Unsteady modelling of the oscillating S809 aerofoil and NREL phase VI parked blade using the Beddoes-Leishman dynamic stall model

Alvaro Gonzalez and Xabier Munduate
Wind Energy Department, CENER - National Renewable Energy Centre, Ciudad de la Innovacion 7, Sarriguren, Navarra, 31621, Spain
E-mail: agonzalez@cener.com

Abstract. An implementation of the Beddoes-Leishman dynamic stall model has been developed at CENER, for modelling the unsteady aerodynamics on oscillating blade sections. The parameters of the model were adjusted for the S809 aerofoil, using an optimization based on genetic algorithms, and taking into account the values found in the literature and the physics of the aerodynamic process. Once the parameters were fixed to a unique set, oscillating cases of the 2D S809 aerofoil were computed, and compared with experimental data. Thus, the accuracy of the model was evaluated. On the other hand, oscillating cases of different span stations of the NREL phase VI parked blade were computed and compared with experimental data, to analyze the three-dimensionality of the dynamic stall on the blade sections. For the unsteady computations on the blade, the model was fed with the steady data of the blade section, to directly consider the geometry influence. In general, the results of the computations for the 2D aerofoil and 3D blade sections were very encouraging.

1. Introduction
Nowadays, a strong demand for the wind energy development is the advance on wind turbine aerodynamic modelling, mainly due to the complex unsteady modelling. The fluctuations on the angle of attack (AOA) and wind velocity over the blades promote changes on forces and moments with respect to the steady state. One of the most critical situations is the dynamic stall phenomenon, broadly described by J.G. Leishman [1].

The current article presents an effort to improve the modelling of the unsteady aerodynamics, including dynamic stall, on parked blades. Concretely, the study has been focused on the 2D S809 aerofoil and the 3D NREL Phase VI parked blade, that uses exclusively the S809 profile on its sections. Firstly, in section 2, the implementation of the Beddoes-Leishman (BL) model and the adjustment of the parameters are presented. Secondly, in section 3, computational and experimental data of oscillating 2D aerofoil cases are compared, together with a brief analysis of the model accuracy. Later, in section 4, computational and experimental data of oscillating cases on the 47% and 80% sections of the 3D blade are compared and analyzed. For the computed cases of the 3D blade sections, the model was fed with the steady data of the corresponding blade span stations, to consider the geometry influence. Finally, in section 5, some of the main conclusions of the work are summarized.
The steady and unsteady experimental data of the 2D aerofoil was provided by the Ohio State University (OSU), and described by R.R. Ramsay, M.J. Hoffman and G.M. Gregorek [2]. On the other hand, the steady experimental data of the 3D blade was extracted from the sequence L of the NREL phase VI Unsteady Aerodynamic Experiment (UAE), while the unsteady experimental data was obtained from the sequence O of the same database, described by M.M. Hand et al. [3].

Other previous documents about the unsteady characteristics and modelling of the S809 profile have been presented by K.G. Pierce [4], J. Johansen [5], M. Mert [6], S. Gupta and J.G. Leishman [7] and W. Sheng, R.A. McD. Galbraith and F.N. Coton [8].

2. Beddoes-Leishman Model and parameters adjustment

The BL is a semi empirical model originally developed for helicopter applications, suitable for compressible and incompressible flows. The current implementation is based on the articles by J.G. Leishman and T.S. Beddoes [9] and [10]. However, there is one modification associated with the idea mentioned by K.G. Pierce [4], related with the definition of different effective separation points for the lift and drag coefficients. The model outputs the unsteady aerodynamic response, and there are two main inputs, the steady data of the aerofoil or blade section, and the time history of AOA and wind speed.

Before computing the cases with the BL model, the parameters should be selected. In this work, a unique set of values for the parameters was selected for the S809 aerofoil, for all the frequency and mean AOA range available in the OSU experimental data. The values were fixed using an optimization based on genetic algorithms, considering the physical sense of the results, and taking into account the values found in the articles of J.G. Leishman and T.S. Beddoes [9], K.G. Pierce [4], and S. Gupta and J.G. Leishman [7]. For the optimization, representative oscillating cases of the S809 aerofoil were computed. The differences between the computations and the corresponding OSU experimental data, were minimized allowing the variation of the parameters. For some parameters, as it is mentioned in the article of M. Mert [6], the optimization cases give a wide dispersion of values, and the choice was based on values found in the literature and the physical analysis of the results obtained by different parameter combinations. At the end, the values selected for the parameters were: \( c_{n_1} = 2.45 \), \( T_p = 2.8 \), \( T_f = 3.5 \), \( T_v = 7.0 \), \( T_{vl} = 9.0 \).

