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## Abstract


A common operating condition for MW turbines is inflow with considerable shear, either due to shear in the atmospheric boundary layer or due to the wake from an upstream turbine. However, it seems that there is a significant uncertainty in computing rotor loads under such conditions, in particular with engineering codes based on the BEM theory. One implication is that the influence of wind shear on rotor performance is unclear and this has an impact on the procedures for measuring power curves under such inflow conditions. Likewise the effect of using cyclic pitch to optimize the performance or/and decrease the variation in loads in partial wake operation is uncertain due to inadequate induction modeling by BEM under such complex inflow conditions. The subject of improving aerodynamic computations on rotors operating in inflow with shear has therefore been one of the main research themes in work package two (WP2) in the UPWIND project and the results presented in the present paper are based on this work. Computations with advanced vortex and CFD models are used to validate the engineering BEM codes which typically are used in the aeroelastic design codes for computation of induction. The advanced model results show that there is a variation of induced velocity as function of azimuth when shear is present in the inflow and this gives a guidance to how the BEM modeling of shear should be implemented. A speed up effect due to the ground surface is also seen in the advanced model results in combination with shear in inflow and could be implemented in the BEM by an empirical function derived from the advanced model results for different tower height configurations and rotor loadings.



**Keywords:** Blade Element Momentum model, rotor aerodynamics, wind shear, induction.


## 1. Introduction

With the increasing size of wind turbines with rotor diameters for the largest turbines above 120 m, the variation of the mean wind speed over the rotor height due to wind shear can be considerable. As an example the measured wind speed at six different heights at the Test Site of Hoevsoere during a period of 1 day is shown in Figure 1, from Madsen and Fischer [1]. During the night a considerable shear is developing with a difference in wind speed of about 5 m/s from height 40 m to 116 m, Figure 1. Also a considerable variation in wind direction as function of height is seen in the lower part of Figure 1.

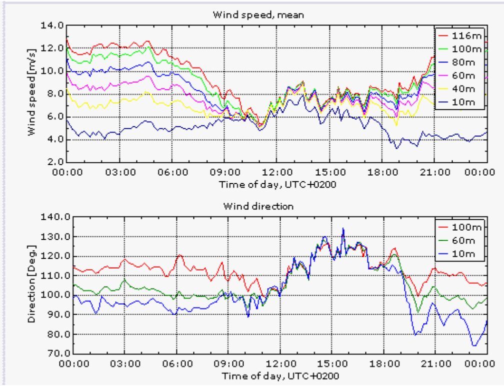


Figure 1: The figure shows wind speed and wind direction measured over one day (March 27 2007) at the Hoevsoere wind turbine test site in Denmark. Data from Madsen and Fischer [1].

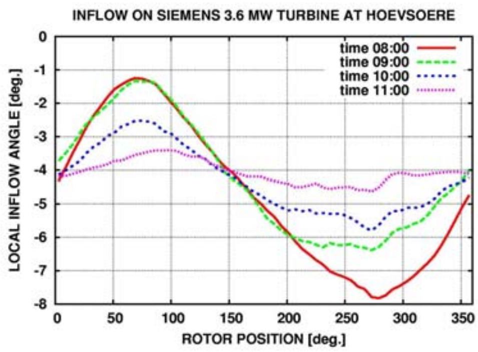


Figure 2: Measured local inflow angle with a five hole pitot tube at 36 m radius on the Siemens 3.6 MW turbine on the test site measured at different times during the same day as the wind data in Figure 1. Data from Madsen and Fischer [1].

During the same period the local inflow angle at a blade radial position of 36 m on the Siemens 3.6 MW turbine was measured [1]. The variation of the local inflow angle (mean value not calibrated) as function of blade azimuth position is shown in Figure 2 at four different times, binned over a period of 10 minutes, during the morning hours. At 8 o'clock there is a considerable variation of about 7 deg. during one revolution but during the next four hours this variation reduces considerably and correlating with the meteorology mast data in Figure 1 it is the same period where the wind shear almost disappears.

The wind data have been monitored over a longer time at the Hoevsoere test site and Antonio et al. [2] have presented the results of analyzing and categorizing the different wind shear over a period of one year as shown in Figure 3. For the most frequent wind shear profiles there is a difference in wind speed of 3 m/s from height 40 m to height 160 m which is comparable to the diameter of a MW turbine like the Siemens 3.6 MW turbine on the site. It is also seen that for the most extreme wind shear category the difference in wind speed from bottom to top is close to 5 m/s.

