

# Validation of the Beddoes-Leishman Dynamic Stall model in the HAWT Environment, using the MEXICO data

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## **Summary:**

It was the aim of this study to assess the load predicting capability of the Beddoes-Leishman dynamic stall(DS) model in a horizontal axis wind turbine(HAWT) environment, in the presence of yaw-misalignment. The DS model was tailored to the HAWT environment, and validated against unsteady thick airfoil data. Posteriorly the DS model was implemented in a blade element-momentum(BEM) code for yawed flow, and the results were compared with data from the MEXICO database. Generally speaking reasonable to good agreement was found. When large yaw-misalignments are imposed, poor agreement was found in the downstroke of the movement between the model and the experiment. Still, over a revolution the maximum normal force coefficient predicted was always within 8% of experimental data at the inboard stations, which is encouraging especially if blade fatigue calculations are being considered.

## **Introduction:**

For the same angle of attack range **dynamic stall**(DS) is known to impose a large load amplitude on the airfoil section, when compared to the static loading characteristic. This phenomenon is expected to occur in HAWT operation, especially when yaw misalignment is present, and consequentially it becomes crucial to predict the load magnitudes DS will impose on the blades. Several DS models have been proposed, with different degrees of complexity. It was chosen to use the Beddoes-Leishman approach since it is of a semi-empirical nature, i.e. it tries to model the physical phenomena occurring during DS, even though it is relatively simple to implement and requires few empirical constants.

This document starts by explaining how the Beddoes-Leishman DS approach was adapted to the HAWT environment and validating the DS model using thick airfoil unsteady data. Posteriorly the implementation of the DS model and rotational corrections in the BEM code are described. Afterwards it is explained how the MEXICO pressure data was processed and used for comparison with the computational results. Finally experimental and computational results are compared, both qualitatively and quantitatively, and the results are discussed.

## **Methodology:**

### **Adapting the Beddoes-Leishman DS model**

The Beddoes-Leishman DS model was originally developed for helicopter applications, and consequentially it includes the effects of the air's compressibility. In a HAWT environment the expected Mach numbers of operation are  $M < 0.3$ , and accordingly the DS model was simplified by assuming **incompressible flow**.

Another major difference between helicopter and HAWTs are the airfoil sections used. Usually the

profiles for HAWT applications are thick, with relative thicknesses larger than 15%, while helicopter blades are normally equipped with thin airfoil sections.

According to [1], the most critical aspect of DS modelling is to predict the occurrence of leading edge(LE) separation. In the Beddoes-Leishman DS model LE separation is assumed to take place when a certain critical normal force coefficient,  $C_{n,I}$ , is attained. This value can be obtained from the airfoil's static characteristic by taking the normal force coefficient at which a break in the pitching moment curve is visible.

However, when thick airfoils are considered usually significant trailing edge(TE) separation takes place before LE separation occurs. Accordingly the normal force coefficient may decrease with increasing angle of attack before the break in the pitching moment curve occurs. This means that using the criterion from [1] the critical normal force coefficient obtained may actually correspond to a value lower than the maximum  $C_n$ , which is unrealistic. Consequentially it is clear that a different criteria to compute the critical normal force coefficient is needed for HAWT airfoil sections.

In this study **two different LE separation criteria** were implemented in the DS model. The **first approach** was based on the work of Timmer et al[2], where the LE separation angle of attack is related with the LE thickness. In his work Timmer et al obtained a linear empirical relation based on wind tunnel testing for several thick airfoils:

$$\alpha_{LEsep} = 1170.8(y/c) - 1.33$$

In the expression above the nose thickness is represented by the ordinate,  $y/c$  obtained at a relative chordwise position of 1.25%. The critical normal coefficient is the calculated assuming

$$C_{n,I} = (2\pi\alpha_{LEsep} + C_{L,0}) \cos\alpha_{LEsep}$$

The **second approach** used to compute the critical normal force coefficient simply takes the the maximum value of the normal force coefficient, i.e.

$$C_{n,I} = C_{n,MAX}$$

The Ohio State University database of unsteady measurements was used to compare the implemented criteria. Thick airfoils were selected for comparison, and the reduced frequencies of excitation were chosen to be representative of what one may expect to find in a yaw-misaligned HAWT. Some results are shown below:

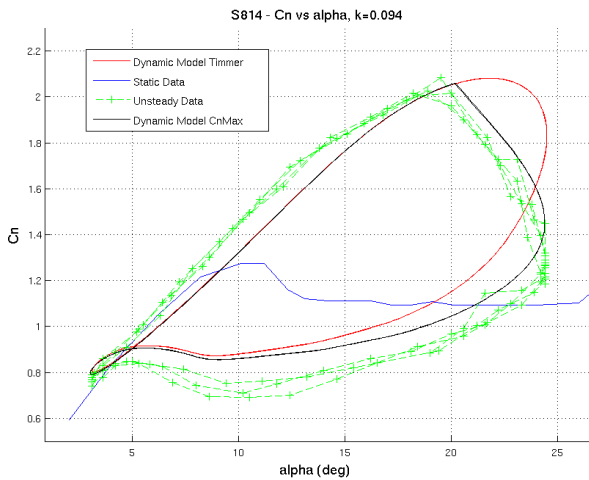


Figure 1: DS model results obtained at high reduced frequency

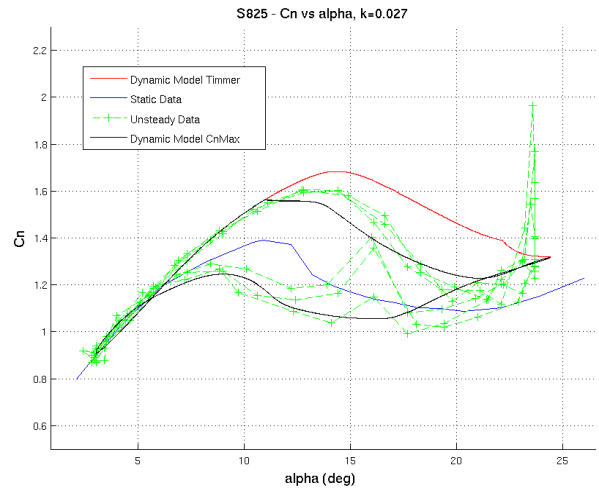


Figure 2: DS model results obtained at low reduced frequency

In the figures above it is clear that the  $C_{n,MAX}$  criterion (represented in black) yielded a better agreement with experimental data (represented in green) than the Timmer criterion (represented in red). Experimental data obtained with other airfoils and at other reduced frequencies also compared better with the  $C_{n,MAX}$  criterion, and consequentially it was used in subsequent calculations.

## Implementation in the BEM code

Considering rotary wings, BEM theory states that the variation of the momentum of the air particles in the cylinder containing the rotor disk is equal to the aerodynamic forces on the blades. In HAWTs the blades will act to slow down the incoming wind, and it is common to express this velocity change by means of induced velocities or induction factors. Usually in BEM codes these induction factors are calculated iteratively.

If yaw-misalignment is present, the induced velocities will change with radial and azimuthal position, and there is no simple theory which accurately describes this velocity distribution. The BEM code implemented in the present study used an **empirical model** for the induced axial velocities from Schepers et al[3]. Even though there are also induced tangential velocities, the present BEM model does not take them into account, based on the fact that these should be of a much smaller magnitude than the axially induced velocities.

This 'empirical' BEM code was used since previous work [4] showed it performed better than a 'classical' BEM code, i.e. than the approach suggested in classical HAWT aerodynamic literature such as [5].

Rotational augmentation of the aerodynamic coefficients was also included, based on the recommendations given in [6]. For the lift coefficient the correction of Snel was implemented:

$$C_{l,3D} = C_{l,2D} + 3 \left( \frac{c}{r} \right)^2 \Delta C_l$$

where  $\frac{c}{r}$  is the ratio between the local chord and the local radius, and  $\Delta C_l$  represents the difference between the static airfoil characteristic and the potential lift coefficient. For the drag coefficient, the correction of Chaviaropoulos and Hansen was used:

$$C_{d,3D} = C_{d,2D} + 2.2 \left( \frac{c}{r} \right) \cos^4(\theta_{tw}) \Delta C_d$$

where  $\theta_{tw}$  is the local blade twist angle, and  $\Delta C_d$  is the difference between the 2D drag coefficient and the drag coefficient obtained when the angle of attack is zero.

The DS model and the rotational corrections were implemented in the BEM code, and the "complete" model was obtained. The model was run considering an azimuthal increment of 10 degrees, and 15 elements in the spanwise direction.

