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ANALYSIS OF THREE WING SECTIONS

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Abstract. Three wing sections FX66-S-196VI, E603 and AH82-150A were analyzed. Measured data of these wing sections are published. First wing section was measured in Stuttgart University and in Delft University of Technology, when other two wing sections were measured in Stuttgart University. These wing sections have different behavior in the region of maximum lift. FX66-S-196VI wing section has sharp drop in lift. The stall of the second and third wing sections is smooth, though different. All wing sections are affected by laminar separation bubbles. The calculations were performed using three codes: Eppler Program System, XFOIL and RFOIL. Eppler's code uses non-interacted inviscid plus boundary layer method. Influence of separation is estimated using empirical correction in this method. XFOIL code of Mark Drela, MIT uses interacted zonal viscous/inviscid method. The wall transpiration model in this code approximates the displacement effect on the outer inviscid flow. RFOIL is a modification of XFOIL code for application in wind turbines performed at Delft University of Technology. The code's prediction of the airfoil performance around the two dimensional maximum lift was enhanced. The comparison of calculated and measured data is presented and analyzed.

Keywords: wing section, calculation, comparison with experiment.

1. Introduction

Although the progress in Navier-Stokes methods for aerodynamic analysis and design is very significant during the last decades, the zonal viscous-inviscid methods are still used in research and engineering problems for two-dimensional wing sections.

Richard Eppler developed at Stuttgart University his

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code PROFIL for the design and analysis of airfoils and published it in the NASA report (Eppler *et al.* 1980). Later Mark Drela developed at Massachusetts Institute of Technology the code XFOIL for analysis and design of low Reynolds number airfoils (Drela 1989). These codes are used for analysis and design of low speed airfoils. There are a few modifications of these codes of other authors. For example, R. van Rooij modified XFOIL code for better stall prediction of airfoils (Timmer *et al.* 2003).

This work was carried out to compare calculated airfoils characteristics, obtained using mentioned codes, with published measurements data of some airfoils. Three wing sections FX66-S-196VI, E603 and AH82-150A were analyzed. The first wing section was measured in Stuttgart University and in Delft University of Technology, while other two were measured in Stuttgart University. The prediction of data for wing section at stall is necessary for calculation of wing characteristics at high angles of attack (Pakalnis *et al.* 2005).

2. Calculations methods

The calculations were performed using three codes: PROFIL05, XFOIL and RFOIL.

Eppler's Program System PROFIL is a non-interacted inviscid plus boundary layer method (Eppler *et al.* 1980, Eppler 1990). It 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 (Eppler 1990). 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, consist all new features (Eppler 2005). Influence of separation is estimated using empirical correction. This code has been successfully applied at Reynolds numbers from $3 \cdot 10^4$ to $5 \cdot 10^7$.

XFOIL code of M. Drela is an interacted zonal viscous/inviscid method (Drela 1989). The code uses linear-vorticity stream function formulation, which is designed specifically for compatibility with an inverse mode, and for a 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 e^n envelope method. In the latest versions it is possible to compare the results from envelope method and individual frequencies (Drela 2001). 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.

RFOIL is a modification of XFOIL code for application in wind turbines performed at Delft University of Technology (Timmer *et al.* 2003). The code's prediction of the airfoil performance around the two dimensional maximum lift was enhanced.

3. Airfoils

Three wing sections FX66-S-196VI, E603 and AH82-150A were analyzed. The form of these wing sections is shown in figures 1 to 3.

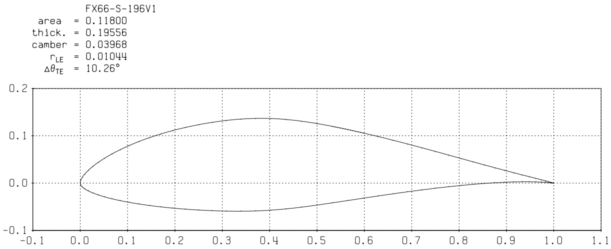

Fig 1. Airfoil FX66-S-196VI

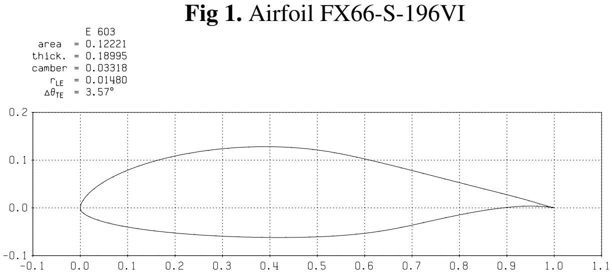

Fig 2. Airfoil E603

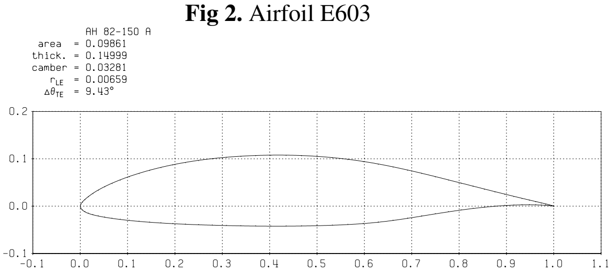

Fig 3. Airfoil AH82-150A

All these airfoils are low drag airfoils. These wing sections have different behavior in the region of maximum lift. FX66-S-196VI wing section has sharp drop in lift. The stall of the second and third wing sections is smooth, though different. All three wing sections are affected by laminar separation bubbles.

