Vortex identification in wind resource assessment: Application of a new vortex criterion for an improved wind resource analysis

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ABSTRACT

A pertinent task during wind power project development studies is the post-processing analysis of the wind resource simulation results. There is widespread interest in extracting more information from typical commercial software – like WindSim, OpenWind, Meteodyn, WAsP – at a minimal cost during the prospection and/or the development stage of some wind power project.

The current paper proposes the aforementioned enriching post-processing analysis using a vortex criterion capable of extracting further information from a standard wind field.

Vortex identification is a non-consensual topic of discussion among fluid mechanics researchers. Classical criteria such as Q and Δ are hereby confronted with a new definition. The proposed methodology of vortex identification in flows contributes with a more sophisticated wind resource analysis. It is also worth noting that the additional financial investment and computational effort to perform this stage's calculations is negligible when compared to the previous analysis.

Keywords: *Wind Resource Assessment, Vortex Identification, Horizontal Extrapolation, Wind Resource Grid, Atmospheric Stability, Reliability and Risk Mitigation.*

INTRODUCTION

Vortex, as an entity, is not consensually defined in the literature, being a recurrent topic of discussion among fluid mechanics researchers. Classical criteria such as Q and Δ are hereby confronted with a new definition following the ideas proposed in [1,2]: an Eulerian approach that focuses on manifestation of the phenomenon (kinematics) and its independence from the observer (objective). The motivation for this work is to show a useful application of vortex identification assessment in wind power projects. It is worth mentioning that Brazil has shown a great wind energy potential and has already more than 500 wind farms [3].

Thanks to a considerable advance in computational capacity as well as the development of methods to map and measure variables – like wind speed and direction; terrain elevation; and roughness – a large amount of data can now be acquired and feed computational tools that are widely used during micrositing assessment of wind power projects.

Regarding the key aspect of any micrositing analysis: the wind resource assessment, there are two main computational methods available: the numerical implementation of simplified physics models; and Computational Fluid Dynamics (CFD) models. Simplified physics models, such as mass conservative model – OpenWind – and linearized methods – WAsP –, require less computational cost to estimate the Wind Resource Grid (WRG) as well as CFD tools, such as WindSim, computes the WRG through some Reynolds Averaged Navier-Stokes (RANS) model implementation and requires a higher computational effort. Therefore, one can notice that the core activity during wind resource assessment analysis is directly dependent on the WRG simulation and, as a result of that, this aforementioned Wind Resource Grid is a valuable and expensive data base in the wind energy market.

On the other hand, the turbulence intensity in atmospheric flows is very important for a decisive stage of a wind power project: the class selection of the wind turbines. It is well known that commercial horizontal axis wind turbines are sensitive to turbulence, impacting their mechanical efforts and aerodynamic performance. As vortex intensity is intrinsically related to turbulence, its identification and classification is important for a deeper understanding of the characteristics of atmospheric flow and for contributing to a judicious choice of wind turbines to adequately fulfill the project’s lifespan.

Thus, as mentioned in the beginning of this section, the current paper reports a study designed to extract unusual information from the widely used WRG data base and, consequently, applying vortex identification assessment to improve wind power project development via costless post-processing analysis of the Wind Resource Grid (WRG).

The proposed methodology of vortex identification in flows is used to refine wind resource assessment analysis calculating unusual entities alongside the standard outputted results – like pressure fields; average flow velocity fields per sector; spatial turbulence intensity distribution; and others. In the end, it is also important to note that the additional financial investment to perform this stage of post-processing calculations is low and the additional computational effort is negligible when compared to the previous calculation steps, such as wind resource simulations via CFD – the current paper considers only CFD models to estimate the WRG data base and feed the developed post-processing vortex tool.

THEORETICAL BACKGROUND

This section presents the mathematical background used to perform the flow simulation and the post-processing stage. The subsection *“Flow Simulation via CFD”* presents the WindSim mathematical background, and the subsection *“Vortex Identification Criterion”* presents the mathematical background of the new vortex identification method. It is also important to specify that WindSim was the CFD computational tool selected to estimate the WRG data base that will feed every further vortex analysis in the current work and that this tool was used taking into account the thermal stability coupling enabling the vortex assessment of a detailed WRG.