When running the "complete" BEM model, initial values must be prescribed to some of the aerodynamic variables included in the DS model, namely the dynamic point of separation and the vortex time parameter. For this reason it is understandable that some iteration time must be allowed before the model reaches a definite solution. The figure below shows the evolution in time, represented in azimuthal coordinate, of the calculated loads at different spanwise stations:

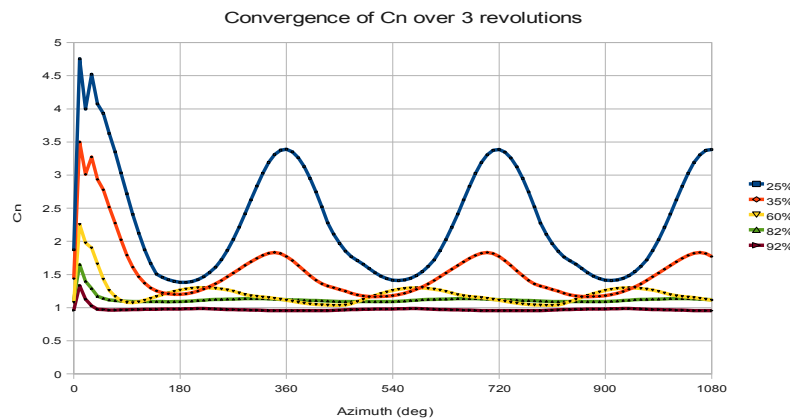


Figure 3:  $C_n$  variation with azimuth angle

One can see in the figure above that after one revolution (360 deg), the results obtained seem to no longer be influenced by the initial condition imposed, based on fact that the normal coefficient variation over the second revolution (from 360 to 720 deg) is indistinguishable from the curve corresponding to the third revolution (from 720 to 1080 deg). For this reason, the results obtained in the third revolution were taken as a converged solution of the computational approach.

## **Experimental Data Used for Comparison**

The MEXICO experiment was a project developed by the European Union with the main goal of providing a database of aerodynamic measurements of a HAWT. For this purpose, an extensively instrumented 4.5m diameter HAWT model was tested in the German-Dutch Wind Tunnel under several flow conditions. In this study the results obtained with the “complete” BEM model are validated against MEXICO data, using the **normal force coefficient** for comparison.

The experimental force coefficient was computed from the MEXICO pressure measurements. A **cubic interpolation** of the **pressure** measured by each sensor<sup>1</sup> was performed over the airfoil surface, and this pressure distribution was integrated over a cubic interpolation of the airfoil surface, yielding the **normal force**. To obtain the normal force coefficient, the computed forces were divided by the maximum pressure occurring over the airfoil, taken as the **maximum of the cubic interpolation** of the pressure sensors, according to

$$C_{n,MEXICO} = \frac{F_{n,Interp}}{P_{max,Interp}}$$

It should be mentioned that some inconsistencies were found in the MEXICO pressure data. Particularly at the 35% spanwise station odd pressure readings were obtained in some MEXICO trials, indicating some pressure sensor malfunction. Consequentially a preliminary visual inspection was conducted for each trial before computing the experimental sectional forces.

Dynamic stall phenomena are expected to occur mostly at **inboard sections**, since at these spanwise stations usually larger angles of attack are found, and yaw-misalignments will cause large angle of attack variations over a revolution. Consequentially emphasis is given at the 25 and 35% spanwise stations of the MEXICO data.

The advance/retreating blade effect present in the MEXICO yawed configuration imposes a minimum angle of attack at the vertically downward azimuthal position, which in the current study corresponds to  $\psi = 180 \text{ deg} \Rightarrow \alpha_{min}$ , and maximum incidence at the vertically upward angular coordinate,  $\psi = 0 \text{ deg} \Rightarrow \alpha_{max}$ . Since this effect will be dominant at the inboard stations when large wind speeds are considered, the **upstroke** of the cycle, i.e. the period when the angle of attack is increasing, corresponds to **azimuthal positions from 180 to 360 deg**. By analogy, the **downstroke** of the cycle, i.e. the period when the angle of attack is decreasing, corresponds to **azimuthal positions from 0 to 180 deg**.

## **Results and Discussion**

The azimuthal variation of the normal force coefficients obtained experimentally (in red) and with the computational model (in blue) is now presented. To assess the influence of the DS model, the results obtained without the DS model (in yellow) are also shown.