F.X. Wortmann designed airfoil FX66-S-196VI for application in sailplanes. The coordinates and measurements data are publishes in (Althaus 1972) and (Gooden 1979).

R. Eppler designed airfoil E603 for sailplane Astir. The coordinates and measurement data are published in (Eppler 2005) and (Althaus 1996).

The coordinates and measurement data of airfoil AH88-150A, designed of D. Althaus, are published in (Althaus 1996).

4. Measured data

Measurements data are taken from tests in laminar wind tunnels at Stuttgart University (Althaus 1972, Althaus 1996) and Delft University of Technology (Gooden 1979). Turbulence levels in these wind tunnels are very low: about 0.04 %. The airfoil drag measurement method is very similar in these wind tunnels; namely, Section profile-drag coefficients were obtained from the wake-rake pressures using the method of Squire-Young.

Lift coefficient and pitching-moment coefficient are obtained using different methods. In Delft 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 Stuttgart the lift is determined via integration of the pressure distributions along the opposite two tunnel walls. The equally spaced bores are connected via identical tubes to common reservoirs which yield the average pressure along the opposite tunnel walls. The difference between both average pressures is proportional to the lift. The pitching moment is determined via the mechanical torsion about the quarter chord pivot point.

5. Results and discussion

5.1. Airfoil FX66-S-196VI

Figure 4 depicts the comparison of calculated and measured data of the airfoil FX66-S-196VI at $Re = 1{\cdot}10^6$. The value N_{crit} in Eppler's code has different meaning; namely it corresponds to most amplificated individual frequency of disturbance. In XFOIL and RFOIL codes N_{crit} is a value of approximated envelope. The polar curves show, that Eppler's code predicts the drag better for this airfoil and Reynolds number. All three codes predict the region of low drag. The lift curves show that measured maximum lift is different. The difference of maximum lift may be caused by different measurement methods. The RFOIL code better predicts the lift curve in the post stall region. Both XFOIL and RFOIL codes predict the pitching moment curve including post stall regime similar to the test in Delft. Eppler's code PROFIL does not model the influence of boundary layer on potential flow and can not predict maximum lift.

Figures 5 and 6 shows the comparison of calculated and measured data of the airfoil FX66-S-196VI at $Re = 1.5{\cdot}10^6$ and $Re = 1.5{\cdot}10^6$.

The comparison of calculated and meassured data in figure 5 and 6 is very similar to that of figure 4. The main difference is measured at the moment curve in Stuttgart at Re = $1.5{\cdot}10^6$ in the post stall region. Most likely the measurement of the moment coefficient from pressure distribution in Delft is more precise compared with mechanical torsion, obtained in Stuttgart.

5.2. Airfoil E603

Figure 7 depicts the comparison of calculated and measured data of the airfoil E603 at $Re = 1{\cdot}10^6$. All three codes underpredict the drag, but curve form and region of low drag is modeled well. The RFOIL code better predicts the maximum lift but overpredicts the lift in the post stall region.

The drag comparison in figure 8 at Re = $3{\cdot}10^6$ is similar to figure 5. The code RFOIL predicts very well the maximum lift and lift curve form even in poststall region.

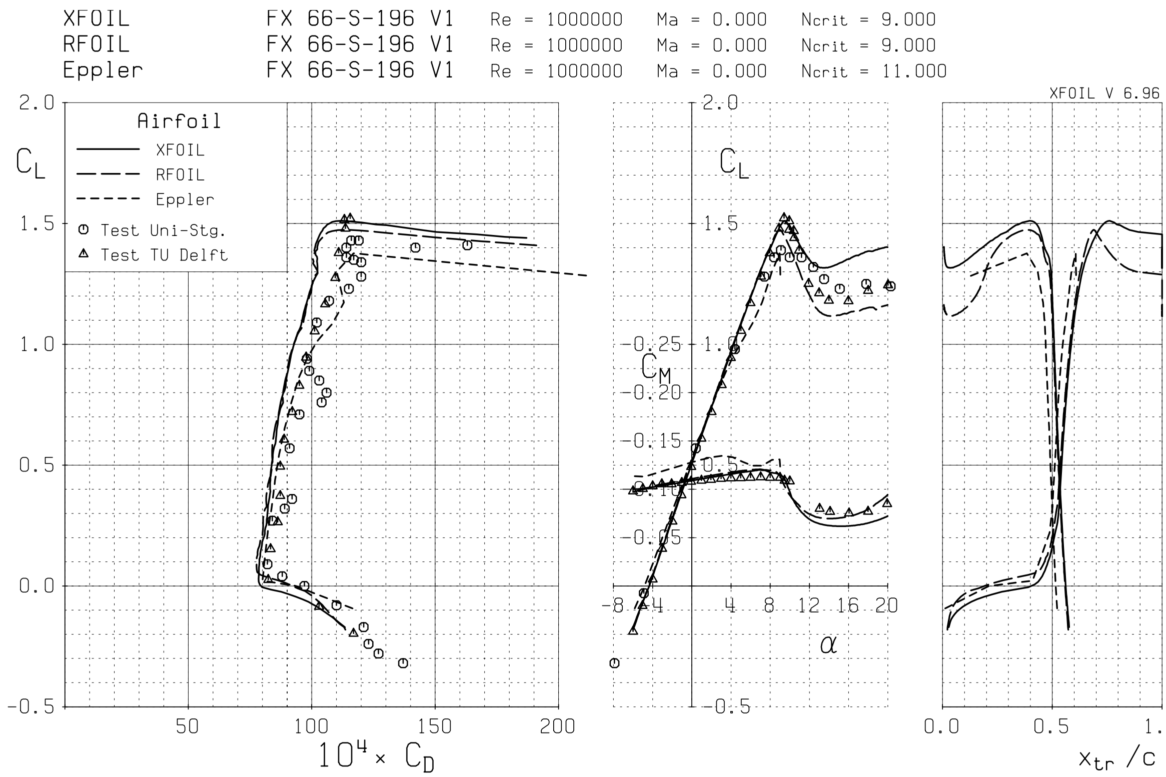

Fig 4. Comparison of calculated and measured data of FX 66-S-196VI airfoil at $Re = 1{\cdot}10^6$

