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Validation of DYSTOOL for unsteady aerodynamic modeling of 2D airfoils

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Abstract. From the point of view of wind turbine modeling, an important group of tools is based on blade element momentum (BEM) theory using 2D aerodynamic calculations on the blade elements. Due to the importance of this sectional computation of the blades, the National Renewable Wind Energy Center of Spain (CENER) developed DYSTOOL, an aerodynamic code for 2D airfoil modeling based on the Beddoes-Leishman model. The main focus here is related to the model parameters, whose values depend on the airfoil or the operating conditions. In this work, the values of the parameters are adjusted using available experimental or CFD data. The present document is mainly related to the validation of the results of DYSTOOL for 2D airfoils. The results of the computations have been compared with unsteady experimental data of the S809 and NACA0015 profiles. Some of the cases have also been modeled using the CFD code WMB (Wind Multi Block), within the framework of a collaboration with ACCIONA Windpower. The validation has been performed using pitch oscillations with different reduced frequencies, Reynolds numbers, amplitudes and mean angles of attack. The results have shown a good agreement using the methodology of adjustment for the value of the parameters. DYSTOOL have demonstrated to be a promising tool for 2D airfoil unsteady aerodynamic modeling.

1. Introduction

Nowadays, the improvement of the unsteady aerodynamic modeling of wind turbine blades is considered critical for the rotor and the entire wind turbine development. The variable environment and the dynamics of the components of current and future designs, lead to complex unsteady conditions for the wind turbine blades. The influence of the variable wind speed and angle of attack along the blade sections should be considered and carefully accounted for in the aeroelastic modeling of large wind turbines. The accurate estimation of separated flow and dynamic stall conditions in the blade is essential in order to adequately simulate the real wind turbine operation.

Engineering tools based on the Beddoes-Leishman model (Refs. [1] and [2]) have been broadly used for unsteady aerodynamic modeling of airfoils, and extended to the modeling of blades through the blade element momentum (BEM) theory. This approach offers a good balance between accuracy and computational efficiency, and is a suitable choice for design applications and load estimation. However, the Beddoes-Leishman model is based on several empirical parameters and physical models, coupled using time delays that can be adjusted depending on the state of the different processes. This leads to very different implementations of the same model with a huge influence in the results. Some previous relevant implementations with different characteristics can be found on References [3], [4], [5] and [6].

Taking advantage of the experience in unsteady aerodynamics of wind turbines, CENER developed in 2006 an in-house code for airfoil modeling, called DYSTOOL. The tool is based on the Beddoes-

Leishman model, but some particular modifications have been included in order to improve the model to wind turbine applications. The work presented in the current paper is part of an extensive validation of DYSTOOL using oscillating airfoils in different unsteady conditions. The steady and unsteady experimental data used in the validation have been provided by the Ohio State University (OSU) in the case of the S809 airfoil (Ref. [7]), and the University of Glasgow (GU) in the case of the NACA0015 (Ref. [8]). A brief introduction to the validation was presented in Ref. [9]. Apart from the 2D validation of the code presented here, results of the modeling of a 3D parked blade were presented in Ref. [10], compared with the experimental data.

Next chapter 2 describes the main characteristics of the model and the implementation of the code. Chapter 3 presents some relevant results obtained during the validation. Finally, chapter 4 includes the main conclusions of the paper.

2. Description of DYSTOOL

DYSTOOL is an unsteady aerodynamic tool for airfoil modeling, including separated flow and dynamic stall conditions. The chart included in Figure 1 shows the general workflow of the code. DYSTOOL is based on the implementation of the Beddoes-Leishman model, with four different blocks for attached flow, trailing edge (TE) separated flow, leading edge (LE) separation and dynamic stall. For wind turbine applications, the main modification with respect to the classical model is related to specific model parameters, whose values are allowed to be adjusted depending on the airfoil or operating conditions.

