Implementation of a New Numerical Tool to Simulate the Wake Rupture in Large-Scale Horizontal-Axis Wind Turbines

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Abstract—**With the objective of increasing knowledge regarding the behaviour of Large-Scale Horizontal-Axis Wind Turbines (LSHAWTs) and provide a correct design for them, aerodynamic, aeroelastic and aeroservoelastic studies have become of interest in the last years. A new numerical method to simulate the wake rupture against the supporting tower is developed in this paper. This simulation scheme is implemented using an existing computational code and it represents an improvement in the process of detecting wake vortex segments passing through the supporting tower. The numerical tool is based on a modified version of the well-known unsteady vortex-lattice method. In order to validate the efficiency and robustness of the proposed wake rupture method, numerical results obtained in this work are compared with results obtained using a numerical scheme developed previously by other researchers. Moreover, a qualitative analysis of shape variations of the wake rupture as a function of the number of aerodynamic elements on both the blades and the tower is carried out. In order to analyse quantitatively the influence of aerodynamic discretization of the blade on the wake rupture model, the starting and ending times of the first rupture are computed. Finally, conclusions are drawn.**

Resumen— **Con el fin de aumentar el conocimiento del comportamiento aerodinámico de turbinas eólicas de eje horizontal y de gran potencia y lograr así un correcto diseño de las mismas, los estudios aerodinámicos, aeroelásticos y aeroservoelásticos de estos sistemas de generación de energías limpias han recobrado interés durante los últimos años. En este trabajo se presenta el desarrollo e implementación computacional de un nuevo método de simulación del fenómeno de ruptura de las estelas vorticosas generadas por las palas al impactar la torre portante; dicha componente influye de manera directa en el comportamiento de la potencia mecánica de la turbina. La nueva técnica numérica se implementó en un código computacional ya existente, basado en una versión modificada del método de red de vórtices no lineal y no estacionario. Con el objetivo de poner en evidencia la eficiencia y robustez del nuevo método de ruptura, se comparan los resultados numéricos con un esquema desarrollado con anterioridad. Además, se analiza cualitativamente la forma de la ruptura al variar el número de elementos aerodinámicos utilizados para discretizar las palas y la torre. Finalmente, para analizar cuantitativamente la influencia de la discretización aerodinámica de la pala en el modelo de ruptura, se calculan los tiempos dimensionales de comienzo y finalización de la primera ruptura de estela y se extraen conclusiones.**

I. INTRODUCTION

With the objective of increasing knowledge about wind turbine performances, structural, aerodynamic and aeroservoelastic studies applied to these machines have grown significantly in the last years.

Recently, the study and design of efficient wind farms is a multidisciplinary research field which involves structures, aerodynamics, and control, among other disciplines. From an aerodynamics point of view, efficient wake models are necessary to estimate the life time of wind turbines, optimize the location of turbines in a farm, and determine the overall performance of a wind farm. In this way, some experimental studies on wind turbine wakes were carried out in situ[1] as well as on scale models used in wind tunnels[2]. Moreover, because of the high costs of the experimental analysis and of the latest advances in computational technologies, the use of numerical models have been gaining ground on the aerodynamic studies of wind turbines. Generally, two approaches can be found: the widely used prescribed wake models[3] and [4], and those which consider free-deforming wakes [5].

Another interesting aspect related to wind turbine aerodynamics is to understand how the turbine support tower affects the production of aerodynamic loads on the turbine blades. It is worth mentioning that although the blade-tower interaction has been a subject of study for wind turbines in downwind configuration [6], with the growth of the rotor dimensions, this topic has become more important and it has been included in the study of horizontal-axis wind turbines in upwind configuration [7].

In order to perform an aerodynamic analysis as accurate as possible and taking into account the aspects aforementioned, it is necessary to consider the rupture of the wake due to the support tower. In this paper, we present a new numerical tool for the detection of wake rupture against the tower of a Large-Scale Horizontal-Axis Wind Turbine (LSHAWT).

There are different methods for modelling the aerodynamics of a wind turbine with different levels of complexity and accuracy, such as the Blade Element Momentum (BEM) theory[8], vortex methods[9], Computational Fluid Dynamics (CFD)[11] and a combination of them[11]. The current simulation framework implements a modified version of the well-known unsteady vortex-lattice method (UVLM) to account for the aerodynamics loads. It includes an improved wake rupture model based on a previous work[12].

