Wind farm flow field prediction for real-time energy yield assessment

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Abstract

The wind energy industry is the fastest growing energy sector in the world, with wind capacity forecast to grow by over 324 gigawatts by 2023. Wind farms typically comprise dozens, if not hundreds, of wind turbines working together to generate electricity. Grouping wind turbines together in this way allows for a reduced levelised cost of electricity (LCOE), but it also introduces new design problems, such as inter-turbine flow interactions, or "wake effects", which are known to reduce the wind farms' total energy yield, while simultaneously increasing the fatigue loading of the downstream wind turbines. This paper describes the development of a framework for the real-time assessment of the energy yield and the wind loads on the individual wind turbines within a large wind farm. To this end, we are currently investigating several empirical models which are able to instantaneously compute the flow fields throughout large wind farms, taking into consideration both the wake-induced velocity deficit, as well as the wake-added turbulence. The adopted methods have been validated against site data from the literature, and their advantages and disadvantages in terms of computation time and accuracy are evaluated by comparison with other, higher fidelity computational tools.

Keywords: wind farm, flow field, real-time, energy yield, wind load assessment, wake effects

I. Introduction

In order to increase energy security and decrease carbon emissions, the Pacific island nation of Taiwan has, in recent years, been aggressively promoting the development of a localised renewable energy industry. Due to Taiwan's world-class wind resources, the focal point for much of the Ministry of Economic Affairs' (MOEA) attention has been the development of the local wind energy industry: the MOEA recently raised its 2025 installed capacity target to 6.9 GW (1.2 GW onshore and 5.7 GW offshore), with total investment estimated at over NT$ 1 trillion [1].

The planning, development, and financing of such wind energy projects necessitate accurate, reliable tools for wind resource and energy yield assessments so as to reduce risk and maximise return on investment. In the case of the MOEA's "Thousand Wind Turbines" project, the energy yield assessment is further complicated by so-called wake interaction effects, such as wake shadowing and unsteady wake meandering [2]. In addition to significantly reducing the amount of wind energy available to downstream wind turbines, thereby reducing the wind farm's total energy yield, these unsteady wake effects also give rise to increased load fluctuations (fatigue loading) [3].

II. Jensen's wake model

One of the oldest wake models is that developed by N.O. Jensen in 1983. It is a very simple model, based on 1-D momentum theory, which assumes a linearly expanding wake downwind of the target wind turbine with a velocity deficit that is a function of the distance behind the rotor x and the wind turbine's thrust coefficient C_t. The diameter of the wake D_w is given by

$$D_w = D(1 + 2ks) \tag{1}$$

and the velocity in the (fully developed) wake given by

$$u = U_\infty \left[1 - \frac{1 - \sqrt{1 - C_t}}{(1 + 2ks)^2}\right] \tag{2}$$

where $s = x/D$ is the non-dimensionalised distance behind the rotor, and k is the Wake Decay Constant, which is an indicator of the level of atmospheric turbulence. Despite its simplicity, the Jensen wake model has been shown to be very reliable [4], and is the default model adopted by Risø DTU's WAsP, GH's WindFarmer, UL's OpenWind, and EMD's WindPRO, to name a few.

For the case of multiple wakes, the present study employs the "sum of squares of velocity deficits" wake combination model proposed by Katic [5]:

$$\left(1 - \frac{u_j}{U_\infty}\right)^2 = \sum_{i}^{N} \left(1 - \frac{u_{ji}}{u_i}\right)^2 \frac{A_{\text{shadow},i}}{A_0} \tag{3}$$

where u_j is the wind speed at turbine j due to all upstream turbines, u_i is the wind speed at upstream turbine i, u_{ji} is the wind speed at turbine j due to the wake of turbine i, and the summation is taken over the N turbines upstream of turbine j. For the case of partially overlapped wakes, the velocity deficit is weighted by the fraction of the overlapping area A_{shadow} to the rotor area of the down-stream turbine A_0. For the standard Jensen model, where the transverse velocity distribution in the wake is uniform, A_0 may be calculated analytically [6]. However, it has been shown [7] that a Gaussian or cosine profile better represents the actual velocity distribution in the downstream wake (as illustrated in Figure 1). To allow us to incorporate different velocity distributions into our wake model, we decided to calculate A_0 numerically, by discretising the rotor/wake plane onto a Cartesian grid (Figure 2).