Flow Simulation via CFD

WindSim solves the mean velocity and mean pressure fields using RANS equations coupled with mass and energy conservation equations, in which the k-ε model is employed to compute Boussinesq’s turbulent viscosity. The system of equations which include the transport equations for k and ε are numerically solved via Finite Volume Method – utilizing PHOENICS solver.

Initial and boundary conditions are inputted by the user so WindSim calculates a timed average solution. This model exports a probabilistic distribution of wind and turbulence as a WRG data base. RANS model and the thermal stability coupling can be formulated as [4].

Vortex Identification Criterion

In contrast to the largely used vortex identification criteria, the addressed criterion is objective. Thus, it avoids a tricky question that cannot be easily answered by those standard criteria: Which observer should be elected as the legitimate one?

The theoretical background that supports this criterion is based on a concept stated in [5], in which an elliptical domain is defined as the region where the flow defies the tendency dictated by the symmetric part of the velocity gradient tensor ($\underline{\underline{D}}$).

The Thompson's criterion uses a different mathematical foundation to translate that concept by considering the directional tendency established by $\underline{\underline{D}}$. Therefore, the elliptical domain is defined as the region where $\underline{\underline{M}}$, the time convective covariant derivative of $\underline{\underline{D}}$, defies the directional tendency established by $\underline{\underline{D}}$.

The mathematical treatment of this concept is based on the idea that any tensor can be decomposed into two distinctive parts with respect to a symmetric tensor, namely the in-phase and the out-of-phase parts of the main tensor [1]. In the given context this mathematical procedure is applied decoupling the tensor $\underline{\underline{M}}$ into a part that is in-phase with $\underline{\underline{D}}$ and a part that is out-of-phase with respect to $\underline{\underline{D}}$. Hence, the criterion employed in this work can spatially express domains where $\underline{\underline{M}}$ does not support the directional tendency established by $\underline{\underline{D}}$, using the information provided by the in-phase and out-of-phase parts of $\underline{\underline{M}}$ with respect to $\underline{\underline{D}}$.

The covariant convected time derivative tensorial operator $((\,)^{\Delta})$ is commonly employed in the continuum mechanics literature [6]. Tensor $\underline{\underline{M}}$ is expressed by the following equation:

$$\underline{\underline{M}} = \underline{\underline{D}}^{\Delta} = \underline{\underline{\dot{D}}} + \underline{\underline{D}}\left(\underline{\underline{D}} + \underline{\underline{W}}\right) + \left(\underline{\underline{D}} - \underline{\underline{W}}\right)\underline{\underline{D}} \tag{1}$$

It is easy to demonstrate the objectivity of $\underline{\underline{M}}$

$$\underline{\underline{D}}^{\Delta^{*}} = \underline{\underline{Q}}\,[\underline{\underline{\dot{D}}} + \underline{\underline{D}}\left(\underline{\underline{D}} + \underline{\underline{W}}\right) + \left(\underline{\underline{D}} - \underline{\underline{W}}\right)\underline{\underline{D}}]\,\underline{\underline{Q}}^{T} = \underline{\underline{Q}}(\underline{\underline{D}}^{\Delta})\underline{\underline{Q}}^{T} \tag{2}$$

in which: $\underline{\underline{D^{\Delta^*}}}$ is the description of the tensor $\underline{\underline{M}}$ for an observer who experiences an arbitrary motion with respect to the reference observer.

The objectivity of the classifier proposed here is thus demonstrated, since such a kinematic identifier of vortices depends solely and exclusively on objective tensors – $\underline{\underline{D}}$ and $\underline{\underline{M}}$.

Finally, there is the mathematical treatment of this concept. In order to make possible an easier and more useful implementation for other areas of knowledge that investigate complex flow behaviour, the orthogonal-coaxial tensorial decomposition is applied. In this view, the $\underline{\underline{M}}$ tensor is decoupled in coaxial and orthogonal parts in relation to $\underline{\underline{D}}$, a symmetrical tensor.

$$\underline{\underline{M}} = \underline{\underline{\phi}}_M^{\,D} + \underline{\underline{\tilde{\phi}}}_M^{\,D} \qquad (3)$$

in which: $\underline{\underline{\phi}}_M^{\,D}$ is the coaxial part of the $\underline{\underline{M}}$ tensor (in phase) in relation to $\underline{\underline{D}}$; and $\underline{\underline{\tilde{\phi}}}_M^{\,D}$ is the orthogonal part of the $\underline{\underline{M}}$ tensor (out of phase) in relation to $\underline{\underline{D}}$.

