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The influence of free and disturbed laminar-turbulent transition for the Wortmann FX 66-S-196 V1 and Eppler E 385 airfoils at low Reynolds numbers

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1. Introduction

The flow of the airfoil at low Reynolds numbers is usually better when the laminar boundary layer is constrainedly transformed to turbulent. Therefore, it is very important to investigate this disturbed turbulent stream. Nowadays such investigations can be made by using calculated codes or computations of modelling.

The analysis of the free and disturbed laminar-turbulent transition was performed with two airfoils and at low Reynolds numbers. The theoretical calculations were obtained using three codes – Eppler program systems PROFIL [1], XFOIL [2] and RFOIL [3]. The tests were taken from data published in Stuttgart University and in Delft University of Technology.

The earlier paper showed FX 66-S-196 V1 airfoil at low and medium Reynolds numbers [4].

Most authors also researched and compared similar airfoils according to calculated and experimental results. Moreover, there are a few studies done about the impact of the free and disturbed laminar-turbulent transition. However, they did not analyze the FX 66-S-196 V1 and E 385 airfoils at low Reynolds numbers.

2. The airfoils

For the calculations and analysis two different low drag airfoils were taken.

F.X. Wortmann designed the FX 66-S-196 V1 airfoil for sailplanes. This airfoil was tested by J.H.M Gooden [5], D.F. Volker's [6] and D. Althau's [7, 8] in different wind tunnels. The coordinates of the FX 66-S-196 V1 airfoil are published in [7], and its form is shown in Fig. 1. The horizontal axis is a chord of the airfoil which is equal one and the vertical axis is thickness of the airfoil.

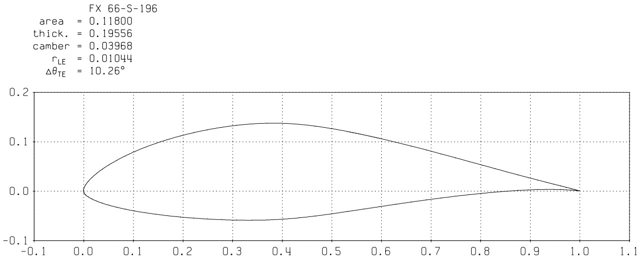

Fig. 1 The FX 66-S-196 V1 airfoil

R. Eppler designed the E 385 airfoil for the model of sailplanes. This airfoil was tested by D.F. Volker's [6] and D. Althau's [8] in different wind tunnels. The coordinates of the E 385 airfoil are published in [8], and its form is shown in Fig. 2.

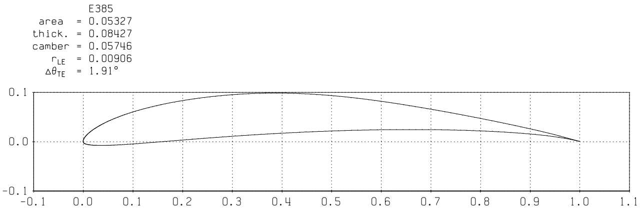

Fig. 2 The E 385 airfoil

3. The methods of calculations

All calculations were performed by using three codes: PROFIL, XFOIL and RFOIL. PROFIL is used in a noninteracted inviscid plus boundary layer method [1] and XFOIL and RFOIL codes are used in an interacted zonal viscous/inviscid method [9].

Richard Eppler program system PROFIL combines a conformal-mapping method for the design of airfoils with prescribed velocity distribution characteristics, a panel method for the analysis of the potential flow about given airfoils, and an integral boundary-layer method. An empirical criterion for laminar-to-turbulent boundary-layer transition was used in the earlier versions of the code [10]. Later Richard Eppler made major improvements into the code: a fast method for predicting transition by means of the e^n method for individual frequencies and additional drag due to transitional separation bubble. The version of R. Eppler, used in this work, consists of all new features [11]. Influence of separation is estimated using empirical correction.

The XFOIL code of Mark Drela uses linear-vorticity stream function formulation, which is designed specifically for compatibility with an inverse mode, and for natural incorporation of viscous displacement effects. Source distributions superimposed on the airfoil and on wake permit modeling of viscous layer influence on the potential flow. The wall transpiration model in this code approximates the displacement effect on the outer inviscid flow. A two equation lagged dissipation integral method is used to represent the viscous layers. Laminar-turbulent transition is predicted using en envelope method. In the latest versions it is possible to compare the results from the envelope method and individual frequencies [2]. The boundary layer equations are solved simultaneously with the inviscid flow field by a global Newton method. The procedure is suitable for analysis of low Reynolds number airfoil flows with transitional separation bubbles.

The RFOIL code is a modification of XFOIL code basic version 5.4 applied for calculation of the effect of rotation on airfoil performance of wind turbines [3]. Considering the maximum lift in particular, numerical stability improvements were obtained by using the Schlichting velocity profiles for the turbulent boundary layer, instead of Swafford's. Additionally, the shear lag coefficient in Green's lag entrainment equation of the turbulent boundary layer model was adjusted and deviation from the equilibrium flow has been coupled to the shape factor of the boundary layer [3].

4. The measured data

Measurements data of both airfoils are taken from published tests in low-speed and low-turbulence laminar wind tunnels. The tests were performed by J. H. M Gooden [5] and D. F. Volker's [6] in Delft University of Technology and by D. Althau's [7] in Stuttgart University.

