PART OF MY FORTY YEARS OF TEACHING AND RESEARCH IN BOUNDARY-LAYER FLOWS: THE LAMINAR SEPARATION BUBBLE

by

J.L. van Ingen

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On occasion of his retirement

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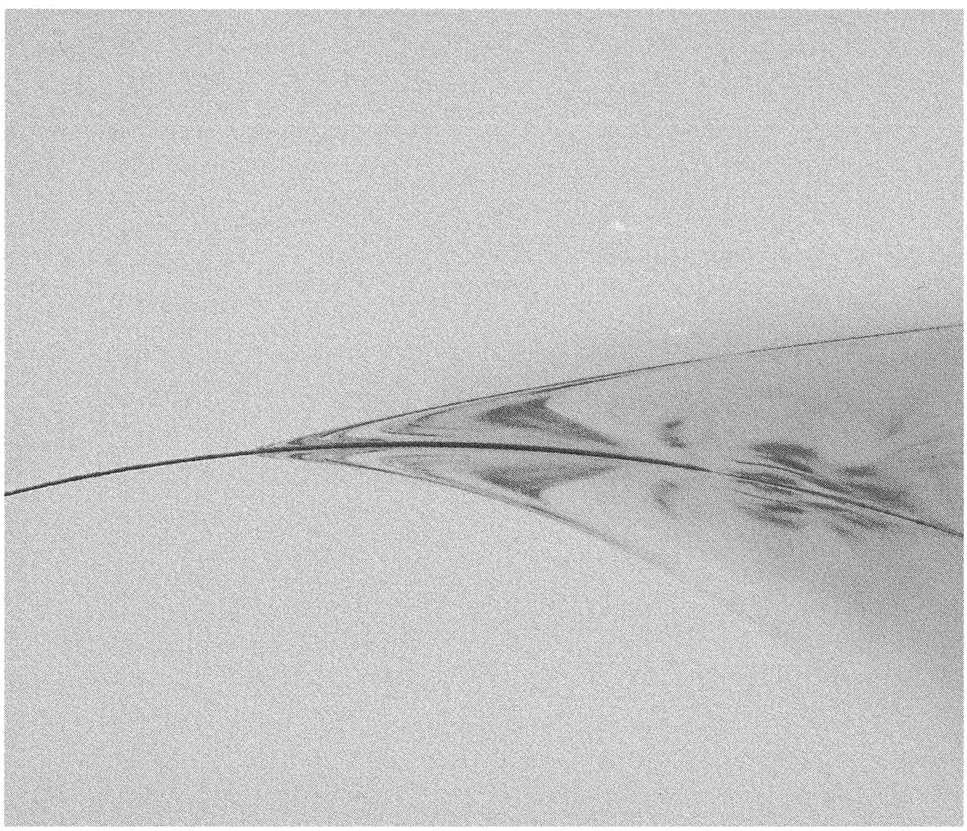

Part of My Forty Years of Teaching and Research in Boundary-Layer Flows: The Laminar Separation Bubble[1]

J.L. van Ingen

Delft University of Technology,
Faculty of Aerospace Engineering,
Kluyverweg 1, 2629 HS Delft, The Netherlands
(Also participant in the J.M. Burgers Centre for Fluid Mechanics)

Abstract

Teaching and research in aerodynamics at an aerospace engineering faculty should show a strong interaction between fundamental aspects and its application in design. The paper illustrates this by discussing a number of research topics of the author's group in relation to airfoil design for low-speed applications. Emphasis is placed on the aspects of separation.

1. Introduction

I came to Delft in 1949 as a first year student in the Faculty of Aeronautical Engineering. This Faculty had been founded in 1940, but of course a real start had only been made in 1945. Later the name of the Faculty has been changed into Aerospace Engineering. In 1949 there were two full professors: H.J. van der Maas, teaching flight mechanics and A. van der Neut, teaching aircraft structures. Applied aerodynamics was taught by senior lecturer E. Dobbinga. Theoretical fluid dynamics was taught by J.M. Burgers and solid state mechanics by C.B. Biezeno and W.T. Koiter, all from the Faculty of Mechanical Engineering. From 1960 onwards theoretical aerodynamics was taught within the Faculty of Aeronautical Engineering itself by J.A. Steketee, a former student of J.M. Burgers. Both Biezeno and Burgers had been appointed in Delft at a very young age (Biezeno in 1914 at the age of 26 and Burgers in 1918 at the age of 23). Burgers had been invited to the newly established chair in Aero- and Hydrodynamics, while still being a Ph.D. student of Ehrenfest in Leiden (see Nieuwstadt and Steketee, 1995).

It should be remembered that the First International Congress of Applied Mechanics was organized in Delft in 1924 by Biezeno and Burgers together with

[1]This paper describes part of the author's research in boundary-layer flows. A more extensive discussion was given in his 39th Ludwig Prandtl Memorial Lecture in Prague on 28 May 1996 (to be published as Van Ingen, 1997)

Prandtl, Von Kármán, Grammel and others, after a preparatory meeting at Innsbrück in 1922. This meeting in Delft laid the foundation for what later has become IUTAM. Since Prandtl died in 1953 and I finished my engineering study in 1954, I never had the privilege of meeting him personally. As is the case with most people of my age, the name of Prandtl became known to me through studying aerodynamic subjects such as wing theory and above all boundary-layer theory. As a student I had taken courses in boundary-layer theory from Burgers and Timman. I had the privilege of following some post-graduate lectures from Burgers in 1954 while he was still struggling with the equation which later was named after him.

During his introductory lectures in applied aerodynamics Dobbinga showed us the "Prandtl film" in which various viscous flow phenomena and the process of the generation of vortices, due to separation at sharp edges, were shown. This film had come to Delft from the National Aeronautical Laboratory (later NLR) which apparently had received it from Prandtl himself in the early 30's. A description of this film is given in Anonymous (1935), which is based on two publications by Prandtl himself (Prandtl, 1927a,b). Still pictures from this film are of course known to numerous generations of students in fluid dynamics through the famous Prandtl-Tietjens volumes.

From 1956 on I was charged, as an assistant at the Faculty of Aeronautical Engineering, with teaching a course on boundary layers. I have been teaching this course during 40 years now and I can say that I enjoyed every hour of it. Of course my inspiration during the development of this course was found in Prandtl's publications, such as his contribution to Schlichting's book. I have witnessed the development of the subject from the time where a practical application of boundary-layer theory was only possible through the use of Pohlhausen-type methods, to the present day where I can demonstrate to my students a rather complicated boundary-layer computation on a PC in the lecture room. I have, however, always tried to put emphasis on understanding of the subject above brute force of computation.

During my work in Delft I have always taken the view that teaching and research in aerodynamics at an aerospace-engineering faculty should show a strong interaction between fundamental aspects and its application in design. In this paper I will illustrate this by discussing some research topics of our group in relation to airfoil design for low-speed applications with emphasis on separation.

2. Teaching two-dimensional incompressible laminar boundary-layer computation

Of course it was only through the genius of Prandtl that the calculation of laminar boundary layers came in sight when he in 1904 simplified the Navier-Stokes equations to the boundary-layer equations. For an orthogonal curvilinear coordinate system in two-dimensional flow these equations read as follows:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U\frac{dU}{dx} + \nu\frac{\partial^2 u}{\partial y^2}; \qquad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

with boundary conditions:

$$u = v = 0 \quad \text{at} \quad y = 0; \qquad u \to U(x) \quad \text{for} \quad y \to \infty. \tag{2}$$

Note that the shape of the body only enters through the pressure-gradient term $U\frac{dU}{dx} = -\frac{1}{\rho}\frac{dp}{dx}$, which is assumed to be known when calculating the boundary layer. When inserting the boundary conditions at the wall into (1) we obtain the *first compatibility condition at the wall* relating the curvature of the velocity profile at the wall to the pressure gradient.

In the beginning of this century it was still too complicated to calculate the boundary layer for arbitrary pressure distributions. Hence at first only similar flows could be calculated, such as the flat plate (Prandtl, 1904; Blasius, 1908), the plane stagnation point (Hiemenz, 1911) and the wedge-type flows (Falkner-Skan, 1930; Hartree, 1937; and the reversed flow solutions by Stewartson, 1954. Non-similar solutions could be obtained for special pressure distributions where the partial differential equations (1) could be reduced to a series of ordinary differential equations (e.g. Blasius, 1908). All of these series solutions failed to converge properly near separation and hence some kind of continuation procedure had to be devised which was either based on the momentum integral equation of Von Kármán (Tani, 1955) or on a direct numerical solution (Hartree, 1939; Leigh, 1955). This work, especially that of Hartree, led to the notion of a singularity at separation. Later on this singularity was clarified by Goldstein (1948) and a further numerical evaluation was given by Terrill (1960).

At first these discussions of the singularity gave rise to the idea that the boundary-layer equations ceased to be valid at separation. Later on it has become clear that the boundary-layer equations can be used through separation for a suitable pressure distribution, but that the result is extremely sensitive to small changes in the pressure distribution. Instead of prescribing the pressure distribution one should prescribe a regular behaviour through separation of a quantity such as the skin friction or the displacement thickness from which the pressure distribution follows. At present it is customary to use the concept of *strong interaction* where the boundary layer is calculated simultaneously with the pressure distribution. Both are coupled through the distribution of the displacement thickness.

Until 1921 boundary-layer theory was not of much use to practical aerodynamicists. This is illustrated by the fact that it was only in 1922 that Burgers, during a visit to Von Kármán in Aachen, heard about the practical application of boundary-layer theory through the use of the Von Kármán momentum integral equation and the Pohlhausen method, based on it. Hence for a long time the practical application of boundary-layer theory was through approximate methods such as Pohlhausen's (1921). It was only in the sixties that direct numerical calculations became feasible, see for instance Smith and Clutter (1963).

