Results of the AVATAR project for the validation of 2D aerodynamic models with experimental data of the DU95W180 airfoil with unsteady flap

C. Ferreira¹, A. Gonzalez², D. Baldacchino¹, M. Aparicio², S. Gómez², X. Munduate², N.R. Garcia³, J.N. Sørensen, E. Jost⁴, S. Knecht¹, T. Lutz⁴, P. Chassapogiannis⁵, K. Diakakis⁵, G. Papadakis⁵, S. Voutsinas⁵, J. Prospathopoulos⁵, T. Gillebaart¹, A. van Zuijlen¹

¹DUWIND, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629HS Delft, The Netherlands
²CENER - National Renewable Energy Centre, Ciudad de la Innovación 7, Sarriguren, Navarra, 31621, Spain
³Technical University of Denmark, Department of Wind Energy, RisøCampus, Frederiksbergvej 399, 4000 Roskilde Denmark
⁴Institute of Aerodynamics and Gas Dynamics (IAG), University of Stuttgart, Pfaffenwaldring 21 Stuttgart 70569, Germany
⁵Laboratory of Aerodynamics, National Technical University of Athens, Greece

E-mail: c.j.simaoferreira@tudelft.nl

Abstract. The FP7 AdVanced Aerodynamic Tools for lArge Rotors - Avatar project aims to develop and validate advanced aerodynamic models, to be used in integral design codes for the next generation of large scale wind turbines (10-20MW). One of the approaches towards reaching rotors for 10-20MW size is the application of flow control devices, such as flaps. In Task 3.2: Development of aerodynamic codes for modelling of flow devices on aerofoils and rotors of the Avatar project, aerodynamic codes are benchmarked and validated against the experimental data of a DU95W180 airfoil in steady and unsteady flow, for different angle of attack and flap settings, including unsteady oscillatory trailing-edge-flap motion, carried out within the framework of WP3: Models for Flow Devices and Flow Control, Task 3.1: CFD and Experimental Database. The aerodynamics codes are: AdaptFoil2D, Foil2W, FLOWer, MaPFlow, OpenFOAM, Q³UIC, ATEFlap. The codes include unsteady Eulerian CFD simulations with grid deformation, panel models and indicial engineering models. The validation cases correspond to 18 steady flow cases, and 42 unsteady flow cases, for varying angle of attack, flap deflection and reduced frequency, with free and forced transition. The validation of the models show varying degrees of agreement, varying between models and flow cases.

1. Introduction

The pursuit for lower Cost of Energy (CoE) for wind turbines has resulted in new concepts with active and passive flow control devices ([1]). Most designs focus on increasing the control authority by either passively or actively changing the boundary conditions at the aerodynamic surface. Pre-bend blades, bend-twist coupled blades and vortex generators are examples of passive-control designs. For active control, most concepts involve local devices: microtabs,
boundary layer control and trailing edge flaps. A review of different actively controlled smart rotor concepts was presented in [2], concluding that trailing edge flaps are among the most promising concepts. In the past years the research continued to further assess and understand the possibilities and mechanisms of trailing edge flaps. In [3], a detail study is presented for the application of flaps in a full rotor by looking at the controller and it’s signal to noise ratio, multiple flap systems and sensor (strain gauges) placement. Model predictive control, a new control concept, has been studied both numerically ([4]) and experimentally ([5]) with promising results. The work by ([6]) studied the concept of controlling the flap based on a pressure difference over the airfoil at different chord-wise positions using potential flow. [7] studied the trailing edge flap concept experimentally to demonstrate, test and determine the potential of the concept. In [8], different control concepts using an aero-servo-elastic code based on CFD are evaluated. More recently, the work in [9] studied three state-of-the-art numerical models (Reynolds Averaged Navier Stokes, inviscid-viscid interaction model and a dynamic stall model) for a pitching and a flapping airfoil.

Unsteady experimental validation data is required to fully understand the capabilities/drawbacks of the different models. A thorough experimental study on the influence of the flap motion on the forces was performed in [10]. The FP7-UPWIND project also considered trailing edge flaps on wind turbine airfoils ([11]). One of the aims of the FP7 Advanced Aerodynamic Tools for Large Rotors - Avatar project is to generate reliable simulation models and software tools to include flow control concepts such as trailing edge flaps on large wind turbine blades. Important issues are to predict the aerodynamic implications of flow devices at sectional and blade level, and to develop and validate low/intermediate models to be included in aeroelastic simulations on wind turbines which use flow devices.