Tensor $\underline{\underline{M}}$ can be rewritten to express the in-phase – it preserves the same eigenvectors as the reference tensor – and out of phase parts – it has orthogonality verified in relation to the reference tensor. This non-traditional expression for $\underline{\underline{M}}$ makes the effective vorticity tensor $\underline{\underline{\overline{W}}}$ explicit, an entity employed by Astarita in his work [7].

$$\underline{\underline{M}} = \underline{\underline{D}}' + 2\,\underline{\underline{D}}^2 + \underline{\underline{D\overline{W}}} - \underline{\underline{\overline{W}D}} \qquad (4)$$

in which: $\underline{\underline{D}}'$ is the material derivative of the $\underline{\underline{D}}$ tensor keeping its eigenvectors fixed.

Entities "$\underline{\underline{D}}' + 2\,\underline{\underline{D}}^2$" (I) and "$\underline{\underline{D\overline{W}}} - \underline{\underline{\overline{W}D}}$" (II) represent orthogonal-coaxial parts of the $\underline{\underline{M}}$ tensor, when it is referenced to $\underline{\underline{D}}$. Both (I and II) are orthogonal to each other, (I) coaxial to D: preserves the inner product and (II) orthogonal to $\underline{\underline{D}}$: preserves the Lie product.

$$\underline{\underline{\tilde{\phi}}}_M^{\,D} = \underline{\underline{D\overline{W}}}\text{-}\underline{\underline{\overline{W}D}} \qquad (5)$$

$$\underline{\underline{\phi}}_M^{\ D} = \underline{\underline{D}}' + 2\,\underline{\underline{D}}^2 \tag{6}$$

In order to classify vortices in the flow, a normalized number is defined, depending on the tensors $\underline{\underline{\phi}}_M^{\ D}$ and $\underline{\underline{M}}$ so that the concept of directional corroboration to the trend dictated by $\underline{\underline{D}}$ is expressed by a number ranging from *0* to *1*. Such a classifier ($\phi_M^{\ D}$) is expressed by the following equation:

$$\phi_M^{\ D} = 1 - \frac{2}{\pi}\cos^{-1}\left(\left\| \underline{\underline{\phi}}_M^{\ D} \right\| \Big/ \left\| \underline{\underline{M}} \right\| \right) \tag{7}$$

The following table is used for the identification of the elliptical domain and, therefore, the presence and intensity of vortices:

Table 1: The criterion for vortex classification.

$\phi_M^{\ D} > 0.5$	Hyperbolic region (volume)
$\phi_M^{\ D} = 0.5$	Parabolic region (surface)
$\phi_M^{\ D} < 0.5$	Elliptical region (volume)

The vortices are assumed to pertain to the elliptical region and the vortical intensity is greater as the value of the classifier $\phi_M^{\ D}$ goes to zero.

In sum, the criterion presented is objective. It is based on a solid concept that defines a vortex in a kinematic perspective and has an easy and pertinent application to most areas of science which can take advantage of complex flows deeper analysis – e.g. the study of atmospheric flow to determine the region's wind quality for a wind resource assessment.

METHODOLOGY

A preliminary data treatment is necessary to generate the required information to feed the computer program, WindSim. Long-term wind speed and direction data series are obtained via linear Measure-Correlate-Predict (MCP) utilizing measurements from meteorological towers inside the region of interest. Roughness and topography are also acquired and georeferenced.

For the numerical simulation, the WindSim program is used with the nesting technique regarding thermal stability. Details about this technique for improving the results of the CFD program simulation are available in [8]. In this paper, the horizontal spatial resolution is 100 m.