In my lectures in Delft I discuss the laminar boundary-layer theory in a mixture of the classical approach for similar flows and series solutions, such as found in Schlichting and a direct numerical approach. The solution of the boundary-layer equations is complicated through the occurrence of boundary conditions at both ends of an, in principle, infinitely long interval between the wall and the edge of the boundary layer. Using a numerical initial value method, such as Runge-Kutta or a Taylor series method, requires the use of a *shooting procedure* where an additional boundary condition at the wall is guessed (e.g. the wall-shear stress) and successively refined until the boundary condition at the edge of the boundary layer is satisfied.

Instead of the shooting method also a finite-difference method can be used in which the boundary conditions at both ends of the interval are satisfied at the same time. For the finite-difference method it appears to be sufficient to discuss the numerical solution algorithm for only one second-order linear ordinary differential equation with non-constant coefficients. This standard form is

$$\overline{u}'' + P(\eta)\overline{u}' + Q(\eta)\overline{u} = R(\eta), \tag{3}$$

with boundary conditions

$$\overline{u} = 0 \quad \text{at} \quad \eta = 0; \qquad \overline{u} = \overline{u}_{\max} \quad \text{at} \quad \eta = \eta_{\max} \quad (\rightarrow \infty), \tag{4}$$

where $\overline{u}$ represents the non-dimensional velocity in the boundary layer. For certain applications where the exact solution is known, the exact value for $\overline{u}_{\max}$ at a finite $\eta_{\max}$ is used in order to be able to evaluate the quality of the numerical procedure. Equation (3) is solved in two ways:

- a 3-point finite difference method with application of the Thomas algorithm to solve the resulting linear algebraic equations.
- a 5-point finite-difference method, which is only a little bit more complicated than the 3-point method, but much more accurate for the same step length.

A first example is the asymptotic suction boundary layer (Schlichting, 1979, chapter 14) for which we obtain $\overline{u}'' + \overline{u}' = 0$ and hence $P(\eta) = 1$; $Q(\eta) = 0$; $R(\eta) = 0$. The exact solution is

$$\overline{u} = 1 - \exp(-\eta).$$

The second example is Stokes' first problem (accelerated infinite flat plate; see Schlichting, 1979, chapter 5). Writing this problem in a frame of reference where the wall is stationary and the outer flow is moving we find:

$$\overline{u}'' + 2\eta\overline{u}' = 0; \quad P(\eta) = 2\eta; \quad Q(\eta) = 0; \quad R(\eta) = 0.$$

Because of the known exact solutions, the preceding examples can be used by the students to get some feeling for the influence of varying $\eta_{\max}$ and the number of steps through the boundary layer and of course also for the merits of the various solution procedures.

The Blasius solution for the flat plate is described by an equation for the non-dimensional stream function f (Schlichting, 1979, chapter 7).

$$f''' + \frac{1}{2} f f'' = 0: \quad \text{with} \quad f = 0, \quad f' = 0, \quad \text{at} \quad \eta = 0; \qquad (5)$$
$$f' \to 1 \quad \text{for} \quad \eta \to \infty.$$

Equation (5) can easily be solved by the shooting method using the Taylor series and the Runge-Kutta method. The equation can also be solved by the finite-difference method by bringing it into the form of our standard equation (3) by substituting $f' = \overline{u}$ which leads to:

$$\overline{u}'' + \frac{1}{2} f \overline{u}' = 0.$$

Apparently we have to take $R = 0$ and $Q = 0$ while $P(\eta) = \frac{1}{2} f$. This is a complicating factor because now $P(\eta)$ is not known and the equation is not linear anymore. This problem is solved by using an iterative procedure where f is obtained from a previous iterate $\tilde{u}$ using

$$f = \int_0^{\eta} \tilde{u} d\eta,$$

and taking $\tilde{u} = 1 - \exp(-\eta)$ as a first estimate for $\tilde{u}$. A few iterations using the 3-point or the 5-point scheme are found to be sufficient.

The Falkner-Skan equation in the well known Hartree form (Schlichting, 1979, chapter 9) for the non-dimensional stream function f and its boundary conditions read:

$$f''' + f f'' + \beta \left(1 - (f')^2\right) = 0; \qquad f = f' = 0 \quad \text{at} \quad \eta = 0;$$
$$f' \to 1 \quad \text{for} \quad \eta \to \infty.$$

This equation allows repeated differentiations and hence the Taylor series method can be used in addition to the Runge-Kutta method for a shooting procedure. The use of the finite-difference method is complicated by the occurrence of two non-linear terms $f f''$ and $(f')^2$.

The first one is treated as in the Blasius equation, the second one is linearized using

$$f' = \overline{u}, \quad \overline{u} - \tilde{u} = \delta u, \quad (\delta u)^2 \approx 0,$$

where $\tilde{u}$ is the value of $\overline{u}$ from a previous iteration. This results into

$$\overline{u}'' + f \overline{u}' + (-2\beta \tilde{u}) \overline{u} = -\beta(1 + \tilde{u}^2),$$

and hence

$$P(\eta) = f; \quad Q(\eta) = -2\beta \tilde{u}; \quad R(\eta) = -\beta(1 + \tilde{u}^2).$$

Again an iterative solution is easily obtained from $f = \int_0^{\eta} \tilde{u} d\eta$ and a first guess $\tilde{u} = 1 - \exp(-\eta)$.

Non-similar boundary layers can be calculated from a form of the boundary-layer equation which to a large extent resembles the Falkner-Skan equation, see for instance Smith and Clutter (1963). However, in this case a partial differential equation results because derivatives of f and f' with respect to x occur. The equation has the advantage that for $x \to 0$ the Falkner-Skan equation is obtained, hence the starting solution is known already. A marching procedure in x-direction can be obtained by replacing the derivatives with respect to x by finite differences based on a few points in x-direction (Hartree-Womersley method). The resulting ordinary differential equation in η can be solved by the shooting method (using the Runge-Kutta procedure) or can be brought in the standard form (3) using the same procedures as for the Falkner-Skan equation. In all direct numerical calculations a singular behaviour near separation is observed. A good estimate for the position of separation is obtained by assuming that the singularity is of the simple Goldstein type where the wall-shear stress approaches zero as the square root of the distance to separation. Hence a linear extrapolation of the square of the wall-shear stress seems to be sufficient. The author demonstrates the various solution procedures in the classroom using a PC with overhead projection on a screen.

3. On the use of the method of integral relations to calculate laminar boundary layers with separation

As was mentioned in the previous chapter, it is rather easy to calculate laminar boundary layers for arbitrary pressure distributions, using a direct numerical approach. Nevertheless the use of the method of integral relations is still discussed in the author's course. On the one hand this is done because of historical reasons and its educational value. On the other hand the better methods of integral relations are still useful in design procedures. For an optimal design of an airfoil it may be necessary to perform a great number of boundary-layer calculations where the short computation time outweighs the disadvantage of a slightly lesser accuracy. Furthermore for airfoil design it is useful to have a method of integral relations with a one-parameter or preferably a two-parameter family of velocity profiles for which the results of stability calculations are available to be used in the e^n method for transition prediction (chapter 5). Also, if we want to calculate through separation using the method of strong interaction, an integral relation method offers advantages with respect to speed of calculation.

In my lectures I still discuss the Pohlhausen method (1921) in the version of Holstein and Bohlen (1940). Basically in this method it is assumed that all velocity profiles can be represented by a fourth-degree polynomial where all parameters except one are determined from boundary conditions and the first compatibility condition at the wall. The one remaining parameter results in a one-parameter family of velocity profiles; this parameter is then determined as a function of x from an ordinary differential equation for which the Von Kármán momentum integral relation is used. With the following definitions

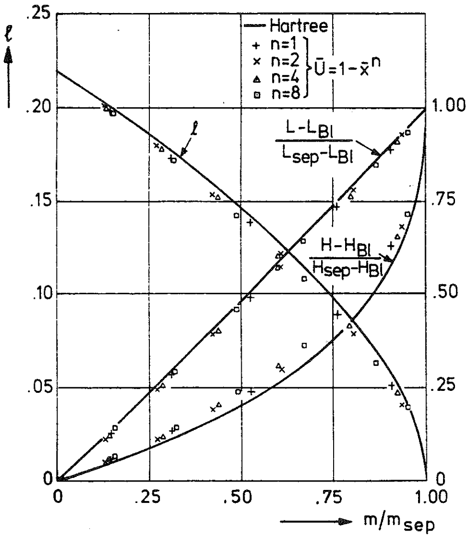

Figure 1: Scaled boundary-layer parameters as a function of m/m_{sep}. BL = Blasius; sep = separation.

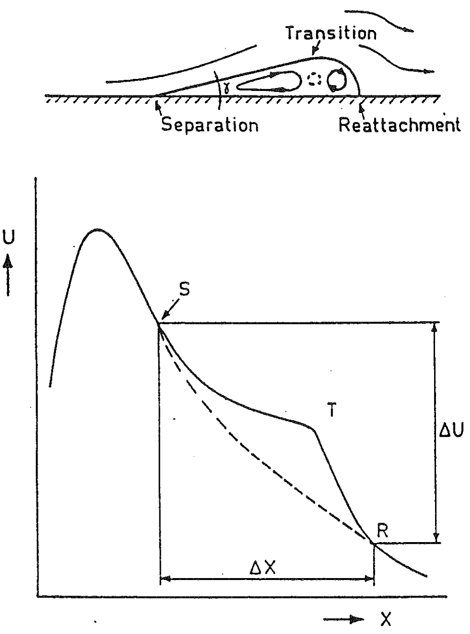

Figure 2: Schematic picture of a separation bubble and pressure distribution.

$$m = -\frac{\theta^2}{\nu}\frac{dU}{dx}, \qquad l = \frac{\tau_0 \theta}{\mu U}, \qquad H = \frac{\delta^*}{\theta}, \qquad F = 2l + 2m(2+H), \tag{6}$$

the momentum integral relation reduces to

$$\frac{d}{dx}\left(\frac{\theta^2}{\nu}\right) = \frac{F}{U}. \tag{7}$$

Due to the one-parameter family concept, all parameters mentioned under (6) are determined by one parameter for which any one of the set (6) can be used. Often F is considered to be a function of m. It was noted by Walz (1941) and later by Thwaites (1949) that $F(m)$ can be approximated by the linear relation $F(m) = a + bm$ which leads to the following solution of the momentum integral relation (7)

$$\frac{U\theta^2}{\nu} = \frac{a}{U^{b-1}} \int_0^x U^{b-1} dx.$$

This simple relation for the momentum-loss thickness θ appears to be remarkably accurate; it has been used by Thwaites (1949) to derive his well known

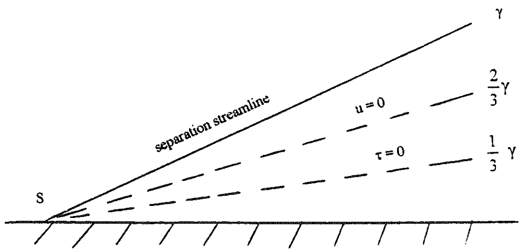

Figure 3: Separation according to Legendre-Oswatitsch.