However, only D. F. Volker's tested these aifoils with trip wire [6]. The FX 66-S196 V1 airfoil was used as a testcase for examining the optimal position of diameter of trip wire, in order to prevent bursting of the laminar separation bubble. The optimal position of the wire, obtained by translating the wire in front of the model, is in the chord of the plane and 0.10*c* from the airfoil model's leading edge.

The trip wire of the E 385 airfoil was 0.043*c* above the chord of the plane and 0.10*c* from airfoil model's leading edge.

5. The wind tunnels

The Institute of Aerodynamics and Gasdynamics at Stuttgart University have an open-return wind tunnel (Eiffel type) with closed test section [8]. The wind tunnel of the Department of Aerospace Engineering at Delft University of Technology is of a closed return type [6].

Turbulence levels in these low-speed wind tunnels are very low. In these wind tunnels the airfoil drag measurement method is very similar. In the Delft wind tunnel section profile-drag coefficients were obtained from the wake-rake pressures using the method of Squire-Young. In the Stuttgart wind tunnel the drag is determined by the pressure distribution in the wake of the airfoil model. The mean value is experimentally determined by an integrating wake rake. The wake rake is moved in spanwise direction and the airfoil drag is averaged over this section. However, the lift coefficient is obtained using different methods. In the Delft wind tunnel the static pressure measurements on the airfoil surface were reduced to standard pressure coefficients and then integrated to get section lift and pitching-moment coefficient. In the Stuttgart wind tunnel the lift measurement is done by a load cell. The pitching moment is measured by strain gages on a torsion pipe.

6. Results and discussion

Fig. 3 depicts the comparison of calculated and measured data of the FX66-S-196VI airfoil at $Re = 0.5 \cdot 10^6$. The left hand side graph shows the polar of airfoil, where the vertical axis is a lift coefficient C_L and the horizontal axis is a drag coefficient C_D. The middle graph shows two dependences. The lift coefficient C_L and the moment coefficient C_M depend on the angle of attack. In the right hand side graph the location of laminar-turbulent transition which depends on the lift coefficient C_L is shown. However, the laminar-turbulent transition is not discussed in this paper.

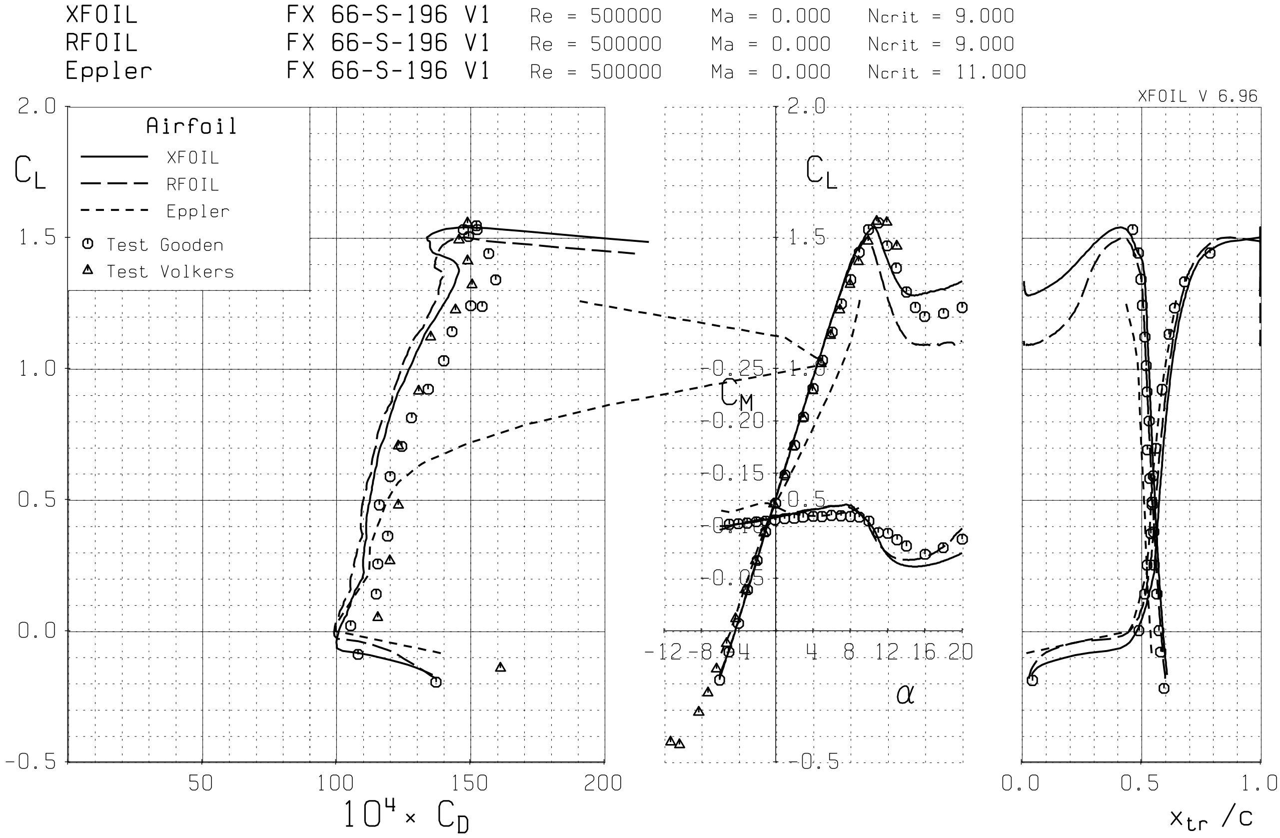

Fig. 3 Comparison of calculated and measured data of FX 66-S-196 V1 airfoil at $Re = 0.5 \times 10^6$ and free transition