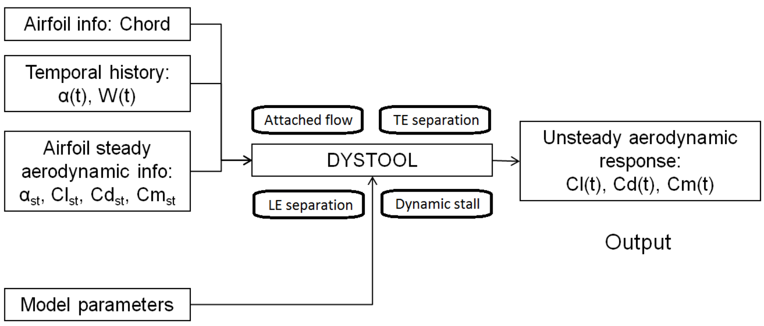

Figure 1. Inputs and outputs of DYSTOOL

The standard inputs of the code are: the airfoil chord (c), the time history in terms of angle of attack (α) and relative wind speed (W) and the steady lift, drag and moment coefficients of the airfoil (Cl_{st}, Cd_{st} and Cm_{st}). This information is supplied to define the unsteady case and the airfoil characteristics (including the Mach number and Reynolds number effect in the steady aerodynamic behavior). The result of the code is the unsteady aerodynamic response of the airfoil, under the operating conditions defined in the input data. The lift, drag and moment coefficients (Cl, Cd and Cm respectively) are obtained in the computation as a function of time.

Apart from the mentioned inputs and outputs, DYSTOOL allows an extra input (the block called model parameters in Figure 1) including the value of a restricted set of parameters of the Beddoes-Leishman model. Different sets of parameters can be provided for different airfoil types or different operating conditions. This allows two different assumptions for the parameters: constants or adjustable values. In the case of adjustable values, it is possible to rely on previous experience to chose the value of the parameters (from similar airfoils, conditions, literature, etc), but a better option is to take advantage of available experimental data or CFD data of the airfoil in unsteady conditions.

In case there are experimental or CFD data available, it can be used to adjust part of the model parameters by means of optimization techniques. The unsteady cases are reproduced using DYSTOOL within an iterative procedure. In each iteration, the results of DYSTOOL are compared with the experimental or CFD data and the selected model parameters are modified. A criteria is established related to the number of iterations or the error based on the least squares method in order to stop the iteration and select the final value of the parameters.

3. Validation

The results of DYSTOOL are validated by comparison with unsteady experimental data of the S809 and NACA0015 profiles among others, although only the two airfoils are presented for the sake of brevity. The results of the S809 have been provided by NREL and the results of the NACA0015 have been obtained from the GU. The comparisons have been performed at different reduced frequencies ($k = \omega c/2W$, where ω is the oscillation frequency in rad/s), Mach numbers (M), Reynolds numbers (Re) and means and amplitudes of the angle of attack. In this section, only 2 cases of the NACA0015 and 2 cases for the S809 are presented compared with experimental data. One of the cases included for the NACA0015 is also presented compared with CFD data.

The highest angles of attack selected are outside the normal operation cases of current wind turbines, but can be present on certain conditions (yaw cases, extreme wind shear, security maneuvers, etc) considered in the certification cases for load calculation. In addition, the conditions can be relevant attending to future wind turbine designs (offshore regimes, large rotors, etc). The Mach number is representative of typical operating conditions. The Reynolds number is low for current wind turbines and probably significantly lower than the expected values for future designs and offshore locations, but this is not affecting the conclusions of the study.

The parameters selected as adjustable in the current work are the time delay T_f for the separation point motion and the critical Cl' for vortex shedding, both explained in References [1] and [2]. The reason of this choice is the important role of the parameters in the dynamic stall progress, and the significant dependency on the airfoil. In the case of T_f, the value also depends on the state or progress of the unsteady conditions (pithing up or down, progress of separation, onset of LE vortex shedding, etc).

For the adjustment of the parameters, unsteady experimental data and CFD data of the S809 and NACA0015 airfoils are used in the optimization routines. Only the dependency on the airfoil is included in the selection of the set of values, because it is considered the most critical influence. Consequently, a different set of values have been used for each airfoil. The values for the S809 are obtained by optimization techniques using unsteady experimental data of the database provided by the OSU, while the values for the NACA0015 are obtained using unsteady experimental data from the GU or CFD simulations of the same cases. The cases compared in the validation and presented in this section are included in the database used to optimize the value of the parameters.

