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Mathieu Dubois, Pauline Bozonnet, Frederique Rossillon, Frederic Blondel,
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► To cite this version:

Mathieu Dubois, Pauline Bozonnet, Frederique Rossillon, Frederic Blondel, Caroline Braud. Calcul et validation des propriétés aérodynamiques d'une éolienne à partir d'un scan de pale. 25e Congrès Français de Mécanique, Nantes, 29 août-2 septembre 2022, Association française de mécanique, Aug 2022, Nantes, France. hal-04280092

HAL Id: hal-04280092

<https://hal.science/hal-04280092>

Submitted on 10 Nov 2023

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Estimating a wind turbine aerodynamic properties from blade scan

M. Dubois^a, P. Bozonnet^b, F. Rossillon^b, F. Blondel^a, C. Braud^c

- a. IFP Energies Nouvelles, 1-4 Avenue de Bois Préau, Rueil-Malmaison, France.
- b. IFP Energies Nouvelles, Rond-point de l'échangeur de Solaize, Solaize, France.
- c. LHEEA, Ecole Centrale de Nantes - CNRS, Nantes, France.

Keywords: Blade scan, CFD, SCADA data, aerodynamic model

Abstract:

This article presents a methodology to estimate and validate the aerodynamic properties of a wind turbine from a blade scan. The estimation process is performed by calculating aerodynamic coefficients of different blade sections with numerical simulations while the validation process is done by generating the turbine's power curve from the aerodynamic coefficients and comparing the power to measurements. First of all, a scan is performed on one blade from which a point cloud is generated. Then, regularly spaced sections of the blade can be extracted and used as a basis to discretize the blades of the turbine. Thanks to a CFD (Computational Fluid Dynamics) code, it is then possible to run simulations allowing the estimation of the aerodynamic coefficients for all the sections. Finally, the computed coefficients are used in a BEM (Blade Element Momentum) model to estimate aerodynamic forces and therefore the power generated by the turbine. Results are compared with SCADA (Supervisory Control And Data Acquisition) data to validate the presented methodology. A very good correlation is observed which encourages the possibility of using a blade scan in the estimation of the aerodynamic properties of a wind turbine.

Résumé :

Cet article présente une méthode d'estimation et de validation des propriétés aérodynamiques d'une éolienne à partir d'un scan de pale. L'estimation se fait en calculant les coefficients aérodynamiques de différentes sections de pale régulièrement espacées grâce à des simulations numériques et la validation est réalisée en générant la courbe de puissance de l'éolienne à partir des coefficients aérodynamiques et en la comparant avec des mesures. Dans un premier temps, un scan en 3D sur une des pales est effectué puis des sections en 2D régulièrement espacées sont extraites du scan pour former une discrétisation de la pale. Ensuite, l'utilisation d'un solveur CFD (Computational Fluid Dynamics) permet le calcul des coefficients aérodynamiques de portance et de traînée pour chacune des sections. Enfin, ces coefficients sont utilisés pour alimenter un modèle BEM (Blade Element Momentum) afin d'estimer les forces aérodynamiques ainsi que la puissance générée par la turbine. Les résultats sont comparés à des données SCADA (Supervisory Control And Data Acquisition) pour valider la méthode présentée. Une bonne corrélation est observée, ce qui encourage l'utilisation d'un scan de pale pour la détermination des propriétés aérodynamiques d'une éolienne.

1 Introduction

The different energy pathways built by the grid system french operator RTE (Réseau de transport d'électricité) consider in France an onshore wind energy installed capacity of 43 to 74 GW and the one for offshore of 22 to 62 GW. Wind energy experiences a significant development everywhere in the world thanks to cost reduction that relies on methodological and technological aspects but also on a better understanding and modelling of physical phenomena that occur in wind farms. Following the trend of wind energy strong development, the ANR (Agence Nationale de la Recherche) funded the project MOMENTA (farM rOtor ModEl accouNting aTmospheric wAKE turbulence). The main objective of the project is to better assess the aero-elastic loads of a wind turbine operating in a turbulent atmospheric boundary layer and the added wake turbulence coming from the upstream wind turbines.

Aerodynamic forces originate from the particular geometry of the blades. However, such geometries are owned by turbines manufacturers and are not openly accessible. This article deals with a scan method used to extract the geometry of a blade to obtain its aerodynamic properties. The calculated aerodynamic properties are validated through computation of the generated power of the wind turbine and with comparisons to measurements. For the rest of the study, we will consider that the blades do not deform and we only focus on the aerodynamic part of the turbine.

