A PIV STUDY OF SEPARATED FLOW AROUND A 2-D AIRFOIL

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ABSTRACT

In order to acquire experimental data on an airfoil at high angles of attack, wind tunnel tests were carried out. The wind tunnel tests were carried out at $Re=1.25\cdot10^6$ *(based on chord length) on a 2-D model with 0.45 m chord and 2 m span based on the FFA-W3-211 airfoil geometry (21% thick). This airfoil is typically used in wind turbine blades.*

The purpose of the study was to examine the flow field and study the recirculating region around the airfoil. The present study was carried at 8° *and* 15° *angle of attack, with more focus on the latter, by using three methods; static pressure measurement, oil flow visualisation and Particle Image Velocimetry (PIV). It was of particular interest to determine the position of the separation and the resulting data could than provide appropriate data for validation of computational numerical calculations (CFD) for separated flow cases.*

Based on the velocity vector field obtained by the PIV data, the velocity profile, boundary layer quantities and the backflow coefficients were derived. The backflow coefficient was then used as a criterion for separation. The position of separation for 15° *angle of attack was determined in the PIV measurements to be at* $x/c=0.39\pm0.03$*, in the pressure measurements at* $x/c=0.40\pm0.05$ *and, somewhat subjectively, in the oil flow visualisation at* $x/c\approx0.42$*.*

The complete report (FFA-TN-1999-52) in pdf-format and the test data in ascii-format are available on request, for comparison with numerical results [3].

1 INTRODUCTION

One challenging area within fluid mechanics is modeling of turbulence. Many research projects are concerned with the development of such models, and to validate these numerical results, it is important to compare them with appropriate experimental data. Experimental data could either be provided by field studies or by wind tunnel tests, which are more common, for example, in studying an airfoil.

Traditionally, wind tunnel data on an airfoil include pressure measurements and/or balance measurements. Other interesting data are the velocity components and other higher order moments, such as fluctuations, in a certain position or a region. With the introduction of Particle Image Velocimetry (PIV), it becomes possible to determine the velocity flow field. Although the velocity field can be determined by other means, such as hot-wire anemometers or rake devices, the PIV method is especially promising because of its non-intrusiveness. PIV is based on the

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principle of introducing particles (seeding) that follow the flow field, and by capturing two consecutive digital images (image pairs), the data are analysed and a velocity field is obtained. The PIV technique is especially valuable in the examination of separated flow.

Separated flow occurs in several applications such as turbomachines and wind mills/turbines. For example, a wind turbine blade operates at a wide range of angles of attack and runs partly under separated flow condition, known as stall condition. This is one of the basic concepts for regulating a wind turbine; the other concepts are pitch and yaw regulation. In order to predict the power and loads on stall-regulated wind turbines it is therefore essential to be able to carry out aerodynamic calculations at separated flow conditions.

The purpose of the study reported here was to examine the flow field around the FFA-W3-211 airfoil at 8° and 15° angle of attack. In particular, the aim was to determine the separation and the recirculating flow field region. The FFA-W3-211 airfoil is one of the geometries used in commercial wind turbine blades design. In addition to the PIV measurement, pressure measurements and oil flow visualisations were carried out on the airfoil.

2 EXPERIMENTAL SET-UP

The present investigation was made in the low speed, fan-driven closed circuit, wind tunnel (L2000) at Re=$1.25 \cdot 10^6$ (based on chord length) at the Royal Institute of Technology (KTH) in Stockholm Sweden. The 5 m long test section has a 2 × 2 m cross-section (octahedron) and the contraction ratio is 7.5. The 2-D airfoil model has a 2 m span, 0.45 m chord and 21% thickness and was equipped with 64 static pressure taps at the mid section.

A horizontal plane was examined in the PIV measurements since the model was vertically suspended. The laser sheet was aligned horizontally and the camera was placed perpendicular to the sheet. In order to examine the spanwise variations, the examined plane was placed at five different vertical positions, z=0.85 m, 0.81 m, 0.77 m, 0.60 m and 0.55 m, from the test section floor.