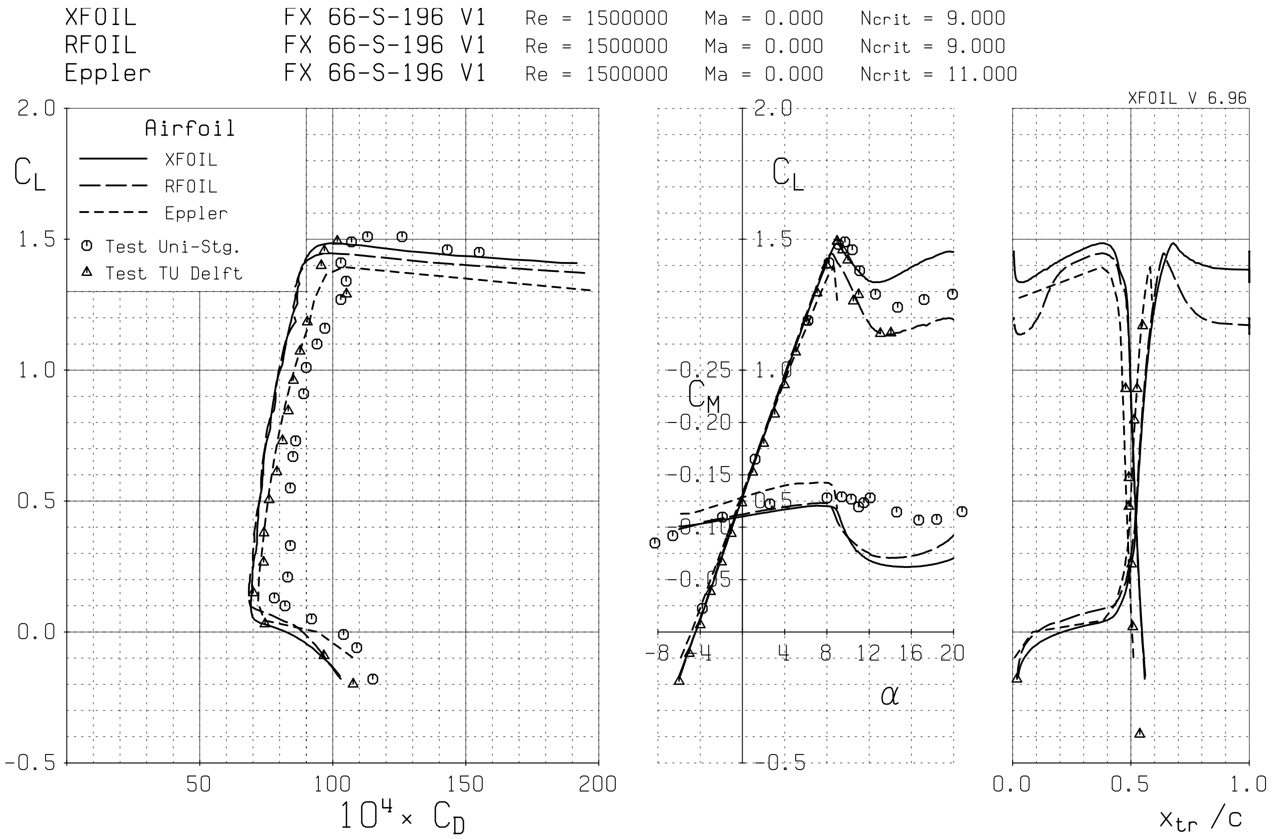

Fig 5. Comparison of calculated and measured data of FX 66-S-196VI airfoil at $Re = 1.5 \cdot 10^6$