This paper presents the validation of seven numerical models against the collected data for measurements on a DU95W180 airfoil equipped with an actuated rigid trailing edge flap with 20% chord in steady and unsteady flow, for different angle of attack and flap settings, including unsteady oscillatory trailing-edge-flap motion, in free and forced laminar-turbulent transition. Different flap oscillation amplitudes and reduced frequencies are employed. The experiments were conducted in the Low Turbulence Wind Tunnel of Delft University of Technology with a model of $c = 0.6\text{m}$ chord at a Reynolds number of $Re \approx 1.0 \times 10^6$. Data includes lift, drag and moment coefficient and pressure distribution over the surface of the airfoil, for both steady and unsteady flow. The experimental campaign was carried out within the framework of WP3: Models for Flow Devices and Flow Control, Task 3.1: CFD and Experimental Database of the FP7-AVATAR project. A digital database of the experimental data is available. The description of the experiment and experimental results is presented in [12].

This work build upon the work presented in [13], which presents the main results of Task 3.2: Development of aerodynamic codes for modelling of flow devices on aerofoils and rotors of the Avatar project.

2. Methodology

Seven aerodynamics codes and models are evaluated in this study: AdaptFoil2D, Foil2W, FLOWer, MaPFlow, OpenFOAM, Q3UIC and ATEFlap. The codes include unsteady Eulerian CFD simulations with grid deformation, panel models and indicial engineering models. A description of the models is presented in [13]. Five of these models (Foil2W, FLOWer, MaPFlow, OpenFOAM, Q3UIC) are validated with steady flow cases, while six (AdaptFoil2D, Foil2W, FLOWer, OpenFOAM, Q3UIC and ATEFlap) are validated against unsteady flow cases.

The experimental validation database encompasses 60 cases: 18 steady and 42 unsteady, varying flap angle, angle of attack, free and forced transition, reduced frequency $k^1$ of the flap

$$k = \frac{\omega c}{U_\infty},$$

where $\omega$ is the frequency of oscillation and $U_\infty$ is the unperturbed flow velocity.
oscillation and amplitude of the oscillation. The list of unsteady cases are presented in Table 1.

In this report, we present the validation using integral load polars for both steady and unsteady cases. Due to the large set of results, only a limited subset of results is presented in this paper. Additionally, four validation terms are used: average lift coefficient for flap angle $\beta = 0^\circ$, and amplitude between upstroke and downstroke values at $\beta = 0^\circ$; and minimum and maximum lift coefficient during the cycle.

The actuation of the flap follow a quasi-sinusoidal shape, as shown by the experimental measurements of flap actuation for two of the cases (Figure 1).

3. Results and discussion

3.1. Results for steady cases

The steady flow cases are defined by the transition (free or forced, see [12]), angle of attack $\alpha$ (based on chord line with no flap deflection) and flap angle $\beta$. Figure 2 presents the steady polars for varying angle of attack, comparing lift, drag and moment coefficient ($C_l$, $C_d$ and $C_m$) for the codes Foil2w, Q$^3$UIC, OpenFOAM, FLOWer and MaPFlow, in free and forced transition. Figure 3 shows the comparison for the pressure distribution at $\beta = 9.2^\circ$, for five angles of attack, in free and forced transition. The results show the validation with steady polars and pressure distributions for maximum flap deflection. The steady results for the case of $\beta = 9.2^\circ$ show significant differences between the results from the models and the experimental results, in particular for the cases of forced transition. These differences are not only visible in terms of stall behaviour and post-stall, but also in the linear region of the lift curve. Differences in pressure distribution are mostly visible in the pressure side, in particular at the flap region.

