# IMPROVEMENT OF THE WIND FARM MODEL FLAP FOR OFFSHORE APPLICATIONS

Bernhard Lange(1), Hans-Peter Waldl(1)(2), Rebecca Barthelmie(3), Algert Gil Guerrero(1)(4), Detlev Heinemann(1)

(1) Dept. of Energy and Semiconductor Research, Faculty of Physics, University of Oldenburg, D-26111 Oldenburg, Germany, phone: +49-441-7983927, fax: +49-441-7983326, e-mail: Bernhard.Lange@uni-oldenburg.de
(2) now at: Overspeed GmbH und Co KG, Oldenburg, Germany
(3) Wind Energy Department, Risø National Laboratory, P.O. Box 49, DK-4000 Roskilde, Denmark
(4) now at: : Lahmeyer International GmbH, Bad Vilbel, Germany

ABSTRACT: The wind farm program FLaP (Farm Layout Program), developed at the University of Oldenburg, has been extended to improve the description of wake development in offshore conditions, especially the low ambient turbulence and the effect of atmospheric stability. Model results have been compared with measurements from the Danish offshore wind farm Vindeby. Vertical wake profiles and mean turbulence intensities in the wake were compared for 32 scenarios of single, double and quintuple wake cases with different mean wind speed, turbulence intensity and atmospheric stability. It was found that within the measurement uncertainties the results of the wake model compares well with the measurements for the most important ambient conditions. The effect of the low turbulence intensity offshore on the wake development was modelled well. Deviations have been found when atmospheric stability deviates from near-neutral conditions. Especially for stable atmospheric conditions both the free flow model and the wake model do not give satisfying results.
Key Words: Offshore, Wake model, Wind farm, Vindeby, Turbulence intensity, Atmospheric stability

## 1 INTRODUCTION

For the planning of large offshore wind farms, modelling of wake losses is an important part of the production estimation. Additionally, an estimation of turbulence intensity in the wind farm is essential for the load assumptions used in the design of the turbines. Some knowledge and considerable experience has been gained in the estimation of these wake effects from wind farms on land, which is available in wind farm models like PARK (Risø National Laboratory, Denmark), Windfarmer (Garrad, Hassan and Partners, United Kingdom) and FLaP (University of Oldenburg, Germany).
Some differences exist between the atmospheric flow on land and offshore and the models used for wake predictions on land might have to be extended for the use in offshore conditions. Two characteristics of the offshore conditions are of paramount importance for the wake development: Sea surface roughness and atmospheric stability.
The roughness of water surfaces is different from land surfaces in that it is much smaller and dependent on the wave field, which in turn depends mainly on wind speed, but also on fetch, water depth, etc. (see e.g. Lange et al. (2001)). This needs to be taken into account in the description of the ambient vertical wind speed profile, but most importantly it leads to a low and wind speed dependent turbulence intensity. Since the wake development largely depends on the turbulence intensity of the surrounding flow, this has important consequences for the modelling of the wake.
Atmospheric stability is important in offshore conditions, since atmospheric stratification departs from near neutral conditions also for higher wind speeds, which are important for wind power production, due to the land-sea temperature difference and the low roughness offshore. This has to be included in the modelling of the ambient flow, but also might have an influence on the wake development.
The wind farm modelling program FLaP has been extended with the aim to incorporate these effects in the wake modelling within the ENDOW project (Barthelmie et al., 2002). For the modelling of the ambient atmospheric flow standard Monin-Obukhov similarity theory (see e.g. Stull (1988)) has been used, employing the Charnock relation (Charnock, 1955) to estimate the sea surface roughness. A two-dimensional, axis-symmetric wake model with eddy-viscosity closure is used, based on the model described by Ainslie (1985, 1988). It has been extended to improve the modelling of the influence of turbulence intensity and atmospheric stability on the wake. Comparisons of model results with results of several other wake models and comparisons of results before and after the improvements are given in Rados et al. (2002) and Schlez et al. (2002).
Model results have been compared with measurements of the offshore wind farm Vindeby for a wide range of ambient conditions. Measurements were available for single, double and quintuple wakes for different ambient wind speed, turbulence intensity and stability. Vertical wind speed profiles in the wake and mean turbulence intensities are compared.