Regarding the aforementioned coupling with thermal stability formulation, parameters can be estimated trough a Markov Chain Monte Carlo Bayesian inference to retrieve a value of Monin Obukhov Length (*L*) for neutral, or stable, or unstable profiles – solved numerically via Newton-Rapson for instable cases as shown in [9,10]. A typical Monin-Obukhov length for the field is used as an input in the CFD model and, thus, a more trustworthy WRG is obtained (c. Figure 1)

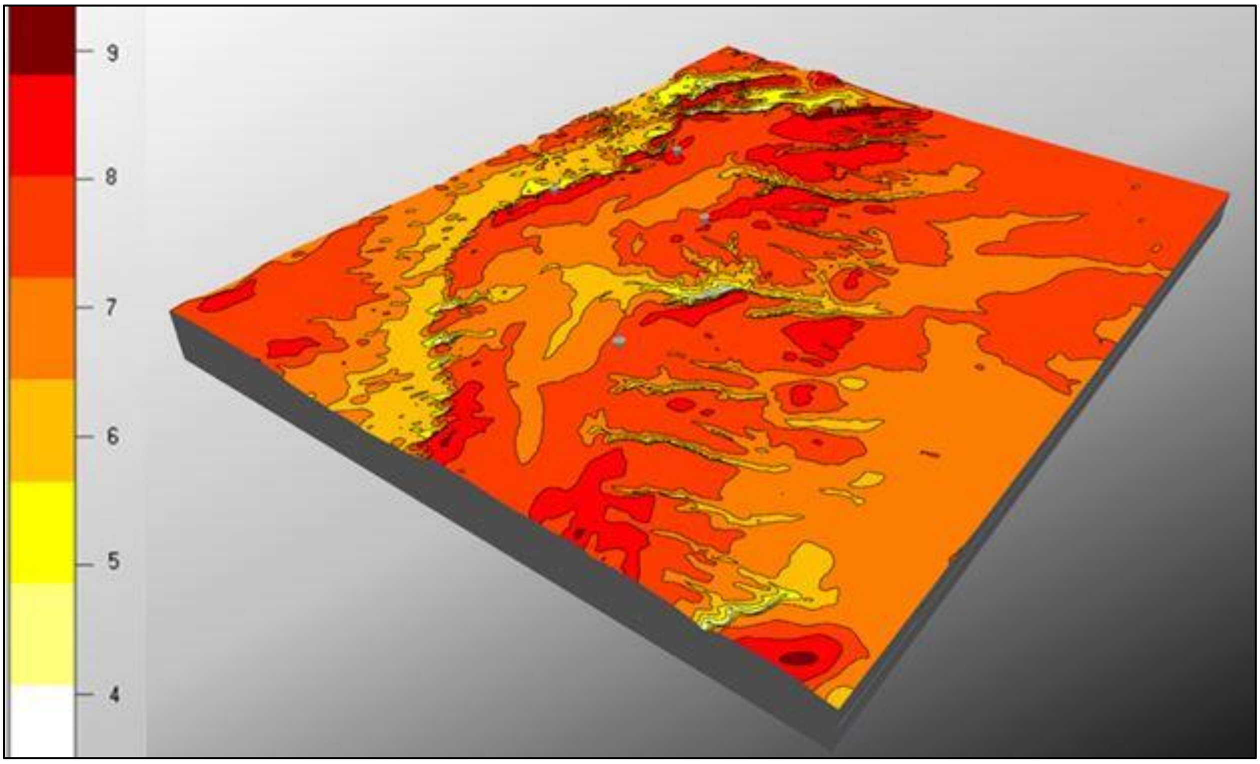

Figure 1: Wind Resource Grid regarding thermal stability [m/s]

Finally, the post-processing stage consists in the application of the vortex identification criterion to the results of the velocity field of a typical WRG. For this purpose, a Python^{TM} algorithm was developed in order to extract the velocity field from a WRG, and a finite difference numerical solution algorithm was implemented in the MatLab® language to apply the vortex identification criterion.

RESULTS

In the following figures, results of the classifier ϕ_M^D obtained from WRGs at 60 m, 80 m and 100 m heights are plotted. (c. Figures 2 to 4)

In short, by the post-processing analysis of the WRG it is possible to identify vortices formed in the atmospheric flow. As pointed out before the presence of vortices are only admitted in the elliptical region and the vortical intensity is greater as the classifier value goes to zero, that is, the more bluish area.