The new numerical technique allows modelling the gradual and non-uniform rupture of vortex segments passing through the tower, when they are convected away downstream.

The results obtained by the proposed numerical tool were compared against those reported in [12]. Moreover, the rupture shape has been studied for variations of the number of aerodynamic panels on both, the blades and the support tower. Finally, some significant remarks are stated based on the results obtained with the current framework.

II. COMPUTATIONAL MODEL

A. *Geometry of the Wind Turbine*

Simulations were carried out using a Sandia–National-Laboratory (SNL) 100-meter baseline wind turbine blade. Its technical characteristics and airfoil distribution data can be found in the technical report in [13]. Other geometric components have been defined corresponding to the IB Class[14] wind turbine under study. Some geometric characteristics are presented in Table I.

TABLE I
WIND TURBINE - GEOMETRIC CHARACTERISTICS

H	**RT**	**RB**	**Φ**	**α**	**β**	**Ψ**
[m]	**[m]**	**[m]**	**[°]**	**[°]**	**[°]**	**[°]**
135	3	5.5	-5	0	2.5	0

Where H is the tower height, RT and RB are the tower radius at the top and bottom sections, respectively (see Fig. 1); Φ is the tilt angle, α is the incidence angle between the airstream vector and the X-axis (such angle is on the XY-plane), β is the cone angle, and ψ is the yaw angle.

B. *Reference System*

The aerodynamic computational code performs the calculations by using coordinates respect to an orthonormal right-handed Newtonian reference system N, fixed to the ground and belonging to the tower's bottom section. The Z-axis coincides with the symmetry axis of the support tower (see Fig. 1).

C. *Unsteady Vortex-Lattice Method*

The enlarged and modified version of the UVLM can be applied to 3-D lifting and non-lifting flows. The flow around the body is assumed to be irrotational and uncompressible over the entire flowfield, except for the area next to the solid boundaries of the body and the wake. It is considered that the boundary layers and the wakes are sheets of vorticity[15].

It is possible to apply the UVLM to this kind of machines because the Reynolds number is high and the operational velocity range is subsonic. Therefore, the fluid is considered uncompressible, homogeneous and the high Reynolds number allows confining viscous effects only on the boundary layers and wakes; outside these regions the flowfield is considered irrotational. Reference [16] has more details about the UVLM.

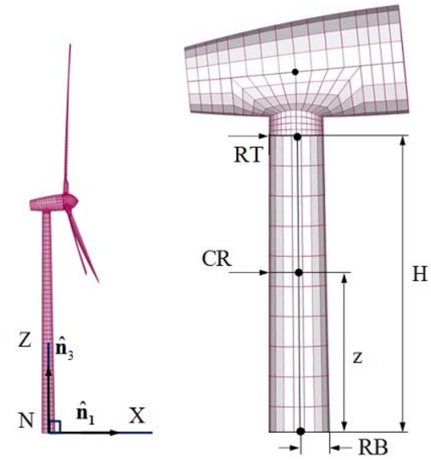

Fig.1. Reference system and tower's geometric measurements

The aerodynamic discretization divides each component surface belonging to the complete turbine into quadrilateral elements of area[16]. These elements are called aerodynamic panels and they have four vortex segments associated. These segments are connected with each other by means of aerodynamic nodes.

D. *Wake Rupture Model*

The detection technique previously implemented in [12] consists in a procedure to determine whether the aerodynamic nodes cross through the support tower.

The rotor and the nacelle are supported by a frustum-conical shape tower, which allows obtaining a good representation of the turbine tower. The computation of the tower radius as a function of the height z, called control radius CR, is straightforward and it is given by:

$$CR = \frac{RT}{H} z + \frac{H - z}{H} RB, \qquad (1)$$

where the parameters and the variable z included into Eq. (1) are depicted in Fig. 1. These geometric dimensions are non-dimensioned respect to the reference length L_{ref}, which is explained further in the text. Then, the wake rupture model verifies whether one aerodynamic node goes through the tower body. Such verification is given by the two conditions shown in Eq. (2);

$$\begin{aligned} x^2 + y^2 &\le CR \\ z &\le H \end{aligned}, \qquad (2)$$

If the conditions in Eq. (2) are satisfied by any aerodynamic node of the wake, then the vortex segments that share such node are cancelled-out along with their vortex intensities. Furthermore, the aerodynamic panel stops being displayed by a visualization software tool.