In the present study, the aim was to force the transition at a defined position on the airfoil without disturbing the flow more than necessary. For this we used a zigzag adhesive tape with wedges of 60° angle on the airfoil. The transition tape was attached with the upstream end of the tape located at x/c=0.026 on the suction side and at x/c=0.312 on the pressure side. The tape thickness was nominally 0.205 mm but was measured to be 0.23 mm mounted on a surface.

The PIV measurements were preceded by oil flow visualisations and static pressure measurements. The oil flow visualisation was carried out using a mixture of kerosene and titanium oxide white.

The static pressure measurements were carried out by means of a Scanivalve pressure transducer acquisition system. The acquisition program determined mean, standard deviation, min. and max. for each channel (each with a PDCR-22 pressure transducer) with a sampling frequency of either 830 Hz during 0.3 seconds or 73 Hz during 10 seconds.

The PIV system included a two-cavity (400 mJ each) Nd:YAG laser (Quanta Ray), with a wavelength of 532 nm and pulse frequency of 15 Hz. The duration of the laser beam was 8.0 ns. Additionally, a digital high-resolution Kodak ES 1.0 CCD-camera (1008 × 1018 pixel) was used. The camera equipped with either a 60 mm lens or a 105 mm lens was able to cover an image of 225 × 225 mm or 90 × 90 mm respectively. The processor and program were delivered by DANTEC Measurement Technology, Denmark. The final resolution of the field varied from 2.5 mm to 5.2 mm depending on the camera lens. In the present study, propylene glycol was used as seeding for the PIV measurements (1,2-Propanediol diluted with 40% water in a ZR-31 smoke generator). The particle size was approximately 2.0-2.5 μm volume median diameter (VMD). The seeding was simply introduced downstream of the test section and, as the wind tunnel was a closed circuit, the seeding was recirculated.

3 RESULTS

The study showed promising result of using PIV measurements on an airfoil with a prominent separated flow. Fig. 1 shows the composite vector plot of mean velocity fields at 15° angle of attack. The separation seems to occur at approximately half of the chord length, and downstream of this position the recirculated region is well represented. The vectors appearing downstream of the trailing edge represent the flow coming from the pressure side since the seeding was global.

The PIV results provided data on the velocity profile, useful for comparison with numerical results, and furthermore, made it possible to derive boundary layer parameters. Fig. 2 and 3 show the velocity profile development for 8° and 15° angle of attack respectively, which show an increased recirculating region. The dots are the measurements and the line is an interpolated trend line.

The position of separation was determined foremost for the 15° angle of attack case and by means of this position the result from the three methods could be compared. For the oil flow visualisation the separation was indicated to be at $x/c \approx 0.42$. This was, somewhat subjectively, determined from photos where the paint was stuck and not swept away further downstream due to zero shear stress at separation. In the pressure measurements, a constant pressure level was assumed to indicate a separated flow region and this was determined to begin at x/c=0.40±0.05. Finally, in the PIV measurements this was determined at x/c=0.39±0.03 and was based on the backflow coefficient, which is further described in section 5 below.

The results of the characteristics of the FFA-W3-211 airfoil are presented in Fig. 4 as lift and drag coefficient, derived from the pressure measurements. The results are compared to an XFOIL-calculation which is based on the method presented by Drela and Giles [2].

4 DATA POSTPROCESSING AND EXPERIMENTAL PROCEDURE

The PIV data post processing was carried out in two steps. In the first step a preliminary calculation of mean velocity and fluctuation (rms) was done by means of the validation criteria in the DANTEC postprocessor (the peak value ratio ≥ 1.2 and global velocity range scale validation). Based on the temporal mean and rms values, the second step was carried out. Velocity vectors within 3 local rms values of the local velocity mean were accepted, but only if they also satisfied the peak value ratio criterion. Thereby, to obtain the mean velocity and fluctuation flow field the actual values in the flow field were treated on a local velocity scale instead of on the global scale used in the first step. The obtained flow fields were based on a number of ”instantaneous” vector fields ranging from 150 to 1300 image pairs. In order to remove some noise in the data, in the form of small random spatial variations, smoothing was applied. The smoothing has the undesirable effect that strong velocity gradients, found for example in the boundary layer, are somewhat dampened. However, since the backflow coefficient, used for determining the separation position, was not smoothed, it was not affected by this damping.