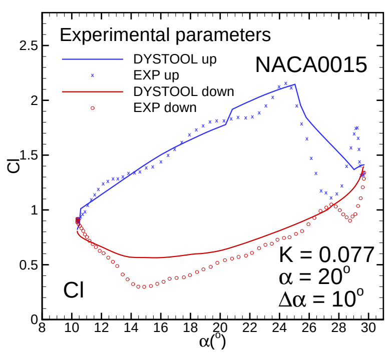

Figure 2. NACA0015 airfoil, c_l vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.077)

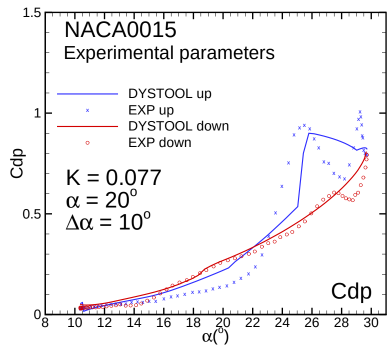

Figure 3. NACA0015 airfoil, c_{dp} vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.077)

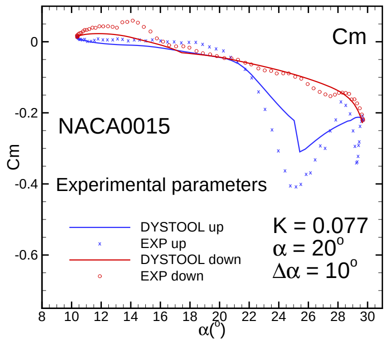

Figure 4. NACA0015 airfoil, c_m vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.077)

Figures 2, 3 and 4 show respectively the comparison of the Cl, Cdp (pressure contribution to the drag coefficient) and Cm between the computations of DYSTOOL and the experimental data of the GU. For all the comparisons between DYSTOOL and experimental data, the upstroke of the oscillation is in blue and the downstroke in red to differentiate the direction of the loops. In this first case, the airfoil is the NACA0015 with $c = 0.55m$ pitching at $M = 0.12$, $k = 0.077$ and $\alpha = 20^\circ \pm 10^\circ$. For the NACA0015, only average data of the cycle is available in the experimental data. The results show a good general agreement between the experimental data and DYSTOOL, with hysteresis loops of similar size and direction, and very close maximum Cl. On the other hand, the negative peak of Cm is slightly underestimated by DYSTOOL and in the reattachment process, the minimum value of the Cl is significantly lower for the experimental data.

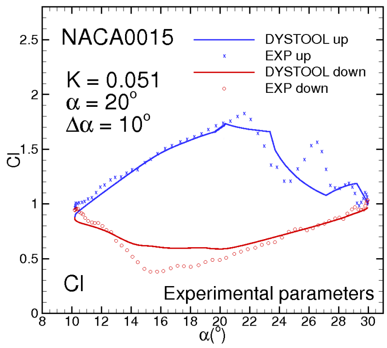

Figure 5. NACA0015 airfoil, c_l vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.051)

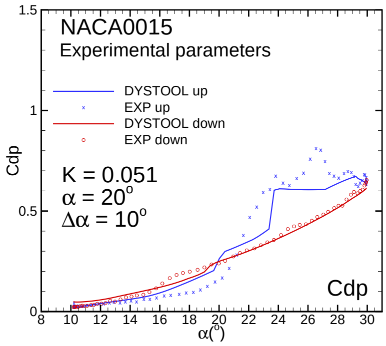

Figure 6. NACA0015 airfoil, c_{dp} vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.051)

Figures 5, 6 and 7 present a new comparison of the Cl, Cdp and Cm between DYSTOOL and the experimental data of the GU. The airfoil is again the NACA0015 with $c = 0.55m$ but the case has a different reduced frequency $k = 0.051$. The experimental data and the results of DYSTOOL reveal similar trends. The hysteresis loops and the maximum and minimum values of Cl, Cdp and Cm are approximately reproduced. However, the deviation in the reattachment is still present for the Cl. In addition, during the pitching up, the experimental case shows a higher frequency of vortex shedding. For this conclusion, each vortex shedding is considered represented by a peak (or a region of high Cl) followed by a decrease of the Cl. The number of structures of increasing and decreasing Cl at the end of the pitching up is bigger for the experimental data.

