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TNO report

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Validation of high Reynolds number, free-transition, RANS-based CFD simulations using the DNW-HDG's airfoil experiment

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Summary

RANS-based CFD simulations have been validated using the DNW-HDG's high Reynolds number, Re, airfoil experiment. The experiment achieved free-transition measurements for Re up to 15 million on the AVATAR-DU00-W-212 airfoil. CFD simulations have been performed by means of OpenFOAM, using the steady-state, incompressible simpleFOAM solver coupled with the k-omega SST RANS turbulence model. Laminar-turbulent transition has been accounted for using the Langtry-Menter's model.

Poor CFD results have been achieved by using the standard Langtry-Menter's laminar-turbulent transition model at high Re. This model provides the user with empirical correlations to determine its input parameter transition onset momentum thickness Reynolds number, $Re_{\theta t}$, based on the flow turbulence intensity. Results indicates that the empirical correlations largely underestimate $Re_{\theta t}$, leading to a too early transition. Better agreement between experiments and CFD simulations (still using the Langtry-Menter's model) can be achieved determining $Re_{\theta t}$ by means of XFOIL (based on the well established e^n transition model), instead of the empirical correlations.

Contents

1 Introduction

In the framework of the AVATAR project, a high Reynolds number, Re, airfoil experiment was carried out in the high pressure wind tunnel in Göttingen (DNW-HDG) [1]. The experiment was performed on the AVATAR-DU00-W-212 airfoil, achieving free-transition measurements for Re up to 15 million. A blind comparison between this experiment and simulations was performed in [2]. The results from both panel- and CFD-based methods have been included in the comparison. Except a CFD tool using the Granville/Schlichting model, all these tools adopted the e^n method to account for laminar-turbulent transition. The comparison of the airfoil coefficients indicated that the e^n model allows panel and CFD tools for reliable predictions of the linear lift region and the low drag bucket, suggesting a correct estimation of the transition position. Furthermore, the authors acknowledged a certain degree of uncertainty of the turbulence intensity, I, measured during the experiment, which would have affected the comparison results.

The purpose of the work reported in this document is to validate TNO's capabilities to perform high Re RANS-based CFD simulations using the DNW-HDG's experiment. TNO's simulations were performed by means of OpenFOAM, using the Langtry-Menter's transition model. Due to the uncertainty in the experiment I, we firstly verified this measurement using an indirect approach based on XFOIL. We then performed a study to show the influence of $Re_{\theta t}$ on the transition location and the airfoil coefficients. Lastly we performed simulations at different angles of attack, AoA.

2 Methods

The results shown in this documents have been obtained by means XFOIL, a code based on panel method, and OpenFOAM, a RANS-based CFD tool. Both methods are briefly described below.

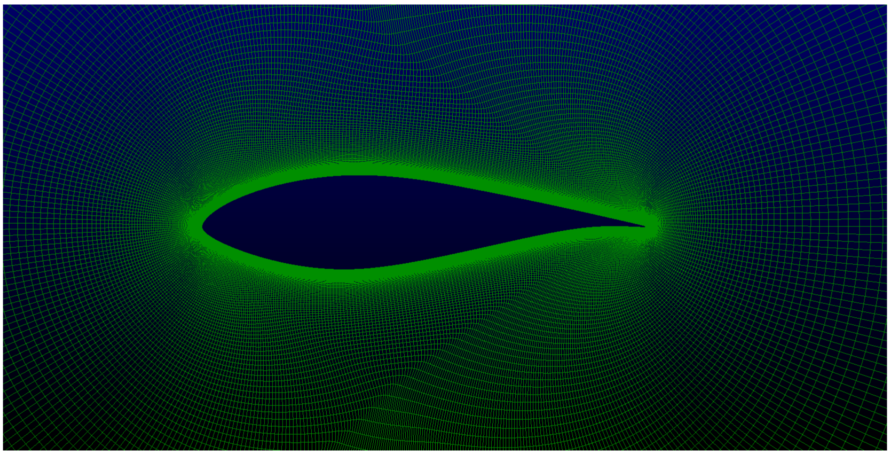
2.1 XFOIL

XFOIL is an airfoil design tool based on a panel method, accounting for the effect of viscosity and the laminar-turbulent transition. Transition is accounted for by XFOIL by means of the well established e^n model, mainly based on the so-called $Ncrit$ parameter. $Ncrit$ is related the ambient disturbance level in which the airfoil operates, encompassing surface roughness, free-stream I and mechanical vibrations.