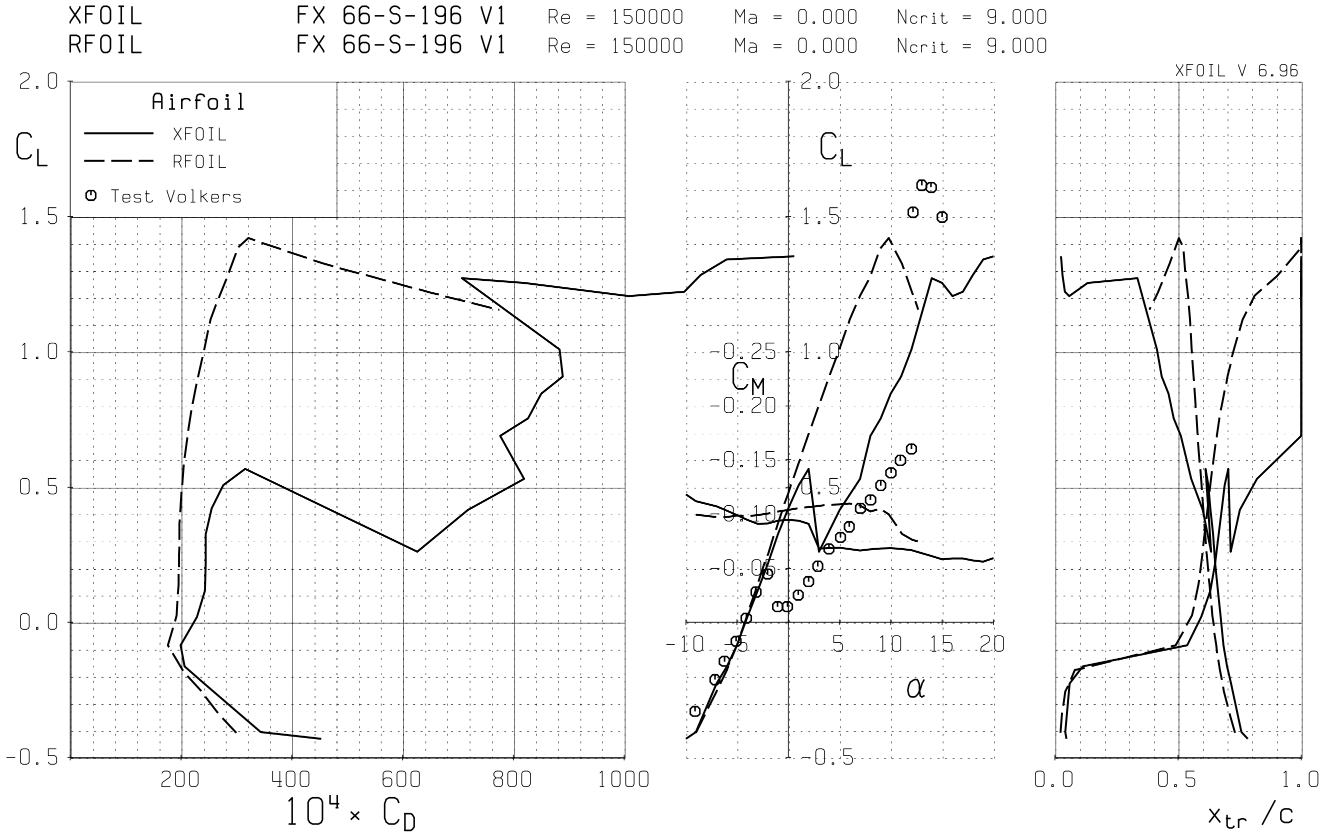

Fig. 4 Comparison of calculated and measured data of FX 66-S-196 V1 airfoil at *Re* = 0.15 × 10^6 and free transition