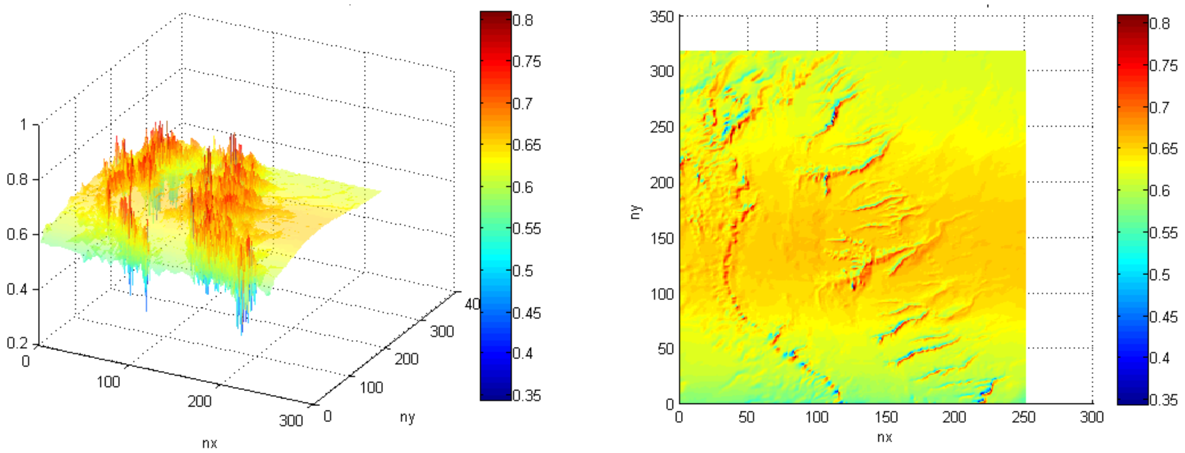

Figure 2: Three-dimensional vortex map view at 60 m height.

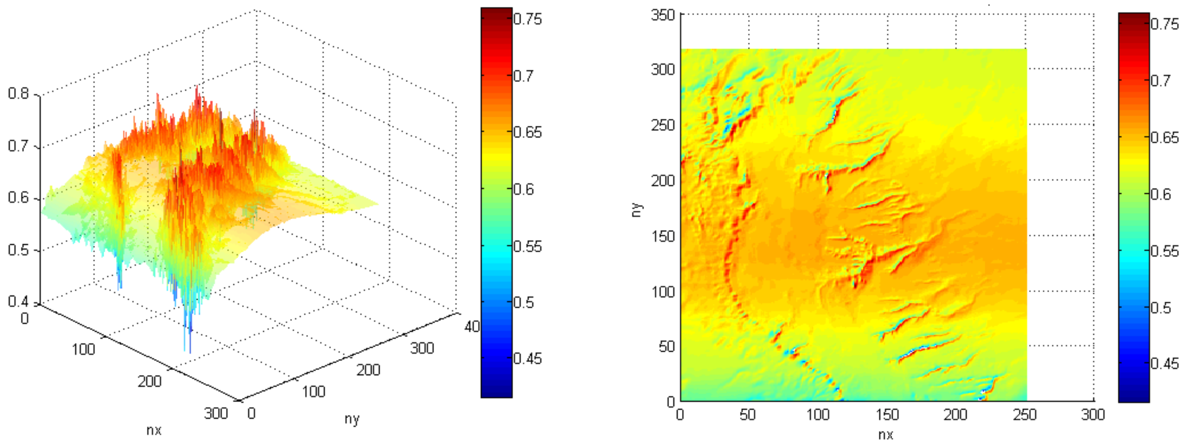

Figure 3: Three-dimensional vortex map view at 80 m height.