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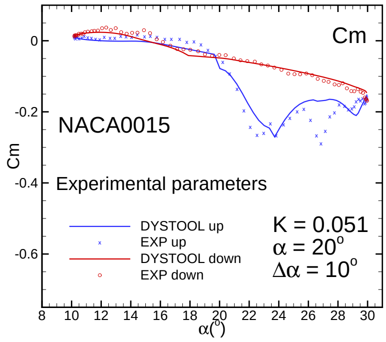

Figure 7. NACA0015 airfoil, c_m vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.051)

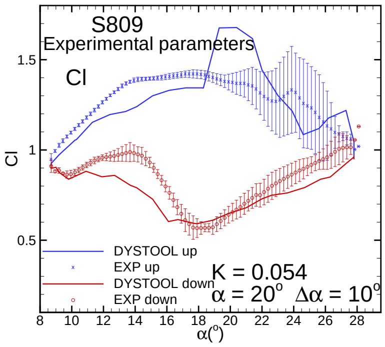

Figure 8. S809 airfoil, c_l vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.1, k=0.054)

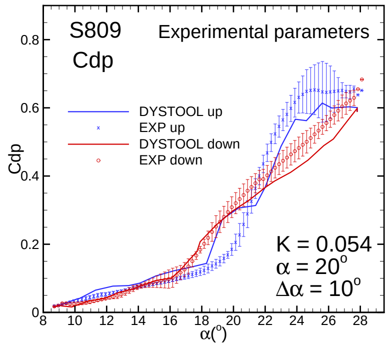

Figure 9. S809 airfoil, c_{dp} vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.1, k=0.054)

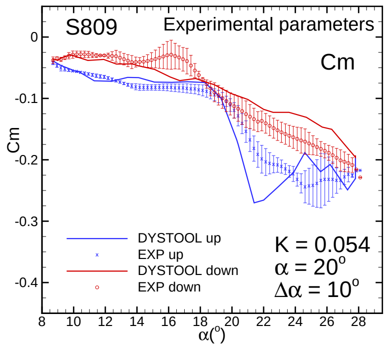

Figure 10. S809 airfoil, c_m vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.1, k=0.054)

Figures 8, 9 and 10 include results of DYSTOOL and experimental data of the OSU, comparing respectively the Cl, Cdp and Cm. The airfoil is the S809, and consequently a different set of parameters have been used for the computations of DYSTOOL. The airfoil have a chord $c = 0.457m$ and is pitching at $M = 0.1$, $k = 0.054$ and $\alpha = 20^\circ \pm 10^\circ$. For the S809, the standard deviation is available in the experimental data and has been included in the comparison. The results of DYSTOOL and the experimental data correlate to a large degree, with similar size and direction of the the hysteresis loops, and similar maximum and minimum values of the load coefficients. However, the vortex shedding is ahead in the computations with respect to the experimental data attending to the peak of Cl. This also affects the location of the negative peak for the moment coefficient.

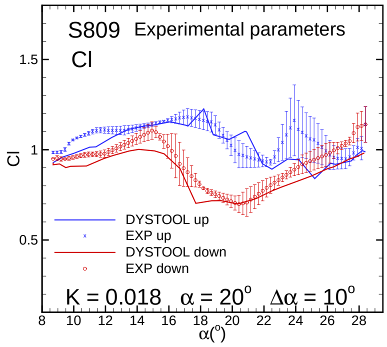

Figure 11. S809 airfoil, c_l vs α ($\alpha = 20° \pm 10°$, M=0.1, k=0.018)

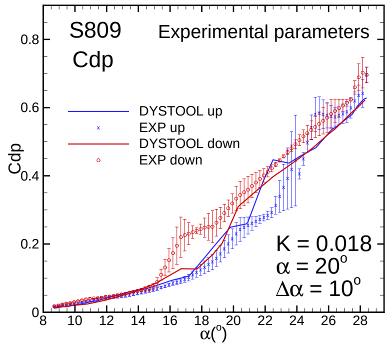

Figure 12. S809 airfoil, c_{dp} vs α ($\alpha = 20° \pm 10°$, M=0.1, k=0.018)

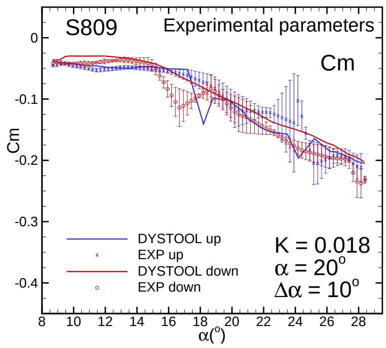

Figure 13. S809 airfoil, c_m vs α ($\alpha = 20° \pm 10°$, M=0.1, k=0.018)

Figures 11, 12 and 13 show a new comparison of the Cl, Cdp and Cm between DYSTOOL and the experimental data of the OSU. The airfoil is again the S809 with $c = 0.457m$ but pitching with a lower reduced frequency $k = 0.018$. Based on the comparison, the results of DYSTOOL and the experimental data agrees to a first order. Apart of the delay of the vortex shedding in the experimental data, the vortex shedding frequency is higher in the results of DYSTOOL as it was for the NACA0015 in the case with lower reduced frequency.