The cosine velocity distribution assumes the following:

- The wake diameter is equal to that given by the standard Jensen wake model;
- The mass flux, calculated by integrating the wind speed in the transverse (cross wind) plane, is equivalent to that given by the standard Jensen model;

The cosine distribution is achieved by Equation 4:

$$u'(r) = (U_0 - u)\cos(\pi \frac{x}{r_w} + \pi) + u \qquad (4)$$

where $u'(r)$ is the velocity distribution in the transverse plane, r is the radial distance from the centre of the wake, and r_w is the radius of the wake at downstream location x. The hub-height flow fields predicted by the standard and cosine Jensen wake models are shown in Figure 3.

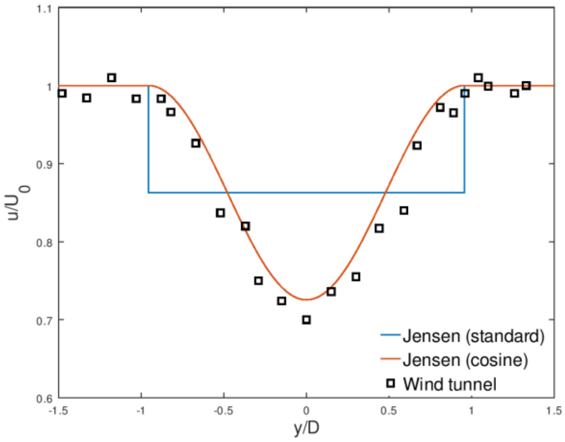

Fig. 1 Wind speed distribution in a turbine wake at 5D downwind

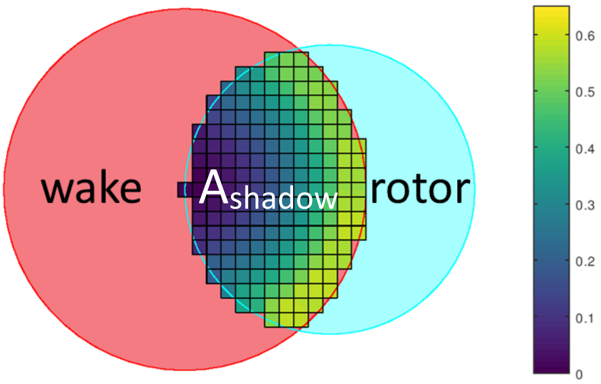

Fig. 2 Wake-overlap area A_{shadow} calculated by discretisation of rotor/wake plane (coloured by cosine velocity distribution)

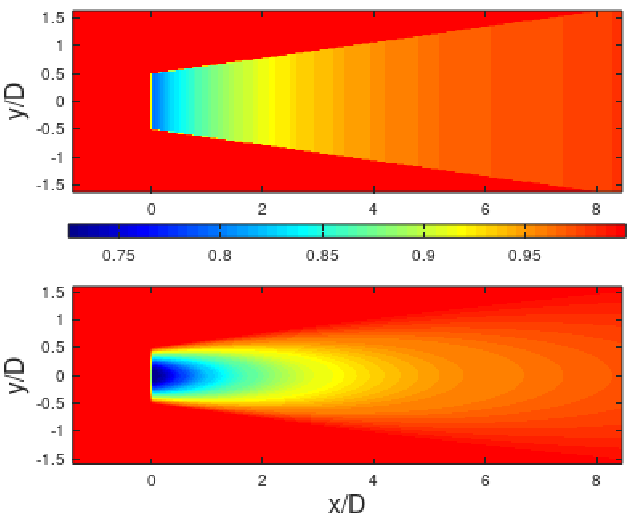

Fig. 3 Velocity distribution behind a wind turbine, as predicted by the standard **(top)** and cosine **(bottom)** Jensen wake models

III. FuHai Offshore Wind Farm

To verify that our standard Jensen model runs as intended, we first compared results with those computed using the Wind Atlas Analysis and Application Program (WAsP) [8], which also employs the standard Jensen model. In this way, we were able to ensure consistency between our two compared tools in terms of input meteorological data and the locations and specifications of the individual wind turbines.