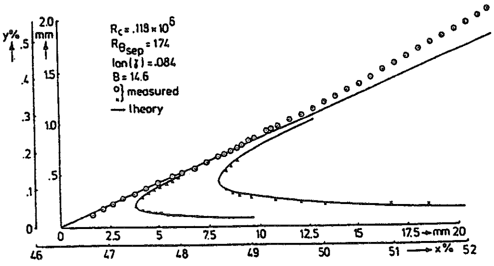

Figure 4: Streamlines obtained from smoke picture. ⊙ × experiments; — eq. (8)

method. Although one-parameter methods can give an accurate estimate of θ, it turns out that the shape of the velocity profiles and hence the position of separation can be rather inaccurate. It was shown by Head (1957), Curle (1967) and the present author (Van Ingen, 1975), that a two-parameter method would be sufficiently accurate for all engineering applications. As an example Fig. 1 shows that the characteristic parameters of a number of boundary layers can be collapsed on single curves if plotted vs m/m_{sep}, where m_{sep} is the value of m at separation (Van Ingen, 1975). It was shown by Curle (1967) that a suitable second parameter (in addition to $\frac{\theta^2}{\nu}\frac{dU}{dx} = -m$) is

$$n = \left(\frac{\theta^2}{\nu}\frac{dU}{dx}\right)^2 U \frac{\frac{d^2U}{dx^2}}{\left(\frac{dU}{dx}\right)^2} = \frac{\theta^4}{\nu^2} U \frac{d^2U}{dx^2}.$$

Note that n only depends on θ and $U(x)$, since θ can already be determined with good accuracy from a one parameter method (such as Thwaites' method), it may be expected that a two-parameter method can be developed without having to employ a second differential equation.

4. On the laminar part of separation bubbles

Laminar separation can occur on airfoils at low Reynolds numbers (e.g. sailplane wings and windturbine blades) but also at higher Reynolds numbers near the leading edge of wings at high angles of attack. At very low Reynolds numbers laminar separation can be followed by laminar reattachment (see section 7), but in practice the more usual case is that the separated flow becomes turbulent and may or may not reattach (bubble bursting).

In sections 2 and 3 we have seen that the calculation of laminar separation may present difficulties due to the Goldstein singularity, which occurs in accurate numerical procedures, while the usual methods of integral relations may not be accurate enough near separation. Since in our work on airfoil design we needed a method to predict the characteristics of laminar separation bubbles we have performed extensive research on laminar separation (Van Ingen, 1975; Dobbinga *et al.*, 1972; Van Ingen, 1986; Van Ingen and Boermans, 1986; Van Ingen, 1990).

Fig. 2 shows a typical pressure distribution for an airfoil with a separation bubble. Between laminar separation (S) and transition (T) the pressure distribution flattens due to the large displacement thickness in the bubble. Between transition (T) and reattachment (R) the turbulent flow shows a substantial pressure recovery. In the present section we will concentrate on the laminar part of the bubble.

To develop an integral-relation method for the calculation of laminar separated flow we needed more information on separation than is given by the Goldstein singularity. In fact this singularity will not occur in real flows. An interesting description of laminar separation is due to Legendre (1955) and Oswatitsch (1958). From a Taylor-series development around a point of zero skin friction it follows that the separation streamline should leave the wall at an angle γ (Fig. 3), where γ and the streamlines are given by:

$$\tan(\gamma) = -3\frac{d\tau_0}{dx}/\frac{\partial p}{\partial x}, \qquad y^2(x\tan\gamma - y) = \text{constant}. \tag{8}$$

Furthermore it follows that the points $u = 0$ are on the straight line under an angle $\frac{2}{3}\gamma$, the zero skin-friction line is under $\gamma/3$ and the pressure-gradient vector is also under $\gamma/3$.

Since in practice γ is only of the order of a few degrees, the pressure gradient normal to the wall remains small and hence it may be expected that the boundary-layer equations remain useful. In fact the relations (8) also follow from the boundary-layer equations (Dobbings *et al.*, 1972; Van Ingen, 1986; Van Ingen and Boermans, 1986; Van Ingen, 1990). It is clear from (8) that a boundary-layer calculation with prescribed pressure distribution for which the Goldstein singularity occurs would lead to the unrealistic result that $\gamma = \pi/2$.

An extensive series of flow-visualization experiments was performed from which the angle γ was determined. It appeared that the streamlines obtained from smoke pictures corresponded well to equation (8). Fig. 4 shows an example. A good correlation existed between γ and the Reynolds number based on U and the momentum-loss thickness θ at separation (Fig. 5). Based on these experimental results a simple one-parameter method was developed using the momentum integral equation and the first compatibility condition at the wall. The Hartree-Stewartson profiles provided the closure relations; a prescribed shape of the separation streamline was used instead of the prescribed pressure distribution. This method was able to give a reasonable description of the laminar part of the bubble (for further details see Van Ingen, 1975; Dobbinga *et al.*, 1972; Van Ingen, 1986; Van Ingen and Boermans, 1986; Van Ingen, 1990).

At a later moment it was tried to validate our experimental observations by a direct numerical approach based on the ideas of Veldman (1981) about interaction. A famous example is the Carter and Wornom trough (Carter and Wornom, 1975), where a flat plate is given a shallow indentation (Fig. 6). Cases

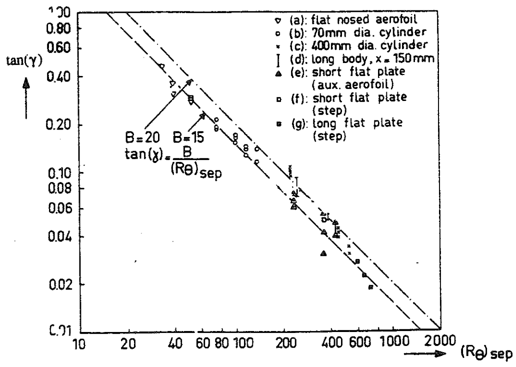

Figure 5: Correlation between $\tan(\gamma)$ and Reynolds number.

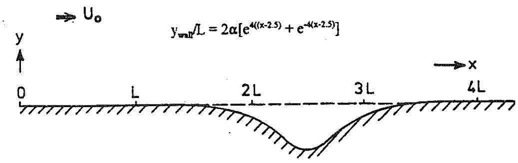

Figure 6: Indented flat plate (Carter and Wornom).

for $\alpha = -0.03$ and -0.05 have been calculated by Henkes (1985) and Henkes and Veldman (1987) and more recently by Meuleman (1996) and Henkes (1997, see elsewhere in these proceedings). The effect of the indentation and of the displacement thickness is taken into account using thin-airfoil theory. Through the displacement thickness the Reynolds number has an effect on the separation bubble. When the Reynolds number is sufficiently decreased, the displacement thickness becomes so large that the boundary layer fills the dip in the surface to such an extent that the separation bubble disappears. Some results of Henkes' calculations are shown in Fig. 7. There appears to be some correspondence to our earlier experiments, except for the sudden disappearance of the bubble at low Reynolds numbers. In the experiments we always tried to obtain bubbles where the separation angle could be measured with some accuracy. Smoke pictures have been obtained for an experimental realization of a Carter and Wornom trough for $\alpha = -0.03$. Since the quality of these pictures is not sufficient for reproduction, only a comparison between the experimental results and the some calculations is shown in Fig. 8. Also shown in Fig. 8 is the result of a calculation with a one-parameter method. At present a two-parameter method is being developed which is based on the Hartree-Stewartson closure relations, supplemented by the finite-difference results of Meuleman (1996) and Henkes (1997).

5. The e^n method for transition prediction

For airfoil design and analysis one has to be able to predict the position of laminar-turbulent transition, also in the case of laminar separation. In addition the characteristics of the initial turbulent boundary layer have to be known to be able to proceed with the boundary-layer calculation. There are many empirical methods known to predict the position of transition of which the e^n-method, based on linear stability theory, is at present the best known. This method was introduced 40 years ago independently by A.M.O. Smith and the present author. Further developments have been made by many researchers, extending

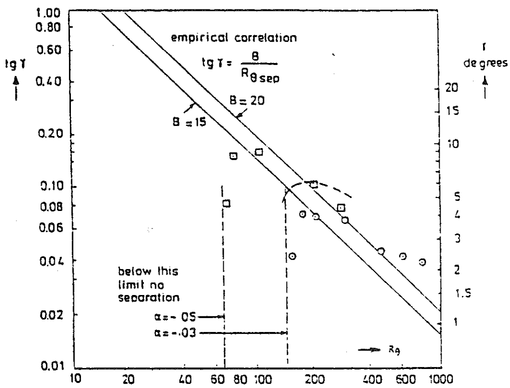

Figure 7: Numerical results for indented plate. ⊙ $\alpha = -0.03$; □ $\alpha = -0.05$; —— one parameter method for $\alpha = -0.03$.