3. 2D aerofoil unsteady results

With the BL model, sinusoidal oscillating cases of the 2D S809 aerofoil, for Reynolds 1x10^6, were computed. The results have been compared with the corresponding experimental data.

Figures 1 and 2 show \( c_l \) and \( c_d \) comparisons respectively, of the lowest frequency, \( k = 0.026 \), and lowest mean AOA, \( 8^\circ \). Predicted \( c_l \) seems to match well the experimental data. However, it is important to highlight a slight overestimation near the maximum AOA at increasing incidence, and a slight overestimation just before the complete reattachment while decreasing the incidence. The \( c_d \) is also well predicted, but the computation is slightly below the experimental data for a range of the increasing AOA and above for some of the decreasing AOA. On the other hand, maximum peak and hysteresis cycles are well represented.

Figures 3 and 4 show \( c_l \) and \( c_d \) comparisons respectively, of the lowest frequency, \( k = 0.025 \), and highest mean AOA, \( 20^\circ \). Increasing the AOA, predicted \( c_l \) seems at first slightly overestimated, near the \( 18^\circ \), but later, near the maximum values of the AOA, experimental values are not captured or extremely underestimated. Decreasing the AOA, the step observed in the experimental data between approximately \( 18^\circ \) and \( 14^\circ \) is smoothed in the computation and maximum and minimum values are not captured. On the other hand, the cycles of the predicted \( c_d \) seem to be well obtained. Predicted \( c_d \) seems to represent well the experimental
data, except the peaks just before the maximum AOA, which are obviously underestimated. The $c_l$ with decreasing AOA seems to be quite well represented.

Figures 5 and 6 show $c_l$ and $c_d$ comparisons respectively, of the highest frequency, $k = 0.077$, and lowest mean AOA, $8^\circ$. The stall incidence for the predicted $c_l$ seems to be slightly delayed. Decreasing the AOA, computed results are always above the experimental data until the region of fully attached flow. For the $c_d$ comparison, the computation is below the experimental data for a range of the increasing AOA and above for some of the decreasing AOA. Furthermore, at the highest AOA, maximum peak is underestimated.

Figures 7 and 8 show $c_l$ and $c_d$ comparisons respectively, of the highest frequency, $k = 0.078$, and highest mean AOA, $20^\circ$. Again for the $c_l$, as for the lowest frequency case with mean AOA $20^\circ$, increasing the incidence, the maximum peaks found near the highest AOA are not captured. Therefore, decreasing the incidence, the step observed in the experimental data between approximately $18^\circ$ and $12^\circ$ is smoothed in the computation and minimum values are not captured. The cycles of the predicted $c_d$ seem to be well obtained, but the peaks increasing the AOA are underestimated. Decreasing the AOA, computed values of $c_d$ are very close to the experimental data.

---

**Figure 1.** 2D S809 aerofoil $c_l$ vs AOA ($AOA = 8^\circ \pm 10^\circ$, $M=0.1$, $k=0.026$)

**Figure 2.** 2D S809 aerofoil $c_d$ vs AOA ($AOA = 8^\circ \pm 10^\circ$, $M=0.1$, $k=0.026$)

**Figure 3.** 2D S809 aerofoil $c_l$ vs AOA ($AOA = 20^\circ \pm 10^\circ$, $M=0.1$, $k=0.025$)

**Figure 4.** 2D S809 aerofoil $c_d$ vs AOA ($AOA = 20^\circ \pm 10^\circ$, $M=0.1$, $k=0.025$)
The results obtained show a good correlation between computational and experimental data. There are mainly two discrepancies observed, one for the dynamic stall vortex modelling, and other for the reattachment process. The first seems to be associated with the S809 vortex shedding, that the model is not capable to capture. The second difference seems to be related with an insufficient delay in the reattachment process. The work presented by W. Sheng, R.A.McD. Galbraith and F.N. Coton [8] also shows discrepancies on the vortex modelling and reattachment region, and a modified dynamic stall model is proposed.

