etc. Finally the use of jet engines - being smaller than piston engines of the same power - led to a cleaner aeroplane with less drag than its predecessors.

The situation now is such that for big airliners the major part of the non-induced drag is due to skin-friction. Values of the non-induced drag found in practice for this type of airplane are about 25°/o higher than the friction drag calculated for a turbulent boundary layer over the aircrafts wetted surface.

In view of this it is clear that a further important reduction of the non-induced drag can only be obtained by a further decrease in friction drag. This can be achieved naturally by a reduction of the wetted surface of the airplane. However, only a limited reduction in drag will be possible in this way since the minimum extent of the wetted surface is dictated by the requirement that sufficient volume should be provided for payload, fuel etc. Hence, for a further drag reduction the intensity of skin friction itself has to be decreased. It is well known that the skin friction is much higher for a turbulent boundary layer than for a laminar one. As an example fig. 1.1.a shows the friction drag coefficient of a flat plate for both laminar and turbulent flow as a function of the Reynolds number $\frac{Ux}{\nu}$ using the familiar logarithmic presentation. Here U is the windspeed, ν the coefficient of kinematic viscosity and x the length of the plate. The curve in fig. 1.1a for the laminar boundary layer follows from Blasius' theory to be discussed in chapter 3. The friction drag for the turbulent flow is given by a formula due to Schlichting ([7], chapter 21) which correlates a number of different experiments. The experimental results indicated in the figure for both laminar and turbulent flow are taken from unpublished measurements in the low speed wind tunnel of the Department of Aeronautical Engineering at Delft Technological University. The experimental observations show that for the smooth plate above a certain Reynoldsnumber there is a gradual change from laminar to turbulent flow. Fig. 1.1.b shows the same results given in fig. 1.1.a but now using a linear scale for c_{d_f} which indicates more clearly the difference in skin friction for laminar and turbulent flow. The situation for an aircraft wing or fuselage is approximately similar to a flat plate and fig. 1.1 can be used to get an idea about the differences in friction drag, which can exist for an airplane with laminar or turbulent boundary layers. For instance for a typical jet airliner in cruising flight the Reynoldsnumber based on wing chord is about 2.5×10^7. Hence, if fig. 1.1 is considered to be applicable to the wing, it follows that the skin friction drag for a laminar boundary layer is only $10^o/o$ of the value obtained for a turbulent flow. For the fuselage the Reynolds number based on length is about 2.5×10^8 and hence the friction drag for the laminar boundary layer is only $10^o/o$ of that for the turbulent case. It is clear therefore that a considerable advance in drag reduction can be made by maintaining laminar flow in the boundary layer along an airplane. A necessary requirement for the occurrence of laminar flow in the boundary layer is that the body surface be smooth. This requirement is not sufficient however since even on a smooth body the boundary layer may become turbulent due to instability against small disturbances. As an example fig. 1.1 shows that for the smooth flat plate the boundary layer becomes turbulent for stations on the plate where the Reynoldsnumber $\frac{Ux}{\nu}$ is higher than about 3×10^6.

It is found (chapter 9) that instability and transition are strongly influenced by a streamwise pressure gradient. When the static pressure increases in the downstream direction the instability and hence the danger of transition to turbulence become very marked. Such an "adverse" pressure gradient is found for instance downstream of the maximum