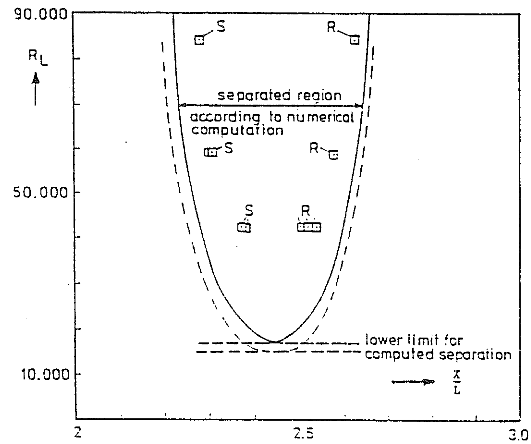

Figure 8: Indented plate; theory and experiment; S = separation, R = reattachment; □ experiment; —— finite-difference method; - - one-parameter method.

it to higher speeds, three-dimensional flows and including the effects of suction and heat transfer. That the method is still being used, is on the one hand due to the inherent difficulties of transition prediction from first principles. On the other hand, the e^n method contains enough physics to allow it to "predict" the distance to transition with only a simple experimental calibration. It was realized from the beginning that not enough physics was included to predict the process of transition itself. Hence providing the characteristics of the initial turbulent boundary layer remains a difficult problem of turbulence modelling (see section 7).

The book edited by Henkes and Van Ingen (1996) gives a recent review of various aspects of transitional boundary layers in aeronautics. Included is a paper by the present author (Van Ingen, 1996) giving a detailed account of the historical development of the e^n method, as well as two other papers by authors from our group (Henkes, 1996; Van Hest *et al.*, 1996).

From the end of the 19th century to about 1940 linear stability theory had been developed by a large number of mathematicians and theoretical aerodynamicists. Only through the famous experiments by Schubauer and Skramstad it was shown that indeed *Tollmien-Schlichting waves* existed (the experiments were done in the period 1940-1945, but due to the war conditions the results became only widely known in 1948). Although Pretsch had already done some amplification calculations, the results of which were presented in charts, it was only in the fifties that it was realized that linear stability theory might be used to bridge the sometimes large distance between the point of first instability and real transition.

It is difficult to specify the initial disturbances from which to start the amplification calculations. In fact this remains an important issue. How are dis-

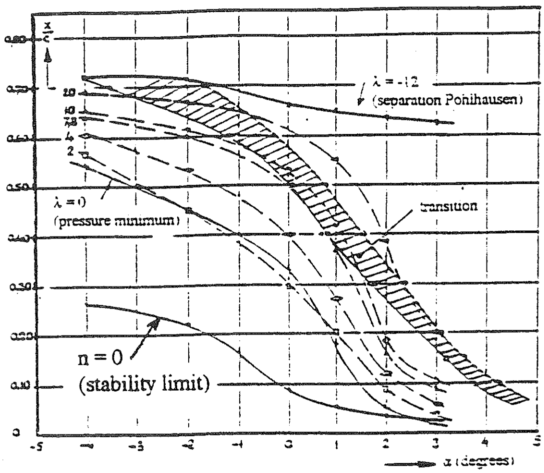

Figure 9: Calculated n-factors and measured transition region for EC1440 airfoil section (Van Ingen, 1956).

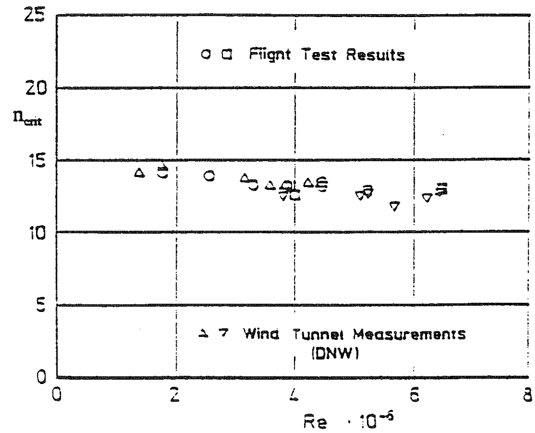

Figure 10: n-factors at transition in flight and in the DNW-windtunnel.

turbances generated inside the boundary layer? How are they related to outside disturbances like free stream turbulence, noise and vibration of the surface? At present this problem is denoted as "receptivity". Therefore we have to be satisfied with the calculation of the ratio between the amplitude of the most amplified disturbance according to linear theory at the experimental transition position and the original amplitude of this disturbance at its neutral position. From Smith's analysis it turned out that in many cases the same amplification ratio of about e^9 was found. The present author considered some of his own transition experiments on an EC 1440 airfoil. Guided by the flat-plate experiment of Schubauer and Skramstad this led him to conclude that the beginning and end of the transition region correspond to amplification ratios of $e^{7.8}$ and e^{10} respectively. On airfoils the transition region is in most cases only a few percent chord in length. Therefore it is not surprising that Smith, putting much emphasis on his results for airfoils, had proposed to a mean value of e^9. The exponent 9 was very close to the mean value indicated by Van Ingen. The early publications on this subject are Smith and Gamberoni, 1956 and Van Ingen, 1956a,b.

Some of the results which the present author produced for the EC 1440 airfoil, making use of the Pretsch charts, are collected in Fig. 9. It should be noted that the factors 7.8 and 10 do not provide a very precise prediction of the transition region. This may have been caused by the fact that the laminar boundary layer was calculated by the Pohlhausen method which is known to be inaccurate near laminar separation. From Fig. 9 it follows that at the higher angles of attack transition occurs near or sometimes even downstream of laminar separation. Stability calculations were not available for separated flows (and hence Pretsch charts had to be extrapolated) and also the Pohlhausen method could not predict separated flows. It should also be realized that only later the possible existence of laminar separation bubbles was realized.

In his Ph.D. thesis, Van Ingen (1965) demonstrated that the e^n method could also be used for the case of porous suction. An extensive series of windtunnel measurements was done (using filtering paper as a porous surface). It should be emphasized that each time one of the components in the whole e^n method is changed (new boundary-layer calculation method, new database for the stability diagrams, possibly improved stability diagrams, new experiments in the same or a different windtunnel or flight tests) the whole method will have to be recalibrated. In this way the present author had come up in 1965 with n-factors of 9.2 and 11.2 for the beginning and end of the transition region for the same EC 1440 results as in Fig. 9. It should be emphasized that the n-factor is not a magic number. It is just a convenient way to correlate into one single number a series of factors which are known from experiment to influence transition. The success of the method is due to the fact that an appreciable fraction of the distance between the point of instability and transition is covered by linear theory.

In 1966 the present author started to be involved in the design of airfoil sections for 2-D incompressible flows. The foundation of this work was laid while spending a sabbatical year at the Lockheed Georgia Research Laboratory. The then available numerical methods for conformal transformation, laminar and turbulent boundary-layer calculation and the e^n transition prediction method were used. Later in Delft these design methods were continuously improved, based on comparisons between calculations and windtunnel tests. A large number of airfoil designs were made (especially by Boermans) and applied in many different sailplanes (Boermans and Blom, 1982; Boermans and Waibel, 1988; Boermans *et al.*, 1989; Boermans and Van Garrel, 1994). It was soon realized that at the chord-Reynolds numbers applicable to sailplanes (and also windturbines) the occurrence of laminar separation bubbles was very important and warranted extensive research (see sections 4 and 6).

The e^n method could be extended to separated flows (Van Ingen, 1975) because stability diagrams had been made available by Taghavi and Wazzan for the Stewartson reversed-flow solutions of the Falkner-Skan equation. Moreover improved stability calculations for the Falkner-Skan velocity profiles had been published by several authors.

In the sixties it had been realized already for quite some time that a constant n factor could no longer be used. That for so long a constant n-factor of 9 had been useful, may have been due to the fact that most modern low-speed, low-turbulence windtunnels had been built according to the same recipe, aiming at a turbulence level of just below 0.1% as had been suggested to be sufficiently low according to the Schubauer and Skramstad experiment. From this experiment it had been concluded that reducing the turbulence level Tu below 0.1% had no use because "transition would not be influenced by a reduction of Tu below 0.1%". Since a further reduction of Tu requires a larger contraction ratio or more screens (and hence more money) most modern low speed windtunnel designs have aimed at $Tu = 0.1\%$.

From an evaluation of various transition experiments on flat plates at various turbulence levels the critical n-factor needed to predict flat-plate transition as a function of turbulence level could be derived. It should be clear that the free-stream turbulence level alone is not sufficient to describe the disturbance

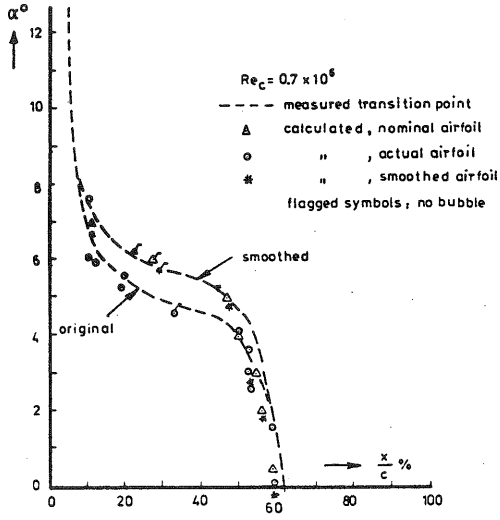

Figure 11: Experimental and computed transition positions for a "wavy" M-300 airfoil.

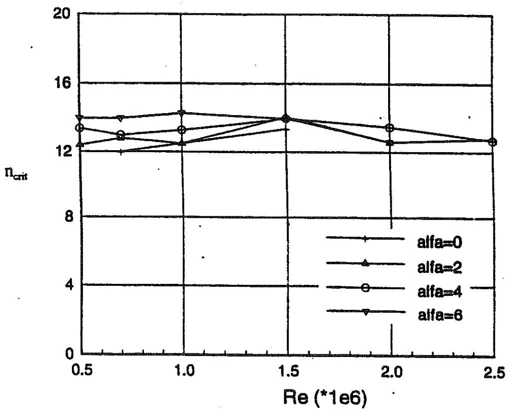

Figure 12: Critical n-factors for the DU89-122 airfoil.

environment. Information about the energy distribution across the frequency spectrum should also be available and in addition to turbulence the acoustic disturbances are important.

