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STUDY OF ISOLATED WAKES AND THEIR SUPERPOSITION IN WIND FARMS, USING DIFFERENT TURBULENCE MODELS

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IMPORTANCE OF WIND ENERGY

Outstanding figures in wind energy sector in Spain (updated at the end of the year 2005)

General

Overall Capacity Installed	9,781 MW
Accumulated Investment	€ 8,774 m
Energy Sold	21,000 GWh
Electricity Market Share	7.5%
Equivalent Consumption	6 million households

Social Benefits

- **More than 550 companies involved in the sector.**

Accumulated Employment

- **Design, Construction and Erection.**

127,000 men-year → Direct 31,750; Non Direct 95,250

- **Operation and Maintenance.**

1,950 permanent jobs (all direct)

Environmental Issues

POLLUTANT	AVOIDED QUANTITY (t) *
SO_2	144,500
NO_x	79,800
CO_2	19,690,000

* In relation to electricity generated by means of national hard coal-fired power plants [CIEMAT and CNE (2001)]

MOTIVATION OF THE STUDY OF WIND TURBINE WAKES

-Typical wind farms consist of several wind turbines of about 1 MW power

- Due to the cost of land and civil works, wind turbines tend to be built as closely as possible to each other

-It is necessary to locate them adequately to minimize interference effects

-The momentum deficit and the increased level of turbulence created by turbines in a wind farm may cause a reduction in power output and unsteady loads on other machines

-There are significant energy losses in arrays spaced at less than 7 turbine diameters, although the most importante effect is that turbulence may increase in arrays, sufficiently to cause measurable damage due to fatigue and dynamic loading

-Also the vertical velocity profile that causes unsteady loads on the blades may be affected by the wake.

KINEMATIC MODELS

-These methods require the solution of ordinary differential equations, and are valid both for single wakes and wind farms.

-In spite of their simplicity they may retain many of the physics of the problem

-They are based on imposed velocity deficit profiles, that are self-similar in the far wake

- Use global momentum conservation to relate the total velocity defect to the thrust force over the wind-turbine.

-Wake growth is due to both ambient turbulence and turbulence generated in the wake itself

-Ground effect is simulated by imaging techniques

-Superposition of wakes in wind farms are both linear (Lissaman et al.) and non-linear (Katic et al.)

-There are also analytical solutions (Larsen et al.) based on the classical solution of an axisymmetric wake .

FIELD MODELS

-Solve the flow partial differential equations with different degrees of approximation to calculate flow conditions at grid points

-Some of them make the equations linear

- They may use either elliptic or parabolic modelization of flow

- Use different models for turbulence closure:

  * Ainslie uses an analytical model for the eddy viscosity which also includes a contribution from ambient turbulence.

  * UPMPARK uses a k-ε model

  * Cabezón et al. Mason etc, use different modifications of k-ε

  * Gómez et al. use a Reynolds Stress algebraic model

  * More recently Large Eddy Simulation is used to calculate the eddy viscosity.

- In this presentation we will include a non-steady version of UPMPARK to study wake meandering contribution to wake turbulence generation

FIELD MODELS PRESENTED RECENTLY AT THE EUROMECH COLLOQUIUM 508, MADRID, OCTOBER 2009

- 4 PAPERS ON RANS CLOSURE MODELS:
Rethore et al., Cabezón et al., Migoya et al. and Crasto et al.

-8 PAPERS ON LES CLOSURE MODELS
Jiménez et al,, Calaf et al., Hahm et al., Steifeld et al., Sanderse et al., Troldborg et al., Larsen et al., Ivanell et al.

- 15 PAPERS ON WAKE MEANDERING

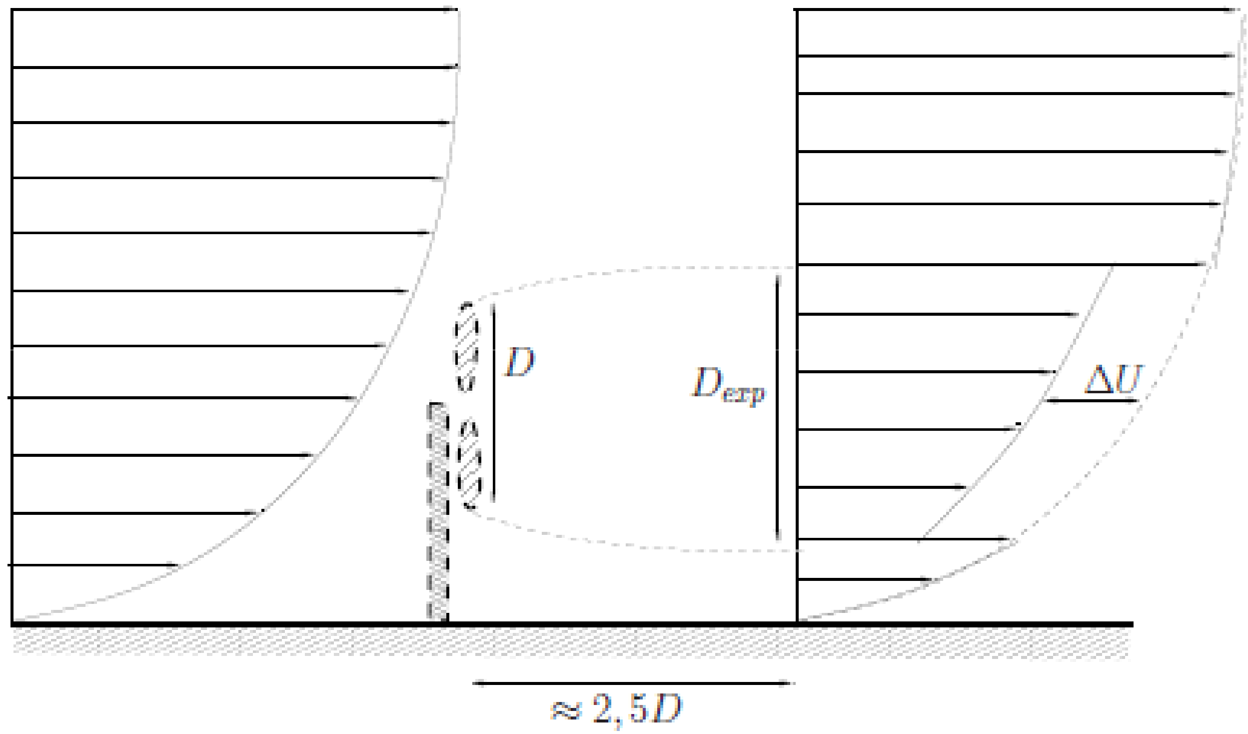
AINSLIE'S MODEL

- Parabolic eddy viscosity model (EVMOD) which assumes axis-symmetric wake flow.
- Only the continuity and the axial momentum equations have to be solved.
- Eddy viscosity is an average value over a cross-section, and variations in turbulent properties across the wake cannot be estimated from the model.
- The model is fairly simple and gives reasonable results when compared with wind tunnel experiments.
- For large-scale experiments the results are corrected by taking into account meandering effects
- Velocity defects are predicted, but the model does not provide information about turbulence characteristics

WAKE MEANDERING AND TURBULENCE GENERATION

-Wake meandering is the large scale movement of the entire wake due to eddies that are large in comparison with the size of the wake itself.
-According to the Dynamic Wake Meandering Model, Larsen et al., this wake meandering mechanism will not only increase the (apparent) turbulence *intensity, but may also significantly change the structure of the (apparent)* turbulence as seen by downstream turbines.
-They calculate velocity deficit profiles using Ainsliés model, that are moved as a passive tracers by ambient low frequency turbulence
- Is the wake meandering taken into account by conventional closure models?
-In our LES model it was barely observed.
-In the following we will retain unsteady terms in the UPMPARK k-ε model to include oscillations of low frequency of the incident wind

UPMPARK TO MODEL WAKES IN WINDFARMS



The wind turbine is supposed to be immersed in a non-uniform basic flow corresponding to the surface layer of the atmospheric boundary layer

UPMPARK TO MODEL WAKES IN WINDFARMS

-UPMPARK model is a CFD code that describes the diffusion of multiple wakes in the atmospheric surface layer parameterized by Monin-Obukhov scaling,

-The equations describing the flow are the conservation equations of mass, momentum, energy, turbulence kinetic energy, and the dissipation rate of the turbulence kinetic energy

-The modelling of the turbulent transport terms is based on the k-ε method for the closure of the turbulent flow equations.