To validate the described method, PIV measurements were made without any model in the test section. The free stream velocity and turbulence intensity was compared with the wind tunnel calibration. The PIV result showed U=40.42 m/s and was 0.4% higher than the wind tunnel control showed, U=40.26 m/s. The turbulence intensity in the PIV data indicated a level of 0.23% (u_{rms}=0.09 m/s) but earlier hot-wire calibration, done at 40.0 m/s, showed 0.15% (u_{rms}=0.06 m/s). The deviation in the fluctuations may be a consequence of an unsuccessful subpixel interpolation, without which the velocity discretisation was 1.4 m/s in the measurements. However, as a means of determining mean velocity field, our PIV measurement showed promising results, even if further improvement of the PIV technique is desirable, but outside the scope of this study .

5 DISCUSSION

In order to determine the separation point in the PIV data, three parameters were studied: backflow coefficient, shape factor and wall shear stress.

The backflow coefficient is a statistical approach and was found to be the most appropriate method in the present study. The backflow coefficient (χ) is defined as the portion of the "instantaneous" velocity vectors projected upstream at a certain chordwise position. Furthermore, mean separation position is defined as the position (or line) where the backflow coefficient at the surface or wall (χ_w) is ≥ 0.5. Since no measurement was acquired at the surface itself the surface backflow coefficient (χ_w) was obtained by linear extrapolation as can be seen in Fig. 5. Fig.5 shows a family of backflow coefficient versus wall normal position for some chordwise positions (x/c=0.35-0.37) and the linear extrapolated line down to the wall for the 15° angle of attack case. This approach and its limitations for weaker separations was also discussed in Dengel and Fernholz [1]. With this method the position of separation was determined to be at x/c=0.39±0.03.

Further downstream, at x/c=0.55-0.84 (see Fig. 6), the backflow coefficient curve family seems to level off at a wall backflow coefficient(χ_w) less than one in a non-linear behaviour in the near wall region and due to the larger number of accepted readings, this trend seems fairly reliable. This means that the flow is not fully reversed, not even for chordwise positions within the recirulcation region. Thus, the linear extrapolation approach to obtain the wall backflow coefficient and determine the separation position seems reasonable in region close to separation, but might be questionable in the recirculated region.

The shape factor, defined as the ratio between displacement thickness and momentum thickness, $H = \delta^*/\theta$, was derived and found to increase as the boundary layer approached separation. There is much disagreement about the existence, universality and value of a critical shape factor for separation, and values from 2 up to 4 are reported (see e.g. [1]). The present study suggested a critical shape factor of H=3.4±0.3 for separation. Regarding the determination of separation position, fortunately, the shape factor H increased rapidly around separation at high angles of attack, so a slightly different critical value did not affect this position significantly.

The wall shear stress could be derived from the velocity profiles through von Kármán's momentum integral equation although the difficulties are in deriving the differential of the momentum loss thickness. The spatial resolution of the data will influence the result and since the resolution was rather coarse near the separation compared to the assumed boundary layer thickness, there were uncertainties in deriving the wall shear stress. Furthermore, the results were a little too noisy to allow accurate derivation in the chordwise direction. In brief, this means that there was substantial uncertainty in determining the separation position using wall shear stress.

The spanwise variation in 2-D tests is a well-known problem and in this present study, was examined by means of oil flow visualisation. The purpose of the oil flow was not only to visualise but also to quantify the spanwise variations. Some instantaneous variations were observed but the average flow pattern was of primary interest. The spanwise variation is dependent on the boundary layer transition and since a forced transition was used in this study (zig-zag tape), the variations were dramatically reduced. Despite this reduction there was still some variation which may be caused by other effects, such as the occurrence of stall cells. This was recently reported by Yon and Katz [4].

In the pressure measurements the mean value was acquired, using the Scanivalve, but some analysis was also carried out on selected pressure taps to determine the time variations in the pressure. The main objective was to make sure no trend appeared during the measurements. Although there were some variations, these did not show any significant influence on the determination of the position of separation or mean results. Whether these variations were due to stalls cells or something else is not fully understood.