thickness of an airplane wing in cruising flight.
In order to increase the extent of the region with laminar flow on a smooth wing the position of maximum thickness has to be moved rearwards. Airfoil sections designed with this objective in mind are the "laminar flow airfoil sections" which have been in use since about 1940.
Another method to stabilise the laminar boundary layer is to make the surface impervious in order to suck away a very small amount of air from the boundary layer. This method has been proposed first, as far as the author knows, by Griffith and Meredith in 1936 [8].
In fig. 1.1 the drag of a flat plate with a sufficient amount of suction to stabilise the boundary layer is shown (see section 9.8). Due to suction the skin friction rises above the value for the Blasius boundary layer but it remains much smaller than the value for the turbulent flow occurring without suction. The power needed to drive the suction pump can be converted to an equivalent "suction drag coefficient" to be added to the wake drag (see appendix 1). For the flat plate the total drag coefficient including the suction drag is also shown in fig. 1.1.
For complete airplanes the nett reduction in power required which would result from laminarisation by suction is substantial (see for instance Lachmann [10]). For a present-day modern jet airliner for instance, skin friction on the wing alone amounts to about 25°/o of the total drag in subsonic cruising flight. Laminarisation of the wing would lead to about 75°/o reduction in its non-induced drag even when allowance is made for the suction power. Hence the total drag in cruising flight would be reduced by about 20°/o if the boundary layer on the wing could be kept laminar. Lachmann states [10] that by laminarisation of the wing and tailplanes and optimisation of the airplane design for the application of suction the lift to drag ratio would be doubled as compared with the optimised conventional airplane.
The potential improvement in aircraft performance indicated above has stimulated so many investigations in the field of laminarisation that a large part of a recent two-volume work on "Boundary layer and flow control" [9] is devoted to this problem. In these books a detailed account of the historical development of the subject may be found. In what follows only

a few of these investigations will be mentioned to place the present work in the proper perspective.

Early wind tunnel investigations have been made by Holstein [11], Pfenniger [12] and Kay [13]. Holstein and Pfenniger tested airfoil sections with suction through a number of slots; Kay applied suction to a porous flat plate. Later experiments were made in flight by Head [14] using a small aircraft to carry an airfoil section model with a porous surface. The geometry of the test airfoil was chosen in such a way that in the suction region the pressure distribution for a flat plate was simulated. The amount of suction needed to keep the boundary layer laminar corresponded approximately to the theoretical predictions of Ulrich based on stability theory (see chapter 9). Subsequent experiments in high speed flight by Head and Johnson [15] and Pfenniger [16,17] showed that also at chord-Reynoldsnumbers of the order of 30×10^6 laminarisation could be achieved by suction.
As suction through a porous surface consisting of very fine pores may present practical difficulties a number of experimental investigations have been made in England with perforated surfaces obtained by drilling small holes in the skin [18]. It appears that these perforated surfaces can be useful for unswept wings but that it will be very difficult if not impossible to design a suitable perforation pattern for a swept wing. Pfenniger's experiments both in the wind tunnel and in free flight have been made with suction through a large number of narrow spanwise slits. A full scale flight experiment using Pfenniger's slot suction scheme is being made by the Northropp Co in the U.S.A. [20,21].

Theoretical investigations have been mainly concerned with porous surfaces because suction through discrete holes or slots is much more difficult to treat theoretically. In calculating the suction flow required to prevent transition most investigators choose the suction distribution in such a way that the laminar boundary layer remains neutrally stable all the way to the trailing edge of the body. Since it is well-known that instability of the boundary layer does not imply that turbulence will immediately appear (see chapter 9) it is clear that this procedure leads to a conservative estimate of the suction flow. As transition can not yet be predicted theoretically it is much more difficult to indicate the - less intense - suction distribution which is sufficient to prevent transition.

One of the aims of the present work was to improve upon this situation by designing a method which allows the calculation of the transition point for arbitrary pressure- and suction-distributions. Such a method for the no-suction case had already been given independently of each other by Smith and Gamberoni [1,2] and the present author [3,4,5]. The method for the case of suction is a straightforward extension of the earlier version.

In this method the amplification of unstable disturbances in the boundary layer is calculated using linear stability theory. It is shown that for different experiments actual transition occurs at nearly the same value of a calculated "amplification factor".

To extend this method to the case of suction it was necessary to obtain experimental results on transition of boundary layers with suction. For this purpose an airfoil section model with a porous surface between the 30 ^{o}/o and 90 ^{o}/o chord positions was tested in the low speed wind tunnel of the Department of Aeronautical Engineering at Delft.

In connection with this work a study was made of available methods for the calculation of laminar boundary layers. A new method of the Pohlhausen type was designed with application to suction problems in mind (chapter 5).

The accuracy of methods of this type is normally assessed by comparison with exact solutions of the boundary layer equations. One of the available exact solutions is due to Pohlhausen [22] and concerns the inflow between non-parallel plane walls without suction. This flow had been studied already in 1916 by Jeffery [23] and Hamel [24] using the Navier-Stokes equations. From a consideration of this flow it appeared that a clear picture could be obtained by studying the solutions of the equations in a plane where shear stress τ is plotted versus the velocity component u parallel to the wall. Also the effects of suction and blowing can easily be shown in this way (chapter 6).