2.2 OpenFOAM

OpenFOAM simulations were performed using the steady-state, incompressible simpleFOAM solver coupled with the k-omega SST RANS turbulence model. Laminar-turbulent transition was simulated using Langtry-Menter's model [3]. The latter model requires, as input, the transition onset momentum thickness Reynolds number, $Re_{\theta t}$. Empirical correlations developed for flat plates, relating $Re_{\theta t}$ to I are given by Menter et al. in [3]. The computational O-mesh used to perform the CFD simulations (Fig. 1) was characterized by 500 points around the airfoil and by a farfield located at 500 chords, leading to around 300000 mesh points.

Figure 1: Details of the O-mesh developed on the AVATAR-DU00-W-212 airfoil.



3 Results

3.1 Verification of the experiment's turbulence intensity

The first step taken in the reported work involved the verification of the experiment's measured I. For this we used XFOIL and an empirical formula developed by Mack [4]. Assuming negligible roughness and vibrations, Mack's formula relates $Ncrit$ to I as follows:

$$Ncrit = -8.43 - 2.4\,\ln(I) \tag{3.1}$$

The verification of the experiment's I was carried out for measurements taken at a Re of 15 million. According to the experiment's documentation, at this Re, the tunnel I was equal to 0.55%. Using Mack's formula this I corresponds to an $Ncrit$ of around 4. Figure 2 shows the experimental and XFOIL polars calibrated with an $Ncrit$ of 4, while Fig. 3 compares the experimental pressure coefficient to that calculated by means of XFOIL (setting up $Ncrit$ equal to 4 as well). The overall agreement between experiments and calculations is excellent. Looking a bit closer at Fig. 3, it is also possible to note that the transition location for both experiments and simulations is also the same. The experiment transition location, for both the suction and pressure sides, can be inferred from a small but visible kinks in pressure distribution. At the suction side the kink is located at 40% chord, while at the pressure side it is located at 38% chord. Looking at the numerical skin friction coefficient distribution, we can notice that the simulations' suction and pressure sides' transitions occur at the same experimental locations, indirectly confirming the correctness of the experiment's I.

Figure 2: Experimental and numerical lift coefficient, Cl, drag coefficient, Cd, and moment coefficient, Cm, as a function of the angle of attack, AoA, for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.