First of all, the methodology used to obtain the blade scan is presented. This step results in collecting a 3D point cloud data from which regularly spaced 2D blade sections are extracted. The post-processing of these data leads to the estimation of the geometrical characteristics of the different sections (chord, twist, thickness, relative position in rotor plane). Then, the aerodynamic lift and drag coefficients for the different 2D sections are calculated after running RANS (Reynolds Averaged Navier-Stokes) simulations with the use of the solver SU² and an analytical extrapolation method. The aerodynamic coefficients are thus calculated for a 360 degrees range of angle of attack. Finally, lift and drag results, upstream wind characteristics, and operational working conditions are used in a BEM model [1] to estimate the generated power of the turbine. In parallel, data from a SCADA system are extracted for the same wind turbine. The SCADA data concern generated electric power, operation conditions but also nacelle wind characteristics. The estimated power by the BEM is compared to the actual real generated power, also extracted from the SCADA data. It is finally possible to conclude about the global coherence of the method.

2 Blade geometrical properties extraction from scan

In this section, we detail the procedure executed to perform the blade scan and data post-processing that leads to the determination of the geometrical properties of the blade.

The scanned blade is part of a 2MW wind turbine of Saint-Hilaire de Chaléon's site operated by VA-LOREM. The main geometrical characteristics of the blade and the turbine are displayed in Figure 1. They are provided by the manufacturer and will serve as a reference to compare results obtained from the scan and hence conclude about the scan quality.

The scan operation was performed during scheduled maintenance of VALEMO with the rotor on the ground. The chosen blade has no cap at the tip, with the blade pre-bend going upward. This blade was maintained by a lanyard. At the time of the scan, it was expected discrepancies with the manufacturer's in-plane and out-of-plane lines. From this scan operation, we get a point cloud from which 2D sections of the blade are extracted. There are 45 sections in total, named R0 to R44, regularly spaced 1 m from

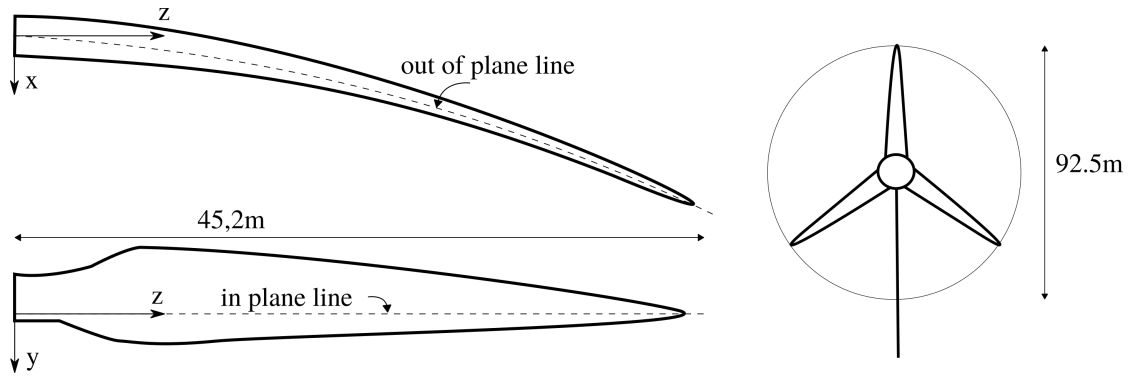


Figure 1 – Blade and turbine main geometry data obtained from turbine manufacturer.

bottom to tip of the blade. A preview of the raw data extracted from the scan can be seen on the left of Figure 2. The coordinates have been arbitrarily modified. Once the sections are extracted from the scan, post-processing is done on the data.