The improved version of the rupture technique presented in this paper allows considering particular cases of wake rupture that the original model does not. One of them, often found during simulations, considers the situation in which the connecting nodes of a vortex segment are outside the tower, but, the segment itself passes through the tower surface. Therefore, the current wakes rupture model checks whether the connecting nodes as well as the centre-point of the segment itself pass through the tower body. This control scheme is carried out according to the conditions expressed in Eq. (2).

III. RESULTS

A. *Computation of the Rotor Power*

The numerical framework developed in this paper allows to compute the aerodynamic load on the wind turbine in each time step. The mechanical power produced by the wind turbine can be calculated from the rotational speed and the torque about the rotation axis [17].

In this work, the turbine power is computed either by including or neglecting the presence of the tower. Both results are compared.

The vortex wake models for both cases, with and without the tower, are shown in Fig. 2. In such figure, it can be observed that the non-uniform wake rupture is developed gradually in time.

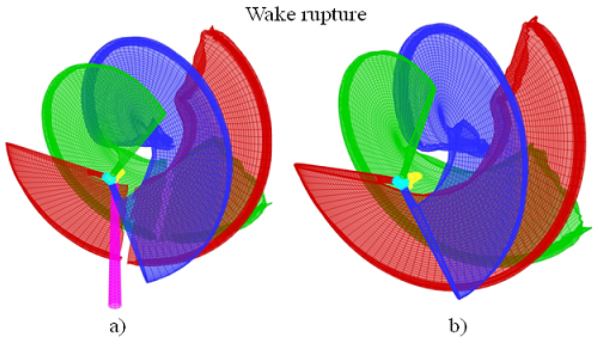

Fig. 2. Development of the vortex wake:a) considering and b) neglecting the tower presence.

The evolution of the turbine power as a function of the azimuthal angle can be visualized in Fig. 3. The power curve shows a number of peaks when the tower is considered, which occurs at exactly the instants the blades pass in front of the tower body. As it can be noted, three peaks appear per rotor revolution generating a periodic component of the power produced by the wind turbine. Such behaviour can be understood as a periodic load applied to the turbine shaft, which may lead to undesired deformations affecting the normal performance of the turbine. Therefore, it has to be studied in detail.

The mean turbine power (P_{mean}) presents a smaller value than the nominal power provided by the manufacturer[13]. The turbine power coefficient is computed from the value of P_{mean}, which was obtained as a result of numerical simulation,

$$C_p = \frac{P}{P_{avail}}, \qquad (3)$$

Where (P_{mean}) is the turbine power, and P_{avail} is the power available for an ideal one-dimension rotor model, given by:

$$P_{avail} = \frac{1}{2}\rho V_{eff}^3 A_{eff}, \qquad (4)$$

where ρ is the air density according to the International Standard Atmosphere, V_{eff} is the effective velocity of the air flow and A_{eff} is the effective area swept by the rotor [18].

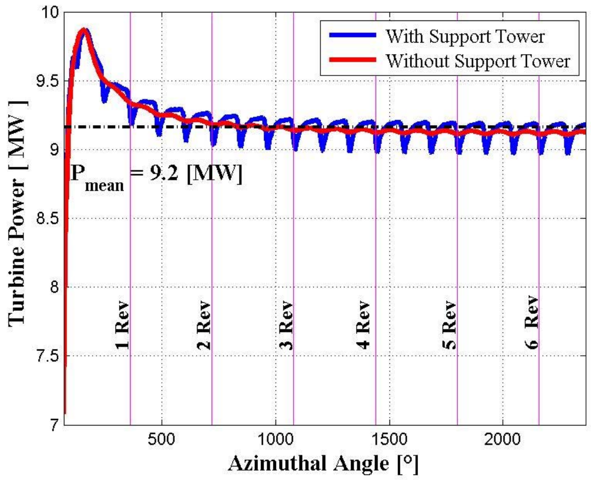

Fig. 3.Turbine power vs. azimuthal angle

From the numerical simulations presented in this work, we obtained a value of $C_p \approx 0.13$, which shows no difference with that obtained in Maza *et al.*[19], that considers the support tower too ($C_p \approx 0.11$), and therefore validate the numerical results displayed.