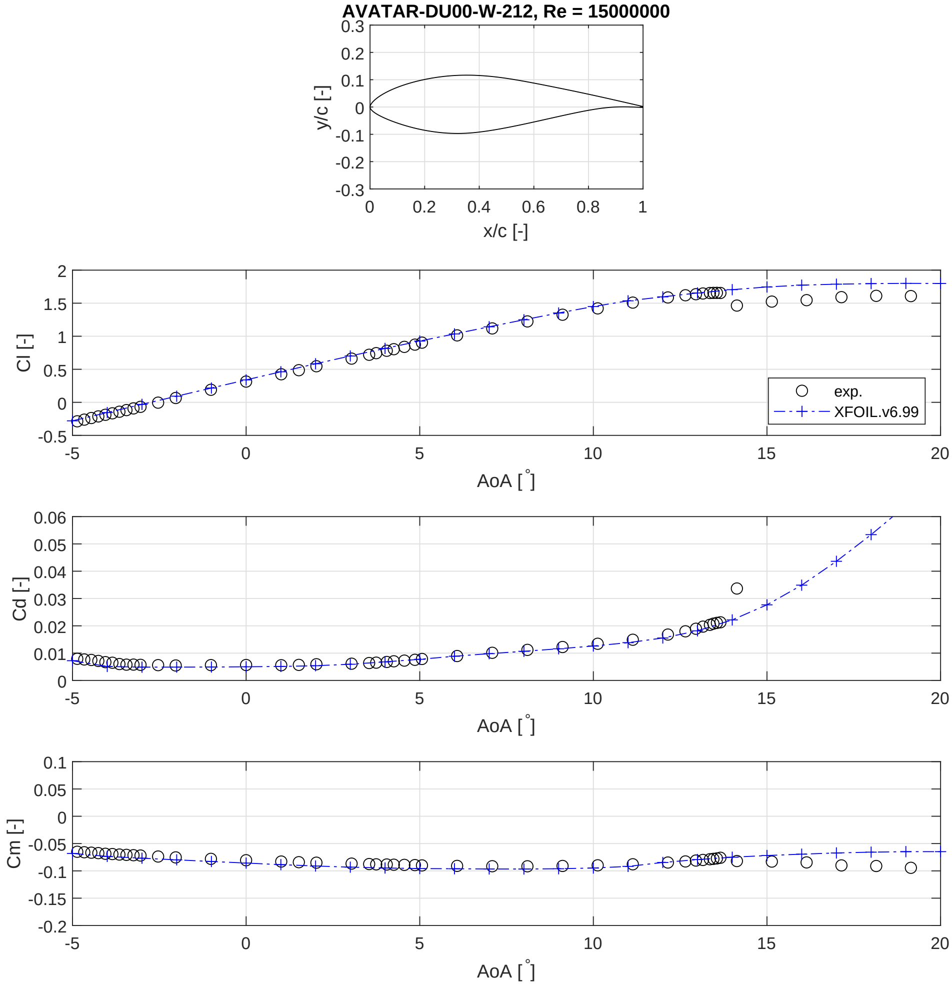
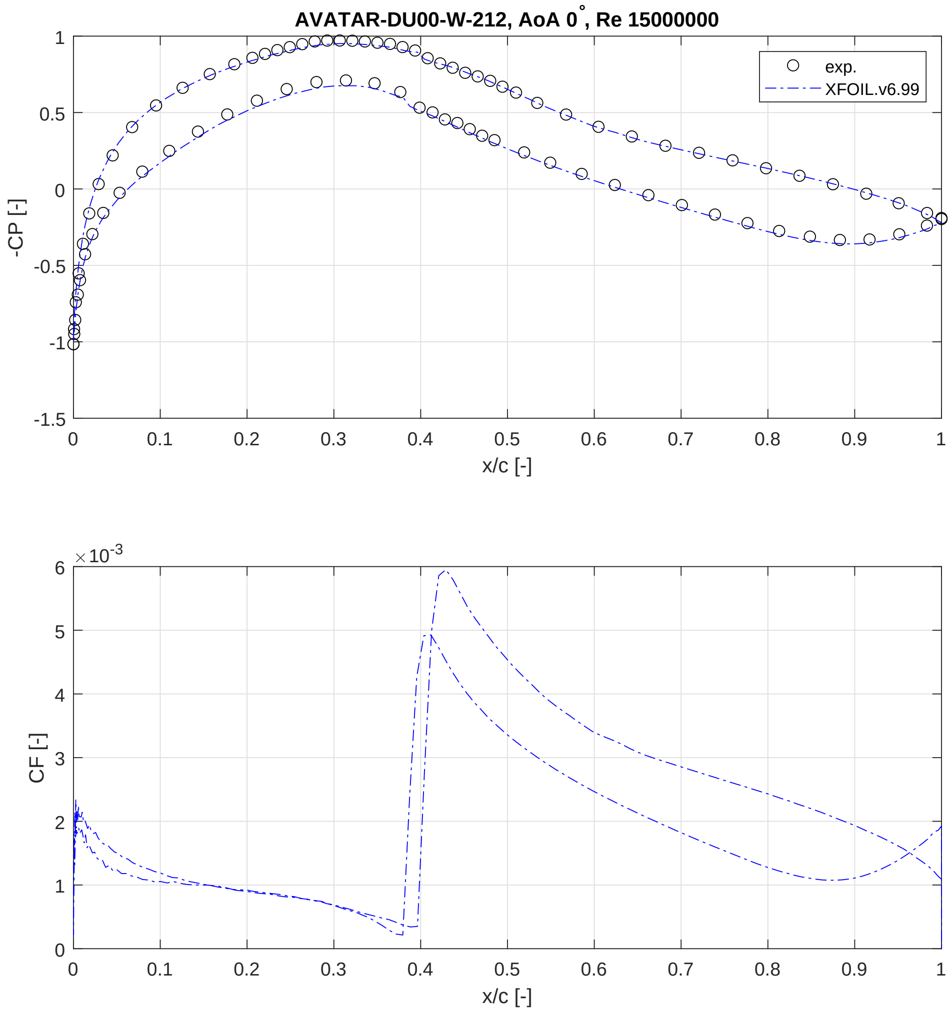


Figure 3: Experimental and numerical pressure coefficient, CP, and skin friction coefficient, CF, for an angle of attack, AoA, of 0° for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.



3.2 Influence of the transition onset momentum thickness Reynolds number

As mentioned above, Langtry-Menter's model provides correlations relating its input parameter $Re_{\theta t}$ to I. According to these correlations, for the measured tunnel's I of 0.55% (at Re of 15 million), $Re_{\theta t}$ should be 703. At an AoA of 0°, Fig. 5 shows that the CFD simulations performed setting up $Re_{\theta t}$ equal to 703 lead to a too early transition. At these conditions, it is therefore possible to conclude the empirical correlations underestimate $Re_{\theta t}$. Instead of using Menter's empirical correlations, we tried to determine the value of $Re_{\theta t}$ using the boundary layer properties predicted by XFOIL, and then use this value as input of Langtry-Menter's model. Using XFOIL we could determine the value for $Re_{\theta t}$ of 2600. Fig. 5 and Figure 4 show that this value leads to closer CFD results to the experiment ones, in terms of both aerodynamic coefficients and transition location.