3.2. Results for unsteady cases

Figure 4 presents an example of the validation of the numerical simulations with the unsteady experimental polars of the DU95W180 airfoil for in several configurations of varying flap angle and fixed angle of attack ($C_l - \beta$, $C_d - \beta$, $C_m - \beta$) at $Re \approx 1.0 \times 10^6$, with free and forced transition. Although the angle of attack is low ($\alpha = 0^\circ$), the results show significant differences in both average value and the hysteresis loop. These differences are more significant for the case of forced transition. With increasing angle of attack, these differences are more significant,

---

2 At the quarter-chord position.
3 Non-dimensioned by the unperturbed dynamic pressure and chord scale.
as seen by the results in Table 3. Table 3 shows the results for lift coefficient for unsteady test cases. Values indicate mean at flap angle $\beta = 0^\circ$, and the difference between upstroke and downstroke values at flap angle $\beta = 0^\circ$. Table 3 presents the results for maximum and minimum lift coefficient in the actuation cycle. Although all models capture the correct trends, the results show significant differences in mean value of the cycles and amplitude for the cases of larger angles of attack, and in particular for the cases of forced transition. These differences might arise not only of unsteady effects, but also from the uncertainty of the models in steady predictions, as seen in the previous section. In a comparison, the different models show similar order of magnitude of error in mean value of amplitude of the cycle; different models perform better for different cases.

4. Conclusions

The sub-set of results presented$^4$ shows that the difference between experimental and numerical results has two sources: an error in the prediction of average steady results; and an error in the prediction of unsteady flow effects. The results for attached flow ($\alpha = 0^\circ$) show that the error in steady flow is also verified in unsteady flow; additionally, the difference in hysteresis amplitude at $\beta = 0^\circ$ demonstrates an error in predicting unsteady effects. For regions of separated flow (or more dominant viscous effects), the models show differences in the estimation of the amplitude of the lift cycle, mostly by over-predicting lift in separated flow. A preliminary observation shows that the accuracy of the models compounds their accuracy in predicting steady loads (there is a small variation of error with reduced frequency) with the accuracy in predicting the hysteresis loop. For attached flow regions, these effects could perhaps be decoupled, providing two terms of validation and model improvement.

Acknowledgments

This project has received funding from the European Union’s Seventh Programme for research, technological development and under grant agreement No FP7-ENERGY-2013-1/no. 608396.

References

[1] Berg D E, Wilson D G, Resor B R, Barone M F, Berg J C, Kota S and Ervin G 2009 Proc. of WindPower 1–12
[2] Barlas T and van Kuik G 2010 Progress in Aerospace Sciences 46 1–27 ISSN 03760421
[3] Andersen P B, Henriksen L, Gaunaa M, Bak C and Buhl T 2010 Wind Energy 13 193–206 ISSN 10954244
[4] Barlas T K, Van Der Veen G J and Van Kuik G A M 2011 Wind Energy 15 757–771 ISSN 10954244
[5] Castaignet D, Barlas T, Buhl T, Poulsen N K, Wedel-Heinen J J, Olesen N A, Bak C and Kim T 2013 Wind Energy 17 549–564 ISSN 10991824
[6] Gaunaa M and Andersen P B 2009 EWEC
[7] Bak C, Gaunaa M, Andersen P B, Buhl T, Hansen P and Clemmensen K 2010 Wind Energy 13 207–219
[8] Heinz J, Sørensen N N and Zahle F 2011 Wind Energy 14 449–462 ISSN 10954244
[9] Bergami L, Riziotis V A and Gaunaa M 2014 Wind Energy ISSN 10954244
[10] Baek P, Jérémiax J G, Kramer P and Gaunaa M 2011 EWEA conference 1–8
[11] Lutz T W A W and Jeremias J 2011 Design and verification of an airfoil with trailing-edge flap and unsteady wind-tunnel tests Upwind wp1b3
[12] Ferreira C S, Baldacchino D, Ragni D, Bernardy S, Timmer N, Gillebaart T and Dedeic A 2015 Unsteady measurements of the du95w180 airfoil with oscillating flap report for task 3.1, FP7 - Avatar project
[13] Ferreira C, Gonzalez A, Baldacchino D, Aparicio M, Gómez S, X M, Barlas A, R G N, Sorensen N N, Trolldborg N, Barakos G, Jost E, Knecht S, Lutz T, Chassapoyiannis P, Diakakis K, Manolesos M, Voutsinas S, Prospathopoulos J, Gillebaart T, Florentie L, van Zuijlen A and Reijerkerk M 2015 Task 3.2 : Development of aerodynamic codes for modelling of flow devices on aerofoils and rotors report for task 3.2, FP7 - Avatar project