-A parabolic approximation was made. Turbulent diffusion and pressure variation in the main flow direction are neglected.

-The developed wake model is three-dimensional and pressure variations in the cross-section have to be retained in order to calculate transverse velocities.

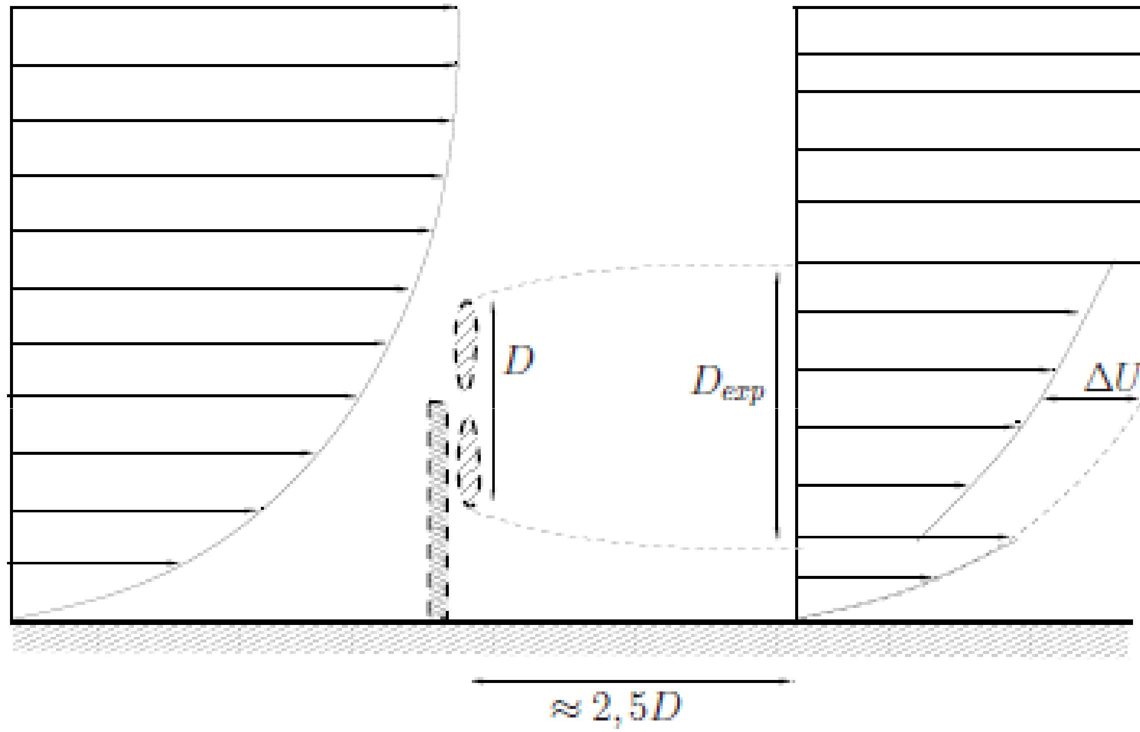
UPMPARK TO MODEL WAKES IN WINDFARMS

-Finite-difference methods were used in the discretization of the equations.

-This set of equations has been solved numerically using the SIMPLE algorithm proposed by Patankar and Spalding (1972).

-The equations were solved numerically by using an alternate-direction implicit (ADI) method.

UPMPARK TO MODEL WAKES IN WINDFARMS



-Consistently with the parabolic approximation, boundary conditions are applied in the expanded wake, where wake pressure is approximately the ambient pressure

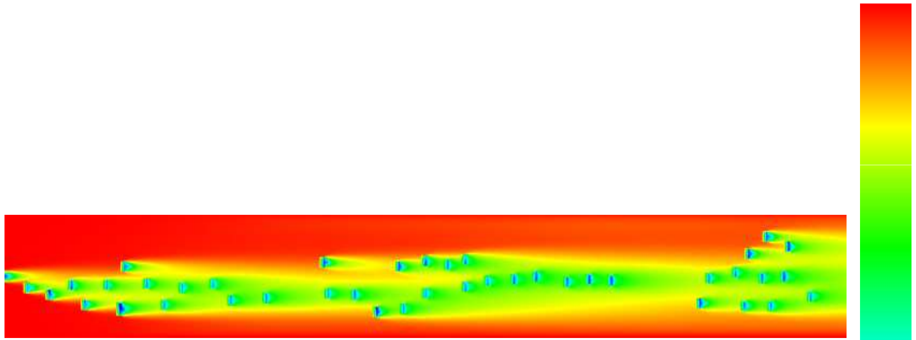
EXTENSION OF UPMPARK TO MODEL WAKES IN WINDFARMS

-UPMPARK is less accurate than LES models, but consume less computing time, and can be used, with moderate computing resources to study the behavior of a whole wind farm.

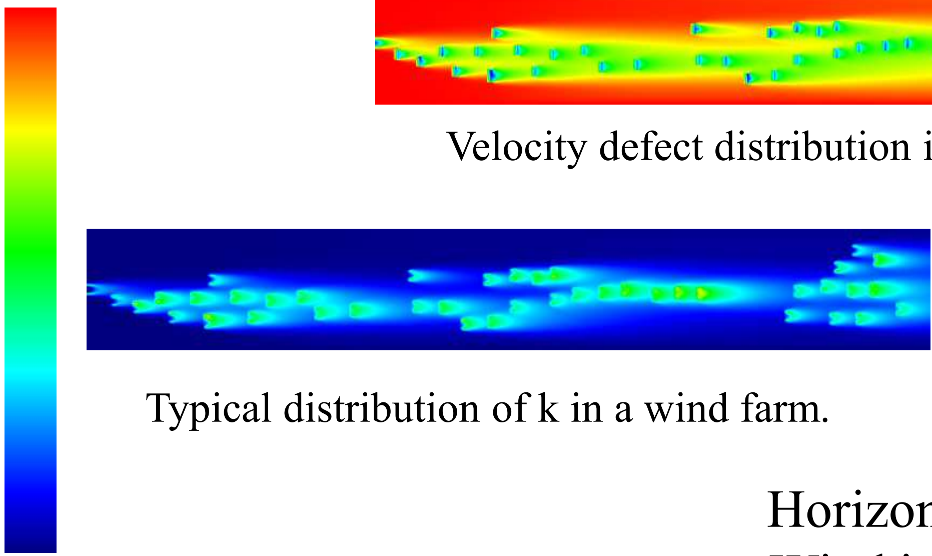
-The code has two options; there is a simplified option in which only the convective terms containing the main flow velocity are retained; in the more complicated version the convective terms containing the velocity components perpendicular to the main flow direction are also retained.