Figure 4: Experimental and numerical lift coefficient, Cl, drag coefficient, Cd, and moment coefficient, Cm, as a function of the angle of attack, AoA, for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.

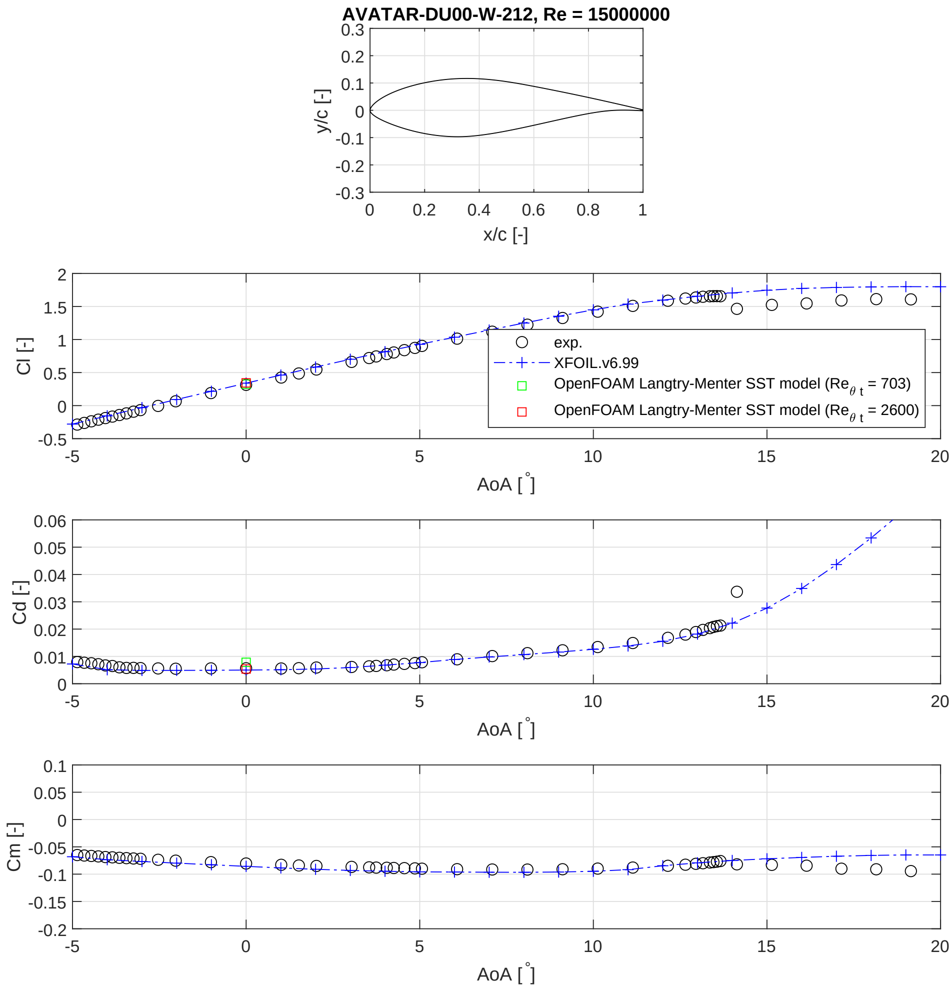
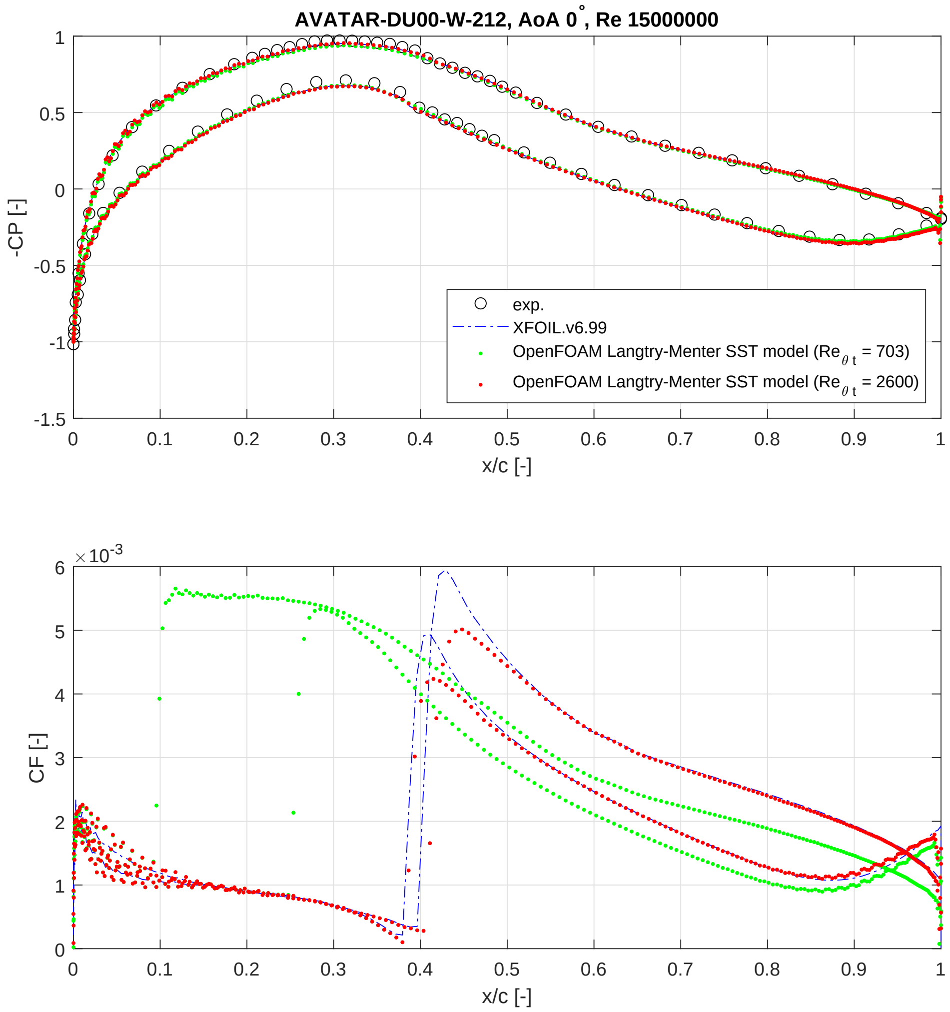