$^4$ A limited set of results is presented due to paper-length limit. A more complete analysis if planned for a future publication.
### Table 1. Unsteady test cases used for the validation of the different codes. All cases at chord based Reynolds number $Re \approx 1.0 \times 10^6$. 

| Case    | Transition | $\alpha$ ($^\circ$) | $\beta$ ($^\circ$) | $k$ | QUIC | Oil2D | FLOWer | AdapOil2D | OpenFOAM | ATERap |
|---------|------------|----------------------|---------------------|----|------|-------|--------|------------|-----------|--------|
| UNST 1  | free       | 0                    | $-5.0 : 3.9$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 2  | forced     | 0                    | $-5.0 : 3.9$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 3  | free       | 0                    | $-5.0 : 3.9$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 4  | forced     | 0                    | $-5.0 : 3.9$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 5  | free       | 0                    | $-4.9 : 3.9$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 6  | forced     | 0                    | $-4.9 : 3.9$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 7  | free       | 0                    | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 8  | forced     | 0                    | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 9  | free       | 0                    | $-10.1 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 10 | forced     | 0                    | $-10.1 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 11 | free       | 0                    | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 12 | forced     | 0                    | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 13 | free       | 8                    | $-5.0 : 3.9$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 14 | forced     | 8                    | $-5.0 : 3.9$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 15 | free       | 8                    | $-5.0 : 3.9$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 16 | forced     | 8                    | $-5.0 : 3.9$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 17 | free       | 8                    | $-4.9 : 3.9$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 18 | forced     | 8                    | $-4.9 : 3.9$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 19 | free       | 8                    | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 20 | forced     | 8                    | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 21 | free       | 8                    | $-10.0 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 22 | forced     | 8                    | $-10.1 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 23 | free       | 8                    | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 24 | forced     | 8                    | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 25 | free       | 10                   | $-5.0 : 3.9$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 26 | free       | 10                   | $-5.0 : 3.9$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 27 | free       | 10                   | $-4.9 : 3.9$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 28 | free       | 10                   | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 29 | free       | 10                   | $-10.1 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 30 | free       | 10                   | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 31 | free       | 18                   | $-5.0 : 3.8$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 32 | forced     | 18                   | $-5.0 : 3.9$        | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 33 | free       | 18                   | $-5.0 : 3.8$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 34 | forced     | 18                   | $-4.9 : 3.9$        | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 35 | free       | 18                   | $-4.9 : 3.8$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 36 | forced     | 18                   | $-4.9 : 3.9$        | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 37 | free       | 18                   | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 38 | forced     | 18                   | $-10.1 : 9.2$       | 0.01 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 39 | free       | 18                   | $-10.1 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 40 | forced     | 18                   | $-10.1 : 9.2$       | 0.05 | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 41 | free       | 18                   | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |
| UNST 42 | forced     | 18                   | $-10.0 : 9.2$       | 0.1  | ✓✓   | ✓✓    | ✓✓     | ✓          | ✓         | ✓      |