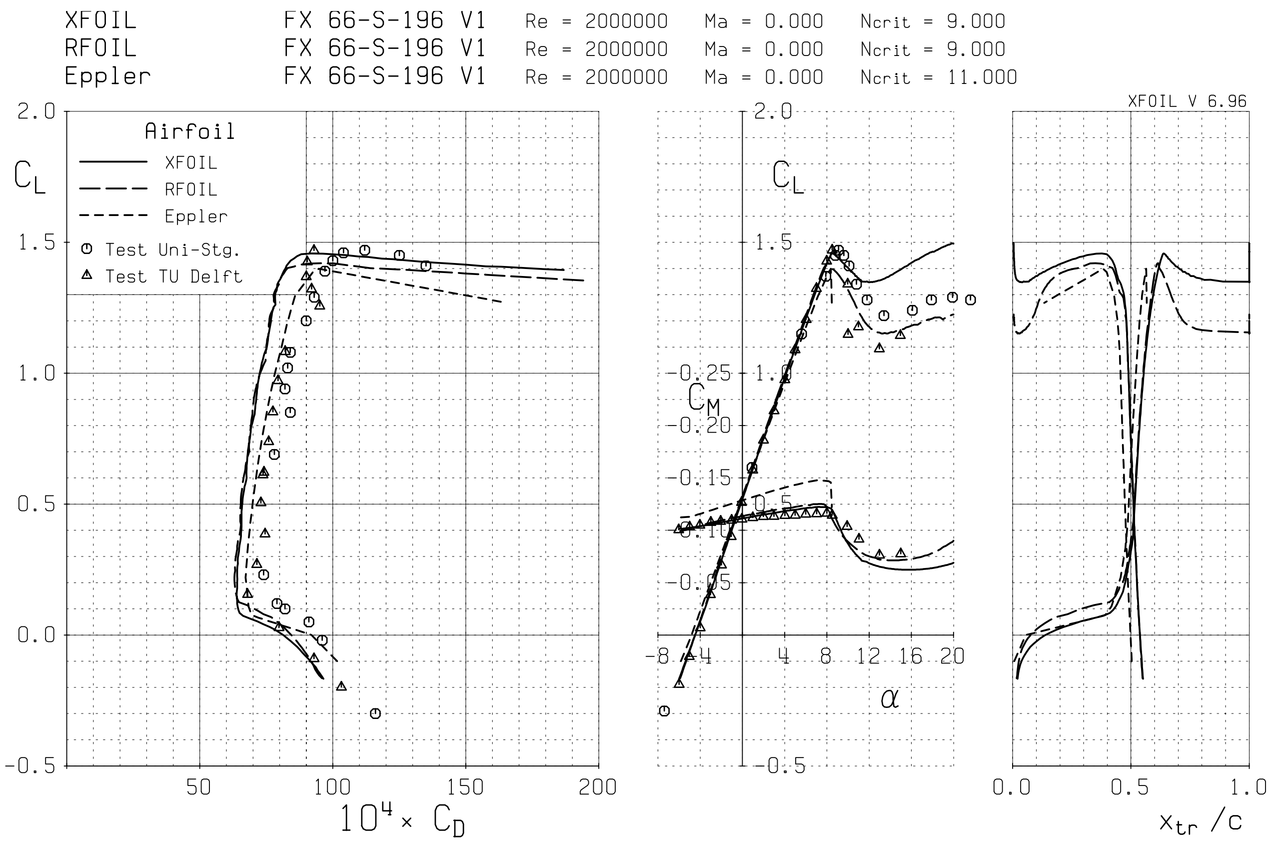

Fig 6. Comparison of calculated and measured data of FX 66-S-196VI airfoil at $Re = 2 \cdot 10^6$