Figure 5: Experimental and numerical pressure coefficient, CP, and skin friction coefficient, CF, for an angle of attack, AoA, of 0° for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.



3.3 Polars and pressure and skin friction coefficients at a Reynolds number of 15000000

Figures from 6 to 9 depict experimental and numerical polars and pressure distributions for the AVATAR-DU00-W-212 airfoil at Re of 15 million for three AoA. CFD calculations here use Langtry-Menter's laminar-turbulent transition model calibrated with $Re_{\theta t}$ extracted from XFOIL at an AoA of 0°. Good agreement between experiment and numerical results are seen at 0°. Less good agreement between CFD and XFOIL is at 10 and 5°, suggesting the need to re-calibrate $Re_{\theta t}$ using XFOIL calculations at this AoA.

Figure 6: Experimental and numerical lift coefficient, Cl, drag coefficient, Cd, and moment coefficient, Cm, as a function of the angle of attack, AoA, for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.

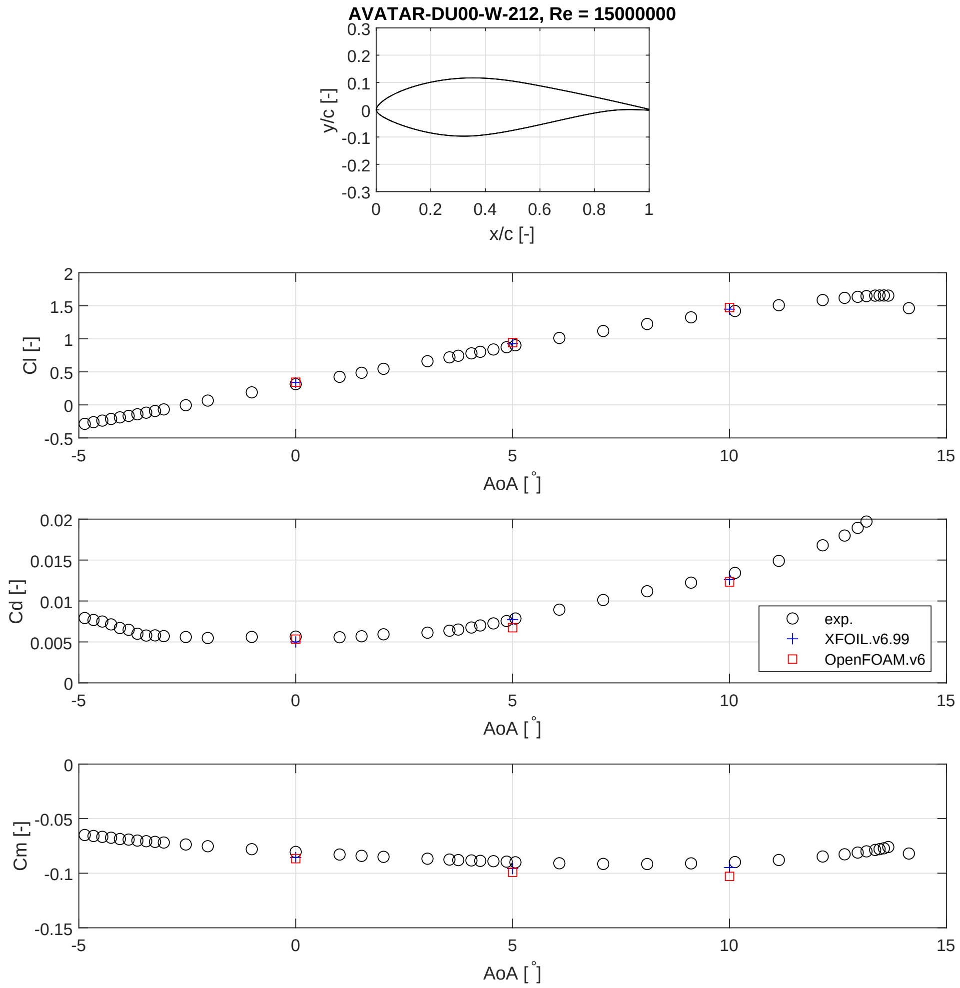


Figure 7: Experimental and numerical pressure coefficient, CP, and skin friction coefficient, CF, for an angle of attack, AoA, of 0° for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.