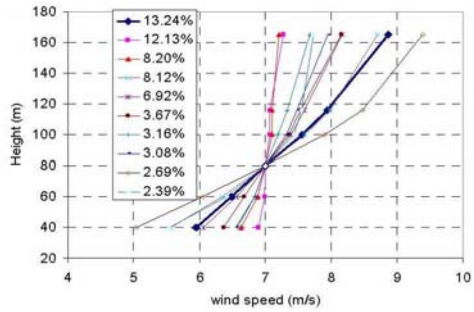


Figure 3: The ten most common normalized wind shear profiles and their percentage of occurrence measured over one year at the Hoevsoere test site. Figure from Antonio et al. [2].

Another major cause of shear in inflow is wake operation. An example of this has been presented by Madsen et al. [3] and shown in Figure 4.

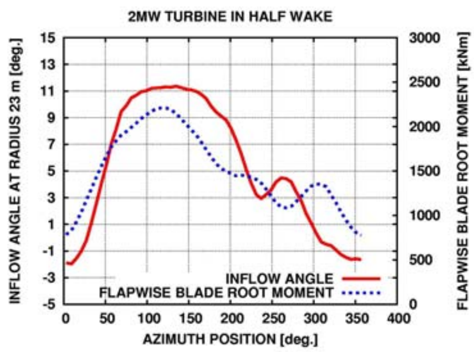


Figure 4: Measured local inflow angle in radius 24 m on a 2MW turbine and compared with the flapwise blade root bending moment during half wake operation. Figure from [3].

Figure 4 shows the measured variation in local inflow angle at about 60% radius on a 2MW turbine operating in half wake and about 3.5D downstream the wake generating turbine. Again a considerable variation of the local inflow angle is seen causing a high variation of the flapwise blade root moment.

The situation with considerable variation of both the instantaneous and the average inflow velocity over the rotor disc is thus quite common for a MW turbine and the question then rises how well this situation is modeled in the common aerodynamic and aeroelastic codes used by industry for design of MW turbines. This has been one of the research themes in work package two (WP2) of the EU-funded UPWIND project and results from this research work is the basis for the present paper.

The blade element momentum model (BEM) is the engineering model for calculation of induction implemented in the aerodynamic and aeroelastic codes such as e.g. FLEX5 [4], GAST [5] and HAWC2 [6,7] used by the industry. However, the specific implementation of the BEM model to handle shear in the inflow can be carried in different ways and there is thus an uncertainty in the modeling of this common flow situation.

An important aspect of turbine operation in shear is how its performance is influenced. This is critical when evaluating measured performance curves as it must be decided if these inflow cases should be left out of the data sets used for derivation of the final power curve for the turbine. Another important aspect is how the turbine control influences the energy capture and the loads in the case with shear in the inflow. One objective with an individual blade control on the turbine could be to maximize the energy capture for strong shear in the inflow. Another strategy could be to alleviate the varying flapwise loads occurring in this situation.

# 2. Approach

The approach in evaluating the uncertainty of the engineering BEM type aerodynamic and aeroelastic codes has been to compare with the results of more advanced codes. A comprehensive comparison has been carried out within the WP2 of the UPWIND project and reported in a task report [8]. The turbine used as test case is the 5MW reference (REF) turbine defined by Jonkman et al. [9].

## 2.1 The codes

Below the codes are grouped according to their details in modeling the flow:

**CFD codes**

- the EllipSys3D code (Risoe DTU and DTU MEK) [10,11,12]
- the actuator line code ACL (DTU MEK) [13] using the EllipSys3D as flow solver

**Vortex codes**

- the GENUVP code (NTUA,CRES) [14]
- the AWSM code (ECN) [15,16,17]

**BEM codes**

- the FLEX5 code (DTU MEK)
- the GAST code (NTUA, CRES)
- the HAWC2 code (Risoe DTU)

It should be noted that EllipSys3D is the only code where just the blade geometry and the operational conditions are input data. The other codes need airfoil data but in the present case exactly the same data set has been used for all the codes.

Further it should be mentioned that the EllipSys3D and the ACL simulations have only been run for cases with the ground present whereas the two vortex models have been run with and without the ground present. In the baseline code-to-code comparison the results obtained with the effect of the ground will be shown whereas investigation of the ground effect will be presented in section 4 by comparing with simulations without the ground present. In BEM computations the effect of the ground has not been taken into account.

Details on the EllipSys3D modeling including the implementation of shear can be found in the TORQUE2010 paper by Zahle and Sørensen [18].