B. *Original Rupture Technique(ORT) and Proposed Rupture Technique(PRT)*

Two cases of wake rupture are studied. One of them is the original rupture technique (ORT) and the other one is the proposed rupture technique (PRT). The simulation results obtained by ORT and PRT are visualized in Fig. 4 and Fig. 5, respectively.

In Fig. 4 there are wake's vortex segments that pass through the tower but they are not detected by the original model. Those segments that were not cancelled-out are convected downstream. It shows the malfunction of the ORT.

In Fig. 5 it can be observed that wake vortex segments are broken as they pass through the tower body. Therefore, from the results analysed in this section, we can infer, at first, that the proposed strategy (PRT) produces a better representation of vortex wake's physics than the original one.

However, the PRT has limitations as well. One of them corresponds to the case where neither the connecting nodes nor the centre point of the vortex segment are inside the tower body. These cases of rupture cannot be modelled by de PRT presented here (see Fig. 6).

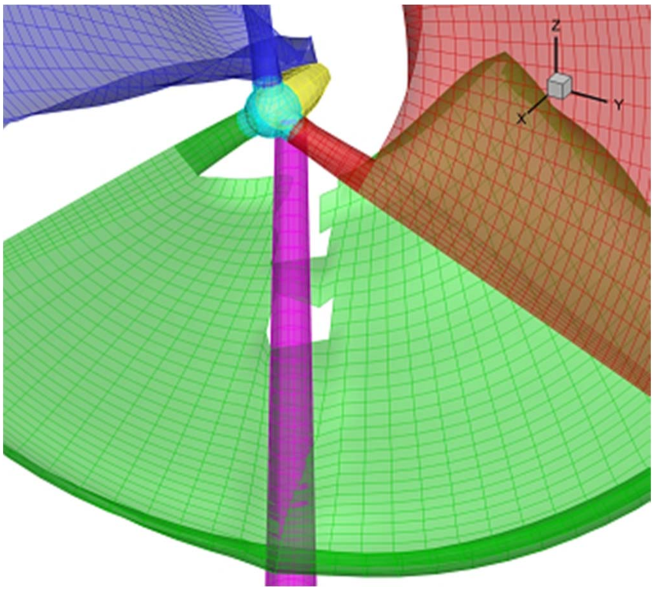

Fig. 4. Simulation of the ORT scheme

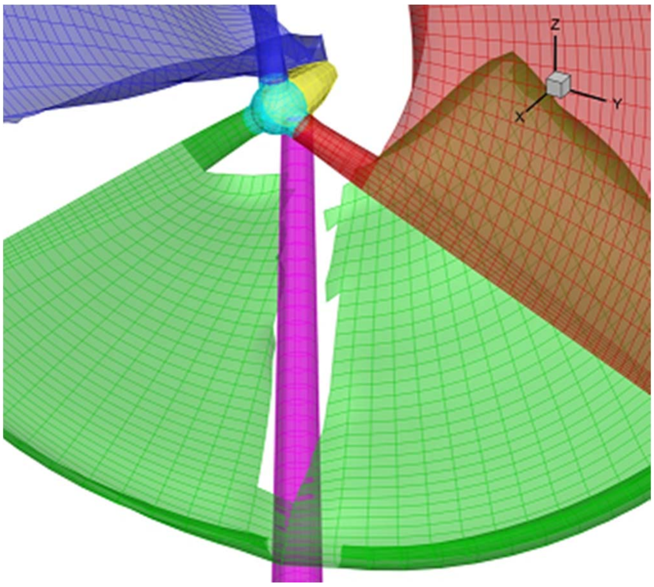

Fig. 5. Simulation of the PRT scheme

The Fig. 6 corresponds to a view from the bottom of the turbine support tower towards the rotor. In the picture, there are segments that belong to zone #1 and zone #2 that go across the tower body and which are not detected by the PRT scheme. However, these segments are cancelled out further in the convection process. Moreover, in zone #2, a strong vortex interaction among the wake and tower aerodynamic panels has been observed.