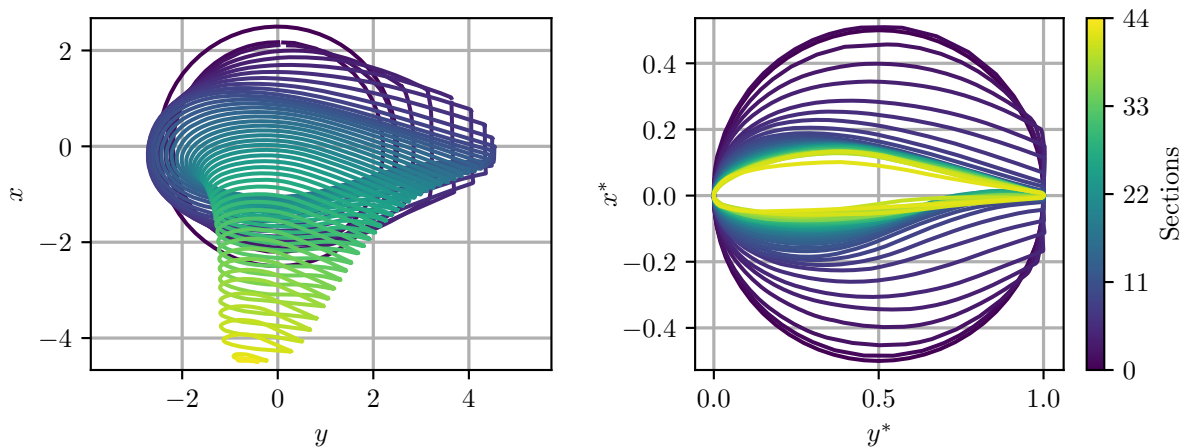


Figure 2 – Sections extracted from the scan (left) and after post processing (right).

2.1 Post processing of scan data

To prepare the flow simulations that will be run on all the sections, it is necessary to align the section chord line with the horizontal axis. Hence, the evolution of the aerodynamic coefficients with a variation of the angle of attack can be easily computed by changing the inflow angle in the simulations. Two techniques have been used to orientate the different sections with the horizontal axis. The first technique consists in taking the points located at the leading and trailing edges of the sections. These two points form a line that is then aligned with the horizontal axis. However, finding the point at the trailing edge of the sections located at the bottom of the blade can be tricky due to their rounded shape. The second technique used for the concerned sections is to consider the scan as a parametric curve f with coordinates x and y as parameters. The curvature k of the scan is then calculated according to equation 1.

$$k = \frac{x'y'' - y'x''}{(x'^2 + y'^2)^{\frac{3}{2}}} \quad (1)$$

With x' and x'' respectively representing the derivative and second derivative with default unitary spacing and with y following the same notation. The trailing edge point location is estimated using the

maximum curvature locations as displayed on Figure 3, with the example of a section located 6 m away from the bottom of the blade. With the use of the curvature, the trailing edge extreme point is then taken as the middle of the two maximum curvature points. The section can be oriented as for the first technique.

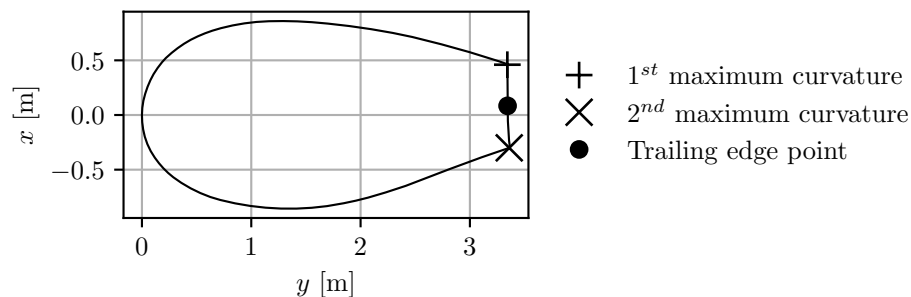


Figure 3 – Curvature technique with the R06 section.

The orientation procedure is executed for all the sections and finally, they are all displaced and resized to have a 1 m chord. Results are displayed on the right of Figure 2. Thanks to the operations performed during the post processing of the blade scan, it is also possible to extract the different blade geometrical properties we are interested in, as detailed in the next paragraph.

2.2 Blade geometrical properties

The orientation and translation procedure make it possible to extract the following geometrical characteristics along the blade:

- In plane displacement
- Out of plane displacement
- Chord section
- Thickness section
- Aerodynamic pitch

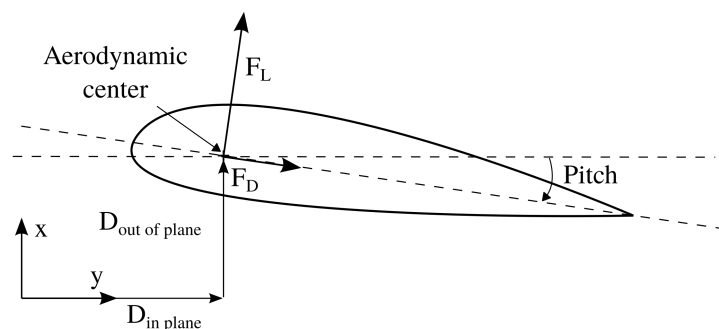


Figure 4 – Definition of airfoil geometry.