UPMPARK TO MODEL WAKES IN WINDFARMS

-Running downwind in the numerical marching procedure associated with the parabolic model, each turbine found at any cross-section of the farm acts as a source (or sink) of the three velocity components, k, and ε.



Velocity defect distribution in a wind farm.

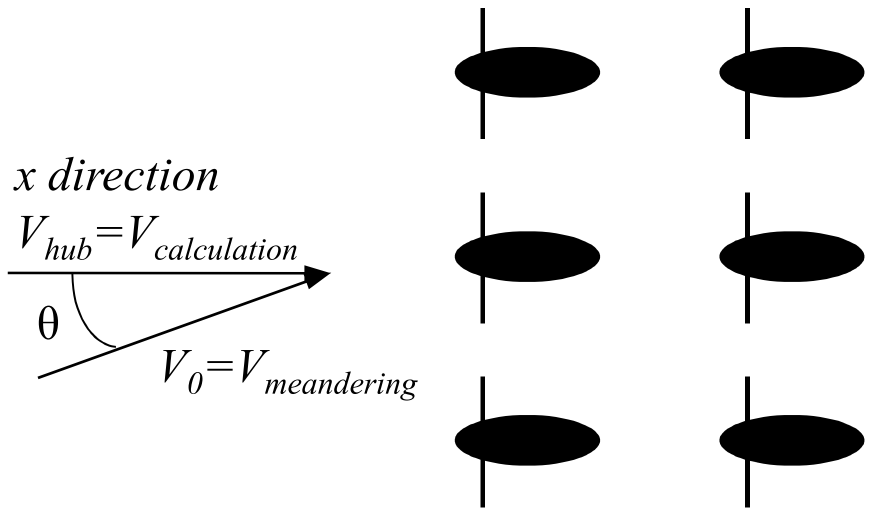


Typical distribution of k in a wind farm.

Horizontal view at hub height
Wind is blowing from the left

UNSTEADY UPMPARK TO MODEL MEANDERING WAKES IN WINDFARMS

-Unsteady terms have been incorporated using a simplified version of UPMPARK that considers convection only in the instantaneous flow direction, whose average is in the direction in which the wind turbines are aligned



$$\frac{\partial J}{\partial t}+\vec{V}_0\nabla J+\ldots=\frac{\partial J}{\partial t}+V_{0x}\frac{\partial J}{\partial x}+V_{0y}\frac{\partial J}{\partial y}+\ldots$$

$$J=V_x, k, \varepsilon$$

-The incident flow oscillates around the *x*-axis in the horizontal direction.

NON-STEADY UPMPARK TO MODEL WAKE MEANDERING

-A stochastic simulation, based in Shinozuka (1971), has been implemented to take into account the horizontal oscillations of the incident wind.

-Kaimal and Von Karman expression could be employed to obtain spectra for x and y directions, IEC-61400.

$$S_{Kaimal\ i}(f)=\frac{4\sigma_i^2\frac{L_i}{V_{hub}}}{\left(1+6\frac{fL_i}{V_{hub}}\right)^{5/3}} \quad i=x,y$$

$$S_{Von\ Karman\ x}(f)=\frac{4\sigma_x^2\frac{L_x}{V_{hub}}}{\left[1+70.8\left(\frac{fL_x}{V_{hub}}\right)^2\right]^{11/6}}$$

$$S_{Von\ Karman\ y}(f)=\frac{2\sigma_y^2\frac{L_y}{V_{hub}}\left[1+189\left(\frac{fL_y}{V_{hub}}\right)^2\right]}{\left[1+70.8\left(\frac{fL_y}{V_{hub}}\right)^2\right]^{11/6}}$$

Model and Component	Kaimal x	Kaimal y	Von Karman x	Von Karman y
Standard deviation, σ_i	σ_x	$0.8\sigma_x$	σ_x	σ_x
Integral scale, L_i	L_x	$2.7L_x/8.1$	L_x	L_x

-Input data: the average incident wind direction, the average and variance incident wind speed and the integral scale.

NON-STEADY UPMPARK TO MODEL WAKE MEANDERING

-Stochastic time series generators are based on the integration of velocity spectrum. Therefore, summations of harmonics, with a random phase and amplitudes which follow one of the previously mentioned spectral density function, are used:

$$V_i = \sum_{j=j_{down}}^{j=j_{up}} \sqrt{\Delta f_j S_i(f_j)} \cos(2\pi f_j t + k) \quad i = x, y$$

$$\frac{f_{highest} W}{V_{hub}} = 1$$

$$V_{meandering} = \sqrt{V_x^2 + V_y^2}$$

$$\theta = \arctan\left(\frac{V_x}{V_y}\right)$$

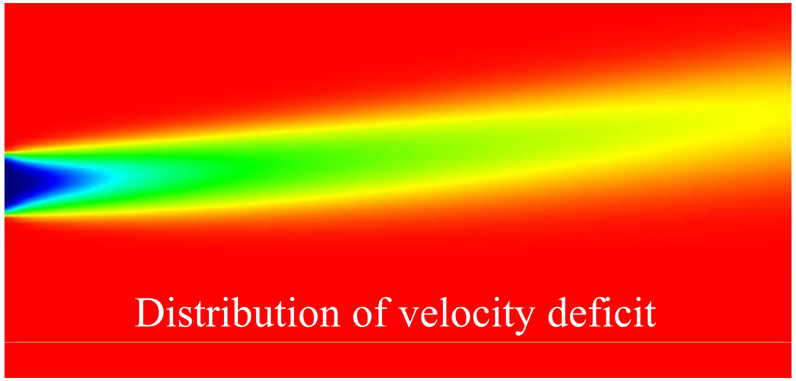
k is a random phase distributed between 0 and 2π,

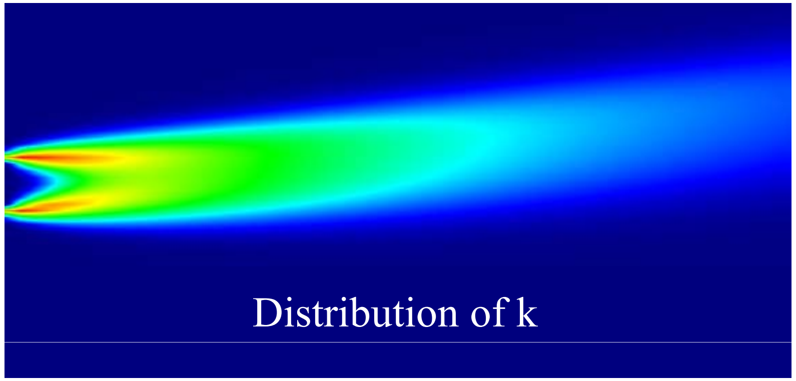
j_{up} and j_{down} mean the index of higher and lower filtered scales and

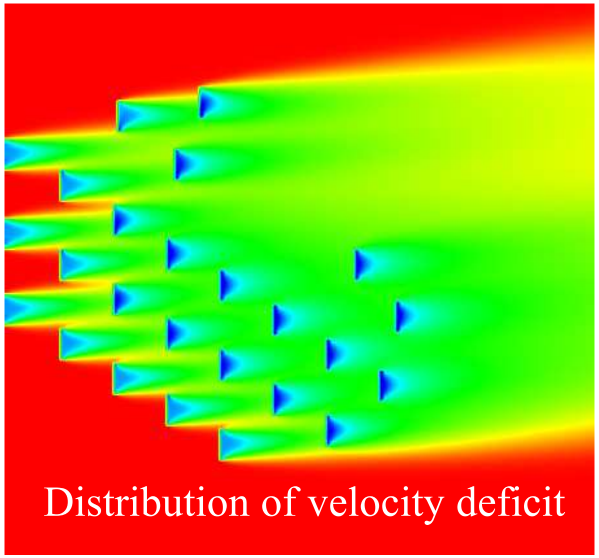
W is a distance of the order the maximum wake width