C. Influence of the Aerodynamic Discretization in the Wake Rupture

In this Subsection we present some numerical results in order to quantify the aerodynamic discretization effects on the wake rupture.

Numerical simulations have been carried out by means of varying the aerodynamic discretization of both the blades and the tower. The studied cases were organized into two groups. The first one, denoted Group #1, qualitatively analyses the shape and development of the wake rupture as the number of aerodynamic panels along the tower increases. The second one, denoted Group #2, quantitatively analyses the starting and ending instants of the first rupture as a function of the density of aerodynamics panels on the blades.

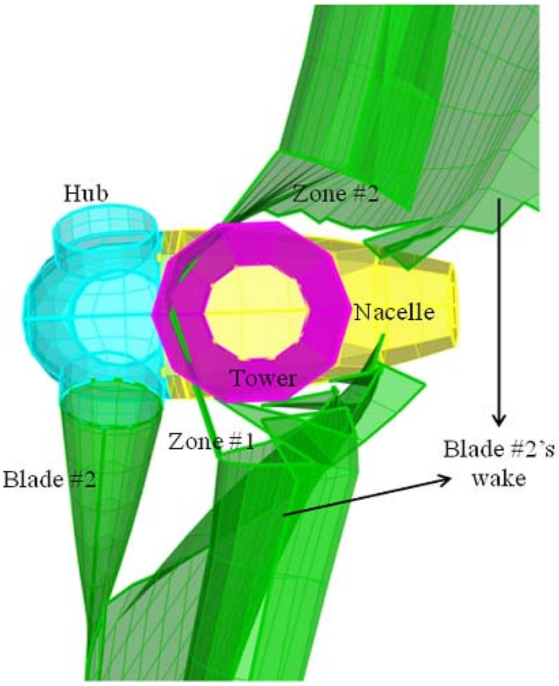

Fig. 6. Wake of the blade #2. Neglected case by PRT scheme

Once those instants were known for each studied discretization case, the lasting time of the wake rupture is computed. It is worth mentioning that to make a valid comparison of the results of Group #2, the simulation parameters and geometric characteristics must be the same (See Table II) and the dimensionless time must be converted into a dimensional quantity, as follows,

$$t_{\mathrm{dim}} = n\,\Delta t_{\mathrm{adim}} \frac{L_{\mathrm{ref}}}{V_{\mathrm{ref}}}, \qquad (3)$$

where $\Delta t_{adim}$is the unit time step used in the UVLM, L_{ref} is the reference length computed from the panels that belong to the blade's lifting surface, V_{ref} is the reference velocity and it has a value equal to the magnitude of the freestream velocity. Finally n is the dimensionless time.

TABLE II
SIMULATION DATA OF THE SNL-100 METERS

NS	NSA	q	V	Ω
[-]	[-]	[°]	[m/s]	[rpm]
600	620	180	15	7

Where NS is the maximum number of time steps, NSA is the minor number of time steps to begin the rupture procedure, q is the pitch angle of each blade, V is the absolute magnitude of the freestream velocity, and Ω is the magnitude of the rotational speed.

Results from Group #1 allow concluding that a change in the density of the aerodynamics panels that belong to the tower does not imply a change in the geometric shape of the wake rupture (see Fig. 7).