Therefore we can only specify an n-factor if an *effective* Tu is known. This effective turbulence level can only be defined through a comparison of measured transition positions with calculated amplification ratios. In fact it has become customary to define the quality of a windtunnel by stating its *critical n-factor.*

It should be realized that the e^n method does not automatically lead to useful results. The airfoil designer should be aware of its shortcomings and should make a judicious choice of the n-factors to be used. A comparison between n-factors obtained in flight and in the DNW low speed windtunnel is given in Fig. 10 (taken from Horstmann *et al.*, 1990).

In the author's group L.M.M. Boermans is the designer using the various calculation methods described above (see also section 8). He also has performed rather extensive windtunnel measurements and has evaluated many flight tests. A number of examples can be found in the references to his work. As an example, Fig. 11, taken from Boermans and Blom (1982), shows results of computations with the e^n method for wavy and smooth versions of the same nominal airfoil. It follows that the e^n method is capable of predicting the shift in transition position due to waves in the surface. Fig. 12 gives the n-factor for the beginning of transition on the airfoil DU89-122 (tests in the low-turbulence tunnel in Delft, using the infrared-imaging technique; Boermans, private communication).

In the past decades the e^n method has established itself as a useful method to predict the distance to transition in 2-D incompressible flow. Apparently the linear stability theory has enough physics in it to account for the effects of pressure gradient, suction, heating and cooling, etc. on transition.

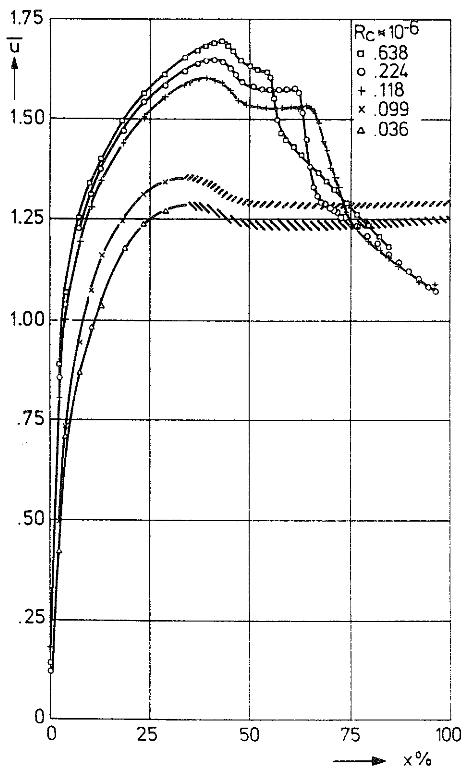

Figure 13: Pressure distribution for FX66-S-196V1 airfoil at various Reynolds numbers.

6. Some further results on separation bubbles

In earlier sections of this paper we discussed the laminar part of separation bubbles. It is in principle possible to calculate fully laminar separation bubbles for arbitrary outside flows with either a full numerical approach or using the method of integral relations (preferably a two-parameter method). In practice however, the separated flow becomes highly unstable such that transition occurs in the separated flow. In general turbulent reattachment occurs, leading to a closed bubble. Sometimes the turbulent flow fails to reattach ("bubble bursting") with very large detrimental effects on lift and drag of airfoils. Even a closed separation bubble may have a large adverse effect on the drag of an airfoil due to the bad characteristics of the turbulent flow just downstream of reattachment. Therefore in our airfoil designs transition is triggered sufficiently far upstream to avoid these adverse effects (see section 8).

Although the e^n method is able to predict with reasonable approximation the transition position in the bubble, the prediction of whether reattachment does or

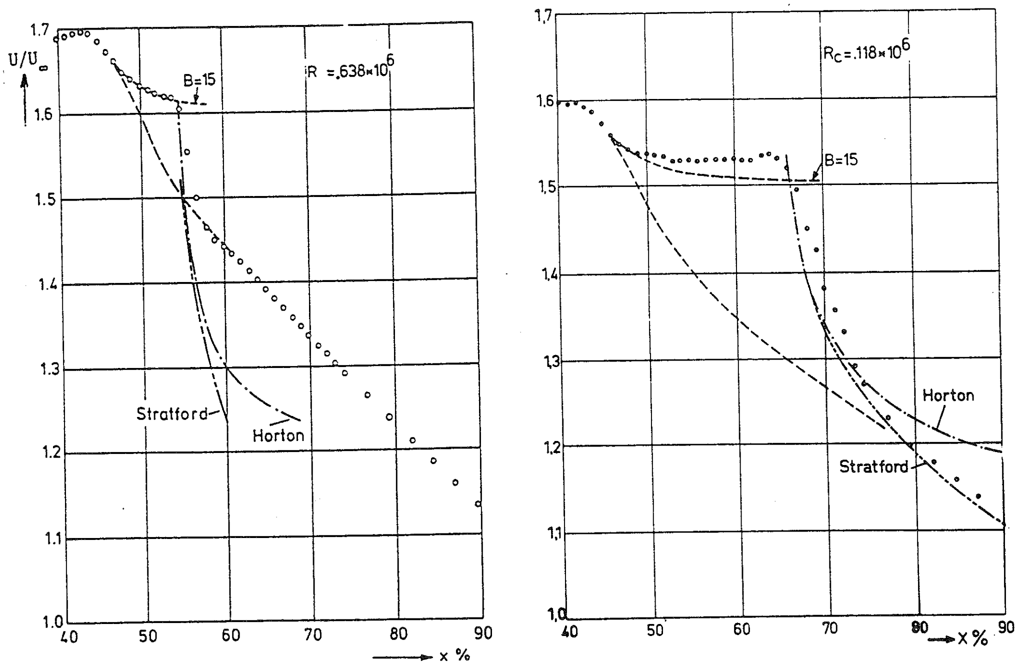

Figure 14: Prediction of reattachment at two Reynolds numbers for the same airfoil as in fig. 13.

does not occur is still a difficult task. Therefore extensive experimental research on separation bubbles has been done in our group at Delft. From this research a practical calculation method has been derived (Van Ingen, 1975). This topic will be illustrated with some figures and a brief comment. Fig. 13 shows the pressure distribution on a Wortmann airfoil for various decreasing values of the chord-Reynolds number. Observe the flattened part of the pressure distribution in the separated area and compare this to the schematic description in Fig. 2. Below R = 118000 bursting of the bubble occurs, leading to a drastic modification of the pressure distribution. The transition position in the bubble is predicted using the e^n method (section 5).

Various empirical criteria for bubble bursting are known from the literature (Gaster, Crabtree , Horton). In our airfoil analysis and design method we use a Stratford (1959) limiting pressure distribution downstream of the transition point T, to discriminate between reattaching and non-reattaching flows (Fig. 14). As soon as the Stratford curve does no longer intersect the basic pressure distribution, which would occur in absence of the bubble, bubble bursting is assumed to occur. It has been found that the resulting method represents with a reasonable accuracy the results of the earlier empirical criteria. An improved method could be developed where the two-parameter method for the laminar part is supplemented with a simple turbulence model to which a switch is made at point T, resulting from the e^n method. Such improved methods should give a continuous changeover to the fully attached and fully developed turbulent

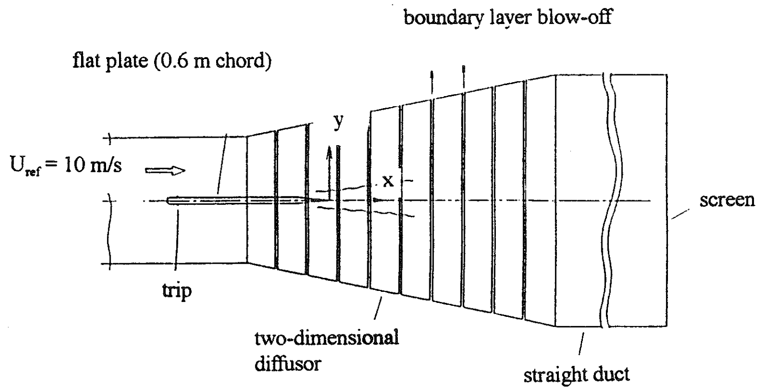

Figure 15: Wake in adverse pressure gradient.

boundary layer downstream of the bubble. Part of the research on turbulence modelling in our group is aimed at this particular region (see next section).

7. Turbulence modelling

For airfoil analysis and design it is a pre-requisite that the turbulent boundary layer and wake should be calculated with a reasonable accuracy. For "standard boundary layers" certain algebraic turbulence models may give acceptable results. However, in our airfoil work we have noticed that the turbulent flow in many cases does not behave in a "standard" way. In all cases providing the initial conditions for the turbulent boundary-layer calculation downstream of transition remains a problem. Although there are attempts to develop methods with a continuous changeover from laminar to turbulent flow, using turbulence models which can represent laminar, transitional as well as turbulent boundary layers, such methods are not yet advanced to such a stage that they can be used in practical airfoil design. Our group contributes in various ways to the problem of turbulence modelling. Henkes (1997) is working on the numerical aspects, and Passchier (1997, see elsewhere in these proceedings) is performing an experimental study on the characteristics of the turbulent boundary layer directly downstream of laminar separation. Absil (1995) has investigated the flow in the vicinity of the trailing edge of an airfoil. Tummers *et al.* (1995) are investigating turbulent wakes in very strong adverse pressure gradients. Starke *et al.* (1997) are investigating the effects of wake curvature on the turbulence characteristics.