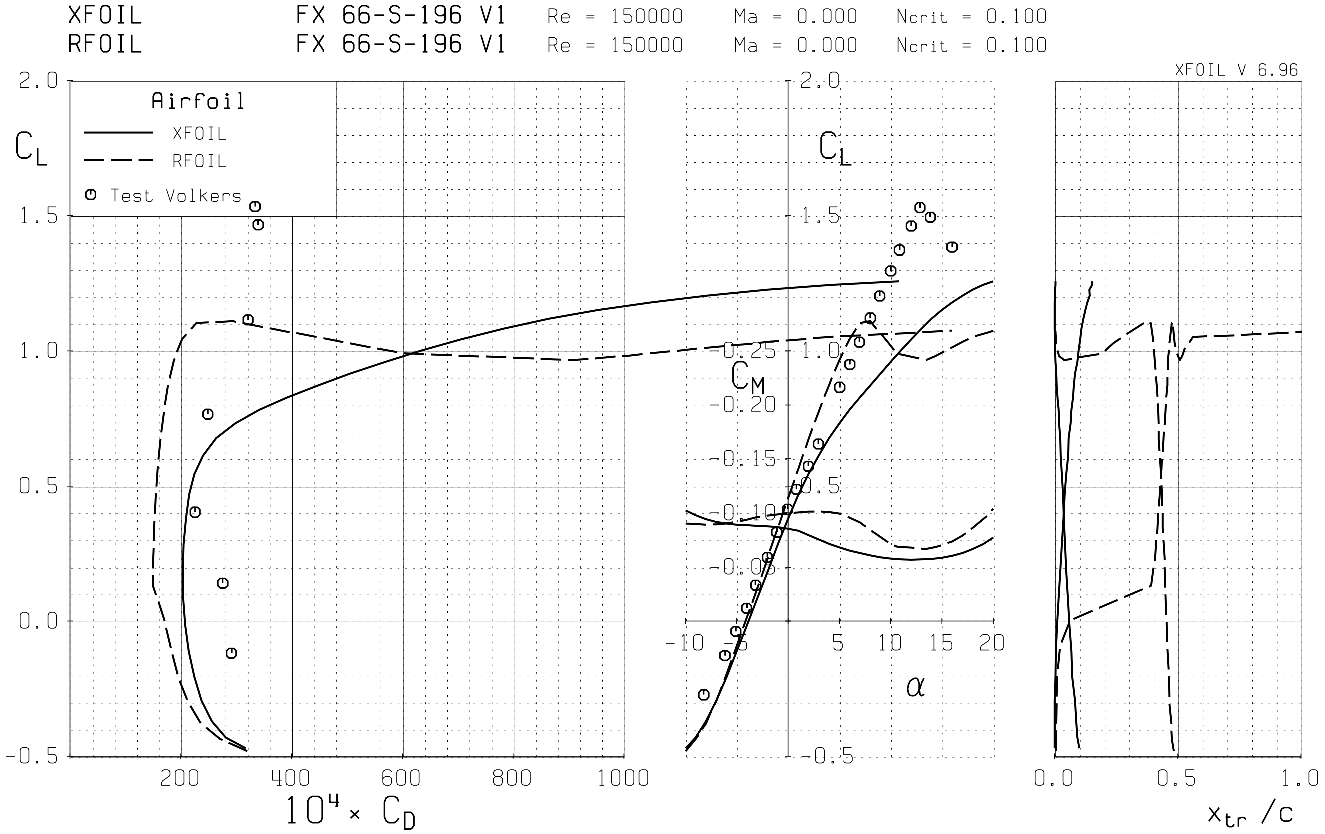

Fig. 5 Comparison of calculated and measured data of FX 66-S-196 V1 airfoil at *Re* = 0.15 × 10^6 and disturbed transition

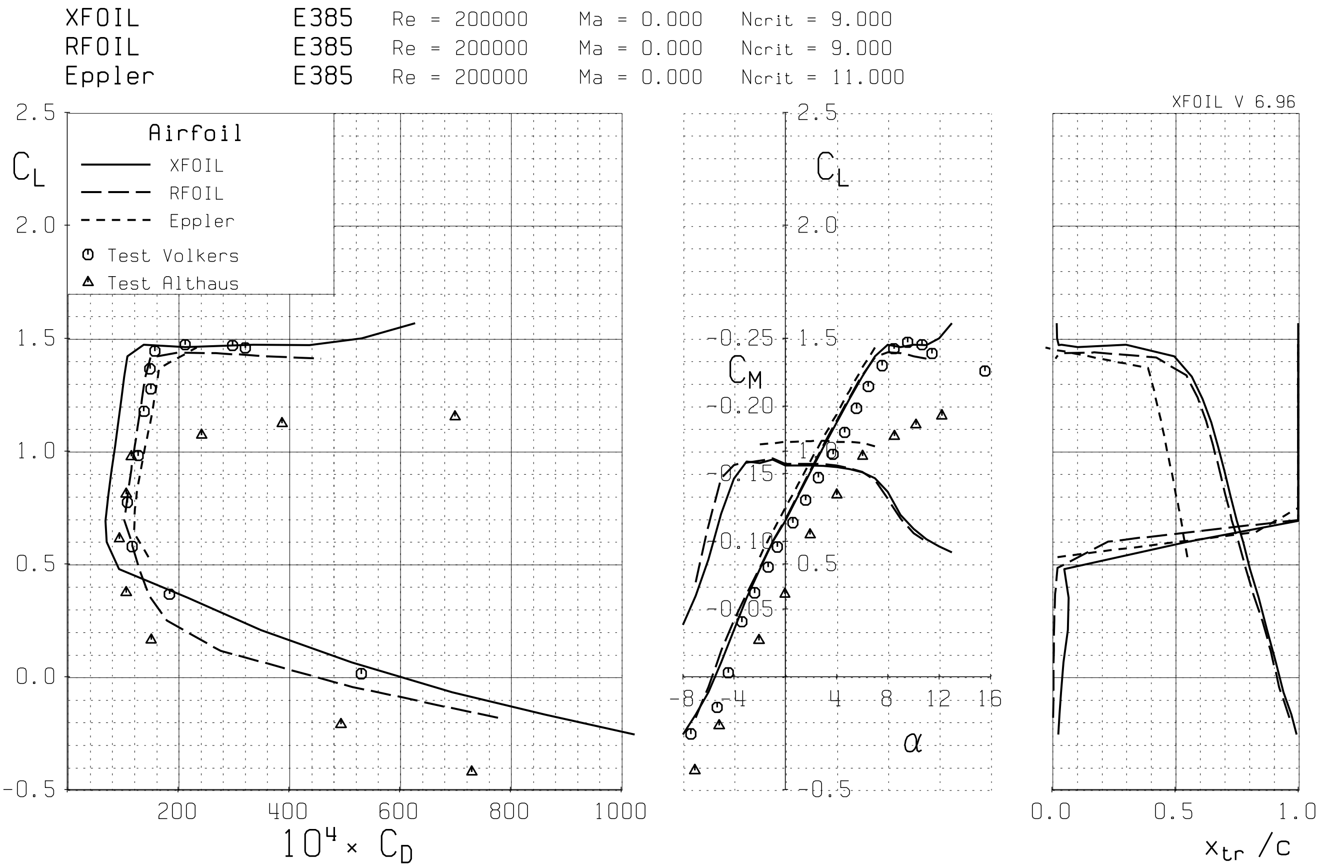

Fig. 6 Comparison of calculated and measured data of E 385 airfoil at *Re* = 0.2 × 10^6 and free transition