In the ACL model the wind shear was generated by use of body forces as described by Mikkelsen et al. [19].

## 2.2 The inflow test case

A test case at 8 m/s has been chosen because it is typically a wind speed where the turbine operates at maximum power coefficient $C_p$ and because it is around the most frequent wind speed for the complete operational interval. Further it has been an

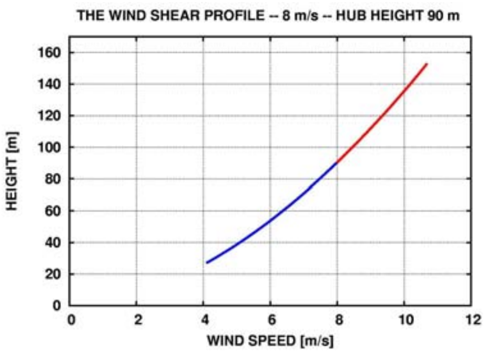


Figure 5: The wind shear used for the numerical simulations.

objective to avoid any major influence from stall on the blades. An extreme wind shear following the power law with an exponent of 0.55 has been chosen for the investigation as shown in Figure 5 for a tower height of 90 m. The following data for mean values over the rotor disc can be derived:

- mean wind speed 7.85 m/s which is 2% lower than the hub wind speed and the uniform flow wind speed of 8 m/s compared with
- mean V**2 is the same as for the uniform flow field
- mean V**3 is 5.8% higher than for the uniform flow field

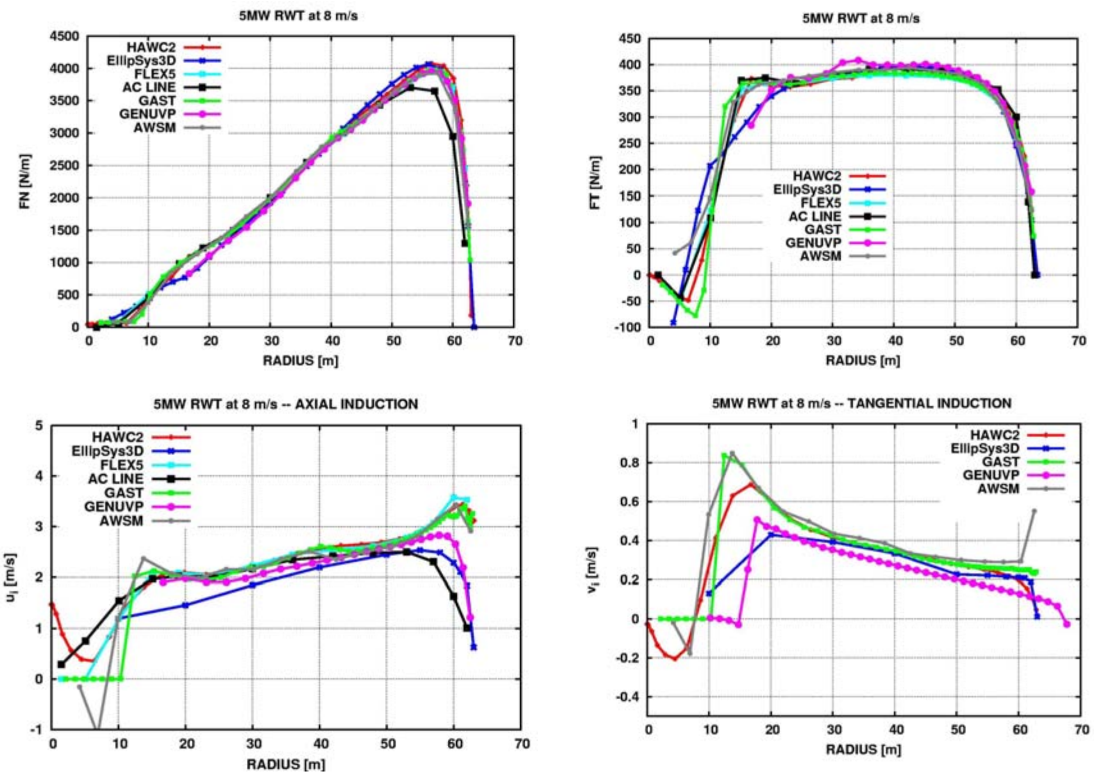


Figure 6: Blade load distribution and induction for four blade positions computed with the different models.