## 2 THE FLAP WIND FARM MODEL

The wind farm program FLaP (Farm Layout Program) has been developed at the University of Oldenburg since 1993. It combines an axis-symmetric wake model, describing the wake of one rotor, a free flow model for the undisturbed vertical wind speed profile and a wind farm model, which takes care of the interaction of all wakes in a wind farm. The program estimates wind speeds and turbulence intensities in wakes and their effect on the power output of the turbines in a wind farm. Noise calculations and automatic layout optimisation are additional features.
Different wake models are implemented. Here an approach based on Ainslie (1985, 1988) has been chosen. It is a two-dimensional (axis-symmetrical) model solving the simplified momentum and continuity equations with an eddy-viscosity closure. The eddy-viscosity is modelled as a combination of contributions from the ambient turbulence of the free flow and the shear generated turbulence in the wake. The model does not include the near wake directly behind the rotor. Instead, it first starts at the end of the near wake with an empirical wake profile as boundary condition.

The result is an axis-symmetric wake profile, which is than convoluted with the incident ambient wind speed profile modelled in the free flow model. For multiple wakes the wind speed incident on a rotor placed in wake(s) is calculated in a multiple wake model from the modelled wake deficits of the incident wakes.

The wake model has been extended to improve the description of wake development in offshore conditions, especially the low ambient turbulence and the effect of atmospheric stability. For a detailed description of the program and validation see Lange et al. (2002) and Waldl (1998).

## 3 THE VINDEBY MEASUREMENTS

Measurements from the Danish offshore wind farm Vindeby have been used for comparison with the model results. The wind farm consists of 11 stall-controlled Bonus 450 kW wind turbines with hub height 38 m and rotor diameter 35 m. They are arranged in two rows oriented along an axis of 325-145º. The distance of the turbines within the row as well as the distance between the rows is 300 m (8.6 D). Since the turbine locations are shifted in the two rows with respect to each other, the minimum distance between turbines of two rows is 335 m (9.6 D).

Three meteorological masts have been erected close to the wind farm, one on land and two offshore. The land mast is located nearly 2 km south of the most southerly turbine in the array. The two offshore masts are placed at distances equal to the row and turbine spacing (335 and 300 m), one to the west and one to the south of the first row. Wind speed measurements with cup anemometers are performed at 46, 38, 20 and 7 m height at the land mast (LM) and at 48, 43, 38, 29, 20, 15 and 7 m height at SMS and SMW. The atmospheric stability is characterised by the Monin-Obukhov-length L, which is derived from temperature and wind speed difference measurements. For a detailed description of the wind farm and measurements see (Barthelmie et al., 1994) and (Frandsen et al., 1996).

Measurements from the years 1994 and 1995 have been used. One minute averages have been calculated to reduce the effect of wake meandering due to wind direction changes during the averaging period. Four cases of direct wake interference were selected where measurements of the wind speed in the wake as well as measurements of the free wind speed are available (see Table 1).

*Table 1: Measured wake cases at Vindeby wind farm*

| wind direction sector | measured wake | free mast | wake mast | stability determined from |
|---|---|---|---|---|
| 18º-28º | single | LM | SMS | LM |
| 18º-28º | double | LM | SMW | LM |
| 70º-78º | double | SMS | SMW | SMS |
| 314º-323º | quintuple | SMW | SMS | LM |

For each of the cases data have been classified according to the three criteria wind speed, turbulence intensity and atmospheric stability at the free mast. Wind speed bins of 4-6m/s, 6-9m/s and 9-11m/s, turbulence intensity bins of 5-7%, 7-9% and 9-11% and atmospheric stability bins of $|L|>1000$, $0<L<1000$, $0>L>-1000$ have been used. For each case and each bin the data were averaged and normalised with the corresponding free stream wind velocity at hub height.