4. 3D parked blade unsteady results
The previous section showed the unsteady behavior of the 2D S809 aerofoil and the ability and restrictions of the BL model to represent the unsteady experimental results. In this section, the capacity of the model to represent the unsteady aerodynamics of a 3D parked blade is revised. Thus, unsteady computations of sinusoidal oscillating cases for the 47% and 80% span stations of the NREL phase VI parked blade, for Reynolds $1 \times 10^6$, are presented and compared with the corresponding experimental data.

For the steady case, the values of the force and moment coefficients for 3D blade sections, are usually different among them and when compared with the 2D aerofoil coefficients. It is
known that these changes are partly related with the different induced AOA promoted on the 3D blade span stations. However, for the parked blade, the article by A. Gonzalez and X. Munduate [11] suggests that, for inboard sections, there are effects distinct from a simple variation of incidence induction, that critically influence the aerodynamic behavior of the blade with respect to the 2D aerofoil. Thus, for the input introduced to the BL model in the unsteady computations of the 3D blade span stations, the experimental steady data of the 3D blade sections is used. Using this methodology, the low frequency oscillating cases of section 3 have been computed for the 47% and 80% blade sections. The results have been compared with the corresponding experimental data, and the differences have been analyzed.

Figures 9 and 10 show the \( c_l \) and \( c_d \) comparisons respectively, of the lowest frequency, \( k = 0.025 \), and lowest mean AOA, 8\(^\circ\), for the 47% blade section. The computation with the BL model is fed with the 47% blade section steady data. This comparison between the computation and the experimental data show a good agreement. Analyzing the figures, it is observed that the computed \( c_l \) seems to fit very well the experimental data. There are only two minimum peaks not captured when the incidence is starting to decrease, but the mean values are well represented in that region. The \( c_d \) shows also a very good agreement between the two curves, although the strong variability of the experimental data near the highest AOA makes the modelling difficult. In general, the extreme values and trend are well represented.

Figures 11 and 12 show the \( c_l \) and \( c_d \) comparisons respectively, of the lowest frequency, \( k = 0.025 \), and highest mean AOA, 20\(^\circ\), for the 47% blade section. The computation with the BL model is carried out again with the 47% blade section steady data. In general, the \( c_l \) computation represents well the mean experimental values. However, due probably to the strong variability on the experimental data, maximum and minimum peaks are not captured. Increasing the incidence from approximately 18\(^\circ\), the experimental data shows a region of peaks that the computation is not able to represent, although the mean values seems to be well captured. Decreasing the incidence, the steps observed in the experimental data between approximately 18\(^\circ\) and 14\(^\circ\) are smoothed in the computation and minimum values are not captured. On the other hand, for the \( c_d \), the mean experimental values are well represented, but the experimental variability is again high making the modelling difficult. Increasing the incidence, there are two peaks not captured, related with the peaks observed for the \( c_l \).

Figures 13 and 14 show the \( c_l \) and \( c_d \) comparisons respectively, of the lowest frequency, \( k = 0.025 \), and lowest mean AOA, 8\(^\circ\), for the 80% blade section. In this case, the computation with the BL model is fed with the 80% blade section steady data. Predicted \( c_l \) and \( c_d \) have in general good agreement with the experimental data. For the \( c_l \), the cycle related with the attached flow region is bigger for experimental data. Therefore, there is a minimum peak not captured when the incidence is starting to decrease. In spite of the differences, the trends and extreme values seems to be relatively well captured. For the \( c_d \), it is only important to highlight that the variability of the experimental data near the highest AOA makes the modelling more difficult.

Figures 15 and 16 show the \( c_l \) and \( c_d \) comparisons respectively, of the lowest frequency, \( k = 0.025 \), and highest mean AOA, 20\(^\circ\), for the 80% blade section. The computation with the BL model is carried out again with the 80% blade section steady data. In general, predicted \( c_l \) and \( c_d \) seems to represent well the mean value of the experimental data, although the maximum and minimum peaks are not easy to capture due to the high variability. For the \( c_l \), as for the 47% span station, there is again a region of peaks that the computation is not capable of represent, and the step observed in the experimental data decreasing the incidence is again smoothed in the computation. For the \( c_d \), the maximum values related with the peaks observed for the \( c_l \) between approximately 20\(^\circ\) and 30\(^\circ\) are underestimated, although in general the mean values seems to be well represented.
Figure 9. 3D blade 47% span station $c_l$ vs AOA ($AOA = 8^\circ \pm 10^\circ$, $M = 0.068$, $k = 0.025$)