# 3. Results

## 3.1 Uniform inflow

The codes were first compared for the uniform inflow case. The distribution of normal and tangential force and normal and tangential induction is compared in Figure 6. In general there is a very good correlation for both the tangential and normal forces and the deviation of the ACL model results is due to a different implementation of the tip correction model. There is also small deviations for the tangential forces in the range from 10-20m where the EllipSys3D results are lower than the majority of the other results but this can probably be ascribed to partial stall modelled more accurately by the EllipSys3D model compared with the models relying on input airfoil data. As concerns the induced velocities the

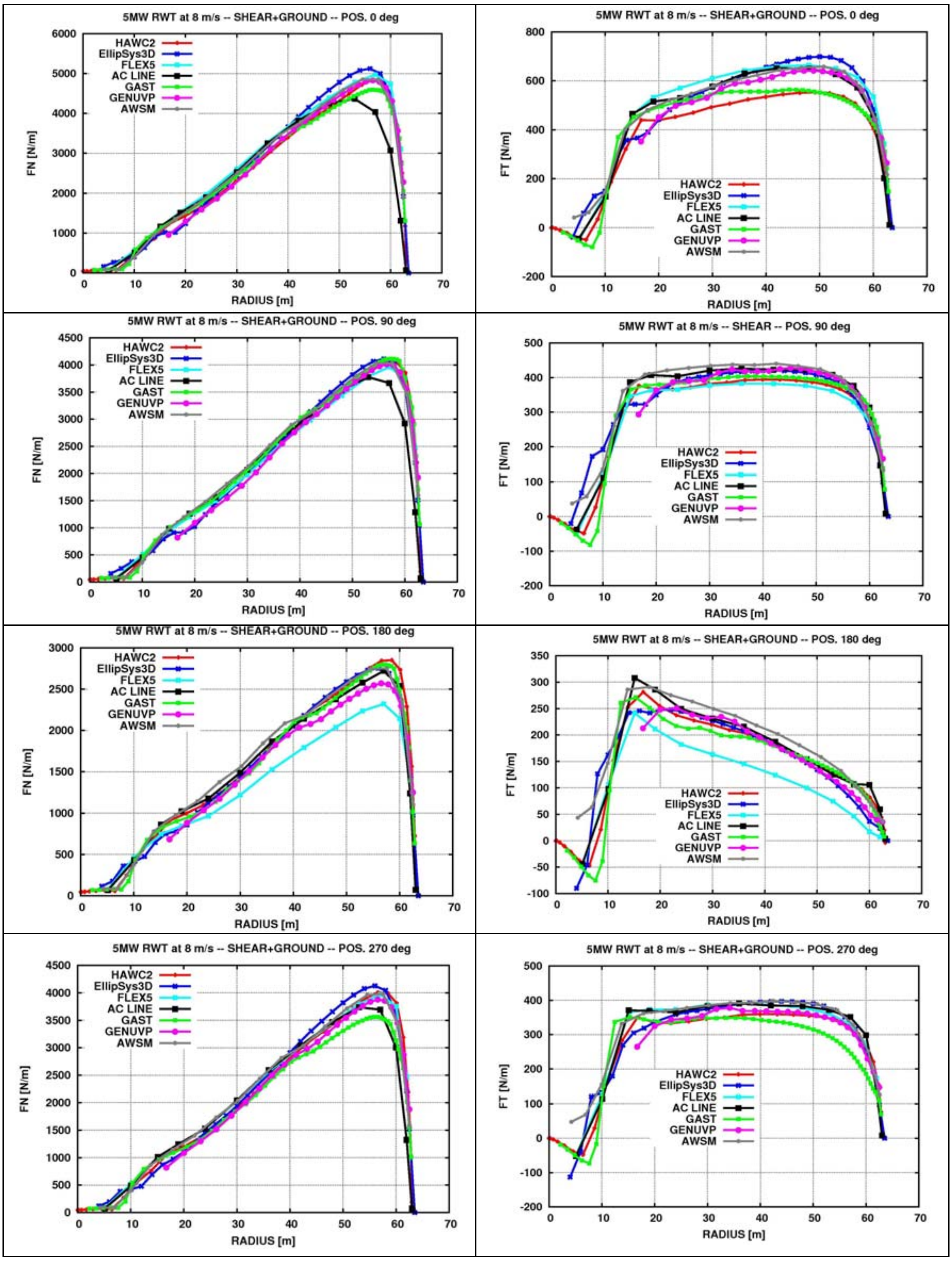


Figure 7: Blade load distribution for four blade positions and computations from different models.

correlation between the models is also quite good except in the tip region. However, these deviations are due to the tip correction applied in the BEM type models giving a local induction whereas for the EllipSys3D and GENUVP results it is the average induction that is shown.