This procedure is analogous to the use of the phase plane in the study of

non-linear oscillations of autonomous systems with one degree of freedom where speed is plotted versus displacement. In the mechanical problem the oscillation can be described by an ordinary differential equation of the first order. Singular points of this equation correspond to equilibrium positions of the oscillation while the type of stability of the motion is determined by the character of the singularity. In the flow problem the singular points are shown to correspond to the edge of a boundary layer. The equation only allows solutions of the boundary layer type - for which the velocity becomes practically constant at large distances from the wall - when the singularity is a saddle point or a stable node.
In the phase plane study, referred to above, it was found that for inflow between impervious walls the boundary layer equations give a solution for which τ^2 is a simple polynomial in u. This observation has been put to advantage for the design of a practical calculation method for boundary layers. In this method τ^2 is assumed to be a polynomial in u with coefficients depending on the streamwise coordinate x (chapter 7).
The boundary layer equation is written in a form where x and u are used as the independent variables and τ^2 as the dependent variable. The coefficients of the polynomial expression for τ^2 are determined from moments and compatibility conditions of this equation.
Essentially the new approach consists of the application of the well known von Kármán-Pohlhausen technique to a slightly changed form of Crocco's boundary layer equation. The moments have been designed in such a way that the degree N of the polynomial can easily be increased without complicating the method too much. For increasing values of N the results of the method seem to converge to the exact solution. For special suction- and pressure distributions the method allows a power series solution.
Results of accurate experimental investigations of laminar boundary layers which might be compared with results of boundary layers theory are very rare. Except for the flat plate - which has been considered by several investigators - the only accurate experiments known to the author are provided by Schubauer's investigation of the boundary layer on an elliptic cylinder [25]. Since the publication of [25] nearly all newly designed calculation methods have been applied to Schubauer's measured

pressure distribution. Some controversy has existed about these data because some calculation methods did not predict separation of the laminar boundary layer while the experiment had clearly shown that separation was present. It appears that the difficulty arises from the sensitivity of the boundary layer calculation to small changes in the pressure distribution near separation. According to Hartree [26] a very small change of the experimentally determined pressure distribution is sufficient to obtain separation.

As Schubauer's investigation has been made with a small chord model (11.78 inches) at the very low chord Reynoldsnumber of 72000 it was thought worth while to undertake an independent investigation on a larger scale. Therefore measurements were performed on a 28°/o thick laminar flow airfoil section with a chord of 1 meter. A detailed survey of the velocity profiles in the laminar boundary layer was made using hot wires and pitot tubes. Special attention was given to the laminar separation point (chapter 10). For the case of suction through a porous surface with a streamwise pressure gradient no results of accurate boundary layer measurements were known to the author. Therefore measurements were made on the model with the porous surface - already referred to - for such a suction distribution that laminar separation occurred in the suction region. Also pressure distributions and wake drag coefficients were measured for this model (chapter 11).

1.2. Outline of thesis.

Chapter 2 reviews the basic equations of two-dimensional incompressible laminar boundary layer flows. Included are Prandtl's boundary layer equations, the von Kármán-Pohlhausen momentum equation, the kinetic energy equation and compatibility conditions of the boundary layer equations. Chapter 3 is concerned with known methods for the solution of the boundary layer equations. Similar solutions and series expansion methods are discussed; finite difference methods are only briefly mentioned. Chapter 4 reviews some existing approximate methods using the von Kármán-Pohlhausen technique. Chapters 2,3 and 4 do not contain new results and therefore readers acqainted with boundary layer theory

can omit this part of the present work.
In chapter 5 the new method of the Pohlhausen type is presented together with some applications. The "phase plane" representation of the boundary layer flow between non-parallel plane walls with and without suction is given in chapter 6. The new calculation method which evolved from this study is described in chapter 7; some applications of both new methods are presented in chapter 8. The following chapter first reviews the subject of transition and linear stability theory and then describes the semi-empirical method for the calculation of the transition region.
Chapters 10 and 11 are devoted to the experimental investigations of the laminar boundary layer on the impervious and the porous airfoil section respectively. Where possible, results of the experiments have been compared with boundary layer theory.
Conclusions about the results of the investigations are mentioned in chapter 12. An important result of the present work is that it has become possible to calculate the characteristics of the laminar boundary layer including the transition position for arbitrary chordwise pressure - and suction distributions. This provides, for the first time, the means for a rational design of the most economic suction distribution needed to maintain laminar flow for a given pressure distribution.