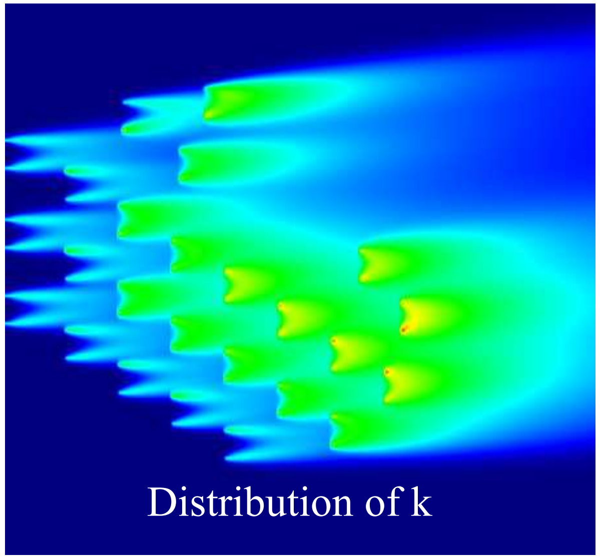
NON-STEADY UPMPARK TO MODEL WAKE MEANDERING

Instantaneous profiles





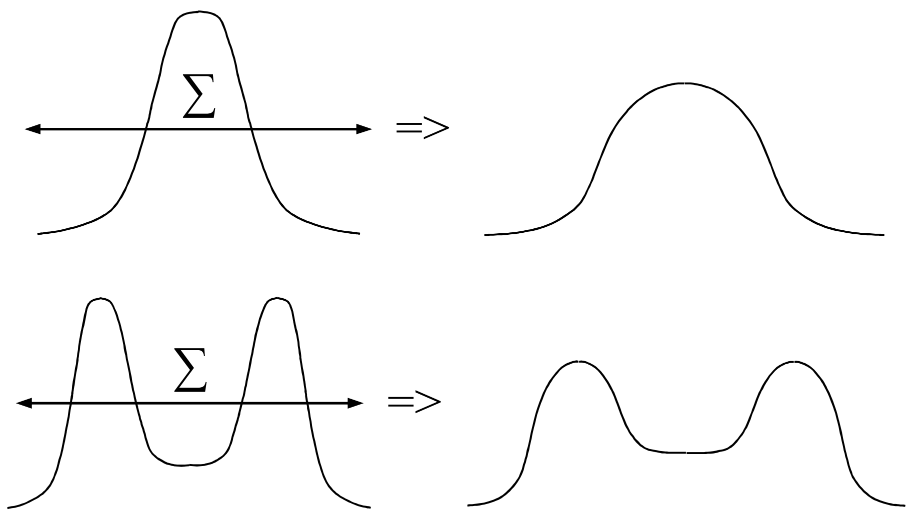




NON-STEADY UPMPARK TO MODEL WAKE MEANDERING

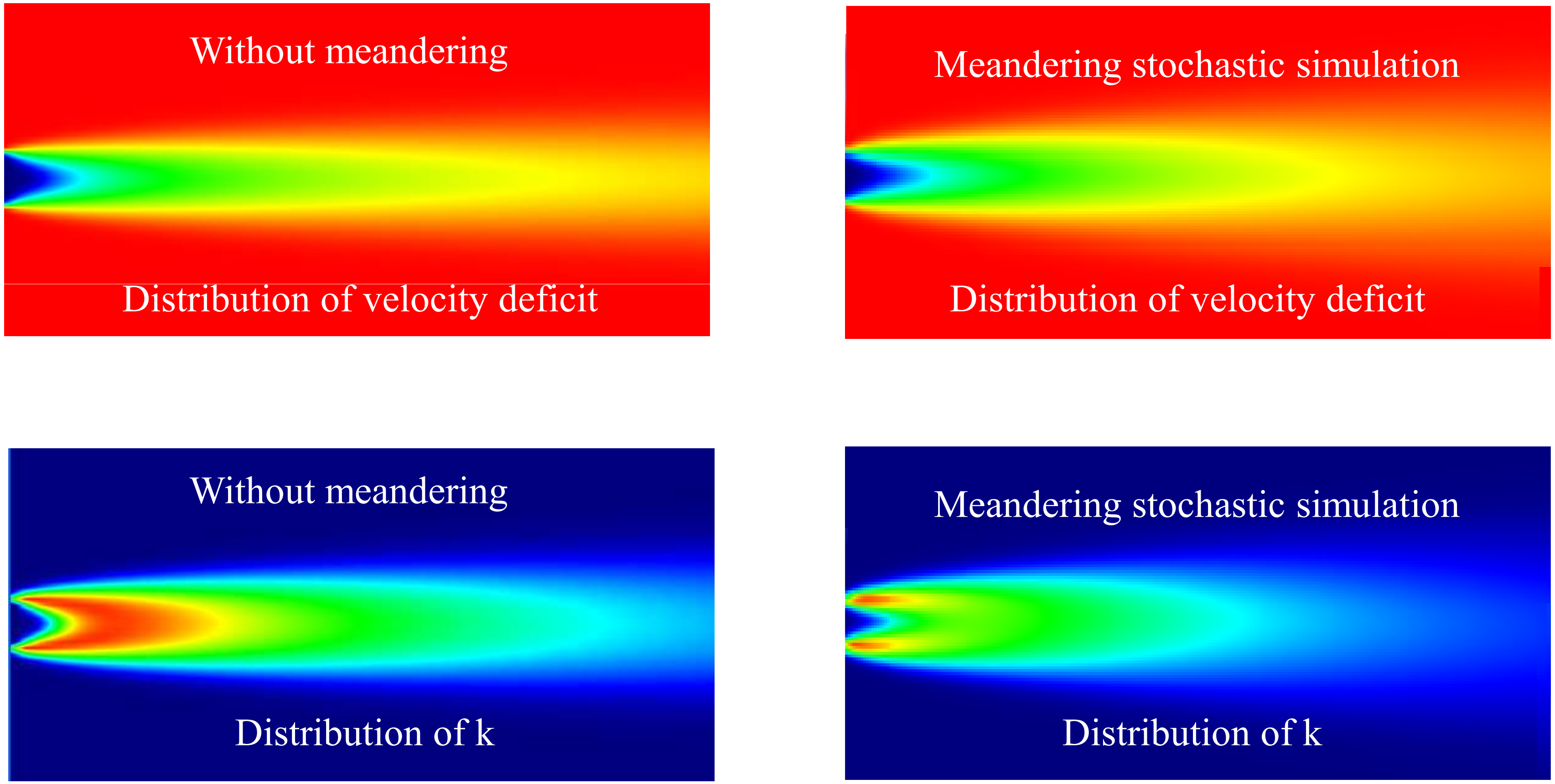
-In the following figures are compared the averaged results with and without meandering.

-Typical non-linear profiles that show a maximum are expected to be softened because of the meandering effect.