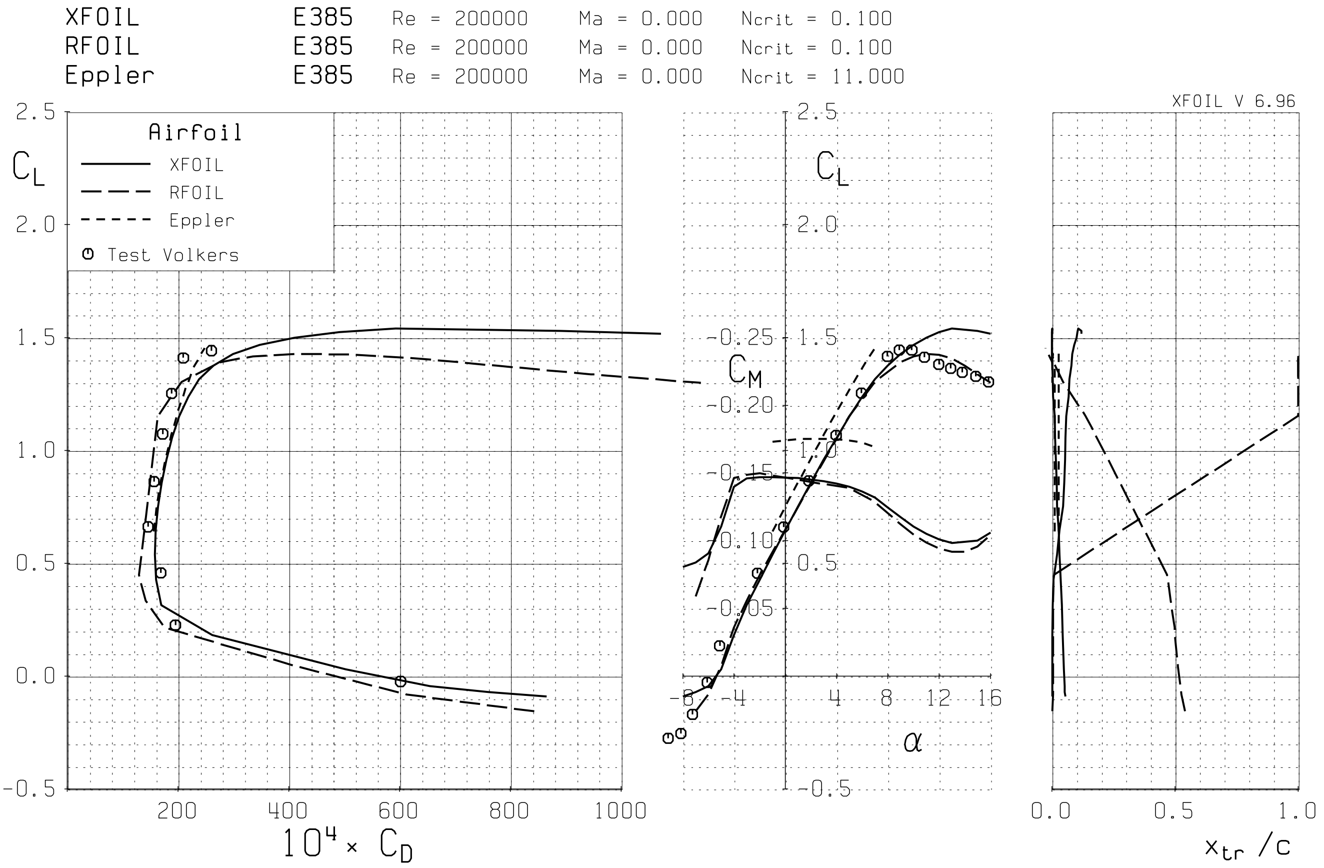

Fig. 7 Comparison of calculated and measured data of E 385 airfoil at *Re* = 0.2 × 10^6 and disturbed transition