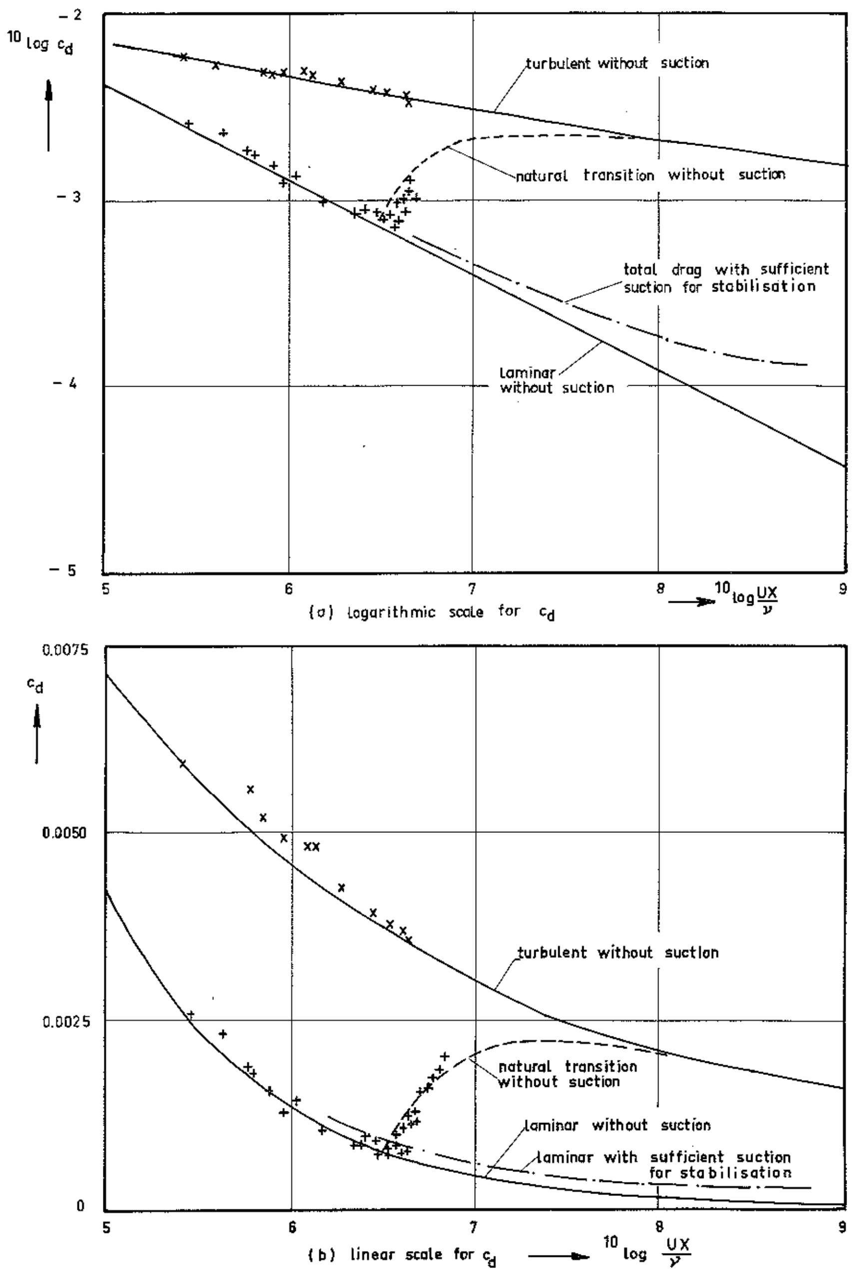

FIG. 1.1: DRAG OF FLAT PLATE WITH AND WITHOUT SUCTION
(see also fig. 9.21)

+ experiment, smooth plate

x " , with tripping wire