## 3.2 Inflow with shear

The computed load distributions for four blade azimuth positions (position 0 deg. is vertical upwards) for inflow with shear are shown in Figure 7. Considerable variations up to 20-30% are now seen for the tangential force distributions and in particular for the blade in position 0 deg., 180 deg. and 270 deg. However, in general the correlation of the results from the more advanced models is better than for the three BEM based codes but as for the uniform inflow case the tip correction modelling causes deviations for the ACL results and in particular for the normal forces distribution for the blade positions 0 and 90 deg.. The tendency for the BEM type based codes is that the GAST and HAWC2 results are close to each other but deviate considerably to the FLEX5 results indicating a different implementation of the BEM model to handle inflow with shear.
The corresponding axial induction results are shown in Figure 8 and as for the loads the correlation between the advanced model results is better than for the BEM models. The deviations for the BEM type models are biggest for blade position 0 deg. and 180 deg.

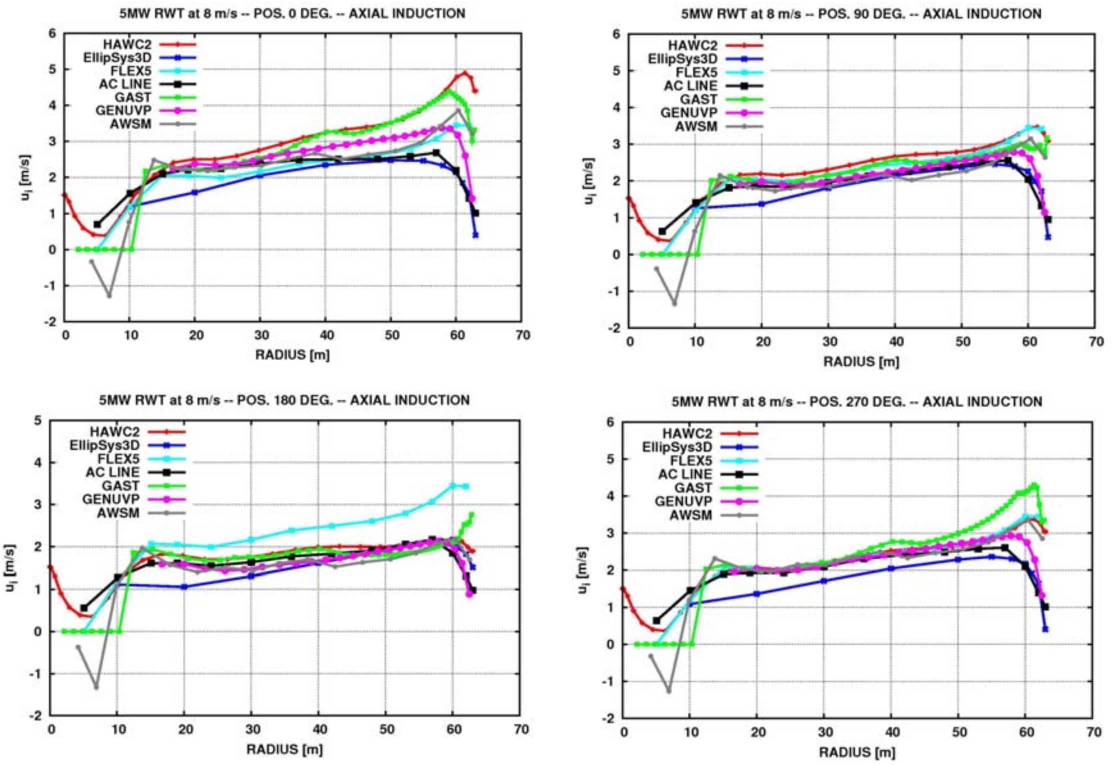


Figure 8: Axial induction for four blade positions computated with the different models.