As displayed in Figure 4, each section is made up of an aerodynamic center where aerodynamic forces apply and a pitch corresponding to a pre-angle that the section has depending on its spanwise position along the blade. Each section experiences a lift force F_L and a drag force F_D . $D_{in\ plane}$ and $D_{out\ of\ plane}$ respectively correspond to in plane and out of plane displacements. Each section also has an elastic center and a center of gravity that are not coinciding with the aerodynamic center, however within the field of this study we do not know any mechanical properties of the blade which makes impossible the localisation of these centers. We therefore consider that elastic and gravity centers coincide with the aerodynamic center.

The blade scan provides information on the location of the aerodynamic center. The point is located on the section chord line for symmetrical airfoils and very close for the cambered airfoil. For the rest of the study, we will consider that the aerodynamic center is located on the chord line due to the low

camber of the sections. However, depending on the section we consider, the aerodynamic center will not be located at the same chord proportion. We therefore assume that the aerodynamic center location linearly varies from $\frac{1}{2} \times \text{chord length}$ for the cylinder root section to $\frac{1}{4} \times \text{chord length}$ for the tip blade section, this latter value being often taken in literature [4]. The aerodynamic pitch corresponds to the angle that the section has when the blade is not controlled by any command. In-plane and out-of-plane pre-bend values correspond respectively to displacements in $[y, z]$ and $[x, z]$ planes. Rotation and translation operations of section 2.1 respectively correspond to the aerodynamic pitch angle and to the in-plane and out-of plane pre-bend values.

Figure 5 shows the comparison of the blade geometrical properties between the data extracted from the blade scan with manufacturer. All data have been normalized. In-plane displacement values from the manufacturer are not displayed as it is supposed to be zero. A good agreement concerning chord and thickness evolution is obtained between values extracted from the scan and manufacturer. Only the first section shows a higher value for chord and thickness but this corresponds to the bolt that has been scanned instead of the blade itself at this position. This successful comparison adds confidence in the quality of the blade scan realization and processing, to be then used to compute airfoil aerodynamic properties.

Larger differences are noticeable concerning pre-bend values. This can be explained by the conditions in which the blade has been scanned. Due to the horizontal position of the blade (blade tip pointing towards the sky), gravity effect and the lanyard, the out-of-plane pre-bend computed from the blade scan is, as expected, smaller than the theoretical pre-bend.

Finally, the aerodynamic pitch angle is also extracted and is equal to the rotation applied to each section during the post-processing.

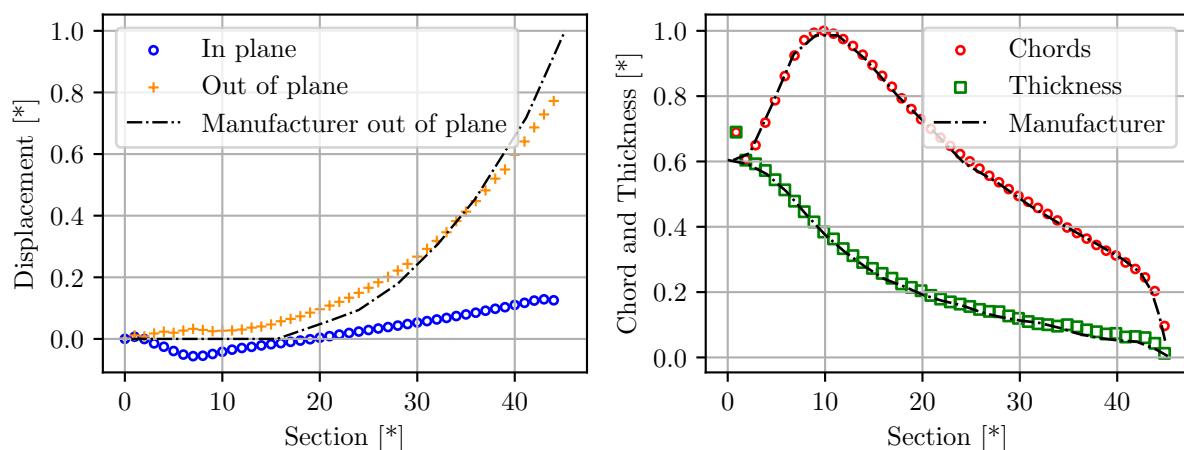


Figure 5 – Comparison of geometrical characteristics extracted from blade scan with manufacturer.

3 Computation of blade elements aerodynamic coefficients

Once all the sections have been processed and correctly oriented, it is possible to run CFD simulations to compute the aerodynamic coefficients. These coefficients are needed as an input in the BEM model to compute forces on the blades and hence the power generated by the turbine.