In the PIV measurement the influence of the remaining spanwise variation was examined, as mentioned in section 2 above, by carrying out PIV measurements at five different vertical positions. The PIV data were compared with the oil flow visualisation and showed a fairly good agreement for the spanwise midsection (z=0.85 m) and the other positions, and poor agreement for the 27.5% off midsection spanwise position(i.e. z=0.55 m). Presumably, this was caused by the occurrence of stall cells on the airfoil which may vary on a different time scale than that of the PIV measurements. However, the wind tunnel did not show any significant time variation of the flow condition which otherwise could have been a possible explanation. The influence of the spanwise variation on the PIV data was concluded to be approximately as large as the uncertainties in the data (see section 3) , which was a satisfying result.

6 CONCLUSIONS

The flow field around the FFA-W3-211 airfoil has been studied for a prominent separation using three different experimental methods. The position of separation determined by the three methods is essentially the same, suggesting that PIV technique can render useful results for this type of flow. The test data is well suited for comparison with CFD results and for studies of separated flow in applications such as wind turbines, where better prediction tools are desirable. Hopefully, even if experimental data, as well as numerical results, always include some uncertainties, the present study and data will provide appropriate data for the improvement of numerical models for separated flow cases.

7 ACKNOWLEDGEMENTS

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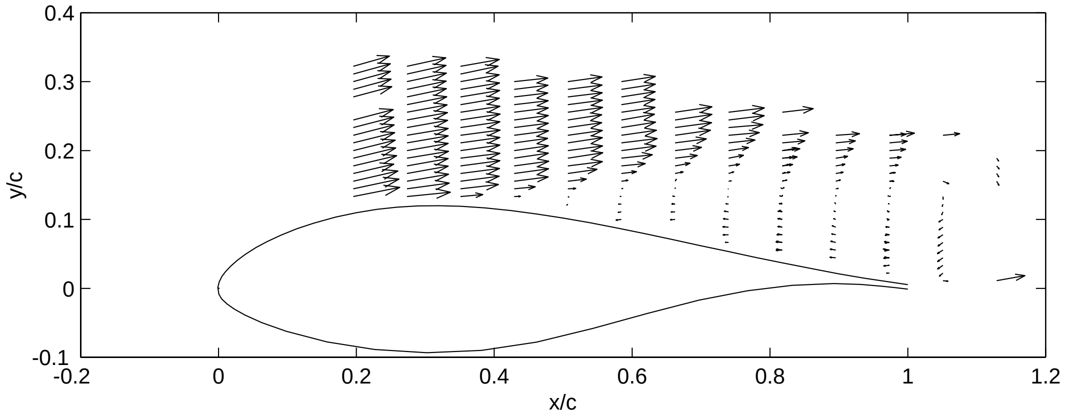

Fig. 1 A composite PIV vector plot of mean velocities at 15° angle of attack

REFERENCES

[1] Dengel P and Fernholz H. An experimental investigation of an incompressible turbulent boundary layer in the vicinity of separation. *Journal of fluid mechanics (JFM)*, Vol. 212, No -, pp 615–636, 1990.