In any CFD code for airfoil analysis and design the trailing-edge region should be given special attention. It is here that small details may have a large effect on lift through the viscous Kutta condition. It should be remembered that in airfoil theory, even if so-called inviscid, viscous effects at the trailing edge play an important role. The well-known Kutta condition states that the (assumed) inviscid flow should leave the trailing edge smoothly. It is often forgotten that

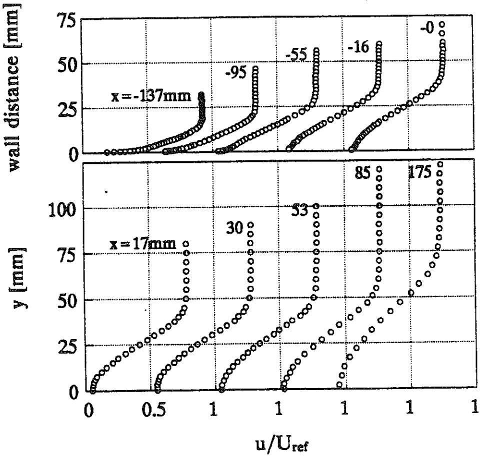

Figure 16: Mean velocity profiles on the plate and in the wake.

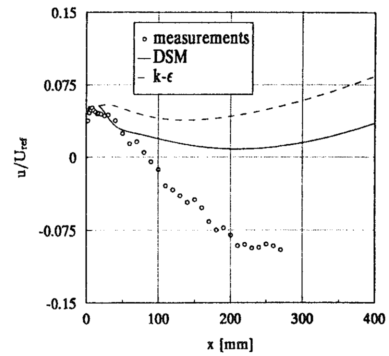

Figure 17: Centre-line velocity in wake (calculations according to the differential Reynolds-stress model and the $k-\epsilon$ model).

this condition is based on a viscous argument; a real viscous flow cannot flow around a sharp edge, however a mathematical inviscid flow can. The implementation of the classical Kutta condition in inviscid flow is straight-forward and leads to a unique relation between angle of attack and circulation. However, what circulation should be chosen in an airfoil analysis and design code based on boundary-layer methods is not at all obvious and requires extensive experimental research.

With this need in mind a long term research project has been performed in our group on the flow in the trailing-edge region of an NLR 7702 airfoil. A detailed discussion may be found in the Ph.D. thesis by Absil (1995). It should be clear that the flow near the trailing edge is a very difficult case for modelling. The two boundary layers from the upper and lower surface separate and merge at the trailing edge. Because in our example the boundary layer on the upper surface is near to separation and on the lower surface is far from separation, the near wake is highly asymmetrical. Within a very short distance of a few percent chord the flow changes from the typical wall-bounded case to the wake.

In practice a wake, resulting from the main airfoil, may be subjected to a very strong adverse pressure gradient in the pressure field above a trailing-edge flap. It is not uncommon that flow reversal occurs in the centre of the wake. The strong adverse pressure gradient, in addition to the curvature of the wake and the high turbulence level in the wake make this flow a suitable candidate for turbulence research and turbulence modelling. Parts of this research have been published in Tummers *et al.* (1995). A forthcoming Ph.D. thesis by Tummers (1997) will give an extensive review of this research. For the present paper we have to be satisfied with presenting some highlights. Fig. 15 shows the experimental set-up.

The wake is generated by a flat plate in the exit of a 0.40 $m \times 0.40$ m windtunnel. The adverse pressure gradient is generated by a two-dimensional diffuser which is followed by a straight duct and a screen. Due to the screen the diffuser can be maintained at an overpressure with respect to the surroundings. Hence natural boundary-layer blow-off occurs at the walls of the diffuser, contributing to the pressure gradient and at the same time preventing separation at the diffuser walls. Measurements were taken, using a three-component dual beam Laser-Doppler-Anemometry system. The development of the mean-velocity profile on the flat plate and in the wake follows from Fig. 16 ($x = 0$ is at the trailing edge of the plate). The centreline velocity is presented in Fig. 17, showing that flow reversal in the centre of the wake occurs at about 85 mm downstream of the trailing edge of the flat plate. In addition to the mean velocity profiles detailed distributions of the Reynolds stresses and triple velocity correlations were measured, thus providing the possibility for a check on the balance of the kinetic energy equation. Computational results have been obtained with various existing methods. It has been concluded that the spreading rate of the mean velocity profiles is predicted well, but that the prediction of the centreline mean velocity and kinetic energy distribution is poor.

8. Some remarks on sailplane design at Delft University of Technology

As was stated already in the Introduction we in Delft try to combine fundamental research in aerodynamics with design activities. The sailplane provides an excellent link between the two activities. On the one hand airfoils can be tested at full scale Reynolds number in our moderately sized (1.25 m $\times$ 1.80 m) low-turbulence, low-speed windtunnel. On the other hand, through contacts with the sailplane industry, designs made in Delft, could be realized in practice. In this way students with different interests (design- or more fundamentally oriented) could work together on projects. In our group L.M.M. Boermans is responsible for the design aspects of this subject. References to his work may be found in Boermans and Blom (1982); Boermans (1982); Boermans and Waibel (1988); Boermans *et al.* (1989); Boermans and Van Garrel (1994).

Our first project, in collaboration with Alexander Schleicher Segelflugzeugbau in Germany, was the modification of the wing of the ASW-19 sailplane which increased the maximum glide ratio from 37.5 to 41. At the flight Reynolds numbers for sailplanes it is possible through proper shaping of the airfoil to maintain very long regions of laminar flow. This leads in general to the occurrence of laminar separation bubbles which has inspired the research described in sections 4 and 6.

Fig. 18 gives an example of the distribution of the momentum loss thickness over the upper surface of the same airfoil as in Fig. 13 at various Reynolds numbers. In all cases transition occurs downstream of separation, leading to a laminar separation bubble. Note that at the lower Reynolds number there is a very strong increase of θ between T and R, leading to a high value of θ at the trailing edge and hence to a large profile drag. Hence the designer

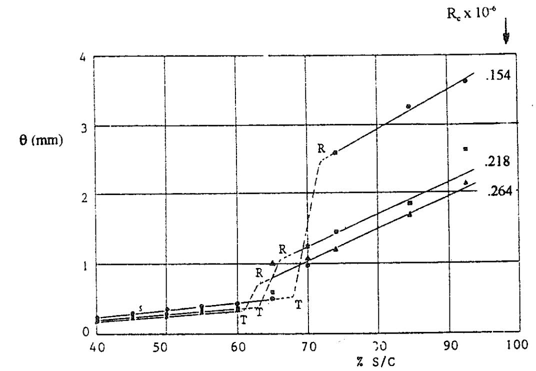

Figure 18: Momentum-loss thickness for same airfoil as in Fig. 14.

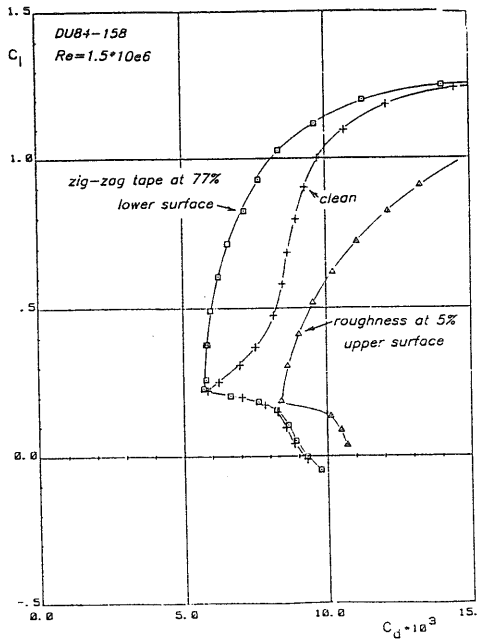

Figure 19: Drag curves for airfoil DU 84-158.

should try to obtain long laminar flow regions but to avoid detrimental separation bubbles. This has led to the customary procedure to trip the boundary layer to the turbulent state at a short distance downstream of separation for which pneumatic turbulators are very often used. In this case air is blown out of the surface through a spanwise row of small holes; the blowing pressure is provided by a very small total head tube. As an example it can be mentioned that for the ASW-19 a tube diameter of 6 mm proved to be sufficient. Also the cheaper zig-zag tapes are used to trigger transition. It should be realized that the use of these boundary-layer trips is only practicable if the airfoil is designed in such a way that laminar separation occurs at very nearly the same chordwise position for a range of angles of attack and of course the variable flight Reynolds numbers corresponding to the changing angles of attack. In practice, the zig-zag tape can become submerged in the laminar separation bubble, thus becoming ineffective, while pneumatic turbulators blow through the dead-air region and remain effective.

Fig. 19 shows the drag curves for the airfoil applied in the ASW-24 with and without the use of a zig-zag tape. The present state of the art is such that airfoils for sailplane applications can be designed which maintain laminar flow over 75% chord on the upper surface and 95% chord on the lower surface. A further improvement of the performance of such airfoils may only be achieved through the use of active boundary-layer control such as suction. Our group is working on this subject.