3.1 Validation case with SU²

The BEM model requires polar curves of blade elements, i.e. lift, drag, and moment coefficients against the angle of attack of the airfoil. Before running simulations on all the sections, a validation case has been run and results are compared with experimental results. The considered airfoil is the S809, dedicated to wind energy and designed by the NREL [8]. Wind tunnel tests have been performed by the OSU (Ohio State University) with Reynolds numbers varying from 0.75 to 1.5 million [7].

The simulations for the aerodynamic coefficients calculations make use of the SU² CFD flow solver [3]. This open-source, finite volume solver is developed by Stanford University. For the current simulations, the incompressible flow solver based on the Chorin approach is used [2]. Computations are run using a RANS framework and an unsteady dual time-stepping scheme is employed due to the separation of the boundary layer at high angles of attack and the potential formation of unsteady vortices behind extrados of the airfoil. Simulations are run with a Reynolds number of 1 million and the boundary layer is assumed to be fully turbulent. The $k - \omega$ SST turbulence model is chosen.

The mesh is generated with the use of the open-source meshing tool Construct2D [5]. A total of 76544 cells are generated with a domain radius of approximately 500 chords. An "O-grid" is generated around the airfoil and the mesh is refined at the boundary layer in order to ensure y^+ to be strictly inferior to 1 in the first cell. Simulations are run for angles of attack ranging from -20 to 25 degrees and results are compared to experimental data from OSU on Figure 6.

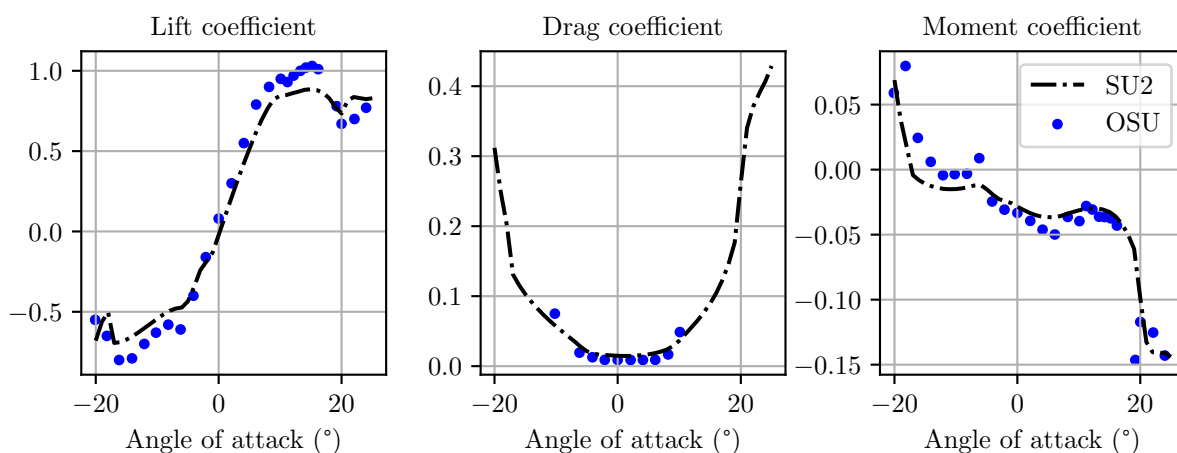


Figure 6 – Results of SU² compared to experimental results.

An overall good correlation is observed, but some discrepancies with the experimental results are also noticed. A good correlation in the linear zone of the lift coefficient is obtained, however, the value of maximum lift is underpredicted. The angles of attack at which stall and maximum lift occur are correctly predicted though. Concerning drag, a very good correlation is observed with experimental results, however, at high angles of attack, we cannot compare values due to the lack of measurements because of technical difficulties of the wind tunnel experiment. Finally, concerning moment coefficient, SU² shows an overall good correlation with the OSU measurements.

The validation case of the S809 airfoil has shown the ability of the flow solver SU² to accurately estimate the aerodynamic coefficients of the airfoil in the attached zone and with some small discrepancies at stall conditions. For the rest of the study, the same configuration of simulation described above is kept to run simulations on the 45 sections extracted from the blade scan. Results will be extracted and then

extrapolated to the 360° range thanks to the Viterna method [10] to be finally used within the BEM model.