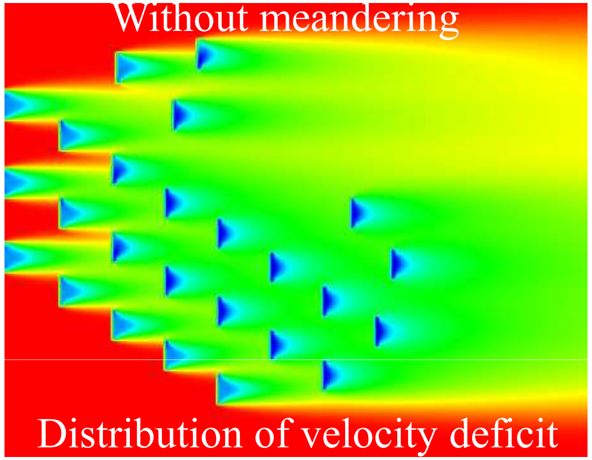


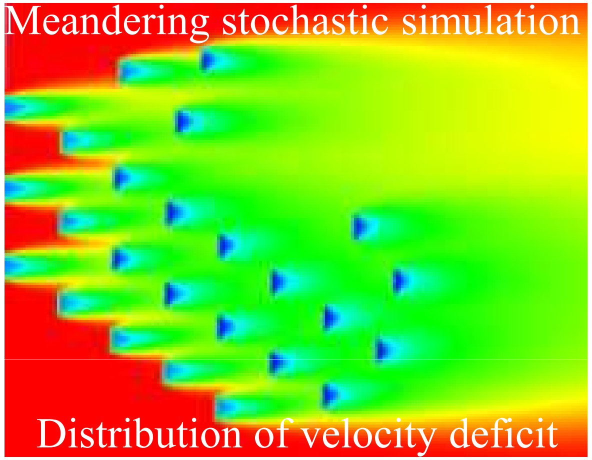
-Comparison with experiments will be made in following works.

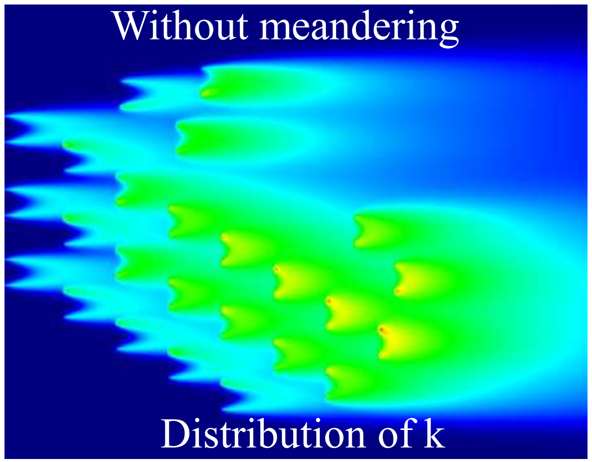
NON-STEADY UPMPARK TO MODEL WAKE MEANDERING