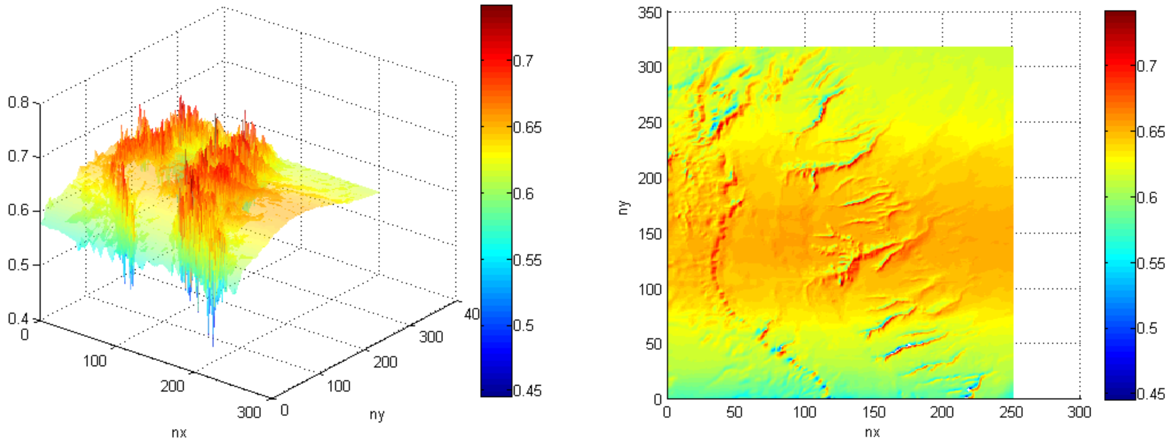

Figure 4: Three-dimensional vortex map view at 100 m height.

CONCLUSION

First, it is important to point out that the new methodology presented here was enough to deliver further information from the widely used WRG data base.

Regarding the aforementioned results, it is possible to observe that vortex intensity increases in the lowest height of the simulated wind due to the fact that the influence of soil and vegetation is higher at lower heights.

Finally, presented results add new information to standard wind project assessments. With this approach, requirements can be better fulfilled in equipment choice, turbine layout arrangement and, consequently, diminish annual energy estimate uncertainties and losses.

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BIOGRAPHIES

Daniel A. Ramos – Born in the city of Rio de Janeiro on July 15th, 1993. He graduated in mechanical engineering at the Federal University of Rio de Janeiro in the beginning of 2016, with emphasis in aerodynamics and numerical simulations of turbulent flows - by the end of the undergraduate course he also started his activities in the wind power market as micrositing analyst.

While active in the wind power market Eng. Daniel also concluded his master's degree in Aerodynamics at PEM / COPPE-UFRJ one year before the scheduled time - during this time he was also research fellow at the Electric Energy Research Centre (Cepel) with a few published articles related to wind energy applications.

In 2017 Daniel Ramos finished his graduate executive education course jointly offered by UC Berkeley and COPPEAD Institute. In August 2017 he founded Ventus Inovação e Energia (VIE) where he is currently developing wind power projects aimed at distributed generation using innovative solutions and technologies.

Roney L. Thompson – Born in the city of Houston, Texas, USA on March 9th. He has doctoral (2001) and master (1997) degrees in Mechanical Engineering at PUC-Rio and a master's degree in Economics (2006) at IBMEC-RJ. Dr. Thompson is an associate professor at the Department of Mechanical Engineering of the Federal University of Rio de Janeiro. He has been working on turbulence modeling and on flow classification for many years, publishing a number of articles in relevant journals.

Sergio R. F. C. Melo – Born in the city of Rio de Janeiro on December 13th, 1983. He graduated in electrical engineering at CEFET in the beginning of 1996, with emphasis in power systems and geoprocessing - by the end of the undergraduate course he also started his activities in the working with energy planning. At the end of 2004, he began his activities in the wind power market as micrositing analyst. While active in the wind power market Eng. Sergio also concluded his master's degree in Mathematical Modeling and Scientific Computing at PEC / COPPE-UFRJ. M.Sc. Sergio has worked in the wind energy sector over the past 14 years at Cepel - Electrical Energy Research Center.

Vanessa Gonçalves Guedes – Born in the city of Rio de Janeiro on 31 October. She graduated in mechanical engineering at the Federal University of Rio de Janeiro in 1995. Her master's and doctor's degrees at PEM / COPPE-UFRJ, were completed in 1996 and 2003, respectively, with specialization in aerodynamics and numerical simulations of turbulent flows. Dr Guedes has worked in the wind energy sector over the past 14 years at Cepel - Electrical Energy Research Center. Her performance in the area consists of several projects for the Eletrobras System companies and publications and contributions for final course projects and master thesis for institutions such as IME, INPE and UFRJ.

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