The target wind farm for this test was the FuHai Offshore Wind Farm, located off Taiwan's west coast. The reason for selecting an offshore wind farm for this test case was to avoid introducing further uncertainty to the flow field computation in the form of topographical effects. The FuHai wind farm proposal consists of 29 Siemens SWT-4.0-120 wind turbines. The adopted power and thrust coefficient curves and the locations of the 29 wind turbines are shown in Figures 4 and 5, respectively.

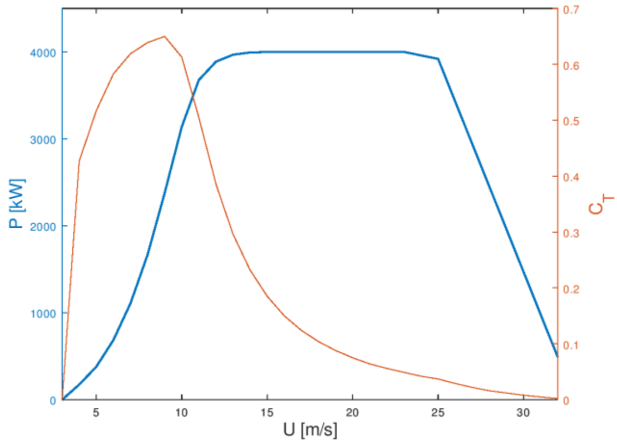

Fig. 4 Adopted wind turbine power/thrust curves

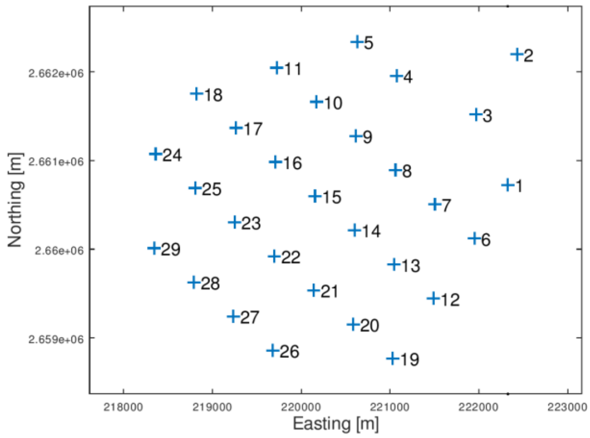

Fig. 5 Wind turbine locations in FuHai OWF

The wake model was run for the full range of operational wind speeds, from 3.5 m/s to 32.5 m/s, with 1 m/s steps, and for the full range of wind directions, from 0.5° to 359.5°, with 1° steps. The directional results were then binned into the eight principal wind directions, or sectors.

The energy yield assessment was based on meteorological data collected at the site over the course of one year, from the 1st of January to the 31st of December, 2008. The WAsP energy yield prediction was based on sector-wise probability distributions of the wind speed, specifically two-parameter Weibull distributions:

$$f(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} e^{-(u/A)^k} \quad (5)$$

where f is the probability of occurrence of a given wind speed u, and k and A are, respectively, the shape and scale factors of the probability distribution function (PDF). The Weibull shape and scale parameters are estimated by curve-fitting Weibull PDFs to sector-wise histograms of the wind speed data. The sector wise Weibull parameters are listed in Table 1, the total Weibull PDF is plotted in Figure 6, and the sector-wise mean wind speeds are plotted in Figure 7, all of which are taken from the WAsP report.