Results are shown imposing a moderate and large yaw angles,  $\beta = [30; 45] \text{ deg}$

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<sup>1</sup> It should be noted that the pressure measured by each sensor in the MEXICO rotor blades is the gauge pressure, i.e. the pressure relatively to the atmospheric pressure

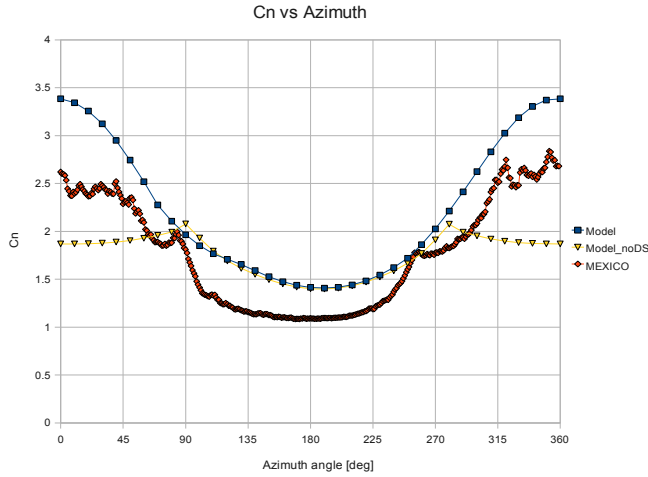


Figure 5: 25% Spanwise Station, Beta=30 deg

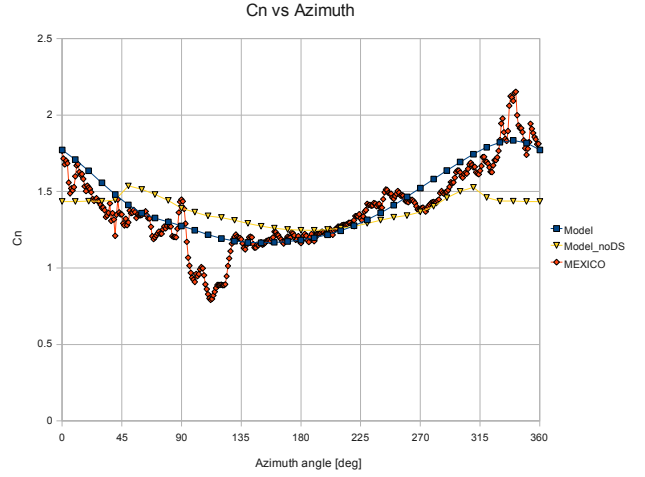


Figure 4: 35% Spanwise station, Beta=30 deg

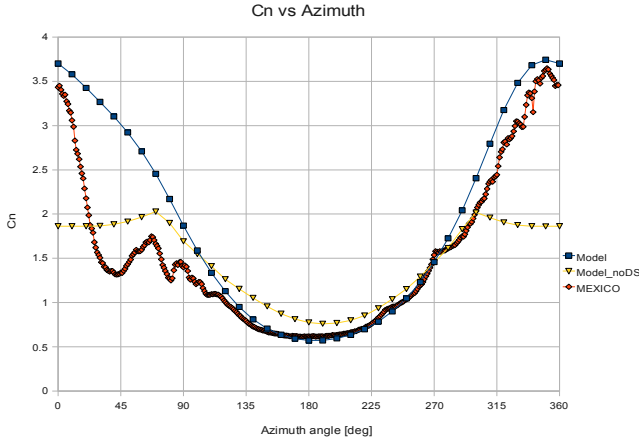


Figure 6: 25% Spanwise Station, Beta=45 deg

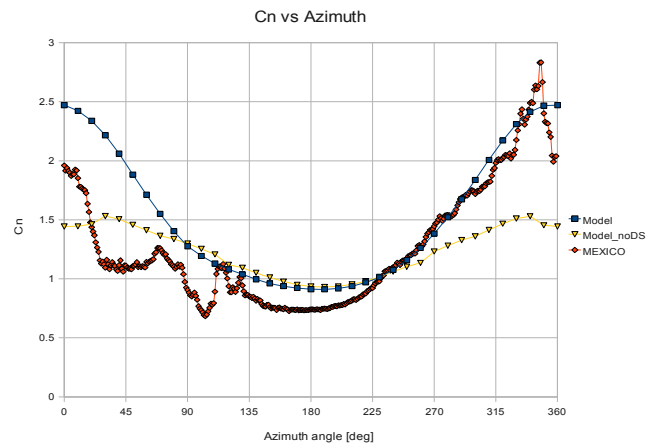


Figure 7: 35% Spanwise station, Beta=45 deg

Generally speaking reasonable to good agreement was found between the predicted loading and the MEXICO data. Including the DS model in the BEM code improves the load prediction capability when compared to the static BEM, especially when large angles of attack are imposed. When considering large yaw-misalignments the agreement found is not so good; in the downstroke motion measurements seem to indicate that significant separation occurs, denoted by an abrupt drop in the normal force coefficient, while the implemented model does not predict this trend. However, quite good agreement was found in the upstroke motion, and consequentially the amplitude of the loading over a revolution is well predicted.