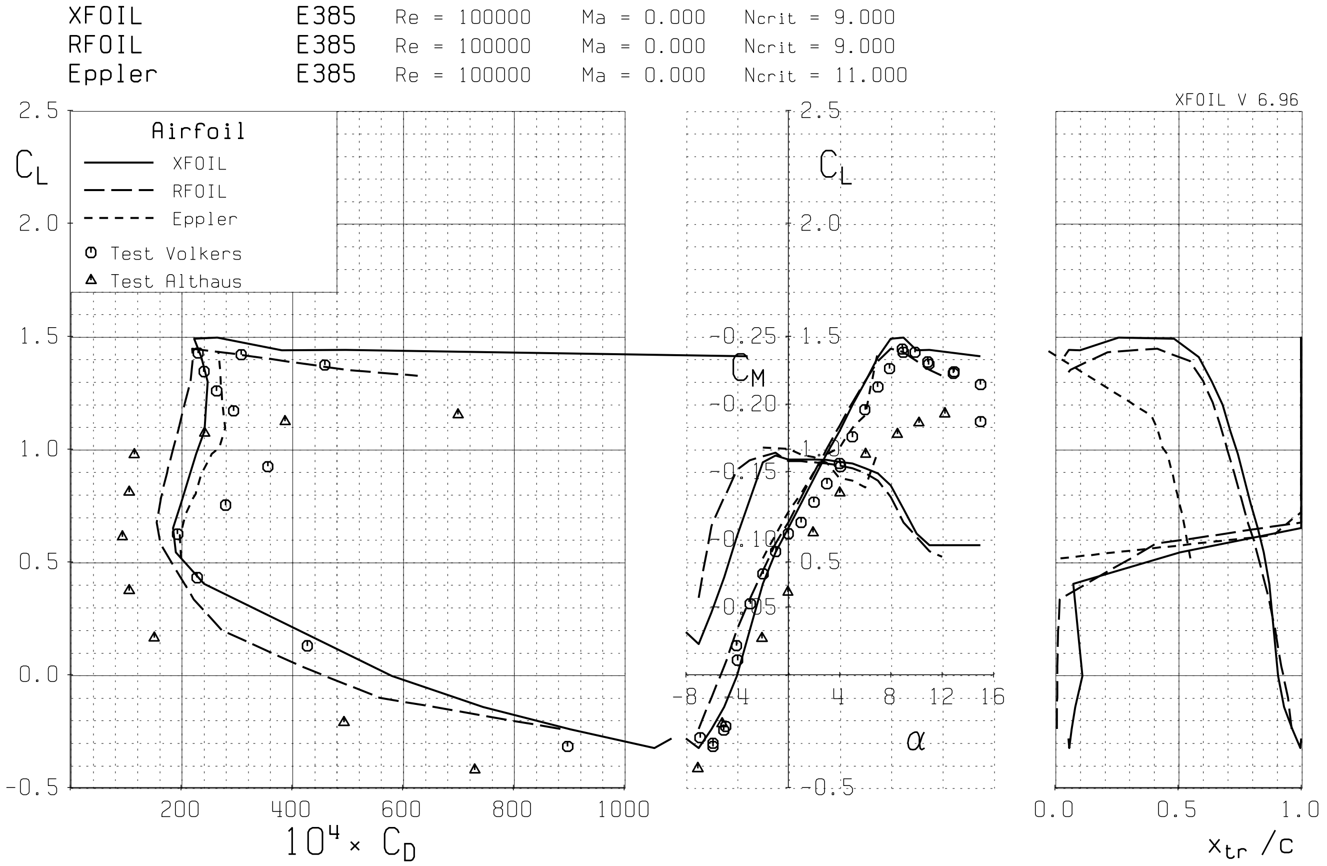

Fig. 8 Comparison of calculated and measured data of E 385 airfoil at *Re* = 0.1 × 10^6 and free transition