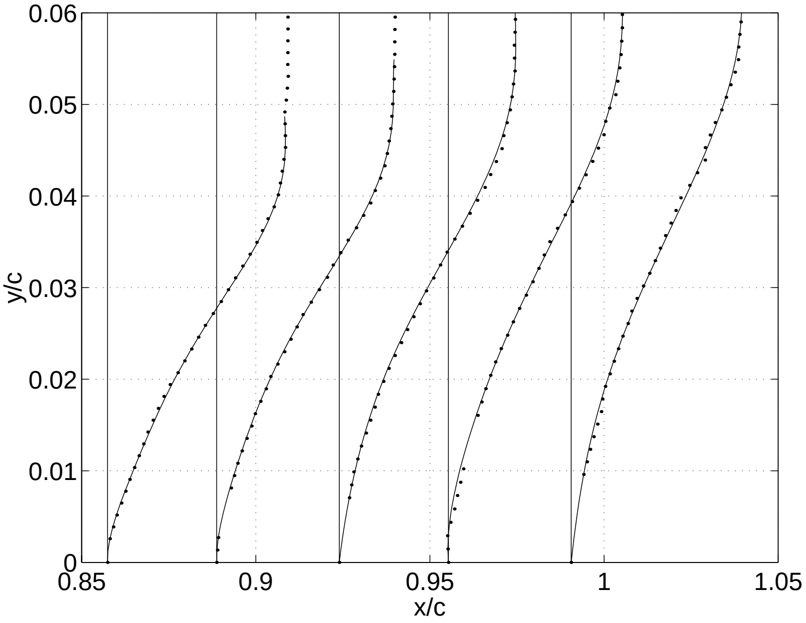

Fig. 2 Velocity profile development for 8° angle of attack.

[2] Drela M and Giles B. Viscous-inviscid analysis of transonic and low reynolds number airfoils. *AIAA Journal*, Vol. 25, No 10, pp 1347–1355, 1987.

[3] Holm R and Gustavsson J. *A PIV Study of Separated Flow around a 2-D Airfoil at High Angles of Attack in a Low Speed Wind Tunnel FFA-TN-1999-53*. 1st edition, FFA, 1999.

[4] Yon S and Katz J. Study of the unsteady flow features on a stalled wing. *AIAA Journal*, Vol. 36, No 3, pp 305–312, 1998.

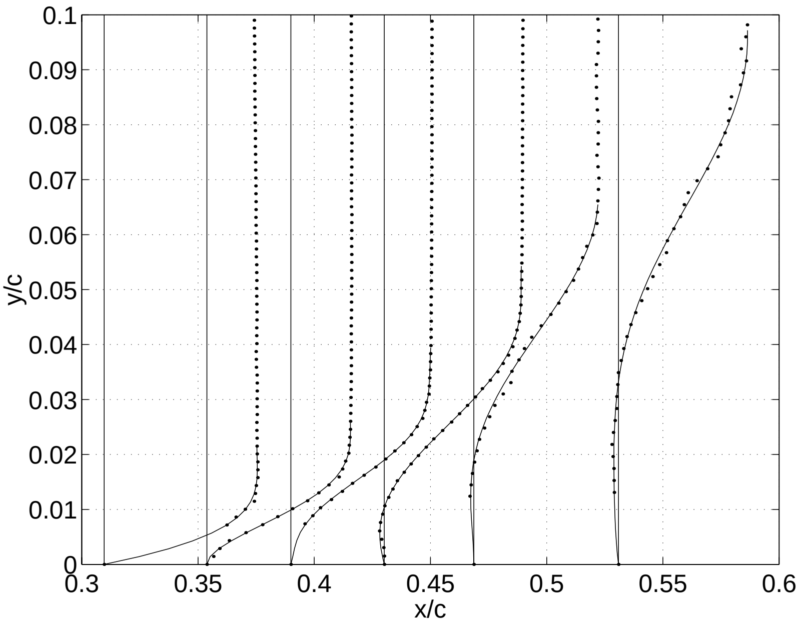

Fig. 3 Velocity profile development for 15° angle of attack.

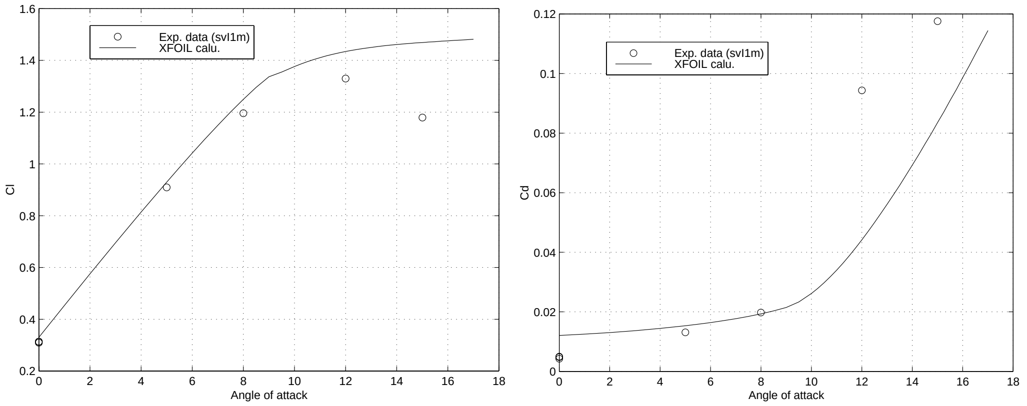

Fig. 4 The lift coefficient (left figure) and drag coefficient determined from pressure measurement, experimental data and XFOIL calculations.