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Curriculum Vitae of prof. dr ir J.L. van Ingen

Personal
Born on 30 January 1932 in Puttershoek, The Netherlands

Education

June 1949	Diploma Secondary Education ('HBS-B')
May 1954	'ingenieur' Aeronautical Engineering (= M.Sc.); (cum laude)
October 1965	Ph.D. at TU Delft (cum laude)

Career

1952 - 1954	Student assistant at TUD-Aeronautical Engineering (later Aerospace, indicated by its Dutch abbreviation LR)
1954 - 1962	Assistant professor at TUD-LR
1962 - 1966	Associate professor at TUD-LR
1966 - 1967	Consultant at Lockheed Georgia Research Laboratory
1967 - 1971	Senior Lecturer in Aerodynamics at TUD-LR
1971 - 1997	Full Professor in Aerodynamics at TUD-LR
1997	Retired professor at TUD-LR; charged with the international relations of the Faculty

Functions within TUD-LR

1972 - 1974	Dean of the Faculty
1986 - 1990	Vice Dean of the Faculty
1991 - 1997	Dean of the Faculty

Functions within Delft University

1970 - 1976	Member and chairman of the Board of the TUD computing centre
1989 - 1997	One of the initiators of the Working Group 'J.M. Burgers' for Fluid Dynamics and its first chairman. This working group later became the J.M. Burgers Centre for Fluid Mechanics, first chairman, member of the management team

Scientific functions in gremia external to TUD

1970 -	Member of the Sub-Committee on Aerodynamics of the Scientific Committee NLR/NIVR (National Aerospace Laboratory/Netherlands Agency for Aerospace Programs) (chairman since 1995)
1970 -	Member of the AGARD Fluid Dynamics Panel and as such member of numerous program committees for symposia
1976 -	Member of the Advisory Committee of the German-Dutch Windtunnel (DNW)
1981 -	Member of the Governing Group for Cooperation in the Field of Aeronautics between Indonesia and The Netherlands
1989	Member of the Scientific Committee for the IUTAM Symposium 'Transition', Toulouse, 1989
1990	Member of the Scientific Committee for the IUTAM Symposium 'Separated Flows and Jets', Novosibirsk, 1990
1990 - 1993	Member of the Working Group 'Fluid Dynamics and Heat transfer'; F.O.M. (Fundamental Research of Matter)
1992	Member of a discussion panel on the future of aeronautical activities in The Netherlands
1993 -	Member of the Board of the National Aerospace Laboratory
1995	Chairman of the International Colloquium of the Royal Netherlands Academy of Arts and Sciences: 'Transitional Boundary Layers in Aeronautics (1995)'
1995	Knight in the Order of the Netherlands Lion
1996	Invited by GAMM and DGLR to hold the 1996 Prandtl Memorial Lecture (May 1996, Prague)

Membership of Professional and Social Organizations

1954 -	Royal Institute of Engineers
1975 -	Netherlands Society of Aeronautical Sciences (chairman 1975-1984)
1975 - 1984	Member of the Board of the Royal Netherlands Society for Aeronautics
1975 - 1993	Member of the Board of the National Aviation Museum 'Aviodome'
1981 -	Member of the Board of the National Aviation Fund Fokker-van den Berch-van Heemstede
1980 -	Member of the Board (chairman since 1990) of the Delft Branch of the Cooperative RABO Bank
1986 -	Rotary Club Delft
1997 -	Member AIAA

Membership of National Advisory Committees

1976 - 1989	Advising the Minister of Economic Affairs on the application of wind energy
1985 - 1987	Advisory Committee for the 'Lievense Project' for an energy storage water basin

Selection of publications by prof. dr ir J.L. van Ingen

1. Report VTH-71: Een semi-empirische methode voor de bepaling van de ligging van het omslaggebied bij onsamendrukbare twee-dimensionale stromingen (July 1956). In Dutch.

2. Report VTH-74: A suggested semi-empirical method for the calculation of the boundary layer transition region (September 1956); also published in *Proceedings Second European Aeronautical Congress*, Scheveningen 1956.

3. Memorandum M-1: Een twee-parametermethode voor de berekening van de laminaire grenslaag met afzuiging (July 1958). In Dutch.

4. Memorandum M-2: Enige opmerkingen over de toepassing van afzuiging voor het laminair houden van de grenslaag bij vliegtuigen (July 1958). In Dutch.

5. Report VTH-112: Windvaanonderzoek van de stroming over de vleugel bij het overtrekken van het vliegtuig Fokker S12, PH-NDC. Co-author ir. G.L. Lamers. October 1962.

6. Report VTH-118: Phase plane representation of the incompressible viscous flow between non-parallel plane walls (September 1964).

7. Report VTH-124: theoretical and experimental investigations of incompressible laminar boundary layers with and without suction (October 1965). Ph.D. Thesis.

8. Report VTH-132: A method of calculating the transition region for two-dimensional boundary layers with distributed suction. See also Jahrbuch WGLR, 1965, pp. 208.

9. Onderzoek van laminaire grenslagen met afzuiging. De Ingenieur, March 1967, pp. L9-L16. In Dutch.

10. Phase plane representation of the incompressible viscous flow between non-parallel plane walls. *Z.A.M.P.* January 1967.

11. A program for airfoil section design using computer graphics. Lockheed Georgia Research Laboratory, Marietta, Georgia, February 1967.

12. Computer Graphics techniques applied to airfoil design. Software Age, Vol. 1, nr. 1, September 1967. pp. 34-42. Co-author M.E. Haas.

13. De ontwikkeling van vleugelprofielen. Public lecture, March 1968, Published by Waltman, Delft.

14. Advanced Computer Technology in Aerodynamics: A program for airfoil section design utilizing computer graphics. Published as 'Lecture Notes' Von Karman Institute for Fluid Dynamics, Brussel, part of a 'Short Course on high Reynolds number subsonic Aerodynamics, April 21-25, 1969 (also published in Agardograph 97).

15. On the design of airfoil sections utilizing computer graphics. De Ingenieur, 24 October 1969, pp. L110-L118.

16. A multimoment method for the solution of the laminar boundary layer equations in two-dimensional incompressible flow using a series of Chebyshev polynomials for the interpolating function. Lecture Fluid Flow Symposium, NASA Georgia Tech., Atlanta Georgia, April 1967.

17. A survey of boundary layer research in Belgium, Denmark and The Netherlands. AGARD Specialist Meeting, Napels 1965.

18. Advanced computer technology in aerodynamics; a program for airfoil section design utilizing computer graphics, AGARD Lecture Series 37 on *High Reynolds Number Subsonic Aerodynamics*, April 21-25, 1969.

19. Some current research at the Department of Aerospace Engineering Delft on laminar separation bubbles. Euromech colloquium 14 on Aerodynamic testing techniques and detection methods for forced transition in boundary layers. Skokloster, Sweden, June 16-18, 1969.

20. Theorie en experiment in de stromingsleer. Inaugural Lecture, Delft, 1971.

21. Some research on two-dimensional laminar separation bubbles. AGARD CP-102, paper nr. 2, Lisbon, 1972. Co-authors E. Dobbinga and J.W. Kooi.

22. On the calculation of laminar separation bubbles in two-dimensional incompressible flow. In: AGARD CP-168, *Flow Separation*, Göttingen, 1975.

23. Transition, pressure gradient, suction, separation and stability theory. AGARD CP-224, *Laminar-Turbulent Transition*, Copenhagen, 1977.

24. Low speed airfoil section research at Delft University of Technology. ICAS-80-10.1, Munich, October 1980. Co-authors L.M.M. Boermans and J.J.H. Blom.

25. On the analysis and design of low speed airfoils using potential flow methods and boundary layer theory. Report LR-365, Department of Aerospace Engineering, Delft University of Technology, 1982.

26. Onderzoek van laminaire-turbulente omslag op de rotorbladen van de 25 m HAT windturbine. Report LR-390, Faculty of Aerospace Engineering, 1983. Co-authors G.J.H. van Groenewoud and L.M.M. Boermans. In Dutch.

27. Design studies of thick laminar-flow airfoils for low speed flight employing turbulent boundary layer suction over the rear part. Paper 15 in *Improvement of Aerodynamic Performance Through Boundary Layer Control and High Lift Systems.* AGARD CP-365, 1984. Co-authors J.J.H. Blom and J.H. Goei.

28. Research on laminar separation bubbles at Delft University of Technology in relation to low Reynolds number airfoil aerodynamics. In: *Proceedings of the Conference on Low Reynolds Number Airfoil Aerodynamics*, pp. 89-124. Ed. Th.J. Mueller, Univ. Notre Dame, UNDAS-CP-77B123, 1985. Co-author L.M.M. Boermans.

29. Aerodynamics at low Reynolds numbers; a review of theoretical and experimental research at Delft University of Technology. Paper nr. 1 in *Proceedings of the International Conference on Aerodynamics at low Reynolds numbers.* October 1986, R.Ae.Soc. London. Co-author L.M.M. Boermans.

30. Het gebruik van CAD-faciliteiten bij het analyseren en ontwerpen van vleugelprofielen. Proceedings CAD/CAM symposium, Delft, 1987. Co-authors J.J.H. Blom and L.M.M. Boermans. In Dutch.

31. Classical separation, trailing-edge flows and buffeting. Section 4.6., pp. 306-337. In: *Boundary Layer Simulation and Control in Windtunnels.* AGARD AR-224, 1988.

32. Experimental aerodynamic characteristics of the airfoils LA 5055 and DU 86-084/18 at low Reynolds numbers, pp. 115-130. In: *Low Reynolds Number Aerodynamics*, Proceedings Conference Notre Dame 1989, Springer Lecture Notes in Engineering, nr. 54, 1989. Co-authors L.M.M. Boermans, F.J. Donker Duyvis and W.A. Timmer.

33. Digital phase stepping holographic interferometry in measuring 2-D density fields. *Experiments in Fluids*, 1990, pp. 231-235. Co-authors Th.A.W.M. Lanen and C. Nebbeling.

34. Phase stepping holographic interferometry in studying transparent density fields around 2-D objects of arbitrary shape. *Optics Communications*, 76, 1990, pp. 268-275. Co-authors Th.A.W.M. Lanen and C. Nebbeling.

35. Experimental investigation of Tollmien-Schlichting instability and transition in similar boundary layer flow in an adverse pressure gradient. In: *Laminar-Turbulent Transition*, pp. 31-42. D. Arnal en R. Michel (eds). IUTAM Symposium, Toulouse, 1989. Springer Verlag, 1990. Co-authors F.J.M. Wubben and D.M. Passchier.

36. Research on laminar separation bubbles at Delft University of Technology, pp. 537-556. In: *Separated Flows and Jets.* V.V. Kozlov and A.V. Dovgal (eds). IUTAM, Novosibirsk, 1990. Springer Verlag, 1991.

37. An introduction to boundary layer flows for aeronautical engineering students. Report LR-656, Faculty of Aerospace Engineering, Delft, August 1991.