The comparison of measured and modelled wakes is very sensitive for measurement uncertainties in the wind speed measurements, since the wake deficit is a wind speed *difference*. As a rough estimate of the total measurement uncertainty due to systematic errors can be assumed to be in the order of 5%. This means that for a typical wake deficit of 15% the measurement uncertainty in wake deficit is about 30%.

The bin-averaged measurements are compared with model runs where the nominal (mid-bin) values of turbulence intensity, wind speed and stability are used as input. For wind direction the averaging of the measured values over a range of wind directions has been modelled by also averaging model runs for the same wind direction range in 1º steps. For multiple wakes the calculation is simplified by neglecting the effect of the increase in turbulence intensity in a wake for the modelling of the wake profile. Instead, the ambient turbulence intensity has been used for all wakes.

## 4 RESULTS OF THE COMPARISON

### 4.1 Comparison for near neutral stability

From the Vindeby measurement 16 scenarios with near-neutral stability, wind speed bins 5, 7.5 and 10 m/s and turbulence intensity bins 6 and 8% contained sufficient data for the bin averaging. Model results were within the estimated measurement uncertainty for all scenarios. Examples of the comparison for single, double and quintuple wake situations are given in Figure 1 for the most frequent turbulence intensity bin, 6%, and the most frequent wind speed bins, 5 m/s and 7.5 m/s. Some observations should be noted:

Comparing the form of the profiles of the modelled single wakes a tendency can be seen that the wake ‘width’, i.e. their vertical extension, is larger than measured. This is not visible for double and quintuple wakes.

Double wakes are measured in two different wind direction cases. Large differences can be seen between these two measured profiles. The measurements for the 70º-78º case show large velocity deficits at low heights, even down to 7 m, while the measurements for the 18º-28º case show generally smaller wake deficits.

### 4.2. Comparison for stable conditions

In total 5 scenarios were available from the measurements for stable conditions, one each for single and quintuple wakes and 3 for double wakes. As already in the comparison of the free flow models, the comparison of model results with measurements for stable stratification is not as good as for near-neutral stratification and in some cases unsatisfying.

Figure 2 (top) shows examples for the comparison of single, double and quintuple wake situations with measurements for 6% turbulence intensity and 5 / 7.5 m/s (single wake / double and quintuple wakes). Some observations:

In the single wake case the measured wind speed in the wake at 30 m height shows a value, which would almost be expected in the free flow. This unexpected behaviour can not be explained.

For the double wake case the measured wind shear is larger than modelled as already in the near-neutral cases for this direction. The form of the measured profiles is unexpected with large velocity deficits at low wind speeds. This is not reflected in the model results.

For quintuple wakes it can be seen that already the free flow wind shear is predicted too small. As the free flow is a part of the modelled wake the same is also present in the wake model result.

4.3 Comparison for unstable conditions

In total 11 scenarios were available from the measurements for unstable conditions.

As for stable conditions, the comparison of model results with measurements for unstable stratification is not as good as for near-neutral stratification and in some cases unsatisfying.

Figure 2 (bottom) shows examples for the comparison of single, double and quintuple wake situations with measurements for 6% turbulence intensity and 7.5 m/s mean wind speed. Some observations:

The comparison is generally god for the single wake case, while for double and quintuple wakes larger deviations occur.

For the double wake case the model overpredicts the wake deficit. For the 70º-78º case also the wind shear deviates between model and measurement, as also was found for near-neutral and stable stratification for this wind direction case.

For the quintuple wake case a slight underprediction of the wake deficit can be seen. Additionally, the measured free flow profile has a larger wind shear than modelled, which was also found for stable stratification.