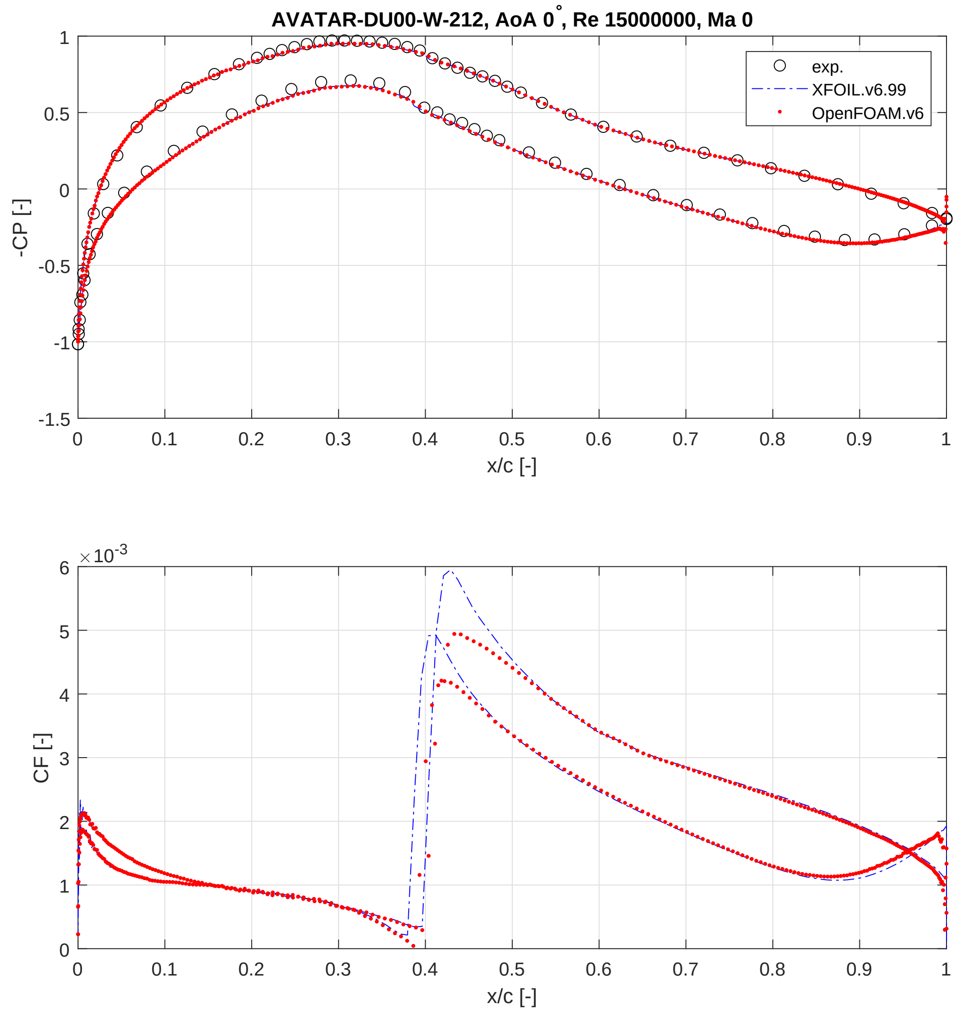


Figure 8: Experimental and numerical pressure coefficient, CP, and skin friction coefficient, CF, for an angle of