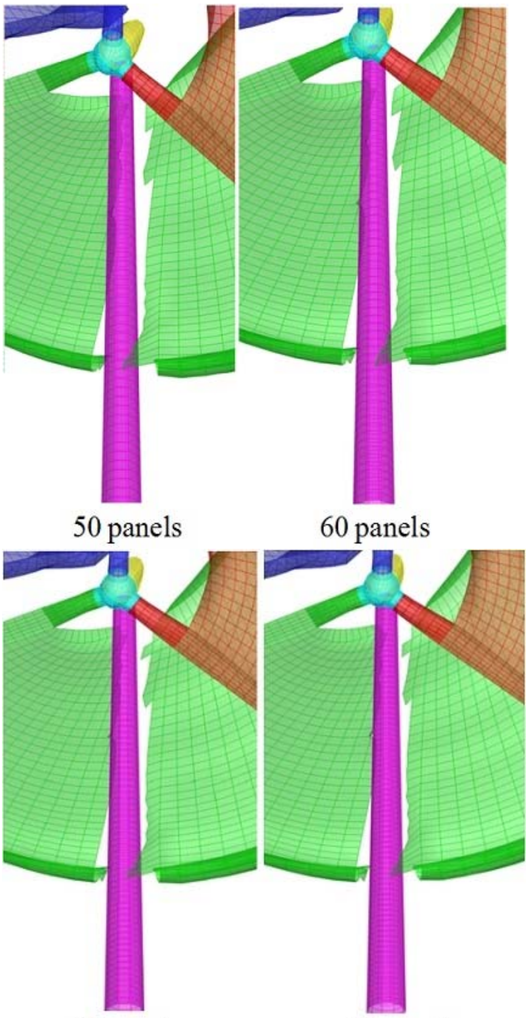
50 panels 60 panels
70 panels 80 panels

Fig.7. Shape of rupture for different aerodynamic discretizations of the tower

TABLE III
SIMULATION RESULTS OF GROUP #2

NBP	L_{ref}	t_{dim} RS	t_{dim} RE	t_{dim} of RE-RS
[-]	[m]	[s]	[s]	[s]
324	1.37	2.01	3.02	1.01
396	1.23	1.96	3.03	1.06
432	1.19	1.98	2.77	0.79
468	1.12	1.94	2.84	0.90
540	1.04	1.93	2.90	0.97
624	0.97	1.93	2.91	0.97
720	0.90	1.86	2.87	0.97
832	0.84	2.02	3.14	1.02
864	0.82	2.02	3.11	1.09
928	0.79	1.95	3.06	1.11
1024	0.75	1.90	3.10	1.20

Results from Group #2 allow performing a quantitative analysis of the starting and ending instants of the first wake rupture, by changing the aerodynamic discretization on the blade surface. The aerodynamic discretization is done in order to keep the quadrilateral shape of the panel unchanged, i.e. the side lengths should not have significant differences from each other.

Table III shows the computed times for the first vortex wake rupture (i.e. the wake of the blade #2, see Fig. 6).

Columns in Table III are in order from the left to the right. The first column is the total number of blade panels (NBP), the second one is the reference length (L_{ref}), third and fourth columns are the starting (RS) and ending (RE) dimensional time of the wake rupture, respectively; and the last column is the difference between the third one and the fourth one (RE-RS).

From Table III, It can be concluded that the time values (columns 3 and 4) do not show a tendency toward a particular value when the blade discretization increases. The dispersion seen in the time values shows the capability of the numerical tool to detect the rupture of wake segments.

IV. CONCLUSION

In this paper, the effect of the support tower in the aerodynamic analysis of a LSHAWT was simulated. The presence of the supporting tower produces a periodic behavior of the turbine power output with the azimuthal angle. Peaks observed in the turbine power output are transformed into load transferred to the rotation axis. The prediction of this kind of load is important in the design of the transmission chain of a wind turbine.

The power coefficient C_p was computed and then compared with other available numerical results for the same wind turbine. No differences were observed between them, which explain the robustness of the numerical tool developed in this paper.

A new computational technique (PRT) to simulate the rupture of wake segments passing through the tower body was developed and implemented. It was successfully compared against the original technique (ORT) of wake rupture. Results show that, the PRT is better than the ORT to model the wake rupture in terms of a good comprehension of the aerodynamic behavior of a LSHAWT considering the support tower.

Future improvements can be implemented to the PRT method although it should be aware that the computational time would grow with each modification of the original scheme.

The simulation results of Group #1 allowed concluding that the shape of the wake rupture did not changed significantly with the increase of the number of panels throughout the tower's lengthwise axis.

The simulation results of Group #2 allowed performing a quantitative analysis about the discretization of the blade's surface and its influence in the starting and ending instants of the wake's first rupture. When the aerodynamic discretization increases, the values of computed times present dispersion and do not show a tendency toward a particular value. Such dispersion shows a remarkable capability of the numerical tool to detect the rupture of wake segments.

ACKNOWLEDGMENT

The authors want to acknowledge to the Programa Pablo Neruda, to the Mechanical Engineering Department at the University of the Andes (Bogotá, Colombia) and to the National Scientific and Technical Research Council

(CONICET) for their contribution to the realization of this work.

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