Table 1 Meteorological data

Wind direction	Weibull parameters A	K	Frequency [%]
N	11.24	1.955	17.3
NNE	12.29	1.963	43.1
ENE	7.54	1.221	5.1
E	4.09	1.033	1.5
ESE	4.10	1.131	2
SSE	4.54	1.143	5.4
S	5.28	1.557	8.4
SSW	7.25	1.814	5.9
WSW	6.97	1.732	4.9
W	6.21	1.893	2.7
WNW	5.33	1.17	1.6
NNW	5.37	1.186	2.3
All	9.52	1.549	100

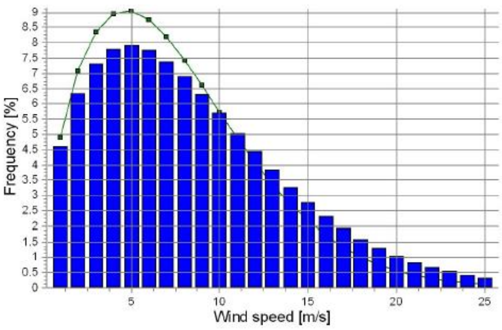

Fig. 6 Total Weibull PDF (from WAsP report)

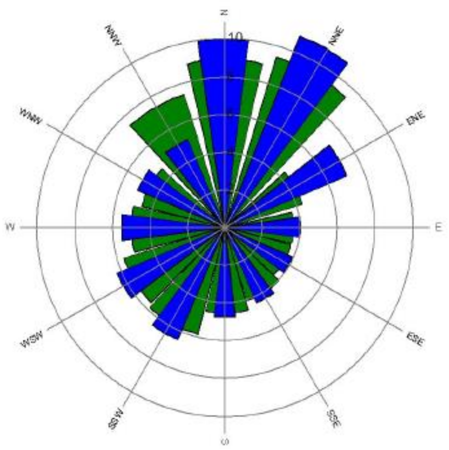

Fig. 7 Sector-wise mean wind speeds (from WAsP report)

The energy yield results predicted by our standard Jensen wake model, for each of the wind turbines in the FuHai Offshore Wind Farm, are plotted in Figure 8, together with the results predicted by WAsP. The results have been normalised by the wind farm's gross (no losses) annual energy yield divided by the number of turbines. To investigate the accuracy of WAsP's Weibull PDF curve fitting procedure, we also assessed the energy yield based on the discrete meteorological site data, which is also shown in Figure 8. The total annual energy yield results for the FuHai OWF are summarised in Table 2.

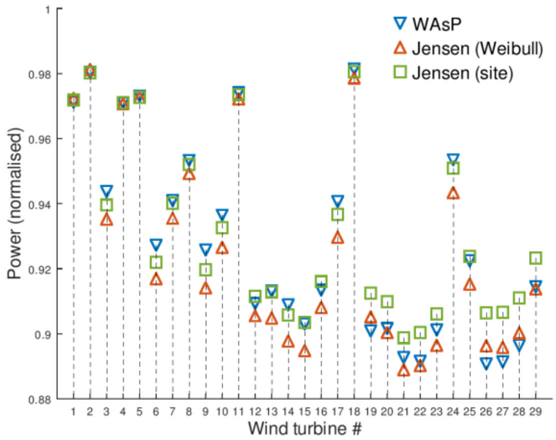

Fig. 8 Energy yield results for FuHai OWF (per WT)

Table 2 Energy yield for FuHai OWF (Total)

Model	Total energy [MWh/y]	Error [%]	Wake losses [%]
WAsP	424072.1	–	7.2
Jensen (Weibull)	423841.1	0.05	7.2
Jensen (site)	426681.0	0.62	6.6

Figure 8 shows that there is excellent agreement between the energy yield results predicted by our standard Jensen wake model, for each of the wind turbines in the FuHai Offshore Wind Farm, and those predicted by WAsP, with a maximum discrepancy of less than 1%. For the most part, the per turbine results based on the discrete meteorological site data show even closer correlation with the WAsP results, except for the farthest downstream turbines, WT #26 to WT #28, for which the discrepancy slightly exceeds 2%.

In terms of total annual energy yield, there is less than 1% discrepancy between our Jensen model results and those from WAsP, with our results derived from WAsP's Weibull PDFs showing just 0.5% discrepancy. The reasons for these discrepancies are still being evaluated, but are most likely due to rounding errors, such as in the adopted Weibull parameters, and possibly due to differences in the binning criteria.

On the whole, the wake losses for this relatively small wind farm were fairly inconsequential, at around just 7% for the total annual energy yield. In terms of model performance, the authors are satisfied that our standard Jensen model runs as intended, and in the following section, we shall validate our model against SCADA data from a larger wind farm.

