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Short communication

A short note on turbulence characteristics in wind-turbine wakes

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ABSTRACT

Analytical wake models need formulations to mimic the impact of wind turbines on turbulence level in the wake region. Several correlations can be found in the literature for this purpose, one of which is the formula proposed in A. Crespo, J. Hernández, Turbulence characteristics in wind-turbine wakes, Journal of Wind Engineering and Industrial Aerodynamics 61 (1) (1996) 71–85, which relates the added turbulence to the induction factor of the turbine, ambient turbulence intensity, and normalized distance from the rotor through an equation with one coefficient and three exponents for the effective parameters. Misuse of this formula with an incorrect exponent for the ambient turbulence intensity is propagating in the literature. In this note, we implement the original and the incorrect formulation of turbine-induced added turbulence in a Gaussian wake model to quantify its impact by studying the Horns Rev 1 wind farm. The results reveal that the turbulence intensity and the normalized power of the waked turbines predicted by the wake model with the correct and the incorrect implementation of turbine-induced added turbulence correlation have a difference equal to 1.94% and 3.53%, respectively, for an ambient turbulence intensity of 7.7%. For an ambient turbulence intensity of 4%, these discrepancies grow to 2.7% and 4.95%.

1. Problem statement

Wake models need to include the impact of wind turbines on turbulence level in the wake region. The turbulence intensity in the wake region can be defined as $I_{\mathrm{w}} = \sqrt{I_0^2 + I_+^2}$, where I_0 denotes the ambient turbulence intensity, and I_+ corresponds to the added turbulence intensity due to the presence of wind turbines. Several studies have been conducted to examine various correlations of turbine-induced added turbulence, yielding valuable insights and recommendations, e.g., Crespo and Hernández (1996), Frandsen (2007), Xie and Archer (2015) and Ishihara and Qian (2018), among others. One of the most widely used formulations to parameterize I_+ was suggested in the paper of Crespo and Hernández (1996). They proposed calculating the maximum added turbulence intensity in the far-wake region with $0.07 < I_0 < 0.14$ through

$$I_{+,\mathrm{org.}} = 0.73a^{0.8325} I_0^{-0.0325} \left(x/d_0\right)^{-0.32}, \quad (1)$$

where a, x, and d_0 denote the axial induction factor of the turbine, the streamwise location, and the rotor diameter, respectively. The scanned paper of Crespo and Hernández (1996) is available, but the minus sign beside the exponent of I_0 is not clearly visible (see Eq. (21) in the original paper). This issue has found its way to many works, e.g., Niayifar and Porté-Agel (2016), Gao et al. (2016), Bastankhah et al. (2021), Lopes et al. (2022), Li et al. (2022), National Renewable Energy Laboratory (2022) and Pedersen et al. (2023), among others, which have a correlation implemented in their structure as

$$I_+ = 0.73a^{0.8325} I_0^{0.0325} \left(x/d_0\right)^{-0.32}. \quad (2)$$

The goal of this short note is to clarify some confusion that seems to propagate in the literature about the misuse of the added turbulence correlation proposed by Crespo and Hernández (1996). In connection with wind-farm flow modeling, the wake recovery rate in more recent and widely used analytical wake models (Niayifar and Porté-Agel, 2016; Bastankhah et al., 2021) depends on the local turbulence intensity estimated by the above-mentioned formula. Therefore, quantification of uncertainties associated with the implementation form of turbine-induced added turbulence is of high importance for the wind-energy community. Note that there exist few studies in the literature, e.g., Vermeer et al. (2003), Xie and Archer (2015) and Zehtabiyan-Rezaie et al. (2023), among others, that utilized the correct correlation of Crespo and Hernández (1996) for estimation of the added turbulence intensity.

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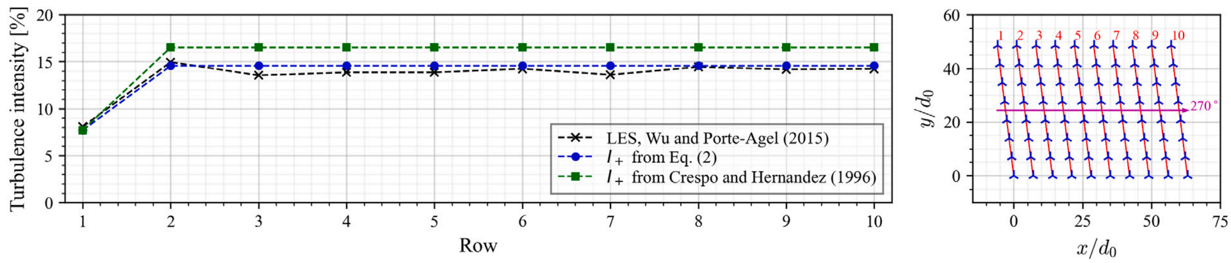

Fig. 1. Left: The turbulence intensity averaged across the rotor upstream of each turbine row, derived from LES (Wu and Porté-Agel, 2015), compared to the values obtained using both the correct and incorrect implementations of the correlation introduced by Crespo and Hernández (1996). The inlet hub-height velocity and ambient turbulence intensity are 8 m/s and 7.7%, respectively. Right: The turbines marked with the red line are used to calculate the average turbulence intensity of each row.