Figure 10. 3D blade 47% span station $c_d$ vs AOA ($AOA = 8^\circ \pm 10^\circ$, $M = 0.068$, $k = 0.025$)

Figure 11. 3D blade 47% span station $c_l$ vs AOA ($AOA = 20^\circ \pm 10^\circ$, $M = 0.068$, $k = 0.025$)

Figure 12. 3D blade 47% span station $c_d$ vs AOA ($AOA = 20^\circ \pm 10^\circ$, $M = 0.068$, $k = 0.025$)

Figure 13. 3D blade 80% span station $c_l$ vs AOA ($AOA = 8^\circ \pm 10^\circ$, $M = 0.1$, $k = 0.025$)

Figure 14. 3D blade 80% span station $c_d$ vs AOA ($AOA = 8^\circ \pm 10^\circ$, $M = 0.1$, $k = 0.025$)
The results obtained for the 3D parked blade modelling shows a good correlation between computational and experimental data. Discrepancies in the dynamic stall vortex modelling and the reattachment process are again detected as for the 2D aerofoil case.

5. Conclusions

This work has demonstrated the capacity of the BL model to represent the unsteady aerodynamic behavior of the S809 profile and NREL phase VI parked blade.

One of the challenges of the work has been to fix the value of the parameters of the model. A unique set of values were shown to be valid for all the computations.

The results obtained for the 2D S809 aerofoil are acceptable, with a good correlation of the computational and experimental data. Nevertheless, there are two main discrepancies, one in the dynamic stall vortex shedding, and the other in the reattachment process. In both circumstances, future work is needed to modify the model trying to reproduce these behaviors.

For the NREL phase VI parked blade, the model has demonstrated the ability to represent the unsteady and dynamic stall behavior on different sections. To study the 3D influence in the dynamic stall process, the corresponding steady data of each blade section were used as input to the model for the unsteady cases. It has been proved that this solution gives good results, and the comparison of the computational and experimental data shows good agreement with the same discrepancies found for the 2D aerofoil case. Therefore, it may be concluded that the 3D dynamic stall on a parked blade can be simulated, as referred to forces, based on a 2D simulation with the appropriated inputs.

6. References

[1] Leishman J G. *Principles of Helicopter Aerodynamics*. First edition, 2000.
[2] Reuss Ramsay R, Hoffman M J, and Gregorek G M. Effects of grit roughness and pitch oscillations on the S809 airfoil. Technical Report NREL/TP-442-7817, NREL, December 1995.
[3] Hand M M, Simms D A, Fingersh L J, Jager D W, Cotrell J R, Schreck S, and Larwood S M. Unsteady aerodynamics experiment phase VI: Wind tunnel test configurations and available data campaigns. Technical Report NREL/TP-500-29955, NREL, December 2001.
[4] Pierce K G. *Wind Turbine Load Prediction Using the Beddoes-Leishman Model for Unsteady Aerodynamics and Dynamic Stall*. PhD thesis, The University of Utah - Department of Mechanical Engineering, August 1996.
[5] Johansen J. Unsteady airfoil flows with application to aeroelastic stability. Technical Report Risø-R-1116(EN), Risø National Laboratory, October 1999.

[6] Mert M. Optimization of semi-empirical parameters in the FFA-Beddoes dynamic stall model. Technical Report FFA TN 1999-37, FFA, June 1999.

[7] Gupta S and Leishman J.G. Dynamic stall modelling of the S809 aerofoil and comparison with experiments. Wind Energy, 9(6):521–547, June 2006.

[8] Sheng W, Galbraith R A McD, and Coton F N. A modified dynamic stall model for low mach numbers. In proceedings of the 45th AIAA Aerospace Science Meeting and Exhibit, Reno, Nevada, January 2007.

[9] Leishman J G and Beddoes T S. A generalized method for unsteady airfoil behavior and dynamic stall using the indicial method. In proceedings of the 42nd Annual Forum of the American Helicopter Society, Washington DC, Washington, June 1986.

[10] Leishman J G and Beddoes T S. A semi-empirical model for dynamic stall. Journal of the American Helicopter Society, 34(3):3–17, July 1989.

[11] Gonzalez A and Munduate X. Three-dimensional and rotational aerodynamics on the NREL phase VI wind turbine blade. In proceedings of the 45th AIAA Aerospace Science Meeting and Exhibit, Reno, Nevada, January 2007.