## 5 CONCLUSION

The wind farm layout program FLaP has been extended to improve the capability to model offshore wind farms. The characteristics of the offshore atmospheric flow most important for wind power utilisation have been addressed: sea surface roughness and atmospheric stability.

Model performance has been compared with measurement results from the Vindeby offshore wind farm. In total 32 scenarios of single, double and quintuple wake cases with different mean wind speed, turbulence intensity and atmospheric stability have been selected. The measurement data have been bin-averaged and compared with the model results. The measurement uncertainty for the bin-averaged wind speed measurements in narrow wind direction sectors has been estimated to be roughly n the order of 5%. Since wake deficit measurements are measurements of wind speed differences this leads to large measurement uncertainties.

Given these measurement uncertainties the FLaP model agrees well with the measurements for the atmospheric conditions, which are most important for wind power utilisation. These are the conditions with important energy content and high frequency of occurrence, i.e. moderate wind speeds, typical turbulence intensities and near-neutral stability.

The model coped well with the low turbulence intensity offshore as no significant deviations were found for low turbulence situations. Modelling was less successful when atmospheric stability deviated from near-neutral conditions. This was the case both for stable and unstable stratification and both for the modelling of the free profile and the wake flow. This shows that the behaviour of free and wake flows in conditions with atmospheric stratification is not understood sufficiently and needs further investigation.

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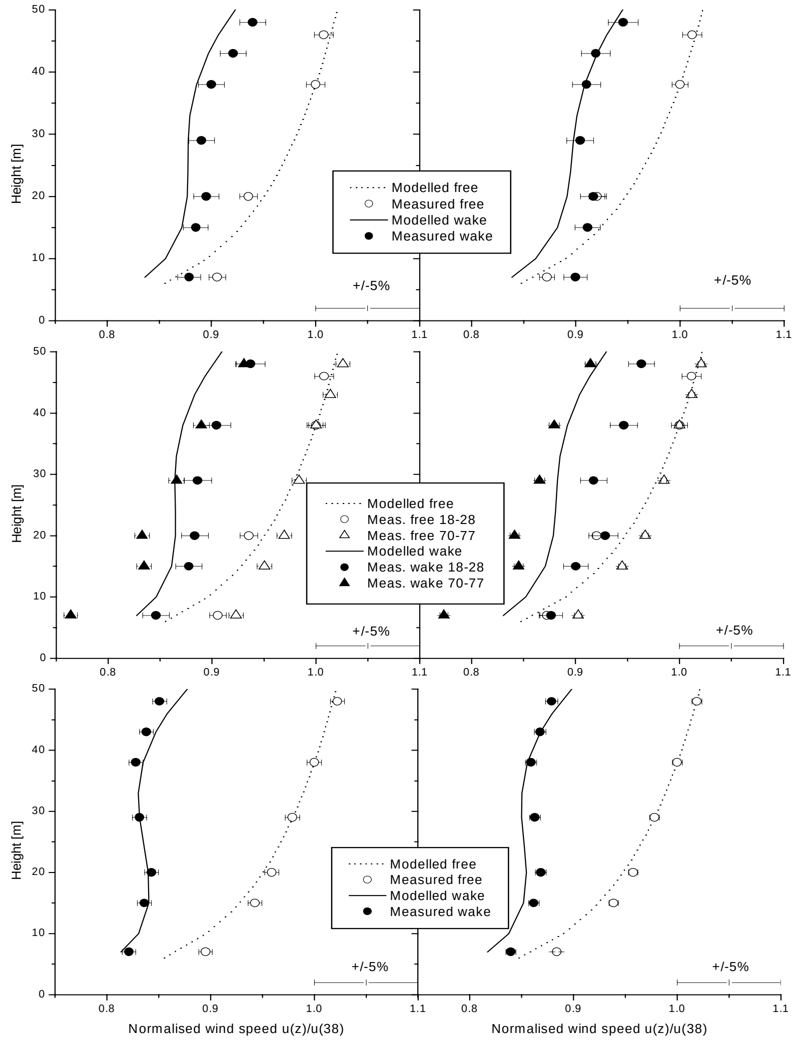