Table 1: Integrated values of rotor power and rotor thrust for the different cases

| | HAWC2 | EllipSys3D | FLEX5 | ACL | GAST | GENUVP | AWSM | BOT |
|---|---|---|---|---|---|---|---|---|
| **Power [kW]<br>no shear** | **1928** | **1937** | **1958** | **1958** | **1934** | **1927** | **1953** | **1931** |
| **Power [kW]<br>shear+<br>ground** | **1870** | **2036** | **1958** | **1942** | **1855** | **1916** | **2078** | |
| **Thrust [kN]<br>no shear** | **391** | **387** | **386** | **374** | **387** | **363** | **382** | **386** |
| **Thrust [kN]<br>Shear<br>+ground** | **381** | **388** | **376** | **370** | **374** | **355** | **386** | |

Finally, the integrated values of rotor power and thrust for the different computations are compared in Table 1. The results from the BEM based code BOT [20] from ECN has also been included in this table. For the no shear case the maximum deviation in computed power is around 1% and somewhat the same for the thrust except for the GENUVP model in which the root of the blade (non aerodynamic part) is not modeled and therefore thrust is expected to be somewhat lower. However, for the shear case the spreading in the results is bigger. The ElliSys3D code and the AWSM code show a an increase in power of about 5% while the the ACL code and the GENUVP code computes a small decrease in power of around 0.5%. The two BEM based codes HAWC2 and GAST show a considerable decrease in power whereas FLEX5 computes the same power as for the uniform inflow.

## 3.3 Discussion of the BEM implementation for inflow with shear

We have seen above that the different implementations of the BEM model give almost identical results for uniform inflow but for the shear flow case bigger deviations are seen. Without going in a detailed discussion of the BEM implementation in the different codes a brief, general illustration of the problem is presented.

We can define a local thrust coefficient $C_T(\theta, r)$ as:

$$C_T(\theta, r) = \frac{\frac{1}{2}\rho W^2(\theta, r) C_y(\theta, r)\, c\, B\, dr}{\frac{1}{2}\rho V_{ref}^2(\theta, r) 2\pi r\, dr} \qquad (1)$$

where $W(\theta, r)$ is the relative velocity to the blade section, $\rho$ is the density of mass, $C_y(\theta, r)$ is the projection of the airfoil lift and drag coefficient in axial direction, $\theta$ is azimuth position, $B$ is number of blades and $V_{ref}$ is a reference wind speed.

Eq. 1 can be reduced to:

$$C_T(\theta, r) = \frac{W^2(\theta, r) C_y(\theta, r)\, c\, B}{V_{ref}^2(\theta, r) 2\pi r} \qquad (2)$$

For the uniform inflow case the variables will not be a function of azimuth and the reference wind speed will be equal to the free wind speed $V_\infty$ and eq. 2 reduces to:

$$C_T(r) = \frac{W^2(r) C_y(r)\, c\, B}{V_\infty^2\, 2\pi r} \qquad (3)$$

Then we can derive the induction $a(r)$ from:

$$C_T(r) = 4a(r)\left[1 - a(r)\right] \qquad (4)$$

and finally compute the induced velocity $u_i(r)$ by:

$$u_i(r) = V_\infty\, a(r) \qquad (5)$$

However, for inflow with shear we are back with equation (2) and some choices must be taken.

One possibility (version 1) is to avoid a variation of induction as function of azimuth.

$$C_T(r) = \frac{\sum_{i=1}^{B} W^2(\theta_i, r) C_y(\theta_i, r)\, c}{V_{ref-av}^2(r) 2\pi r} \qquad (6)$$

where $\theta_i$ is the azimuth position of blade no. $i$ and $V_{ref-av}$ could be the average free wind speed over the annular element or it could be the average free wind speed over the rotor disc. Finally, it could be equal to the mean root square wind speed over the rotor area.

Another option (version 2) is to use the full local version of eq. (2) which then gives the induction for each blade represented by its azimuth position $\theta$. The reference velocity $V_{ref}(\theta, r)$ could be the free wind speed at the particular azimuth and radial position.

The latter version is the one used in GAST and HAWC2. However in the HAWC2 code the reference velocity used is the average value of the free stream velocity over the rotor disc and so the same constant velocity is used for all the calculation points. The specific implementation of BEM in HAWC2 is briefly described in [3].

## 3.4 Induction characteristics derived from the advanced models

In order to come closer to an evaluation of the best way of implementing the BEM model for sheared inflow the induction data from the advanced models are further analyzed.

For each model the axial induction for the blade in four positions are shown in Figure 9. Although the models differ somewhat in absolute level of induction some clear tendencies can be found from these figures:

- the induction is bigger for the blade in top position compared with the down position
- for more of the models this difference is rather constant along the radius and is around 1 m/s
- comparing the data for position 90 deg. and 270 deg. there is a small difference indicating that there is a hysteresis effect in the induction, however not seen in the EllipSys3D results

The advanced model results indicate thus that the BEM should be implemented in a way to allow a variation of the local induction.