**Legend:**

✓: validation through polars $C_l - \beta$, $C_{dp} - \beta$ and $C_m - \beta$.
✓✓: validation includes unsteady pressure distribution.
Figure 2. Validation of the numerical simulations with the steady experimental polars of the DU95W180 airfoil for varying angle of attack and fixed flap angle ($C_l - \alpha$, $C_l - C_d$, $C_m - \alpha$) at $Re \approx 1.0 \times 10^6$, with free and forced transition, for $\beta = 9.2^\circ$ and $-20^\circ < \alpha < 30^\circ$ (cases STDY5 and STDY10).
Figure 3. Validation of the numerical simulations with the steady experimental pressure distribution of the DU95W180 airfoil for several angle of attacks and flap angle $\beta = 9.2^\circ$, at $Re \approx 1.0 \times 10^6$, with free transition (case STDY5).
Figure 4. Validation of the numerical simulations with the unsteady experimental polars of the DU95W180 airfoil for varying flap angle and fixed angle of attack ($C_l - \beta$, $C_{dp} - \beta$, $C_m - \beta$) at $Re \approx 1.0 \times 10^6$, with free and forced transition, for $\alpha = 0^\circ$, $-4.9^\circ < \beta < 3.9^\circ$, $k = 0.1$ (cases UNST5 and UNST6).
| Case | UNST 1 | UNST 2 | UNST 3 | UNST 4 | UNST 5 | UNST 6 | UNST 7 | UNST 8 | UNST 9 | UNST 10 | UNST 11 | UNST 12 | UNST 13 | UNST 14 | UNST 15 | UNST 16 | UNST 17 | UNST 18 | UNST 19 | UNST 20 | UNST 21 | UNST 22 | UNST 23 | UNST 24 | UNST 25 | UNST 26 | UNST 27 | UNST 28 | UNST 29 | UNST 30 | UNST 31 | UNST 32 | UNST 33 | UNST 34 | UNST 35 | UNST 36 | UNST 37 | UNST 38 | UNST 39 | UNST 40 | UNST 41 | UNST 42 |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|      | 0.23   | 0.19   | 0.23   | 0.19   | 0.22   | 0.20   | 0.23   | 0.19   | 0.19   | 0.20   | 0.22   | 1.10   | 0.19   | 1.10   | 0.91   | 1.10   | 1.09   | 0.90   | 1.10   | 0.91   | 1.10   | 0.90   | 1.09   | 1.07   | 0.89   | 1.21   | 1.21   | 1.21   | 1.21   | 1.16   | 1.02   | 0.35   | 0.35   | 0.37   | 0.37   | 0.72   | 0.72   | 0.72   | 0.72   | 0.72   | 0.72   | 0.72   | 0.72   | 0.72   |
|      | 0.025  | 0.018  | 0.087  | 0.065  | 0.134  | 0.125  | 0.044  | 0.034  | 0.182  | 0.141  | 0.290  | 0.232  | 0.012  | 0.001  | 0.066  | 0.111  | 0.108  | 0.035  | 0.023  | 0.095  | 0.035  | 0.023  | 0.066  | 0.127  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  | 0.007  |
|      | -0.008 | -0.033 | -0.032 | -0.001 | -0.070 | -0.017 | -0.010 | -0.030 | -0.066 | -0.043 | -0.147 | -0.036 | -0.002 | -0.001 | -0.002 | -0.037 | -0.081 | -0.001 | -0.005 | -0.005 | -0.006 | -0.012 | -0.001 | -0.011 | -0.007 | -0.011 | -0.007 | -0.007 | -0.008 | -0.007 | -0.008 | -0.007 | -0.007 | -0.007 | -0.007 | -0.007 | -0.007 |
| Codes |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Table 2. Results for lift coefficient for unsteady test cases. Values indicate mean at flap angle $\beta = 0^\circ$, $\lambda$ difference between upstroke and downstroke values at flap angle $\beta = 0^\circ$. Values for Experimental are absolute, values for Codes are relative to Experimental (difference to). |
| Case  | Experimental | QUC   | Foal2W | FOLOW | AdaptFoalD | OpenFOAM | ATEFlap |
|-------|--------------|-------|--------|-------|------------|-----------|---------|
| UNST 1| -0.071   | 0.427 | 0.025  | 0.018 | 0.069      | 0.053     | 0.014   |
| UNST 2| -0.074   | 0.372 | -0.001 | 0.077 | 0.039      | 0.000     | 0.031   |
| UNST 3| -0.065   | 0.418 | 0.036  | 0.015 | 0.027      | 0.043     | 0.030   |