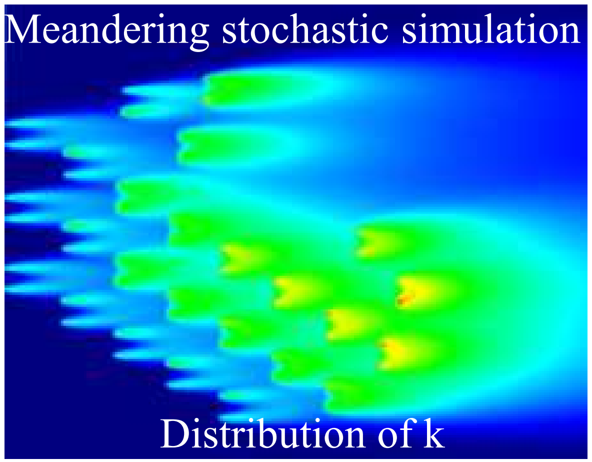


NON-STEADY UPMPARK TO MODEL WAKE MEANDERING







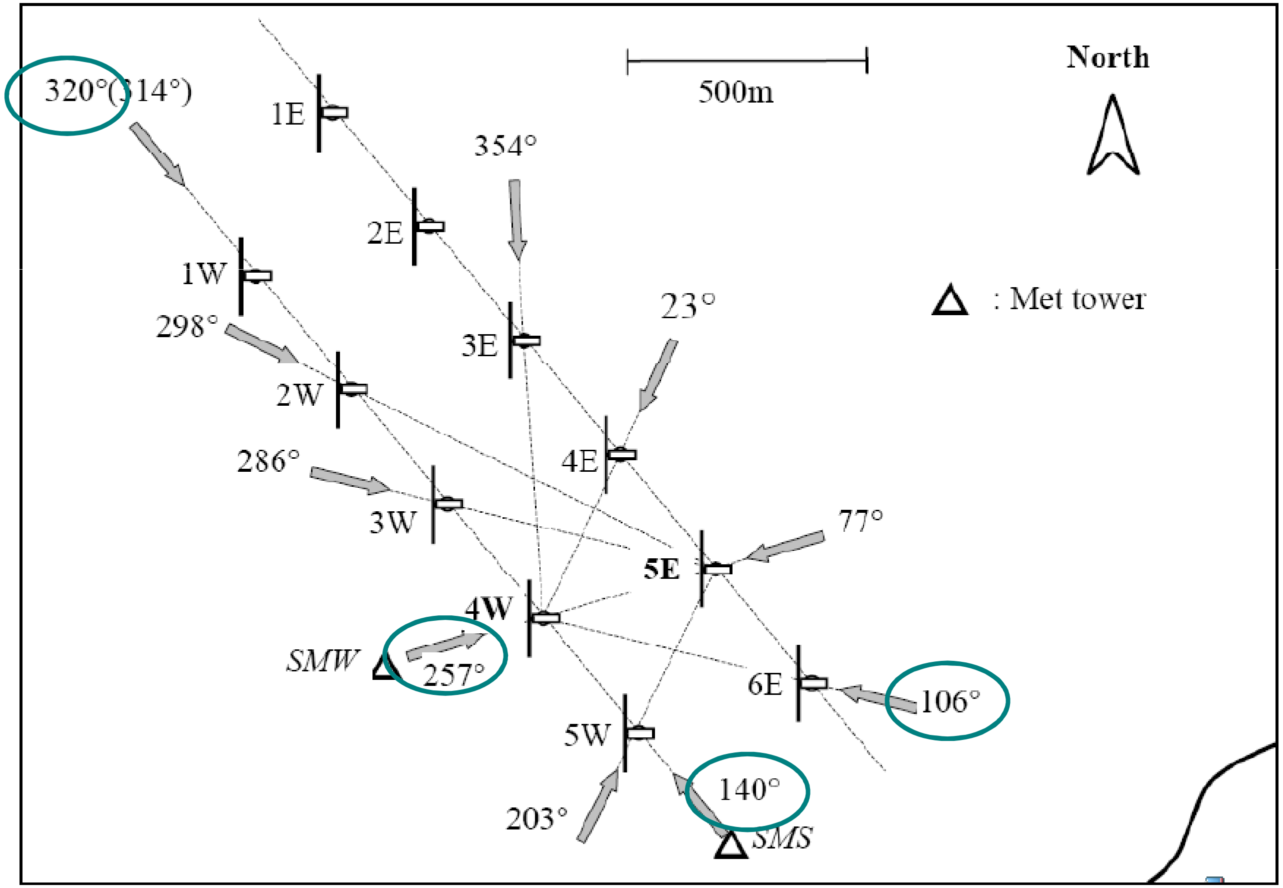


COMPARISON WITH EXPERIMENTS

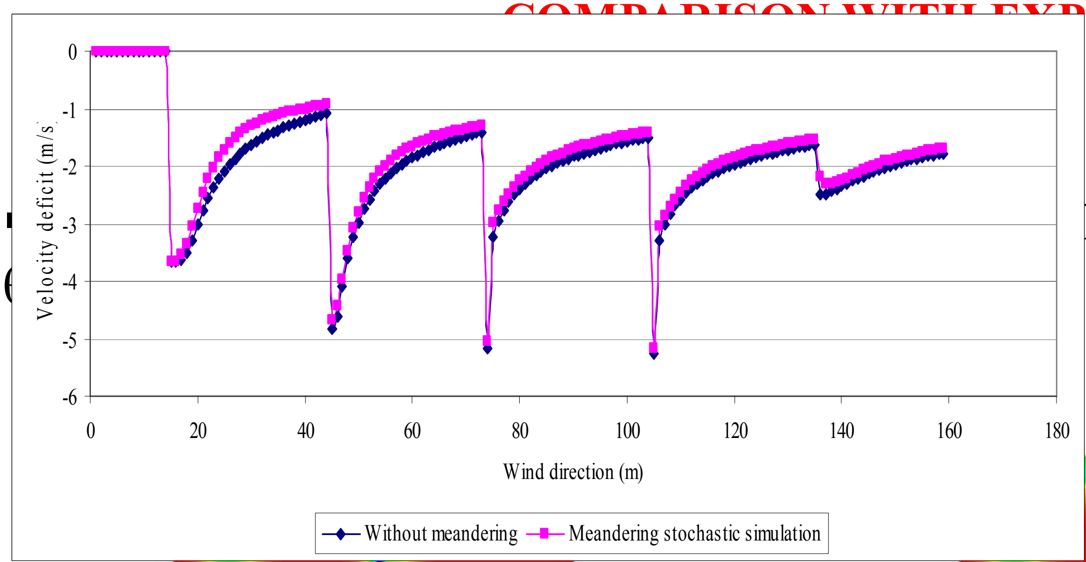
- Take part in inter-comparisons exercises, Danish Noordtank, Vindeby and Tjareborg sites.
- Initially, the intention is to compare speed deficits and turbulent kinetic energy increases.

COMPARISON WITH EXPERIMENTS

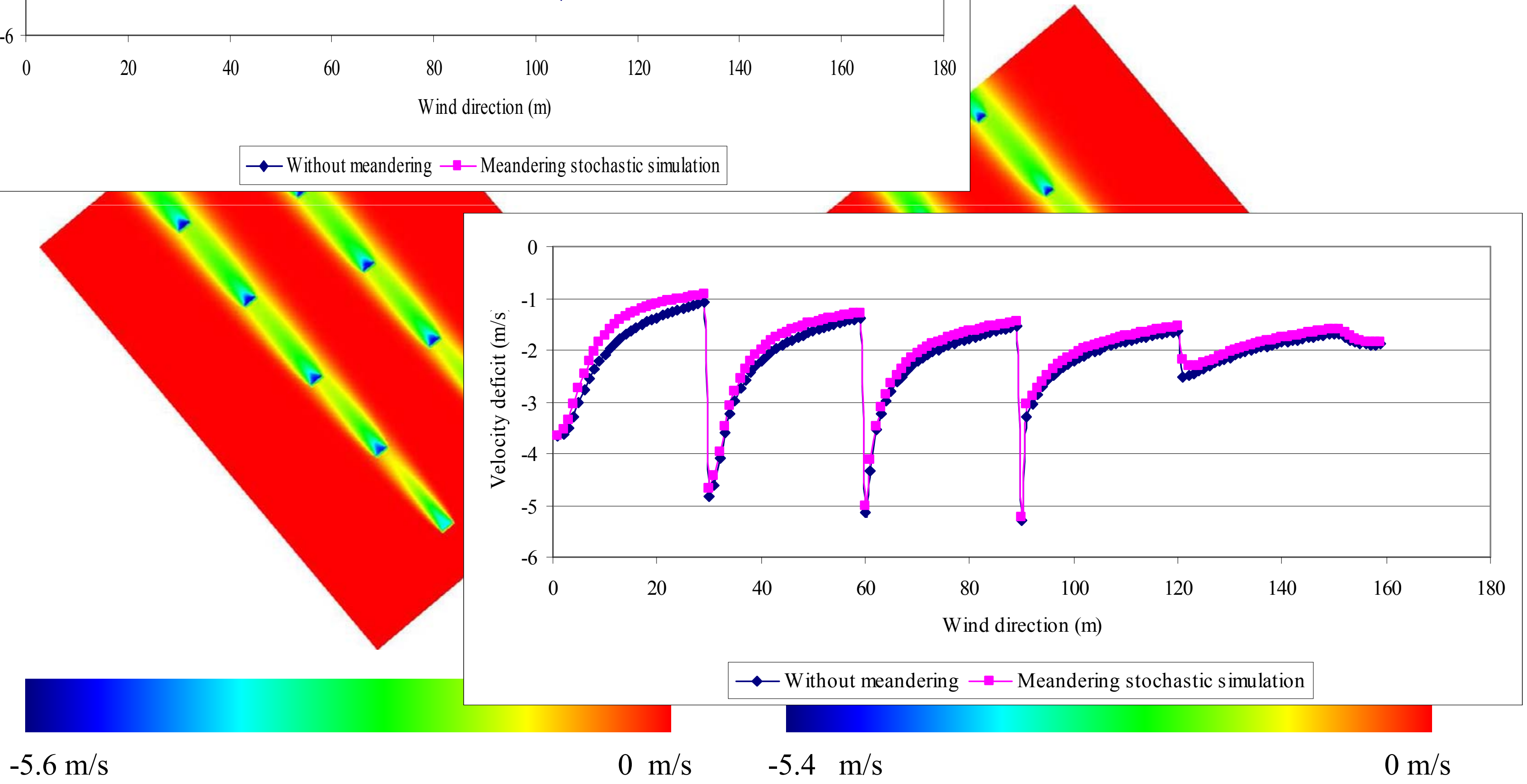
- Preliminary results to Vindeby:11x Bonus 450kW, h=37m D=35m



COMPARISON WITH EXPERIMENTS



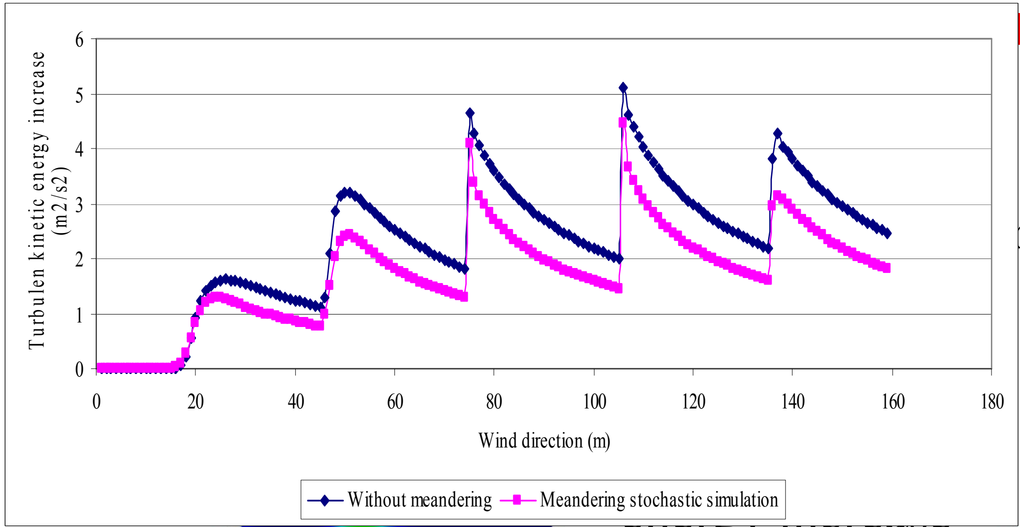
later with experimental results:



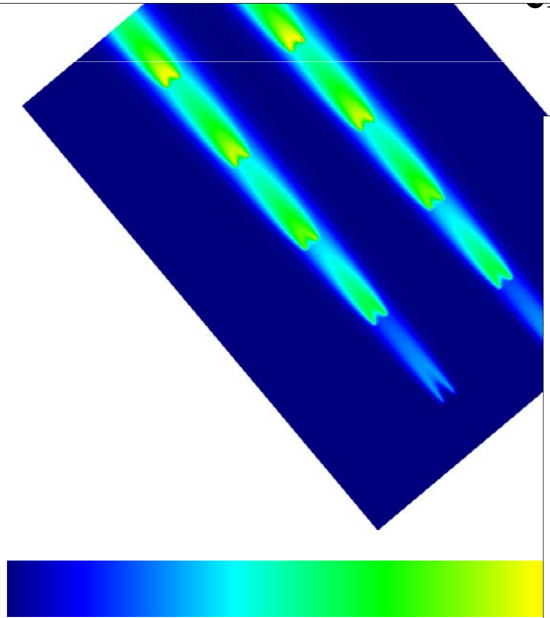
Without meandering Meandering stochastic simulation

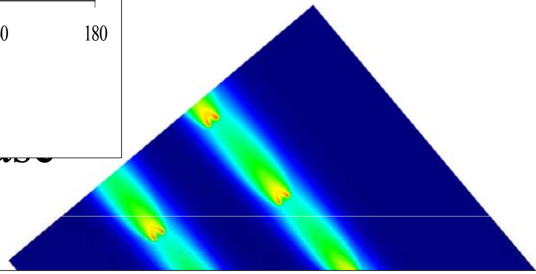
EXPERIMENTS

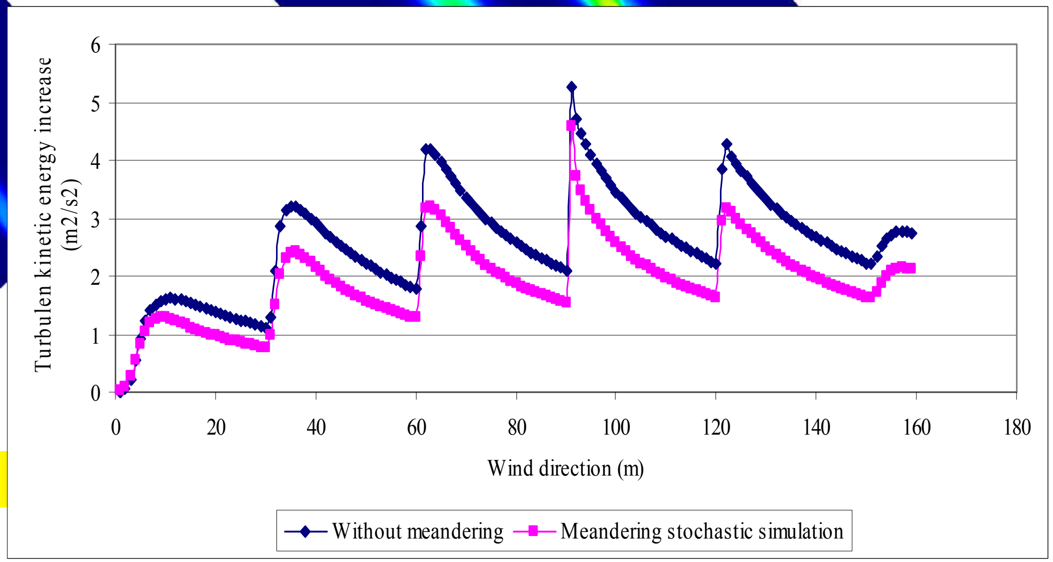
red later with experimental results:



energy increase







0 m^2/s^2

Without meandering

Meandering stochastic simulation

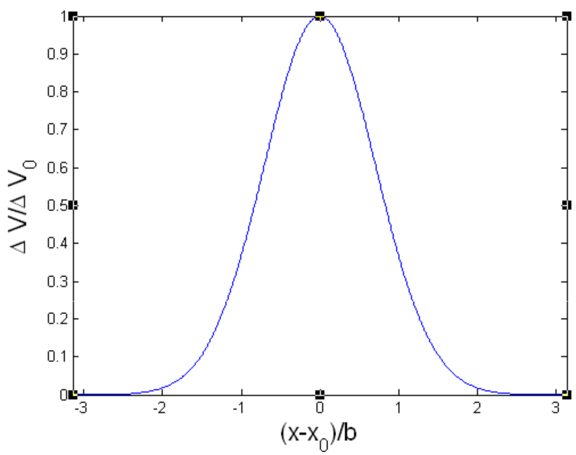
TURBULENT KINETIC ENERGY CREATED BY WAKE MEANDERING

-Recent wake models use Ainslie´s simple model and postulate that a significant part of the turbulence is what is called apparent turbulence intensity, that is associated to the oscillating velocity components as a consequence of meandering, and will not be present in the meandering frame of reference

-A simple kinematic model is proposed to show that this turbulence can not be very significative

KINEMATIC MODEL FOR WAKE MEANDERING

- A Gaussian velocity defect profile is assumed, that makes periodic lateral displacements