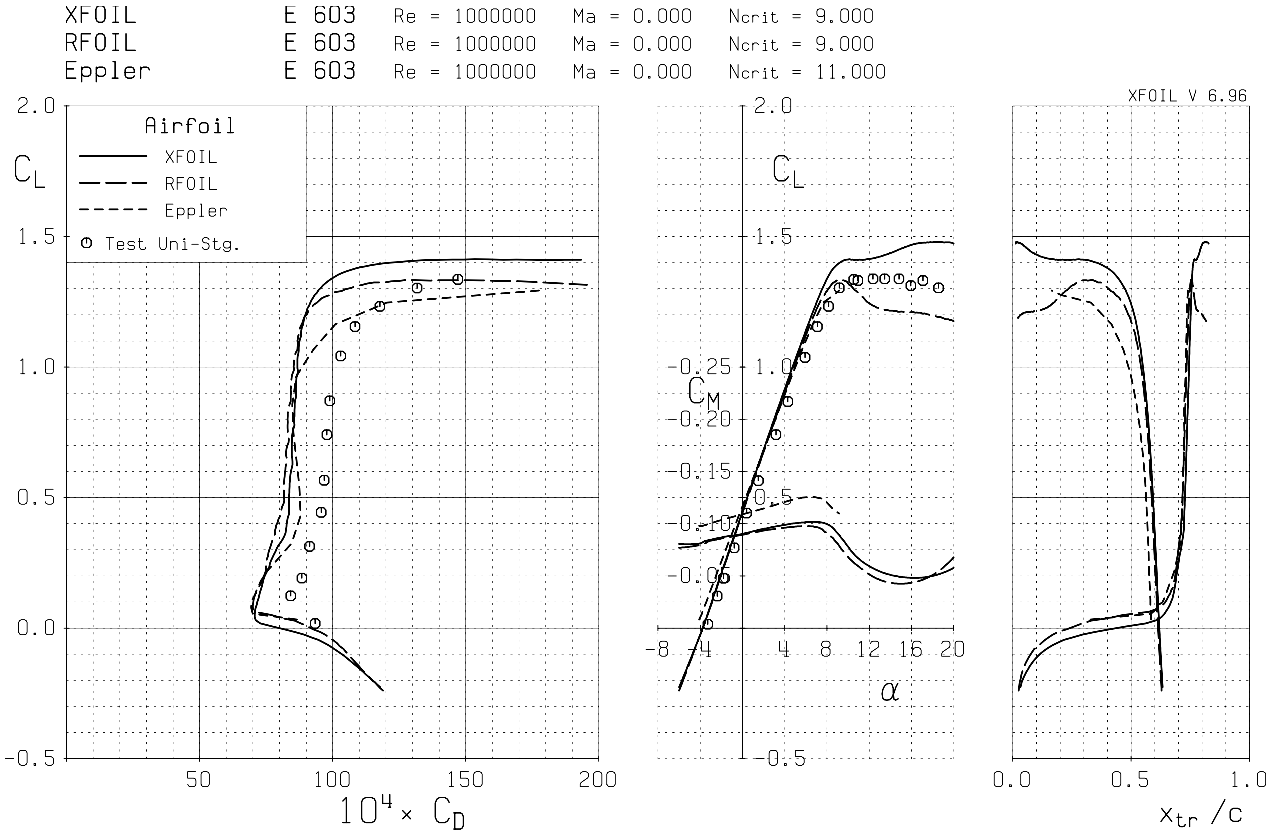

Fig 7. Comparison of calculated and measured data of E603 airfoil at $Re = 1{\cdot}10^6$

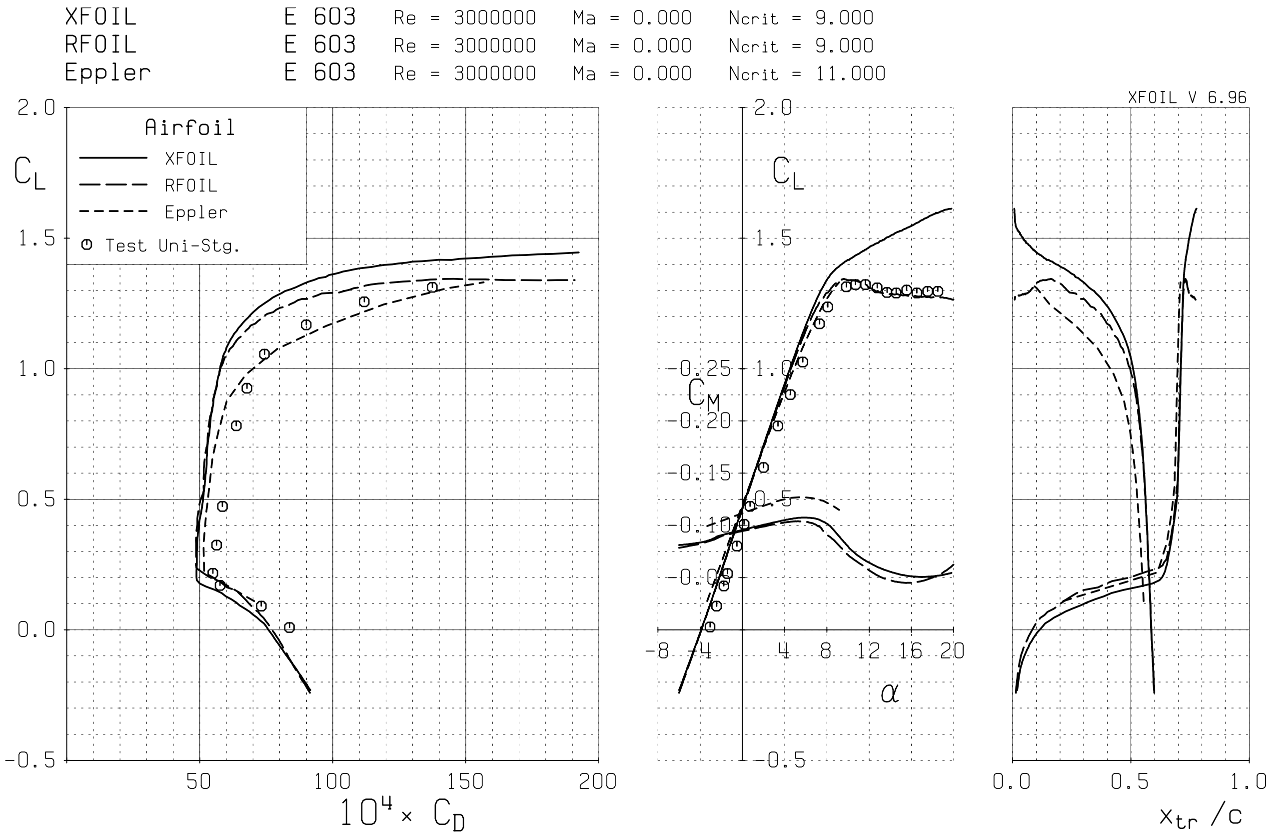

Fig 8. Comparison of calculated and measured data of E603 airfoil at $Re = 3{\cdot}10^6$