| UNST 4| -0.068   | 0.365 | 0.016  | 0.067 | 0.043      | 0.001     | 0.043   |
| UNST 5| -0.051   | 0.401 | 0.042  | 0.015 | 0.040      | 0.038     | 0.037   |
| UNST 6| -0.057   | 0.350 | 0.031  | 0.060 | 0.042      | 0.005     | 0.051   |
| UNST 7| -0.340   | 0.707 | 0.023  | -0.057| -0.034     | 0.070     | -0.048  |
| UNST 8| -0.347   | 0.605 | -0.032 | 0.128 | 0.094      | -0.021    | 0.071   |
| UNST 9| -0.328   | 0.690 | 0.037  | -0.040| 0.002      | 0.054     | -0.017  |
| UNST 10| -0.331  | 0.595 | -0.002 | 0.108 | 0.095      | -0.015    | 0.088   |
| UNST 11| -0.297  | 0.657 | 0.041  | -0.014| 0.022      | 0.045     | 0.008   |
| UNST 12| -0.302  | 0.572 | 0.018  | 0.091 | 0.087      | -0.019    | 0.095   |
| UNST 13| 0.816   | 1.263 | 0.039  | -0.032| 0.047      | 0.094     | -0.060  |
| UNST 14| 0.704   | 1.018 | 0.119  | 0.238 | 0.055      | 0.051     | 0.070   |
| UNST 15| 0.818   | 1.259 | 0.051  | -0.027| 0.067      | 0.091     | -0.044  |
| UNST 16| 0.705   | 1.020 | 0.138  | 0.228 | 0.060      | 0.049     | 0.084   |
| UNST 17| 0.832   | 1.249 | 0.053  | -0.014| 0.080      | 0.088     | -0.029  |
| UNST 18| 0.707   | 1.023 | 0.159  | 0.213 | 0.065      | 0.041     | 0.098   |
| UNST 19| 0.546   | 1.413 | 0.034  | -0.075| -0.012     | 0.076     | -0.039  |
| UNST 20| 0.488   | 1.172 | 0.029  | 0.253 | 0.058      | 0.062     | 0.049   |
| UNST 21| 0.557   | 1.415 | 0.049  | -0.073| 0.025      | 0.084     | -0.010  |
| UNST 22| 0.493   | 1.173 | 0.068  | 0.248 | 0.065      | 0.053     | 0.074   |
| UNST 23| 0.587   | 1.419 | 0.052  | -0.057| 0.049      | 0.081     | 0.004   |
| UNST 24| 0.507   | 1.178 | 0.108  | 0.232 | 0.072      | 0.044     | 0.096   |
| UNST 25| 1.017   | 1.270 | 0.027  | 0.039 | 0.053      | 0.130     | -0.022  |
| UNST 26| 1.017   | 1.270 | 0.030  | 0.041 | 0.063      | 0.137     | -0.022  |
| UNST 27| 1.019   | 1.275 | -0.027 | 0.041| 0.068      | 0.140     | -0.011  |
| UNST 28| 0.773   | 1.351 | -0.013 | 0.143 | -0.024     | 0.128     | -0.005  |
| UNST 29| 0.782   | 1.359 | 0.017  | 0.172 | -0.015     | 0.113     | 0.019   |
| UNST 30| 0.801   | 1.400 | 0.036  | 0.151 | 0.244      | 0.185     | 0.013   |
| UNST 31| 0.914   | 1.101 | 0.356  | 0.315 | 0.137      | 0.208     | 0.047   |
| UNST 32| 0.904   | 1.090 | 0.380  | 0.330 | 0.224      | 0.217     | -0.003  |
| UNST 33| 0.925   | 1.084 | 0.333  | 0.384 | 0.362      | 0.392     | 0.143   |
| UNST 34| 0.910   | 1.079 | 0.362  | 0.392 | 0.317      | 0.401     | 0.227   |
| UNST 35| 0.918   | 1.091 | 0.317  | 0.401 | 0.315      | 0.254     | 0.217   |
| UNST 36| 0.908   | 1.082 | 0.340  | 0.413 | 0.340      | 0.259     | 0.110   |
| UNST 37| 0.822   | 1.181 | 0.315  | 0.254 | 0.315      | 0.254     | -0.015  |
| UNST 38| 0.803   | 1.175 | 0.340  | 0.259 | 0.263      | 0.367     | 0.144   |
| UNST 39| 0.826   | 1.177 | 0.263  | 0.367 | 0.303      | 0.384     | 0.241   |
| UNST 40| 0.792   | 1.160 | 0.206  | 0.405 | 0.206      | 0.405     | 0.241   |
| UNST 41| 0.821   | 1.187 | 0.206  | 0.405 | 0.206      | 0.405     | 0.241   |
| UNST 42| 0.793   | 1.168 | 0.237  | 0.424 | 0.206      | 0.405     | 0.241   |

Table 3. Results for lift coefficient for unsteady test cases. Values indicate minimum and maximum. Values for Experimental are absolute, values for Codes are relative to Experimental (difference to).