38. Bakker, P.G., R. Coene and J.L. van Ingen (eds); *Essays on Aerodynamics*, Delft University Press, Delft, 1992, 412 pp.

39. Falkner-Skan and Hartree revisited in the phase-plane. In: P.G. Bakker (ed); Essays on Aerodynamics. Delft University Press, Delft, 1992, pp. 153-173.

40. Bartels, J.J.C., P.N.J. Deken, J.L. van Ingen, H. Keus, and H.J. Raaymakers; Test of a transition detection chip sensor in the S-1 windtunnel at Modane. Sensor description and data acquisition. ELFIN Technical Report, TR 46, 1992.

41. Development of a transition detection chip sensor for use in industrial windtunnels and in flight. In: Contribution of TUD-LR to the European Laminar Flow Investigation ELFIN, task 2.1: Testing Techniques. Final Report, 1992. Delft, 1992.

42. Tummers, M.J., R.A.W.M. Henkes, D.M. Passchier and J.L. van Ingen; Turbulence models for incompressible wake flows and boundary layers. Poster at second progress meeting of the Brite-Euram project ETMA. December 8-12, 1993, Patras, Greece.

43. Aerospace Engineering Education in The Netherlands. AGARD Highlights, 93/1, 1993, pp. 18-22.

44. Mayer, R., R.A.W.M. Henkes and J.L. van Ingen; Wall-shear stress measurement with IR-thermography. In: Proceedings of Eurotherm Seminar 42, Quantitative Infrared Thermography. Eurotherm, Sorrento, 1994.

45. Hest, B.F.A. van, D.M. Passchier and J.L. van Ingen; The development of a turbulent spot in an adverse pressure gradient boundary layer. In: IUTAM Symposium *Laminar-Turbulent Transition*, Sendai, Japan, 1995, pp. 255-262.

46. Henkes, R.A.W.M., A.R. Starke and J.L. van Ingen; Computations with several turbulence models for boundary layers and wakes. Final Report WP1-T5D7 for the project Brite-Euram/2076/2032 of the EC, on Efficient Turbulence Models for Aeronautics (ETMA). 1995.

47. Ingen, J.L. van, R.A.W.M. Henkes and D.M. Passchier; Final executive report for the project Brite-Euram/2076/2032 of the EC, on Efficient Turbulence Models for Aeronautics (ETMA). 1995.

48. Henkes, R.A.W.M. and J.L. van Ingen (eds); Proceedings of the KNAW Colloquium on *Transitional Boundary Layers in Aeronautics* (Verhandelingen, Natuurkunde, 1e reeks, vol. 46). North Holland Publ., Amsterdam, 1996.

49. Ingen, J.L. van; Some introductory remarks on transition prediction methods based on linear stability theory. In: Proceedings of the KNAW Colloquium on *Transitional Boundary Layers in Aeronautics* (Verhandelingen, Natuurkunde, 1e reeks, vol. 46), R.A.W.M. Henkes and J.L. van Ingen (eds). North Holland Publ., Amsterdam, pp. 209- 224, 1996.

50. Ingen, J.L. van; Boundary layer research in relation to airfoil design at the Faculty of Aerospace engineering at Delft University of Technology. In: Proc. of the 2nd Int. Symp. on Aeronautical Science and Technology in Indonesia. Jakarta, June 24-27, pp. 546-564, 1996.

51. Mayer, R., R.A.W.M. Henkes and J.L. van Ingen; Wall shear stress measurement with IR-thermography. Abstract number D8 at Eurotherm Seminar 50, Quantitative Infrared Thermography, Stuttgart, 2-5 September 1996.

52. Looking back at 40 years of teaching and research in Ludwig Prandtl's heritage of boundary layer flows. 39th Ludwig Prandtl Memorial Lecture, Prague, 1996. Submitted for publication to ZAMM, 1997.

List of PhD graduates supervised by prof. dr ir J.L. van Ingen

1976 - B. van den Berg
Investigations of three-dimensional incompressible turbulent boundary layers.
Promotor: prof. dr ir J.L. van Ingen.

1977 - H. Tijdeman
Investigations of the transonic flow around oscillating airfoils.
Promotores: prof. ir H. Bergh and prof. dr ir J.L. van Ingen.

1989 - H.W.M. Hoeijmakers
Computational aerodynamics of ordered vortex flows.
Promotores: prof. dr ir J.L. van Ingen and prof. dr ir P. Wesseling.

1989 - B. van Oudheusden
Integrated silicon flow sensors.
Promotores: prof. dr ir S. Middelhoek and prof. dr ir J.L. van Ingen.

1995 - L.H.J. Absil
Analysis of the laser Doppler measurement technique for application in turbulent flows.
Promotor: prof. dr ir J.L. van Ingen.

1996 - B.F.A. van Hest
Laminar-turbulent transition in boundary layers with adverse pressure gradient.
Promotor: prof. dr ir J.L. van Ingen.

1996 - D. Sardjadi
Enhanced conformal mapping method for airfoil design and analysis.
Promotor: prof. dr ir J.L. van Ingen.

1996 - B. I. Soemarwoto
Muli-point aerodynamic design by optimization.
Promotores: prof. ir J.W. Slooff and prof. dr ir J.L. van Ingen.

List of students graduated under the supervision of prof. dr ir J.L. van Ingen

Absil, dr ir F.G.J. (1980)
Absil, dr ir L.H.J. (1987)
Adriaens, ir P.J.M. (1976)
Bartels, ir ing. J.C. (1991)
Bennis, ir F.W. (1992)
Bergeijk, ir A.B. van (1991)
Bleecke, ir H.M. (1987)
Boer, ir R.G. den (1981)
Boerema, ir T.M. (1983)
Bosschers, ir J. (1991)
Bosse, ir S. (1989)
Braam, ir A.L.H. (1980)
Broekhoven, ir M.J.W. (1991)
Brok, ir P.H.H. (1992)
Broos, ir S.J. (1974)
Bruining, ir A. (1980)
Budianta, ir W.A. (1991)
Cornelisse, ir E. (1989)
Dwicahyono, ir T. (1995)
Engelen, ir J.A.J. van (1976)
Eringfeld, ir J.A.L.M. (1985)
Es, ir A.J.J. van (1987)
Es, ir G.W.H. van (1994)
Flohr, ir E.E.L.A. (1987)
Fok, ir C.L. (1995)
Forster, ir H.M.P. (1983)
Garrel, ir A. van (1990)
Gelder, ir P.A. van (1977)
Geurts, ir E.G.M. (1985)
Gils, ir J.A.G. van (1986)
Gooden, ir J.H.M. (1976)
Groenen, ir H.F. (1995)
Groenewoud, ir G.J.H. van (1982)
Hack, ir R.K. (1976)
Hakkaart, ir J.F. (1992)
Hazebroek, ir J.C.M. (1979)
Hegen, ir G.H. (1981)
Heidsieck, ir R.D. (1981)
Hendriks, ir F. (1968)
Henkes, dr ir R.A.W.M. (1985)
Heyma, ir P.M. (1992)
Hommersom, ir G. (1980)
Houtman, ir E.M. (1985)
Jongejan, ir W.M.B. (1995)
Jongkind, ir C.B. (1988)
Kapel, ir J.M. (1972)
Kerstens, ir G.A.J. (1976)
Knoppe, ir J.A. (1971)
Koch, ir R. (1983)
Kolk, ir J.Th. van der (1972)
Kooi, ir J.W. (1971)
Kraan, ir D.T.G. (1995)
Kraay, ir R.E. (1972)
Kruisbrink, ir A.C.H. (1984)
Kunen, dr ir J.M.G. (1978)
Leeuw, ir A.M. de (1993)
Letsoin, ir S.J.M. (1988)
Leuven, ir C.H.M. van (1995)
Lindeman, ir K.J. (1974)
Looman, ir J.M. (1994)
Luijendijk, ir R.P. (1995)
Luken, ir E. (1985)

Maarel, dr ir H.T.M. van der (1988)
Maeyer, ir P.O.M. de (1989)
Manen, ir R. van (1987)
Maseland, ir J.E.J. (1990)
Meeder, ir J.P. (1993)
Meuleman, ir C.H.J. (1996)
Moller, ir J.A. (1984)
Naarding, ir S.H.J. (1987)
Nentjes, ir I.W.H. (1995)
Oort, ir H. van (1986)
Oostindie, ir J. (1982)
Ottochian, ir S.P. (1988)
Oudheusden, dr ir B.W. van (1985)
Pagen, ir M.J. (1988)
Philipsen, ir I. (1993)
Potma, ir C.S. (1993)
Ransbeeck, ir P.R.O. van (1989)
Rentema, ir D.W.E. (1994)
Rooij, ir L.P.A. van (1991)
Rooy, ir. R.P.J.O.M. van (1993)
Rozendal, ir D. (1970)
Ruhamaben, ir (1994)
Rustanto, ir J.B. (1988)
Rutten, ir P.B.A.W. (1995)
Schepers, ir J.G. (1986)
Schoonveld, ir E.R. (1982)
Seters, ir F.A. van (1976)
Smith, ir J. (1971)
Snoek, ir L. van der (1979)
Steenbergen, ir W. (1988)
Stoop, ir J.A.A.M. (1976)
Terleth, ir D.C. (1982)
Timmer, ir W.A. (184)
Tummers, ir M.J. (1992)
Vanderstuyft, ir J.L.M.I. (1990)
Veldhuis, ir L.L.M. (187)
Verel, ir E. (1994)
Verhelst, ir J.M. (1993)
Vermeulen, ir P.E.J. (1976)
Voerman, ir G.J. (1976)
Vogelaar, H.L.J. ir (1981)
Volkers, ir D.F. (1978)
Weijters, ir H.C.J.M. (1994)
Willemsen, ir E. ir (1975)
Winkelaar, ir D. (1987)
Wolthoorn, ir C. (1969)
Wubben, ir F.J.M. (1988)