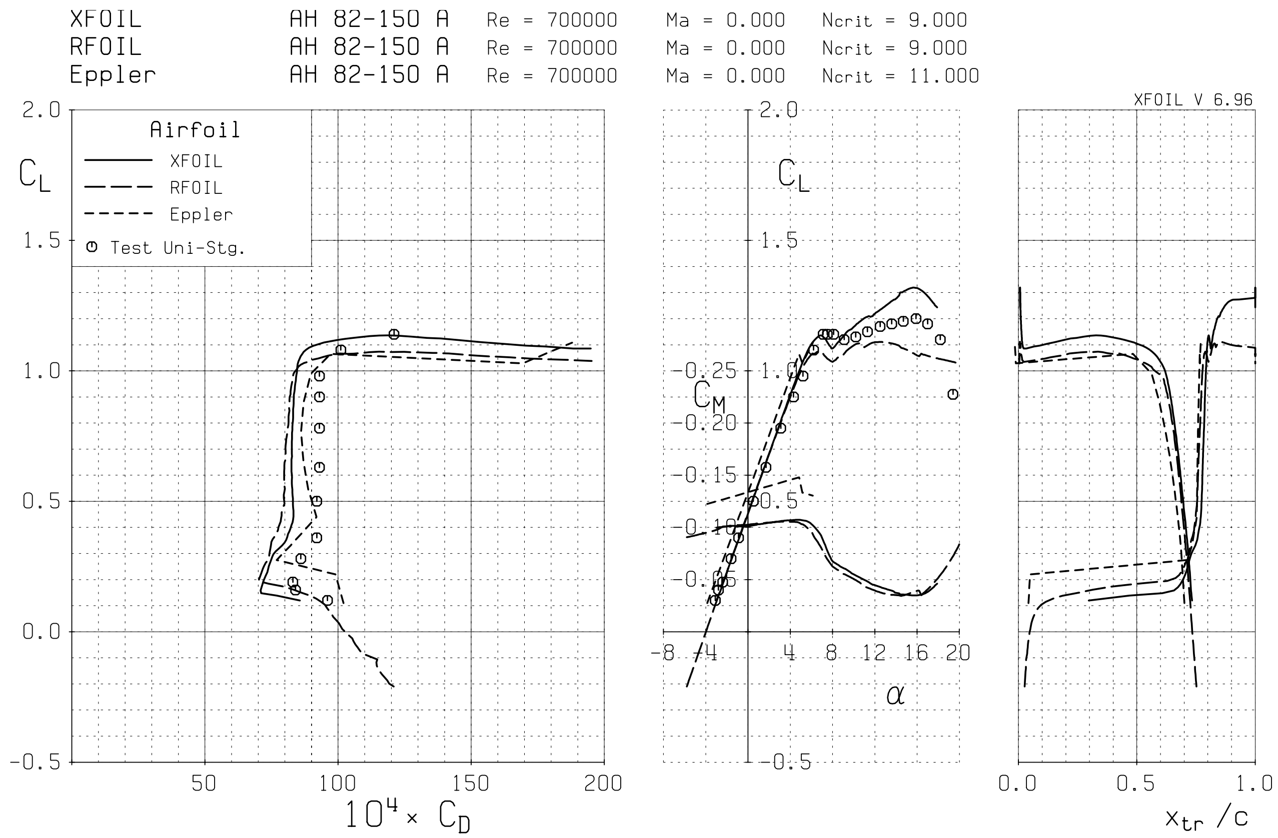

Fig 9. Comparison of calculated and measured data of AH82-150A airfoil at $Re = 0.7 \cdot 10^6$