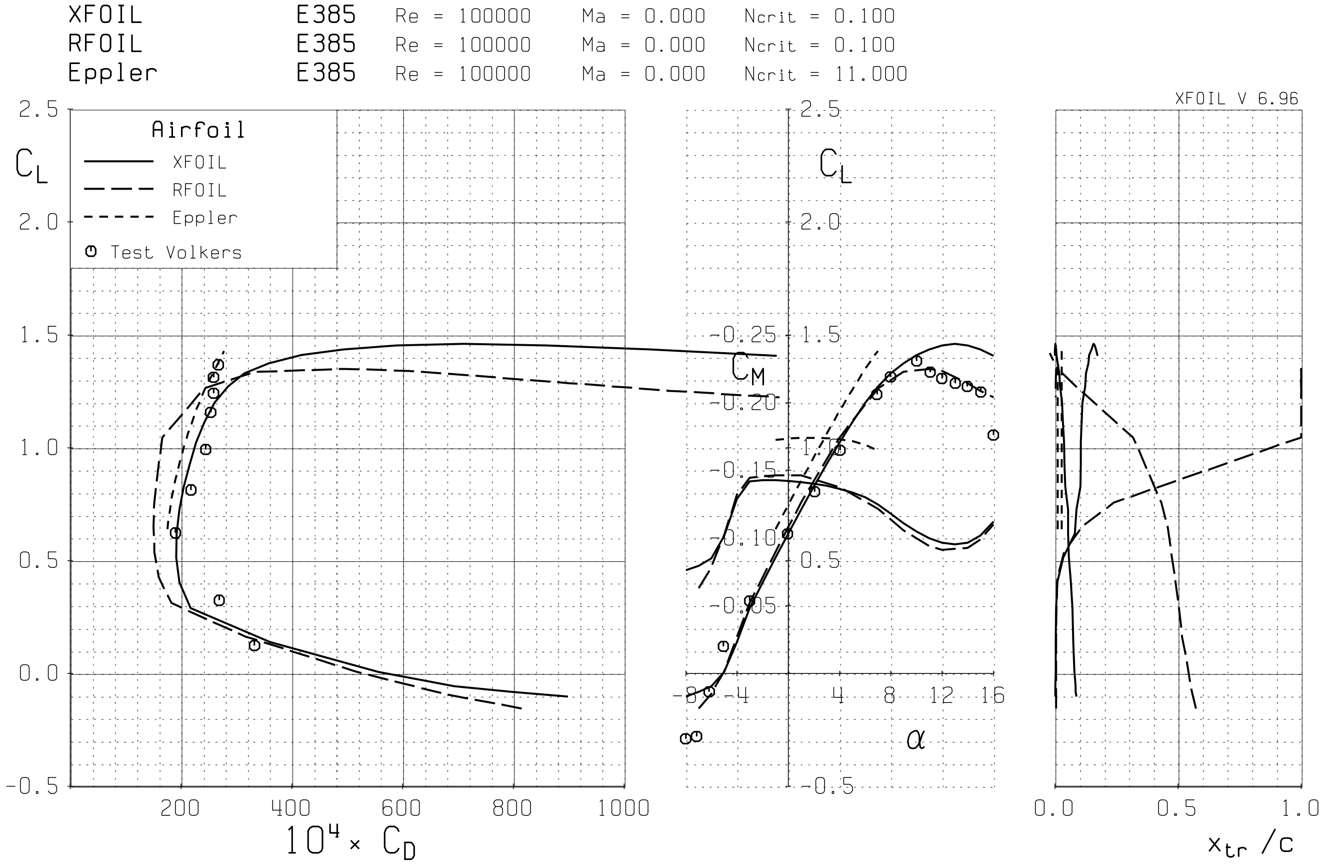

Fig. 9 Comparison of calculated and measured data of E 385 airfoil at *Re* = 0.1 × 10^6 and disturbed transition

Firstly, it can be seen that both calculated and measured polars are of similar form, except for R. Eppler's code results. The value N_{crit} in Eppler's code has a different meaning; namely it corresponds to the most amplified individual frequency of disturbance [10, 11]. In XFOIL and RFOIL codes N_{crit} is the value of approximated envelope. The R. Eppler's code and its results of the FX 66-S-196 V1 airfoil are discussed in [4]. In this paper [4] at $Re = 1.0 \times 10^6 - 3.0 \times 10^6$ PROFIL code is calculated very accurately, especially at a minimal drag coefficient.

The minimum drag coefficient calculated with RFOIL code is approximately 1.5% less than calculated with XFOIL code, but the calculated minimum drag coefficient is much less than measurement data by approximately 5.6%. The Volker's test comparison with the Gooden test measurements shows only small differences at $Re = 0.5 \times 10^6$. In low drag region XFOIL code conformed more accurately with the test by Godden than other calculation codes. The drag coefficient tested by Volker's is a little higher in this area.

At zero lift XFOIL matches better with Godden test and RFOIL code matches with Volker's test. Nevertheless, the difference is not very big, because at zero angle of attack all calculated and experimental results match very well. The lift curves show that measured maximum lift is in a good agreement. The calculated lift curves are different – XFOIL code shows about 2.5% higher lift than RFOIL code, but the measurement data is still higher by approximately 1.1% than the calculated results. The difference of the maximum lift may be caused by different computations of the turbulent boundary layer. Eppler's program system does not model the influence of boundary layer on potential flow and cannot predict the maximum lift. In post stall region XFOIL code better predicts a lift curve until the angle of attack is 14º, but later XFOIL code overpredicts and RFOIL code underpredicts the tests.

Figs. 4 and 5 depict the FX 66-S-196 V1 airfoil at $Re = 0.15 \times 10^6$. Fig. 4 is with free laminar-turbulent transition and Fig. 5 is with disturbed laminar-turbulent transition, when $N_{crit} = 0.100$. This value of N_{crit} roughly models the turbulence of free stream, which is experimentally obtained by a trip wire. The Volker's tests were made by using a trip wire ($d = 0.1$ mm) [6].

Also the calculations were performed at $Re = 0.1 \times 10^6$, but in this paper the graphs are not presented.

At both Reynolds numbers and free laminar-turbulent transition the polars obtained by XFOIL code are very uneven and do not match with RFOIL code results. The Volker's test with a trip wire at $Re = 0.15 \times 10^6$ shows that the drag coefficients are higher than results of both calculated codes.

At both Reynolds numbers the lift curves obtained by XFOIL and RFOIL codes do not conform to the results of the tests. At negative angles of attack some results match, but later calculated results do not match to the experimental tests. In all cases Volker's tests show much higher maximum lift, except for, in free laminar-turbulent transition at $Re = 0.1 \times 10^6$. In this case experimental results are smaller by approximately 0.4 C_L than RFOIL code and by approximately 0.5 C_L than XFOIL code. XFOIL and RFOIL codes show a significat difference from the experimental data. Maybe the codes are not wrong there, but the FX 66-S-196 V1 airfoil does not work at low Reynolds numbers.

To prove this assumption another low drag airfoil was chosen.

Figs. 6-9 show the comparison of calculated and measured data of the E 385 airfoil with free and disturbed laminar-turbulent transition at two Reynolds numbers – $Re = 0.2 \times 10^6$ and $Re = 0.1 \times 10^6$. The tests with free laminar-turbulent transition were made by Volker's [6] and Althau's [8] in different wind tunnels.

At $Re = 0.2 \times 10^6$ the polar calculated with RFOIL code at a low drag region matches with the test by Volker's. The drag obtained by XFOIL code in free laminar-turbulent transition is less by approximately 36% than RFOIL code result and experimental data and even approximately 52% less than that of Eppler program system PROFIL. But in disturbed laminar-turbulent transition XFOIL code drag is approximately 20% bigger than that of RFOIL code and Eppler program system.