IV. Horns Rev I

To investigate the effects of out two tested velocity profiles, we compared the results of our standard and cosine Jensen wake models with operational data recorded by the Supervisory Control and Data Acquisition (SCADA) system of a large scale wind farm.

The target wind farm for this test was Horns Rev I, located in the North Sea, approximately 14 km off Denmark's west coast. Horns Rev was the world's first large scale offshore wind farm, consisting of 80 Vestas V80-2.0 MW turbines, for a total installed capacity of 160 MW. Construction was completed in 2002, and operational data recorded by the wind farm's SCADA system has since been utilised for several wake model benchmarking studies [9, 10, 11, 12]. The adopted power and thrust coefficient curves for the Vestas wind turbines and the wind farm layout are illustrated in Figures 9 and 10, respectively.

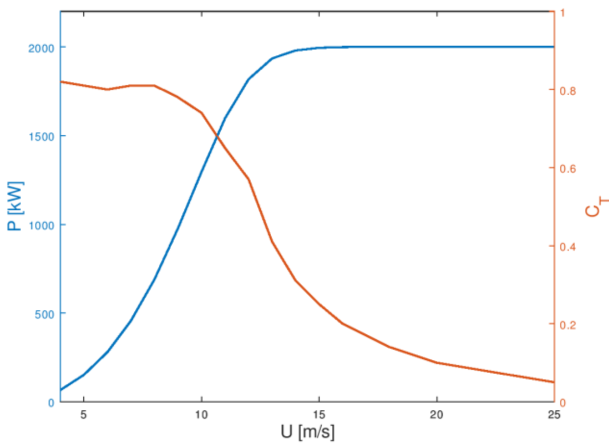

Fig. 9 Adopted Vesta V-80 turbine power/thrust curves

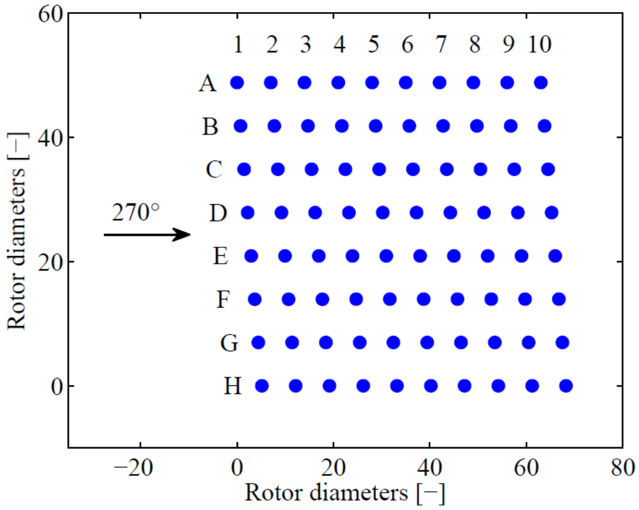

Fig. 10 Horns Rev I wind farm layout [12]

As discussed in the literature, there is a significant degree of uncertainty in the SCADA data, due to such factors as yaw misalignment of the reference turbine, spatial variability of the wind direction within the wind farm, and wind direction averaging period [12]. It is usually found that this directional uncertainty may be reduced by binning the directional data in sufficiently wide bins.

The present study adopted the SCADA data for a westerly wind, i.e. 270° ± 15°. For our test, we took the weighted average of several simulations performed for the same 30° range of "westerly" winds, with 1° steps. The results of this validation test case are shown in Figure 11, which also includes simulated results predicted by Wu *et al.* [13] using large eddy simulations (LES). The results in Figure 11 are those of the 10 wind turbines in Row D (Figure 10), such that WT #1 is upwind, and does not suffer any wake losses. Accordingly, the energy yields of the nine downwind turbines have been normalised against WT #1. The total output power results for the Horns Rev I Offshore Wind Farm are summarised in Table 3.