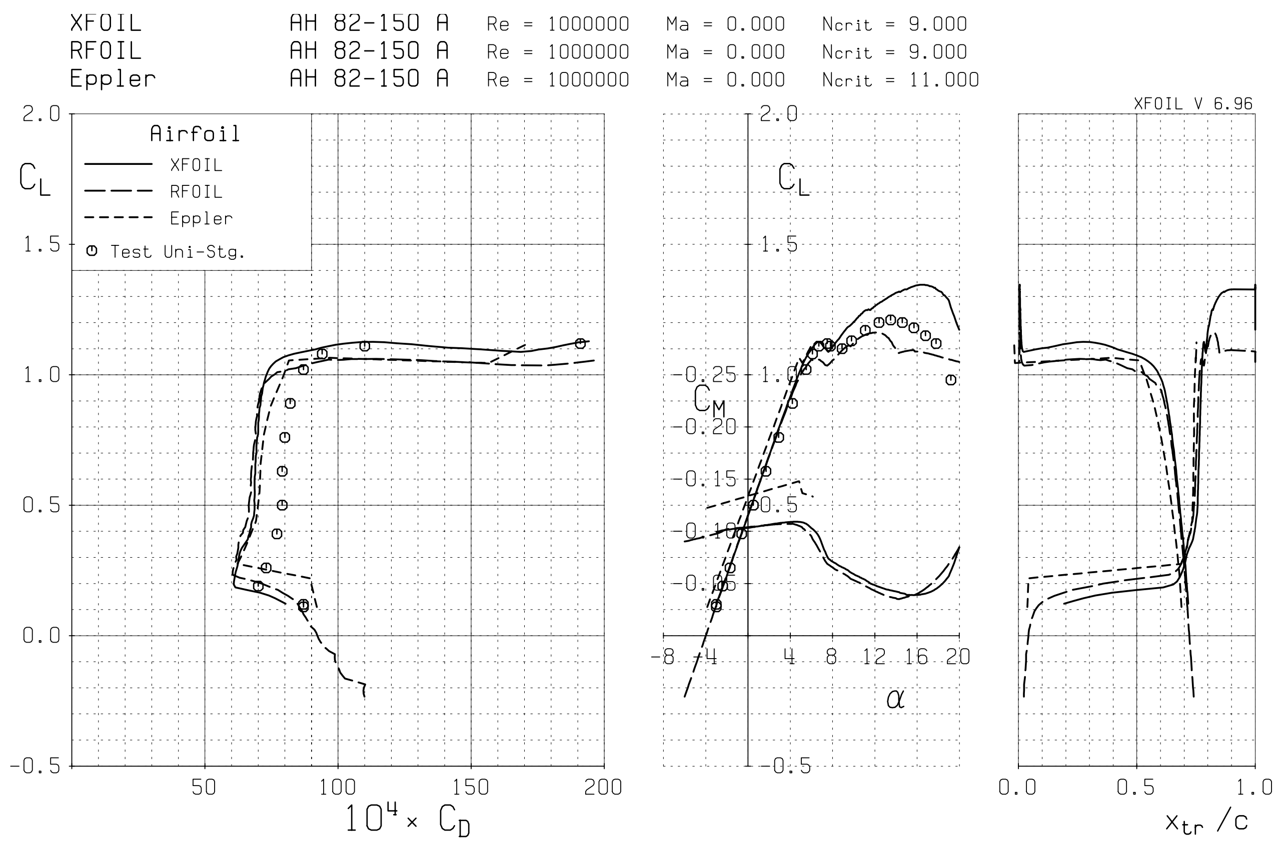

Fig 10. Comparison of calculated and measured data of AH82-150A airfoil at $Re = 1 \cdot 10^6$

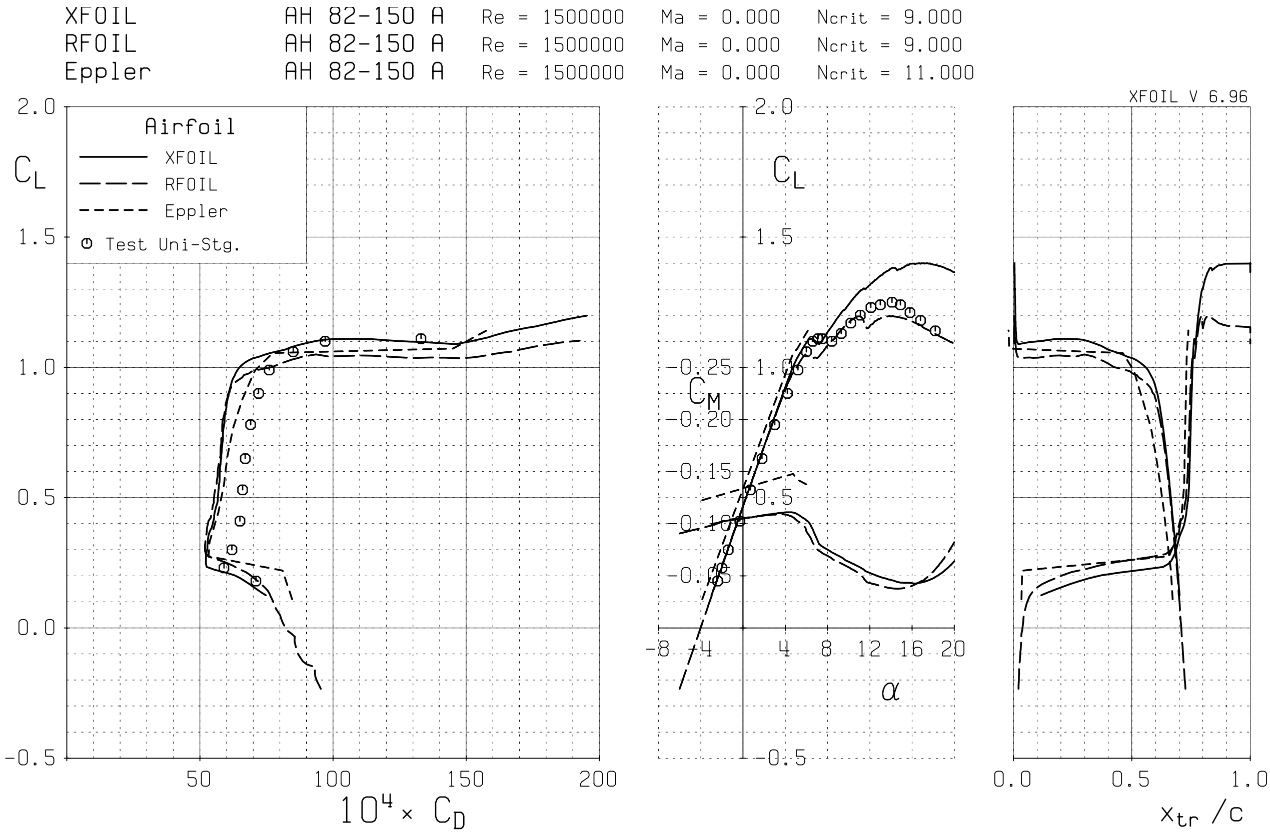

Fig 11. Comparison of calculated and measured data of AH82-150A airfoil at $Re = 1.5 \cdot 10^6$