3.2 Results of CFD and extrapolation on blade scan

A new mesh is generated for all the sections with the same parameters as the one for the validation case. The angle of attack range goes from $\alpha_{min} = -10^\circ$ to $\alpha_{max} = 15^\circ$ where the lift is approximately the highest for the considered airfoil. Then the Viterna method is applied and the lift and drag coefficients are calculated according to the following equations for angles outside of the range $[\alpha_{min}; \alpha_{max}]$:

$$\begin{cases} C_L = A_1 \sin 2\alpha + A_2 \frac{\cos^2 \alpha}{\sin \alpha} \\ C_D = B_1 \sin^2 \alpha + B_2 \cos \alpha \end{cases}, \quad (2)$$

with:

$$A_1 = \frac{C_{Dmax}}{2}, \quad B_1 = C_{Dmax}, \quad (3)$$

$$A_2 = (C_{Lstall} - C_{Dmax} \sin \alpha_{stall} \cos \alpha_{stall}) \frac{\sin \alpha_{stall}}{\cos^2 \alpha_{stall}}, \quad (4)$$

$$B_2 = \frac{C_{Dstall} - C_{Dmax} \sin^2 \alpha_{stall}}{\cos \alpha_{stall}}, \quad (5)$$

$$C_{Dmax} = 1.11 + 0.18AR. \quad (6)$$

With C_L and C_D being respectively the lift and drag coefficients. α_{stall} represents the angle at which stall occurs with the corresponding C_{Lstall} and C_{Dstall} coefficients. Finally, C_{Dmax} is the maximum drag coefficient calculated from the aspect ratio of the blade AR .

Concerning sections at the bottom of the blade, simulations over the whole range $[-180^\circ; 180^\circ]$ are run due to the particular shape of these sections. Their geometry is closer to a cylinder than an airfoil, hence the Viterna method is not adapted to them. Simulations on a 360° range are run on sections R0 to R04. For the rest of the sections, the Viterna method is applied and some results are displayed on Figure 7.

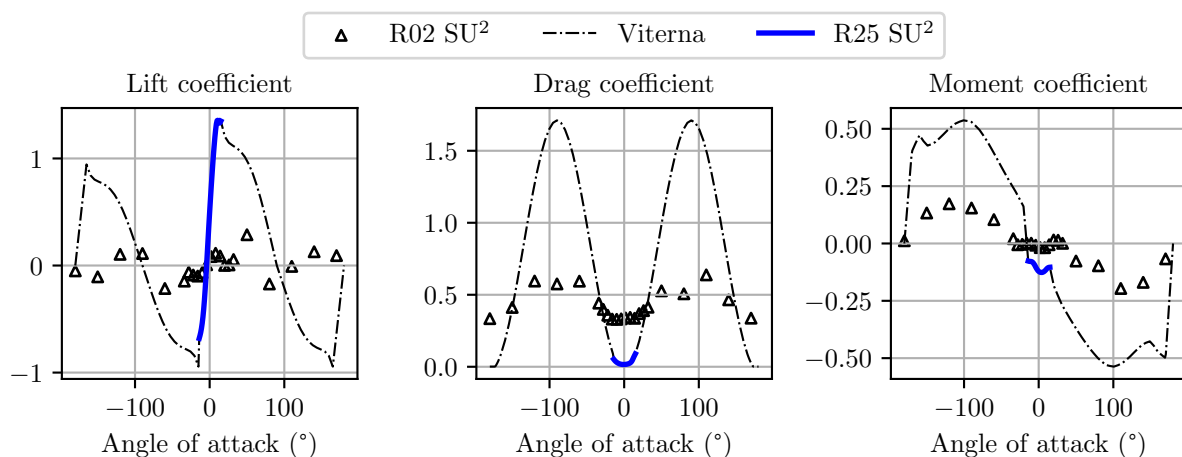


Figure 7 – Results of CFD simulations and Viterna method for R02 and R25 sections.

For sections close to the bottom of the blade, we can see the different variations of the aerodynamic coefficients along with the angle of attack due to the different shape of these sections. This justifies the necessity to run simulations for all angles of attack. The extrapolation process is executed for all sections from R05 to R44 with extrapolated polars being used as the aerodynamic coefficients for the blade elements in the BEM model.

4 Comparison results between SCADA data and BEM

4.1 Filtering SCADA data and transfer function

SCADA data were extracted from the considered turbine between the 30th of October 2020, and the 12th of January 2021. During this time range, the turbine had the opportunity to work in several conditions of wind speed and wind direction which allows us to extract the power curve of the turbine but also the functions of pitch blade and rotational speed against wind speed. These curves constitute the reference to compare with results from the BEM model. However, SCADA data can be imprecise due to different technical problems and some filtering is necessary to apply to work with proper data.