$$\Delta V = \Delta V_0 \exp\left(-\left(\frac{x-x_0}{b}\right)^2\right)$$

$$x_0 = \varepsilon b \sin\left(\frac{2\pi t}{T}\right)$$

Average velocity defect

$$\overline{\Delta V} = \frac{1}{T}\int_0^T \Delta V dt$$

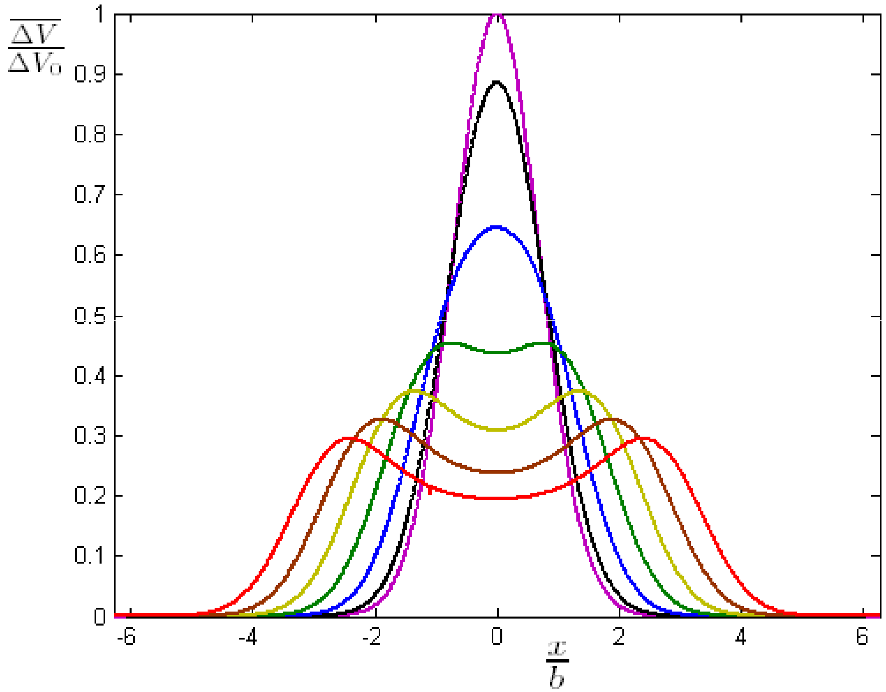
Apparent Turbulent Kinetic energy

$$\Delta k = \frac{1}{2T}\int_0^T (\Delta V - \overline{\Delta V})^2 dt$$

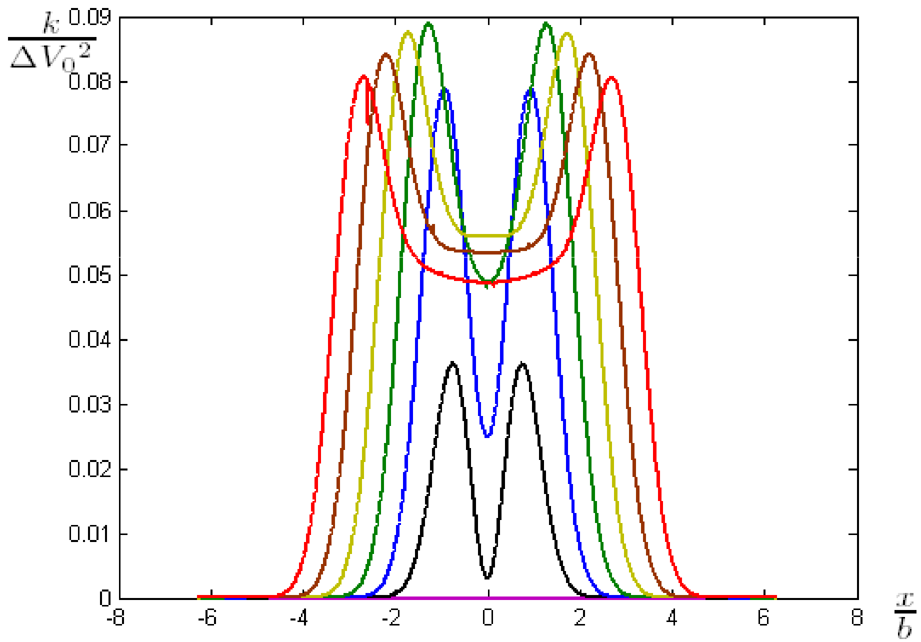
KINEMATIC MODEL FOR WAKE MEANDERING

- The non-dimensional results turn to depend only on the non-dimensional lateral displacement ε

ε=0, ε=0.5, ε=1, ε=1.5, ε=2, ε=2.5, ε=3,



Non-dimensional Average velocity defect



Non-dimensional Apparent Turbulent Kinetic energy, maximum value is 0.09

COMPARISON OF KINEMATIC MODEL AND UPMPARK MODEL FOR WAKE MEANDERING

- Now the turbulent kinetic energy associated to wake meandering will be obtained from UPMPARK calculations and will be extended over the whole meandering period

Average velocity defect

$$\overline{\Delta V} = \lim_{T \to \infty} \frac{1}{T} \int_0^T \Delta V dt$$

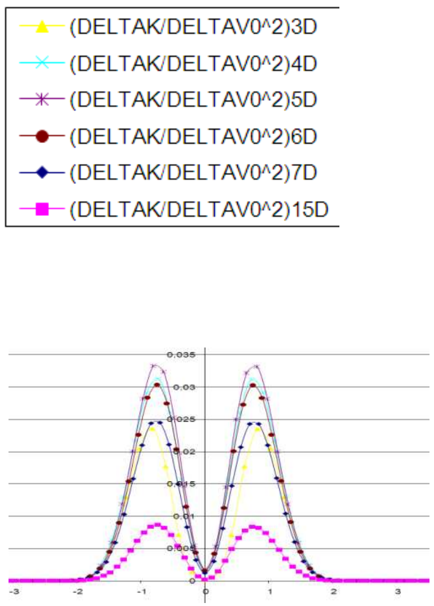
Apparent Turbulent Kinetic energy

$$\Delta k = \lim_{T \to \infty} \frac{1}{T} \int_0^T (\Delta V - \overline{\Delta V})^2 dt$$

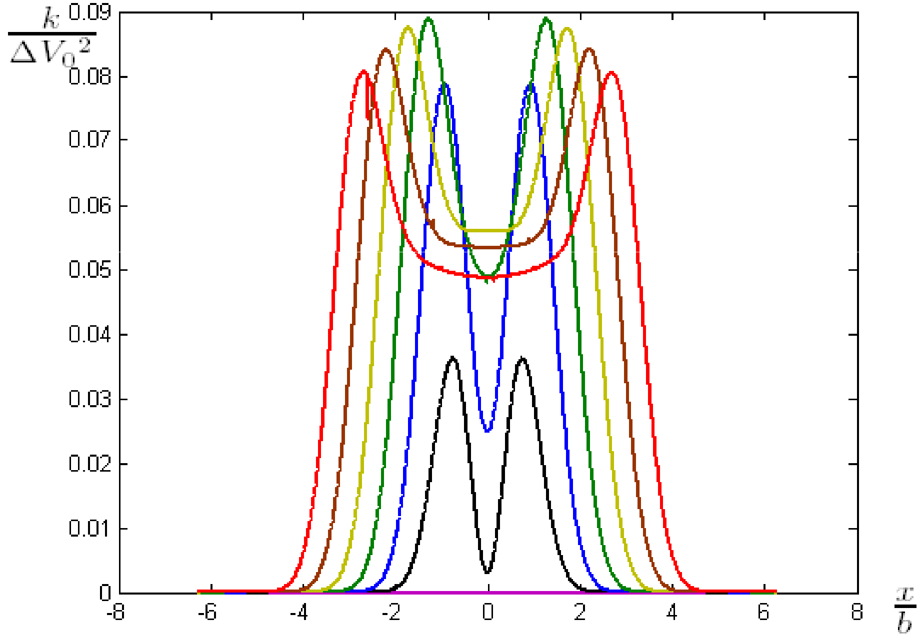
The results obtained are qualitatively quite similar to those obtained with the simple kinematic model. This may be an indication that the assumption that the velocity deficit profile is moved around like a pasive scalar may be correct

COMPARISON OF KINEMATIC MODEL AND UPMPARK MODEL FOR WAKE MEANDERING

ε=0, ε=0.5, ε=1, ε=1.5, ε=2, ε=2.5, ε=3,



Unsteady UPMPARK



Kinematic model

By comparison of the two figures the equivalent lateral displacement of the wake using UPMPARK is ε=0,5, half the wake width

FINAL CONLUSIONS

- At the present stage UPMPARK could be a useful tool for optimization of wind farms. It gives information on both wind velocity and the characteristics of turbulence generated in the wind farm. So that the energy production of every wind turbine and the incident turbulence characteristics that produce fatigue loads can be estimated in a reasonable computer time, for every array configuration.

- Unsteady effects have been incorporated in UPMPARK to reproduce meandering effects. As a consequence of the wake oscillations due to meandering the average of velocity and turbulent kinetic energy profiles are softened; in general the profiles are shorter and thicker. This effect is more important for the turbulent kinetic energy

- But on the other hand additional turbulent kinetic energy created by meandering should be considered. A kinematic model is proposed based on oscillations of velocity defect profiles as passive scalars. It gives good agreement with UPMPARK results, but shows that this additional turbulence is small because the equivalent amplitude of meandering oscillations is also small.