*Figure 1: Vertical profiles of measured and modelled normalised wind speeds for the free and wake flow; Vindeby single (top), double (middle) and quintuple (bottom) wake with wind direction 314º-323º, near-neutral stability, 6% turbulence intensity, 7.5m/s (left) and 10m/s (right) mean wind speed; error bars indicate the standard errors*

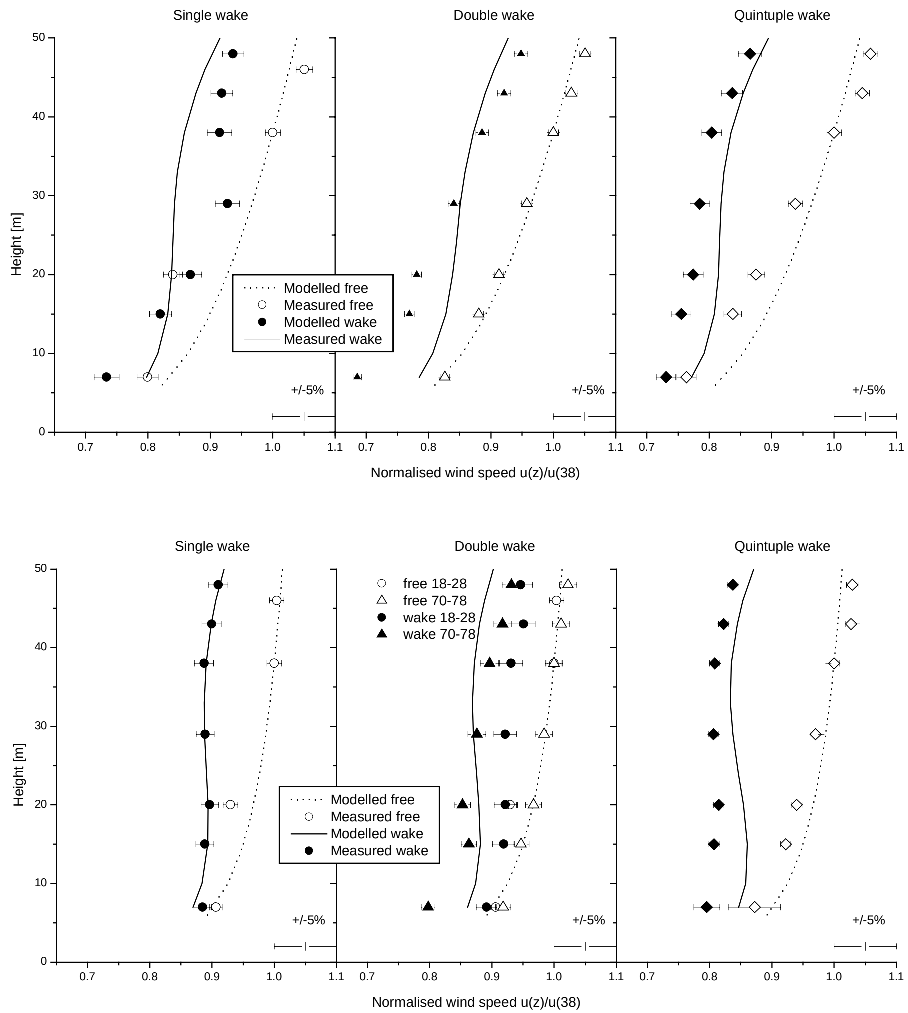


*Figure 2: Vertical profiles of measured and modelled normalised wind speeds for the free and wake flow; Vindeby single, double and quintuple wakes, stable (top) and unstable (bottom) stratification, 6% turbulence intensity, 7.5m/s mean wind speed (except single wake stable: 5m/s); error bars indicate the standard errors*