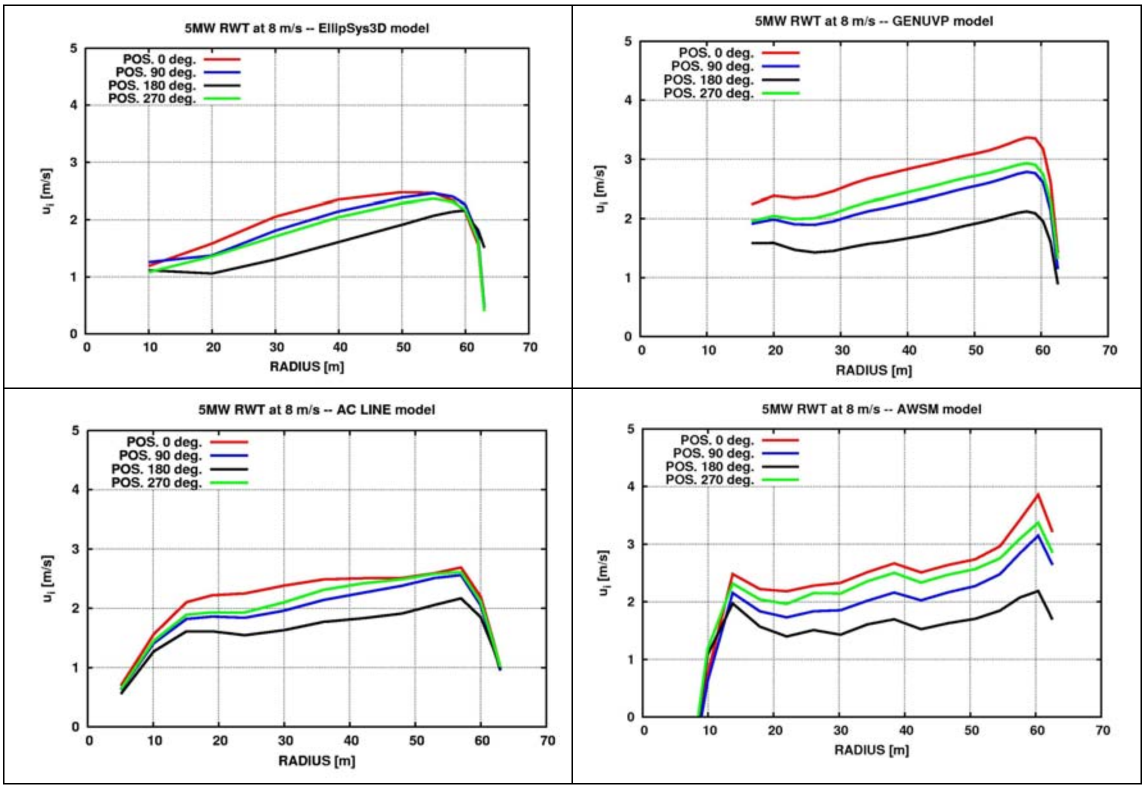


Figure 9: Axial induction for the four blade position computed with the four advanced models.

## 3.5 Results for different implementations of BEM

The BEM implementation in the HAWC2 code was modified in order to test two other BEM versions mentioned above and see how sensitive the integral power and thrust is to the specific version. One of the implementations is version 1 where the induction is assumed constant within an annular element and the reference wind speed is the mean over the rotor disc. The other implementation is version 2 with the reference wind speed equal to the free stream velocity at the specific azimuth and radial position.

The power and thrust for simulation with the different BEM versions is shown in Table 2 and it is clear from these results that in particular the power is rather sensitive to the specific BEM implementation. The power is highest for the version with constant induction over an annular element where it exceeds the power for uniform flow. The full unsteady version gives a power that is around 4% below the power for uniform flow.

Table 2: Test of different implementations of BEM

| BEM implementation in HAWC2 | Power kW | Thrust kN |
|---|---|---|
| std. version - no shear | 1928 | 391 |
| std. version - shear | 1870 | 381 |
| version 1 - shear | 1936 | 380 |
| version 2 - shear | 1848 | 377 |

# 4. Speed up effect from the ground

## 4.1 Modelling ground in the GENUVP and the AWSM model

The GENUVP and the AWSM model was used to study the influence of the ground in combination with different tower heights.

In the GENUVP model the ground is modeled as a thin plate divided in a number of panels, each one carrying constant dipole distribution. The intensities of the dipoles are determined by satisfying non entry condition at the centre of the panels. So there is still some difference compared with the CFD RANS modeling as the velocity component parallel to the wall still exists. It is also important to note that the results are sensitive to the resolution of the grid over the ground plate because since non entry condition is satisfied at the centre of the panel, there will be some outflow if the grid is coarse.