The deviations observed in the reattachment process or in the vortex shedding could be reduced using different sets of parameters not only for each airfoil but also for different conditions of the cases. For example, different sets of parameters could be used depending on the reduced frequency. Furthermore, other parameters could be considered as variable in addition to T_f and Cl'.

In addition to the experimental data, some cases have been simulated using WMB (Wind Multi Block), a CFD method developed by CENER and the University of Liverpool for airfoils and wind turbine aerodynamics analysis (Reference [11]). This later work has been performed during the collaborative project AZIMUT with ACCIONA Windpower. Figure 14 shows the comparison of the Cl between the computations of DYSTOOL and WMB. The airfoil is the NACA0015 with $c = 0.55m$ and the case is the same of Figure 2, pitching at $M = 0.12$, $k = 0.077$ and $\alpha = 20° \pm 10°$. In this case, the parameters T_f and Cl' have been optimized using a database of unsteady CFD computations. The results show a good general agreement between DYSTOOL and the CFD computation in terms of

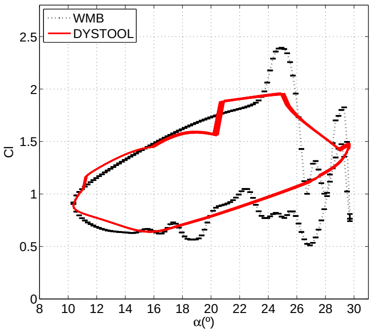

Figure 14. NACA0015 airfoil, c_l vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.077)

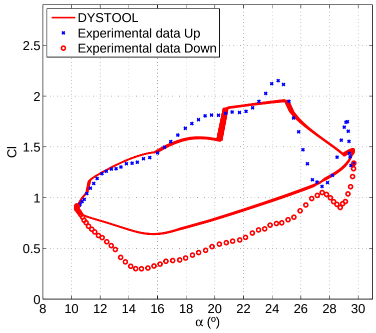

Figure 15. NACA0015 airfoil, c_l vs α ($\alpha = 20^\circ \pm 10^\circ$, M=0.12, k=0.077)

size and direction of the hysteresis loops. However, after the vortex shedding process, the CFD shows strong load oscillations that seems to extend from the vortex shedding up to the reattachment phase. DYSTOOL is not able to reproduce that variability, but seems to capture the mean value smoothing the load variation. Consequently, the maximum and minimum values of the CFD computation are not represented by DYSTOOL.

Finally, in order to evaluate the effect of using different sets of parameters, Figure 15 presents the same comparison shown in Figure 2, between the results of DYSTOOL and the experimental data, but the set of parameters optimized using CFD is used instead of the set of parameters optimized using experimental data. In this case, the peak of Cl is clearly underestimated and the reattachment is not captured in all the extent of the pitching down. This emphasize the importance of using a correct unsteady database for the optimization of the parameters, and the influence of using different sets of values.

4. Conclusions

This paper has presented some of the specific characteristics of DYSTOOL for unsteady aerodynamic modeling of 2D airfoils. The main modification with respect to the classical model is the methodology of adjustment of the model parameters depending on the airfoil or operating conditions. In addition, the validation of the code has been presented. The results have shown an overall good agreement, although there are some deviations, mainly at the vortex shedding and reattachment process. The comparison with CFD results have shown some deviations after the vortex shedding that seems to be associated with the smoother approximation of DYSTOOL to the load variability.

The methodology of optimization has been limited to the parameters T_f and Cl', and a different set of parameters for each airfoil has been considered. For the NACA0015, two different sets of parameters have been obtained using experimental data or CFD for the optimization of the values. The inclusion of additional adjustable parameters and different sets of values depending on the operating conditions could improve the results, and it is considered an interesting line for future investigation.

A limitation of this study is the lack of comparison with other codes for aerodynamic modeling of airfoils. A cross-comparison between commercial or non-commercial codes would be a very interesting exercise to evaluate the accuracy and ranges of deviation of the different tools used in wind turbine design.

The advantage of the methodology presented is the possibility to improve the airfoil modeling adjusting some of the model parameters to take into account the specific aerodynamic characteristics of different airfoils in different operating conditions. The importance of the set of parameters used have been highlighted.

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