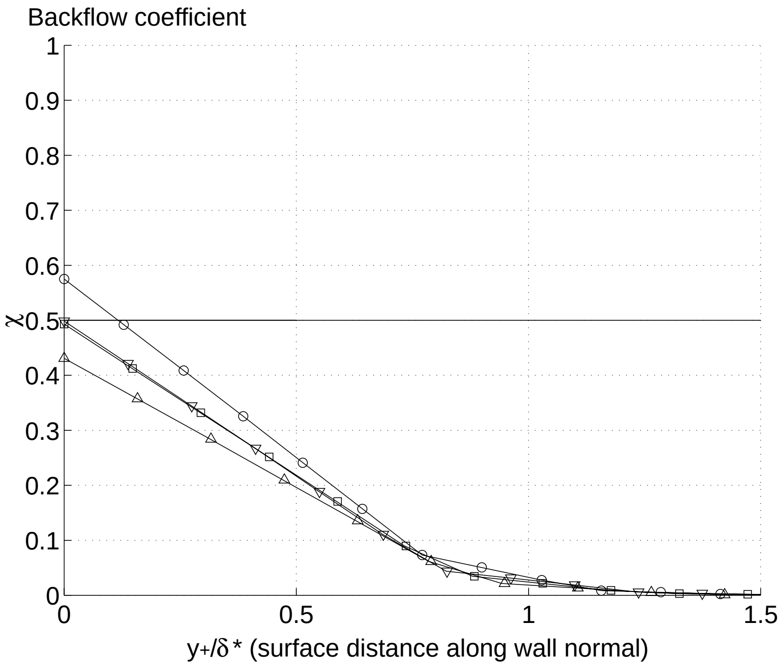

Fig. 5 Backflow coefficient for a curve family for x/c=0.35–0.37 for 15° angle of attack.

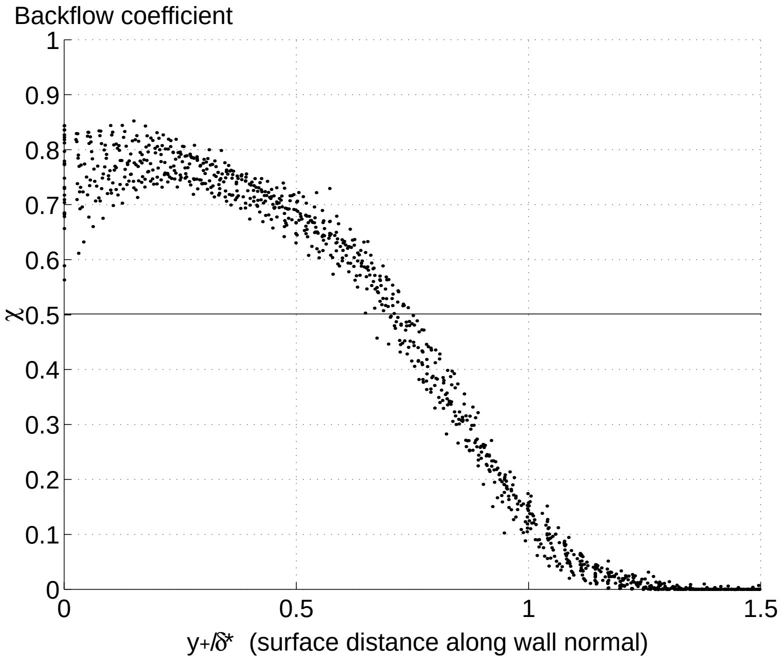

Fig. 6 Backflow coefficient for a curve family for x/c=0.55–0.84 for 15° angle of attack.