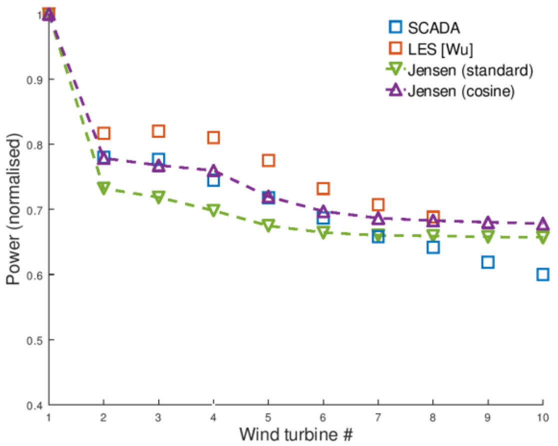

Fig. 11 Energy yield results for Horns Rev I OWF (per WT), normalised against WT #1, for wind direction 270° ± 15°

Table 3 Results for Horns Rev I OWF (Total)

Model	Total energy (normalised)	Error [%]
SCADA	0.723	–
LES	0.769	6.5
Jensen (standard)	0.712	1.4
Jensen (cosine)	0.745	3.1

Figure 11 shows how the standard Jensen model overestimates the wake losses for the first few downstream turbines, particularly WT #2 to WT #6. For these same few wind turbines, the cosine Jensen model shows excellent agreement with the SCADA site data. However, from WT #7 onwards, both of the Jensen models level off to a constant output, while the site data shows that the output power of the downwind turbines continues to fall. By comparison, the LES data captures the trend fairly well, but is shown to overestimate the output power at all of the downwind turbines.

V. Conclusions

This paper describes the development of a framework for the real-time assessment of the energy yield and the wind loads on the individual wind turbines within a large wind farm, with emphasis on inter-turbine flow interactions, or "wake effects", which are known to reduce the wind farms' total energy yield, while simultaneously increasing the fatigue loading of the downstream wind turbines.

In the preliminary stage of this study, we have performed several validation tests for our adopted wake models, namely the standard and cosine Jensen wake models. Our standard Jensen model was shown to correlate extremely well with the standard Jensen model employed by the Wind Atlas Analysis and Application Program (WAsP), giving us confidence in our wake model. We then compared two different velocity profiles with SCADA data from a large scale wind farm, as well as LES results of the wind farm. Once again, the Jensen models were shown to perform very well, with the standard and cosine models deviating from the SCADA data by just 1.4% and 3.1%, respectively. The cosine model showed excellent agreement with the SCADA data for the first few downstream turbines, however, both models were shown to underpredict the wake losses in wind turbines farther downstream.

VI. Future work

The "wake effects" described in this paper have been shown to reduce the total energy yield of large wind farms. However, these wake effects are also responsible for increased fatigue loading of the downstream wind turbines. To this end, our future work will also incorporate a wake meander model, which is to be based on spectral analysis of wake time-history data derived from lidar measurements, such as that illustrated in Figure 12. By generating stochastic time-series for the wake centre-line, we can then model the dynamic effects on the downstream wind turbines by means of lateral motion of the discussed cosine Jensen wake model (Figure 13).

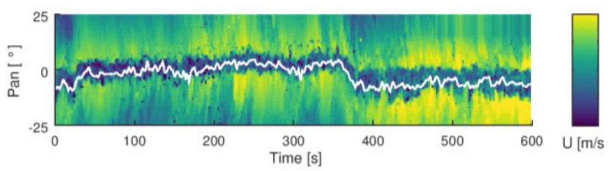

Fig. 12 Time history of wake meander behind a single WT (white line shows wake centre-line)

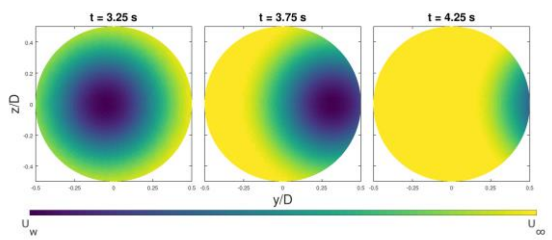

Fig. 13 Meander modelled as lateral motion of wake deficit

Acknowledgements

This research was partially supported by the BSMI Project: 1D171080121-31.

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