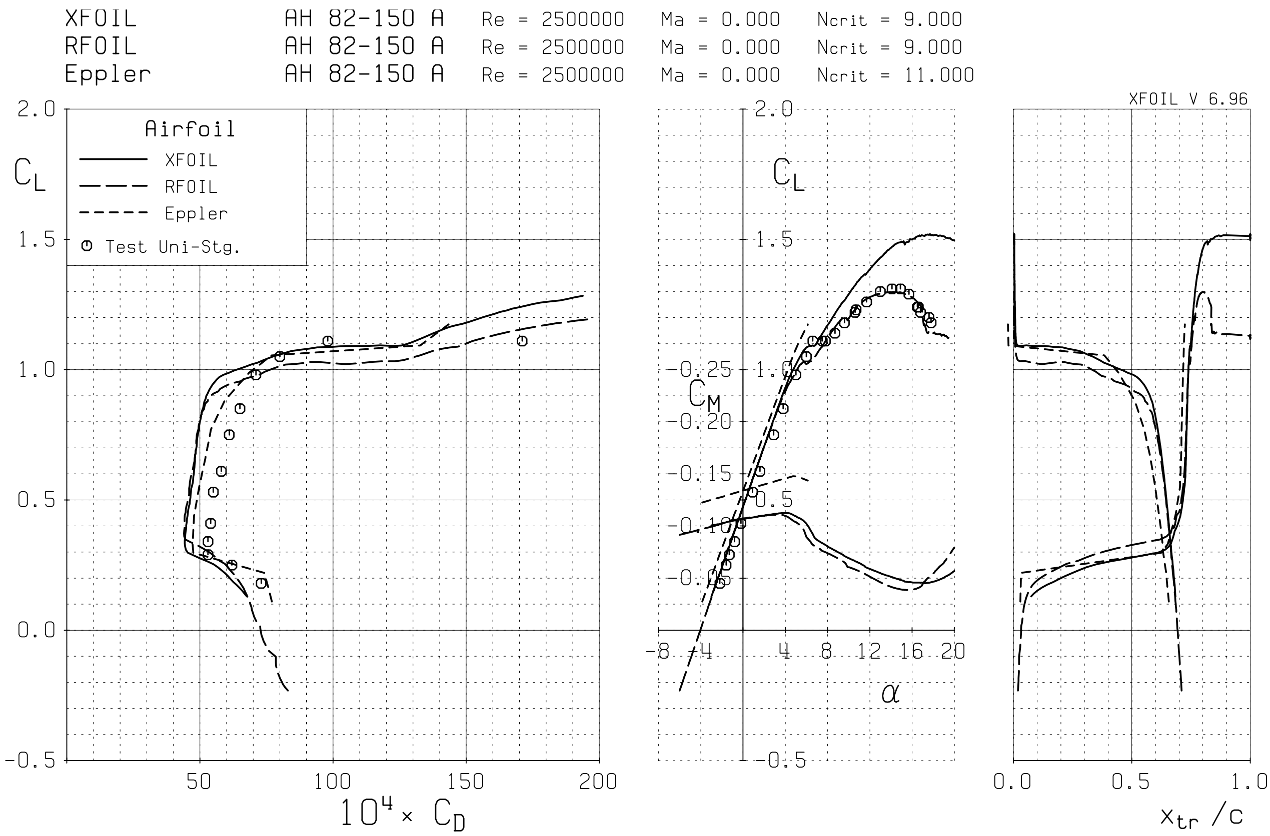

Fig 12. Comparison of calculated and measured data of AH82-150A airfoil at $Re = 2.5 \cdot 10^6$

5.3. Airfoil AH82-150A

The data of airfoil FX82-150A are presented in figures 9–12. The results are similar to the previous airfoils. Calculation predicts well the range of lift coefficient for low drag. In the low drag range the predicted drag is about from 10 % to 20 % lower than measured drag. Eppler's code predicts drag in low drag region better than XFOIL and RFOIL. Eppler's code overpredicts moment coefficient and can not predict maximum lift and lift curve in post stall region. At low Reynolds numbers $Re = 0.7 \div 1.0 \cdot 10^6$ the experimental lift curve is about in the middle between XFOIL prediction and RFOIL prediction in the post stall region. At high Reynolds number $Re = 2.5 \cdot 10^6$ XFOIL code overpredicts maximum lift and the lift in post stall region. RFOIL code predicts lift curve very well even in post stall region.

6. Conclusions

Calculated and measured results of three airfoils comparison reveals that calculation predicts well the range of lift coefficient for low drag. In the low drag range the predicted drag is about from 10 % to 20 % lower than measured drag. Eppler's code predicts drag in low drag region better than XFOIL and RFOIL. Eppler's code overpredicts moment coefficient and can not predict maximum lift and lift curve in post stall region. At low Reynolds numbers $Re = 0.7 \div 1.0 \cdot 10^6$ the experimental lift curve is about in the middle between XFOIL prediction and RFOIL prediction in the post stall region. At high Reynolds number $Re = 2.0 \div 2.5 \cdot 10^6$ XFOIL code overpredicts maximum lift and the lift in post stall region. RFOIL code predicts lift curve very well even in post stall region. Both XFOIL and RFOIL codes predict the pitching moment curve including post stall regime similar to the test in Delft.

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TRIJŲ SPARNO PROFILIŲ CHARAKTERISTIKŲ ANALIZĖ

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S a n t r a u k a

Tyrimuose analizuotos profilių FX 66-S-196 V1, E603 ir AH82-150A charakteristikų teorinės reikšmės, apskaičiuotos XFOIL, RFOIL ir PROFIL05 programomis. Gautos teorinės reikšmės palygintos su jau atliktų eksperimentinių tyrinėjimų rezultatais. Pirmas profilis buvo tyrinėjamas Delft technologijos universitete (Olandija) ir Štutgarto universitete (Vokietija), likę du – Štutgarto universitete. Visi profiliai turi skirtingas maksimalios keliamosios jėgos dalis. Profilio FX 66-S-196 V1 keliamoji jėga mažėja staiga. Kitų profilių keliamoji jėga kinta tolygiai, tačiau skirtingai. Visų profilių charakteristikas įtakoja laminarinis atsiskyrimo burbulas.

Reikšminiai žodžiai: profilis, charakteristikų analizė, palyginimas su eksperimentiniais rezultatais.