attack, AoA, of 5° for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.

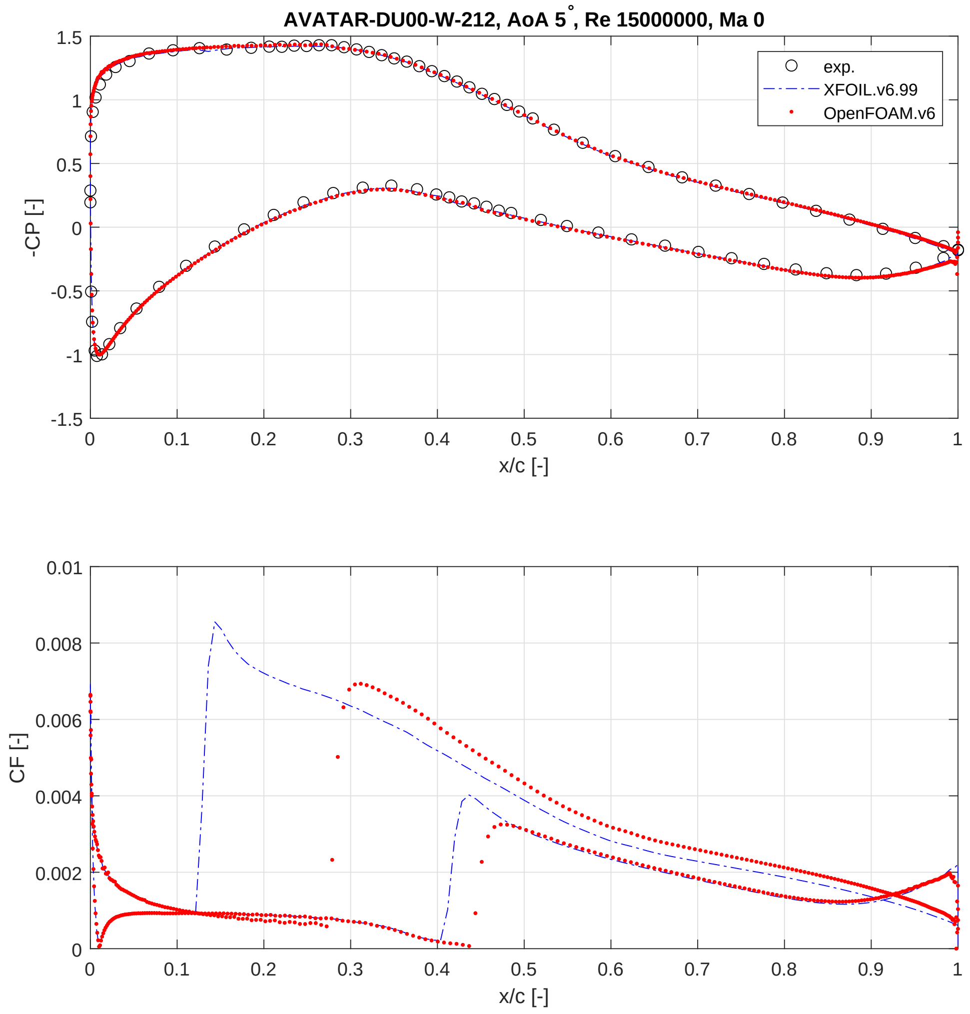
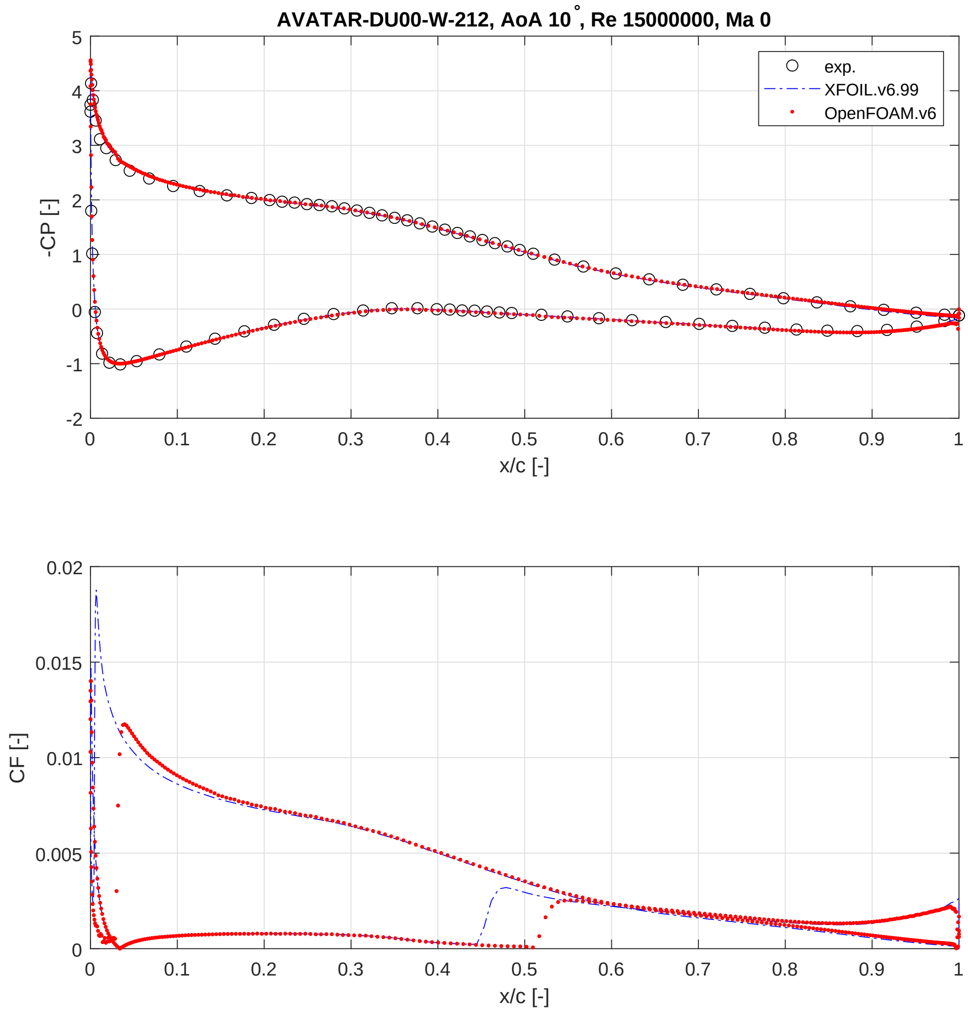