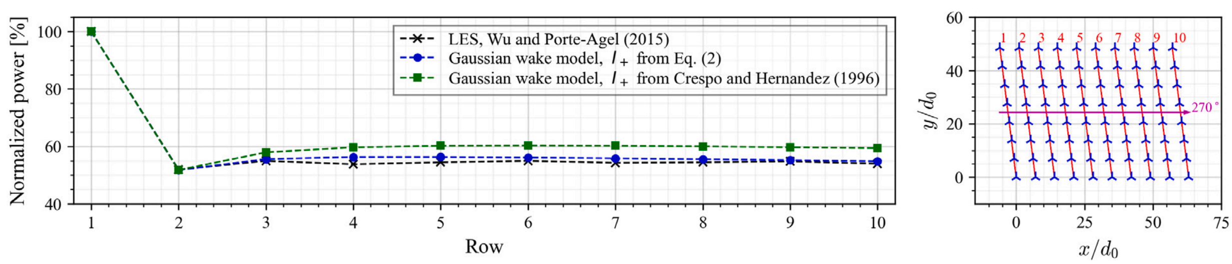

Fig. 2. Left: The normalized mean power as a function of turbine row for a hub-height velocity and ambient turbulence intensity of 8 m/s and 7.7%, respectively. Right: The turbines marked with the red line are used to calculate the average power of each row, and the average value of the first row is used as the reference to calculate the normalized power through $P_{\text{row}}/P_1 \times 100$.

2. Methodology and discussion

We utilize the analytical–empirical Gaussian wake model proposed by Niayifar and Porté-Agel (2016) as the main framework with the original (Eq. (1)) and the incorrect implementation (Eq. (2)) for the turbine-induced added turbulence. The analytical–empirical Gaussian wake model is described in Niayifar and Porté-Agel (2016), and for the sake of brevity, we do not provide the detail on that. We apply the wake model to the operational Horns Rev 1 (HR1) wind farm to evaluate the quantities of interest, e.g., the turbulence intensity within the farm and the normalized power, in the full-wake condition. The HR1 wind farm with a rhomboid-shaped layout holds eighty Vestas V-80 2 MW turbines with hub height (z_{h}) and d_0 of 70 m and 80 m, respectively. For the full-wake condition, i.e., a wind direction of 270°, the spacing between consecutive turbines is $7d_0$ (Wu and Porté-Agel, 2015). Even though this study does not aim to compare the accuracy of the wake model with different added-turbulence formulations, we present the predictions from large-eddy simulation (LES) (Wu and Porté-Agel, 2015) for a hub-height velocity and ambient turbulence intensity of 8 m/s and 7.7% in the following figures.

Fig. 1 depicts the turbulence intensity obtained from LES (Wu and Porté-Agel, 2015), the correlation of Crespo and Hernández (1996) and its incorrect implementation, i.e., as Eq. (2). The layout of the HR1 wind farm is also shown in this figure on the right. The correlation of Crespo and Hernández (1996) gives the maximum added turbulence which appears near the top-tip and the two side-tip regions downwind of the turbine associated with the strong shear at those locations (Abkar and Porté-Agel, 2015, 2016; Eidi et al., 2021). In contrast, LES (Wu and Porté-Agel, 2015) provides turbulence intensity averaged across the rotor, immediately upstream of each turbine. Consequently, the turbulence intensity calculated using Eq. (1) tends to be higher than LES data (Wu and Porté-Agel, 2015). Turning to Eq. (2), due to the missing minus sign beside the exponent of the ambient turbulence intensity, this equation yields smaller values compared to the correlation of Crespo and Hernández (1996). In a case with an ambient turbulence intensity of 7.7%, we can see an absolute difference of 1.94% between the turbulence intensity of the waked turbines predicted by the correct and the incorrect added-turbulence formulation. For a lower ambient turbulence intensity of 4%, the difference grows to 2.7%.

Fig. 2 presents the normalized power for different rows in an incoming wind direction of 270°. As expected, the wake model (Niayifar and Porté-Agel, 2016) using the original formulation for the added turbulence (Crespo and Hernández, 1996) predicts higher values for the normalized power due to a larger turbulence intensity in the wake and, consequently, a faster wake recovery. By using Eq. (2) in the wake model (Niayifar and Porté-Agel, 2016), the average efficiency of the seventy-two waked turbines has an absolute difference of 3.53% compared to the value obtained from the model with the original correlation. The difference is equal to 4.95% for an ambient turbulence intensity of 4%.

3. Conclusions

The purpose of this short note was to address the confusion prevalent in the existing literature regarding the incorrect utilization of the added-turbulence correlation introduced by Crespo and Hernández (1996). To this end, we employed the analytical–empirical Gaussian wake model proposed by Niayifar and Porté-Agel (2016) as the primary framework. Then, we proceeded to analyze both the original implementation (Eq. (1)) and the incorrect implementation (Eq. (2)) of the turbine-induced added turbulence within this model. We applied the wake model to the HR1 wind farm under full-wake conditions and assessed two quantities of interest, i.e., the turbulence intensity in the wake region and the normalized power of the waked turbines. The results showed that employing the original formulation leads to a higher normalized power compared to the value predicted by the wake model coupled with Eq. (2). This was attributed to the increased turbulence intensity within the wake region, resulting in a faster wake recovery.

CRediT authorship contribution statement

Navid Zehtabiyan-Rezaie: Data curation, Formal analysis, Software, Writing – original draft. **Mahdi Abkar:** Formal analysis, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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