At $Re = 0.1 \times 10^6$ in free laminar-turbulent transition calculated polars are nearly in the middle between both tests' results. In the low drag region XFOIL code matches the Volker's test. The Althau's test shows much smaller results of drag and does not conform to any calculation code. Later the drag coefficient after a maximum lift is predicted by RFOIL code very accurately. In disturbed laminar-turbulent transition XFOIL code result matches the tests by Volker's and is about 4.3% bigger than that of Eppler program system and about 26.5% bigger than of RFOIL.

The lift curves obtained by XFOIL and RFOIL codes match with the test made by Volker's at $Re = 0.2 \times 10^6$ and $Re = 0.1 \times 10^6$. It is seen that the calculated and experimental lift curves at zero lift and zero angle of attack conform perfectly. Except for the calculated results in the free laminar-turbulent transition at $Re = 0.2 \times 10^6$ they are just slightly bigger by approximately 7%. The Eppler program system results in free laminar-turbulent transition are near both calculations codes, but in disturbed laminar-turbulent transition are approximately 10% bigger.

The RFOIL code calculated maximum lift and lift curve form even in post stall region conform very well. The XFOIL code shows that the maximum lift is higher in the free laminar-turbulent transition by approximately 2.4% and in disturbed laminar-turbulent transition by approximately 7.6% than that of RFOIL code. On the other hand, the experimental lift curve in free laminar-turbulent transition obtained by Althau's is far less by approximately 21.6%. This difference of lift may be caused by different measurement methods.

Also the calculations were performed at $Re = 0.06 \times 10^6$, but in this paper the graphs are not presented. At $Re = 0.06 \times 10^6$ in free and disturbed laminar-turbulent transition the calculated polars are similar and drag coefficients are smaller than the Volker's tests.

At this Reynolds number in free laminar-turbulent transition a lift curve obtained by experimental methods is between RFOIL and XFOIL codes till zero angle of attack. Then experimental lift curves are much lower than calculated curves. The maximum lift is different for all methods. In the disturbed laminar-turbulent transition test done by Volker's it matches with both calculated codes until the maximum lift. There experimental maximum lift is approximately 10% higher than calculation methods and in post stall region does not match with codes.

7. Conclusions

The FX 66-S-196 V1 airfoil is not suitable for sailplanes when Reynolds number is smaller than $Re = 0.5 \times 10^6$. At $Re = 0.5 \times 10^6$ its experimental and calculated results conform very well, but at decreasing Reynolds numbers all aerodynamic performances become unstable. This is proved by all calculated codes, which were compared with experimental tests.

XFOIL and RFOIL codes can calculate all aerodynamic performances of airfoils at low Reynolds numbers. In cases when calculated curves are uneven the zone of separated stream is big.

This is proved by the E 385 airfoil. At decreasing Reynolds number from $Re = 0.2 \times 10^6$ all calculated results match with experimental data, which were obtained in different wind tunnels. RFOIL code predicts the lift curve very well even in the post stall region.

The disturbance of boundary layer roughly modeling turbulence of stream is caused by trip wire.

Acknowledgment

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LAISVO IR PRIVERSTINIO LAMINARINIO TURBULENTINIO VIRSMO ĮTAKA WORTMANN'O FX 66-S-196 V1 IR EPLERIO E 385 SPARNO PROFILIŲ AERODINAMINĖMS CHARAKTERISTIKOMS ESANT MAŽIEMS REINOLDSO SKAIČIAMS

Reziumė

Šiuo darbu norėta palyginti teoriškai apskaičiuotas profilio charakteristikas su publikuotais eksperimentiniais duomenimis. Išnagrinėta laisvo ir sutrikdyto laminarinio turbulentinio srauto įtaka.

Trimis skaitinio modeliavimo programomis – Epplerio programine sistema PROFIL, XFOIL ir RFOIL – išanalizuota pasienio sluoksnio priverstinio virsmo įtaka Wortmanno FX 66-S-196 V1 ir Eplerio E 385 sparno profilių aerodinaminėms charakteristikoms esant mažiems Reinoldso skaičiams.

Gauti teoriniai rezultatai išanalizuoti ir palyginti su publikuotais eksperimentiniais duomenimis, gautais Delfto technologijos universiteto ir Štutgarto universiteto mažo greičio ir mažos turbulencijos aerodinaminiuose vamzdžiuose.

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THE INFLUENCE OF FREE AND DISTURBED LAMINAR-TURBULENT TRANSITION FOR THE WORTMANN FX 66-S-196 V1 AND EPPLER E 385 AIRFOILS AT LOW REYNOLDS NUMBERS

Summary

This work was carried out to compare theoretically calculated airfoil characteristics with the published measurements data. Furthermore, in this work the influence of free and disturbed laminar-turbulent transitions was analysed.

The calculation of the Wortmann FX 66-S-196 V1 and Eppler E 385 airfoils was made using three codes: Eppler program system PROFIL, XFOIL and RFOIL. The influence of boundary layer disturbed transition on airfoil was analyzed at low Reynolds numbers.

The calculated data were compared with published measurement data. The measurement data were obtained in low-speed, low turbulence wind tunnels of the Department of Aerospace Engineering at the Delft University of Technology and Institute of Aerodynamics and Gasdynamics at Stuttgart University.

Keywords: airfoil, transition, boundary layer.

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