Figure 9: Experimental and numerical pressure coefficient, CP, and skin friction coefficient, CF, for an angle of attack, AoA, of 10° for the AVATAR-DU00-W-212 airfoil at a Reynolds number, Re, of 15000000.



4 Conclusions

Using the DWN-HGD's high Reynolds number, Re, free-transition airfoil experiment we validated RANS-based CFD simulations. CFD simulations have been performed by means of OpenFOAM using the steady-state, incompressible simpleFOAM solver coupled with the k-omega SST RANS turbulence model. The laminar-turbulent transition has been simulated using Langtry-Menter's model. The latter model requires, as input, the transition onset momentum thickness Reynolds number, $Re_{\theta t}$. Empirical correlations developed for flat plates, relating $Re_{\theta t}$ to the turbulence intensity, I, are provided by the Langtry-Menter's model.

In order to deal with the acknowledged uncertainty in the measurement of the experiment's I, we have firstly verified its measured values using an indirect approach based on XFOIL. At a Re of 15 million, this verification confirmed the correctness of the measured I. Based on the I measured at a Re of 15 million, using Langtry-Menter's correlations we then evaluated $Re_{\theta t}$. Poor CFD results are achieved by using the resulting $Re_{\theta t}$. Langtry-Menter's empirical correlations indeed largely underestimates $Re_{\theta t}$, leading to a too early transition. By evaluating $Re_{\theta t}$ with XFOIL, and using this value as input of Langtry-Menter's model, very good agreement can be achieved between experiment and CFD simulations.

Given the results presented in this document, future efforts should be directed towards investigating alternative RANS-based transition models, or alternative formulations of the Langtry-Menter's model, like the one presented by Khayatzadeh and Nadarajah [5]. In this publication the authors showed that a much better agreement with experiments can be achieved by simply tuning a constant used by the Langtry-Menter's model.

5 Bibliography

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