Filtering consists of subdividing the operational wind speed range of the turbine into sub-windows of 0.5 m s^{-1} , calculate the mean value for each of these sub-windows and removing all data that are outside one standard deviation from the mean value. This criterion is applied to the power, rotational speed, and pitch angle variables. Results of the filtering process are shown in Figure 8. After selecting proper data through the filtering process, a nacelle transfer function (NTF) is applied to the extracted set of data. This NTF transforms the data by taking into account the fact that the wind speed SCADA measurement occurs at the level of the nacelle. Hence, the wind speed at this location suffers from aerodynamic impacts such as the induction zone influence from the rotor and the wind speed deficit caused by the wake of the turbine. Therefore, the following NTF is applied on the set of wind speed measurement, $y = a_1x^2 + a_2x + a_3$ with $a_1 = 0.018$, $a_2 = 0.845$ and $a_3 = 0.46$. This NTF comes from the comparison of upwind meteorological tower measurements against nacelle-based measurements of a 1.5 MW General Electric wind turbine [9]. This study has shown an Annual Energy Production (AEP) prediction within 1% of the AEP calculated with upwind measurements.

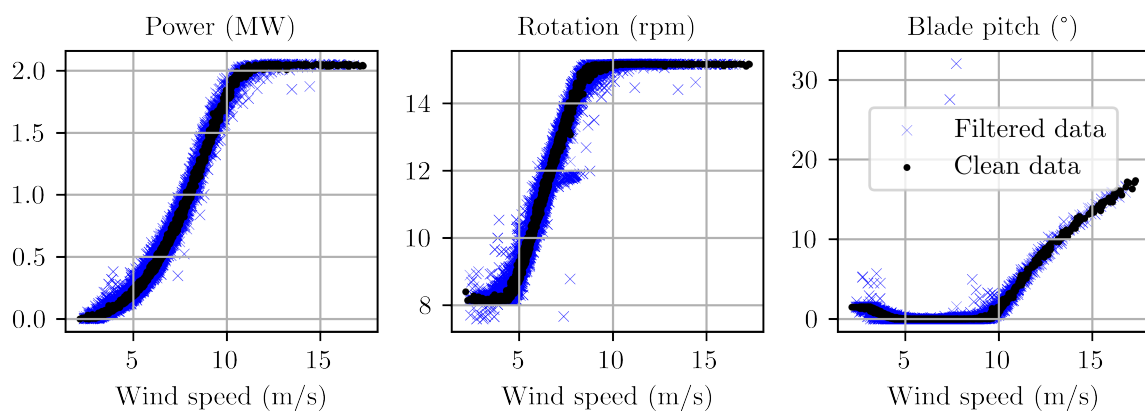


Figure 8 – SCADA data of power, rotational speed and blade pitch after filtering process.

4.2 Results of BEM model

The last step of the study consists of using a BEM model to determine the power generated by the turbine and compare the results to SCADA measurements. SCADA data are representative of the state of work of the turbine, taking into account aero-elastic effects. In the BEM routine, we focus only on the aerodynamic aspects of the turbine, excluding elastic effects from the calculation which may lead to some discrepancies with SCADA data.

The BEM model is the one implemented in the official aerodynamic library of DeepLinesWindTM, AeroDeeP [6]. For a given wind speed, the BEM model needs the rotational speed of the turbine and the blade pitch. From the clean data extracted after filtering the SCADA, an interpolation line passing through the scattered data is generated and is used for the BEM model. These interpolation curves are shown on Figure 9. Due to the lack of SCADA data beyond 15 m s^{-1} the interpolation curve concern-