The performance of the implemented calculation method is assessed by computing the **average relative error** in the **normal force coefficient** obtained with BEM code including the DS model. The magnitude of the error was calculated by averaging the relative error of model results over a revolution and assuming the MEXICO data to be the exact solution:

$$\varepsilon_{C_n, avg} = \frac{1}{360} \sum_{\psi=1}^{360} \frac{|C_{n, Model}(\psi) - C_{n, MEXICO}(\psi)|}{C_{n, MEXICO}(\psi)}$$

The results are shown in the table below for several MEXICO trials. The wind tunnel speed is referred to as  $U$  and the relative error was calculated for several spanwise positions, with the result given in percentage:

Trial	U (m/s)	$\beta$ (deg)	25% span	35% span	60% span	82% span
152	18	30	12.1	8.1	12/03/10	10.3
153	24	30	25.4	7.6	6.5	17.9
160	24	15	12.3	11.1	9.9	14.0
167	24	45	25.1	24.0	14.5	6.4
<b>Average</b>	-	-	<b>18.7</b>	<b>12.7</b>	<b>11.6</b>	<b>12.2</b>

Table 1: Average Relative Error in  $C_n$  over a Revolution

The figures included before show good agreement between the predicted and experimental loading during the upstroke of the movement, even when large yaw misalignments are imposed. Since the extreme loads occurring over a revolution are important in assessing the blade's robustness and fatigue resistance, the **relative error** in the **maximum normal force coefficient** over a revolution was computed, according to:

$$\epsilon_{C_n, MAX} = \frac{|C_{n, MEXICO, MAX} - C_{n, Model, MAX}|}{C_{n, MEXICO, MAX}}$$

The results are shown in the table below for several MEXICO trials, with the error given in percentage:

Trial	U (m/s)	$\beta$ (deg)	25% span	35% span	60% span	82% span
152	18	30	2.0	0.2	9.9	5.9
153	24	30	19.1	15.0	0.1	2.2
160	24	15	5.0	2.4	14.9	1.1
167	24	45	2.5	12.8	13.5	4.2
<b>Average</b>	-	-	<b>7.2</b>	<b>7.6</b>	<b>9.6</b>	<b>3.4</b>

Table 2: Relative Error in the Maximum  $C_n$  over a Revolution

The average error in the predicted loads over a revolution is approximately 12%, except for the 25% spanwise station. However, the predicted maximum normal force coefficient occurring over a revolution was within 10% of the measured values. Specifically considering the inboard stations, where the DS influence is larger, the accuracy obtained in predicting the maximum  $C_n$  was below 8%.

It should be noted that rotational augmentation and DS are complex phenomena which are intrinsically related, but their effects have been superimposed in the current model. Still, the results indicate that, even though the experimental trends were not always captured, the **magnitude of the loading amplitude** occurring over a revolution in a yawed configuration at high wind speeds was reasonably well predicted. This is important especially for blade fatigue calculations and is an encouraging result.

In yawed operation, the reduced frequency an airfoil section is working at is usually estimated using the 1P as excitation source. However one can argue that the local degree of unsteadiness is related with the time derivative of the angle of attack, which is related also with the yaw angle and wind speed magnitude. In future research DS models could thus be validated experimentally for very high reduced frequencies, which might occur when large yaw misalignments are present.

## References

- [1] – Leishman, J. & Beddoes, T., '*A semi-empirical model for dynamic stall*', Journal of the American Helicopter Society, vol 34,1989.
- [2] – Timmer, W. and van Rooij, R., '*Some aspects of high angle-of-attack flow on airfoils for wind turbine application*', European Wind Energy Conference and Exhibition, Copenhagen, July 2001
- [3] – Schepers, J and Vermeer, L., '*Een Engineering model voor Scheefstand op basis van Windtunnelmetingen*', ECN-CX—98-070
- [4] –Santos Pereira, R., '*Validating the Beddoes-Leishman Dynamic Stall Model in a HAWT environment*', Msc Thesis, TUDelft, June 2010
- [5] – Burton,T., Sharpe,D., Jenkins,N. and Bossanyi,E., '*Wind Energy Handbook*', Wiley, 2001.
- [6] – Breton,S., Coton,F. & Moe,G., '*A study on Rotational Effects and Different Stall Delay Models Using a Prescribed Wake Vortex Scheme and NREL Phase VI Experiment Data*', Wind Energy 2008;11:459-482