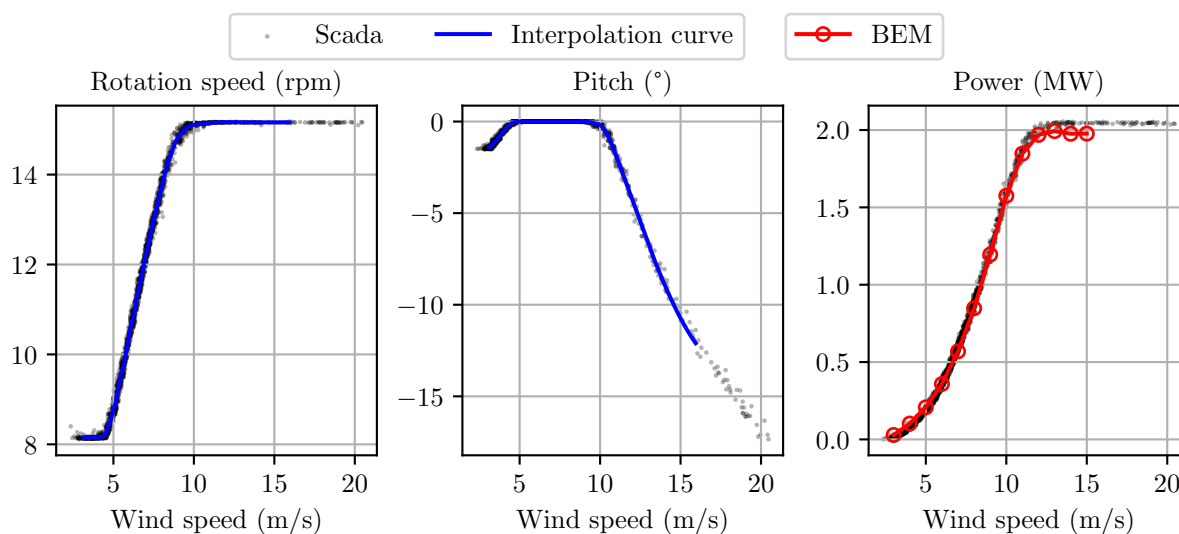


Figure 9 – Interpolation curves for rotational speed (left), blade pitch control (center) and power curve BEM results (right).

ing the pitch control can have various shapes depending on the smoothing method with an influence on the calculated power in the BEM model. Therefore, it has been decided to run BEM calculations until 15 m s^{-1} where SCADA data is dense enough to calculate a proper interpolation curve. Also, the BEM model uses blade elements corresponding to the positions of the sections extracted from the blade scan respectively combined with the aerodynamic coefficients obtained from the CFD simulations. Finally, BEM computations of power generated by the turbine are compared to the power curve extracted from the SCADA measurements. Results are displayed on the right of Figure 9. A good correlation between SCADA power data and results obtained from the BEM computations is observed. The cut-in and nominal wind speed are correctly captured by the BEM model and also the slope of the power curve. However, the power generated by the turbine after nominal wind speed is slightly underestimated with an error of 3%. This can be explained by the sensitivity of the turbine to the blade pitch control law at those high wind speeds: a small degree error in pitch control leads to discrepancies in power results. Moreover, this sensitivity to pitch control also highlights the influence that the NTF has on the results. By modifying the nacelle wind speed measurement to retrieve the upstream wind speed that is actually seen by the turbine, changes in the NTF lead to modification of the blade pitch control law. Hence, the NTF has an influence on the results and may lead to errors in the power computation. Other aspects

like rotor misalignment or controller effect may also lead to small discrepancies between the BEM and SCADA results. Even though the nominal power has a small percentage error, it can be concluded that the SCADA data and the aerodynamic results from the CFD simulations that are used as an input lead to very satisfying results. Hence, the blade scan and the SCADA data have both shown their quality and applicability to the computation of aerodynamic properties energy production of a wind turbine.

5 Conclusion

The aerodynamic properties of an operational wind turbine are not always known. These properties mainly concern lift and drag polar curves of airfoil sections along the blade. Once they are determined they can be used as input to a BEM model and to the computation of the generated power and thus the annual energy production of the turbine. To overcome this lack of aerodynamic knowledge, the present study investigates the possibility of using the scan of a wind turbine blade in order to determine and validate the aerodynamic properties of an operational wind turbine. The methodology consists in extracting regularly spaced airfoil sections among the scan and computing their aerodynamic polar curves for further use in a BEM model. The blade scan has shown the possibility to make available the geometry of many sections along the blade with very good quality. The main geometrical properties of the blade have been retrieved after post-processing the cloud data and comparisons with manufacturer values show the validity of the procedure. Then, aerodynamic polar curves were calculated from the extracted sections with the use of RANS CFD simulations and an extrapolation method. This work delivers lift and drag coefficients for sections along the blade that can be used as input to a BEM model. Finally, the last step of the study compares the power obtained after running the BEM model with the power curve extracted from SCADA data. The rotor rotational speed and blade pitch for a given wind speed are extracted from the SCADA and used as input to the BEM model. A very good correlation is observed between the BEM and the SCADA until 15 m s^{-1} . This result validates the possibility to extract the aerodynamic properties of a wind turbine from a scan of one of its blades. However, a sensitivity to the control parameters of the turbine, in particular the blade pitch is noticed and can lead to discrepancies in the power curve. This aspect underlines the need for care when using SCADA data to extract control laws, especially in tough conditions of wind that happen rarely and lead to a lack of sufficiently SCADA data to perform a proper control law extraction.

Acknowledgement

We would like to thank VALOREM and VALEMO, partners of the MOMENTA project, for providing the blade scan and SCADA data of their turbines. We would also like to thank the ANR for funding the project.

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