In the AWSM model, which is based on Prandtl´s lifting line theory, the ground is "virtually" taken into account by mirroring each "influencing" point on the lifting lines. More specifically, the location of each mirrored point is opposite to the original one compared to the location of the ground and the circulation is also inverted in sign.

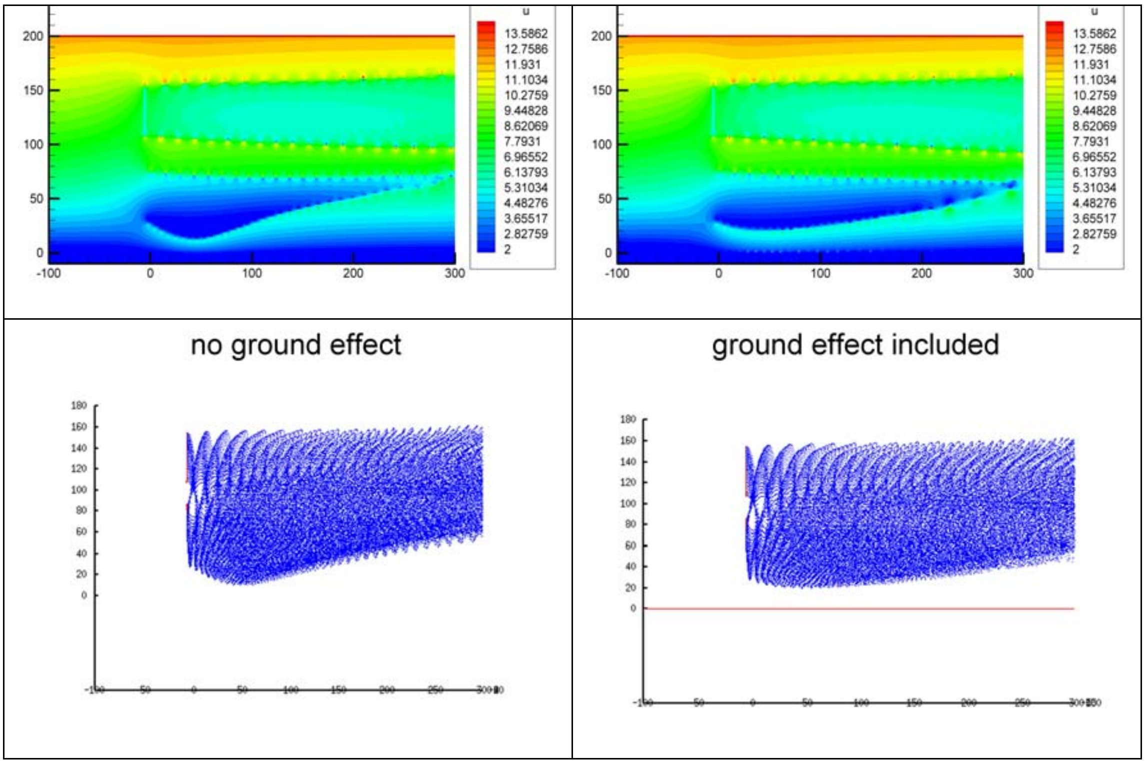


Figure 10: Computations of sheared flow and 90 m tower height with the GENUVP code without (left figures) and with ground effect (right figures). Upper figures showing the contour profiles of axial velocities and in the lower figures the vortex particles paths are shown.

## 4.2 Results on speed up effect from the ground

The GENUVP and AWSM model results show that there is a speed up effect over the lower part of the rotor but only when there is a strong shear in the inflow. Three different tower heights cases, 75 m, 90 m and 105 m and with uniform inflow gave almost the same power output, simulated with the GENUVP model.

An example of simulation of inflow with shear with the GENUVP model for the 90 m tower height is shown in Figure 10. The two left figures are without the ground and the strong expansion is clearly seen in the velocity contour plot (upper figure) as well as in the vortex paths (lower figure).

When the ground is present (right two figures) the expansion is seen to be more moderate and this increases the velocity through the lower part of the rotor.

The influence on rotor power and thrust from the ground is shown in table 3 for

Table 3: Computation for different flow cases and two tower heights with the GENUVP and AWSM code illustrating the speed up effect from the ground on the rotor power and rotor thrust

| | **GENUVP** power kW | **AWSM** power kW | **GENUVP** thrust kN kW | **AWSM** thrust kN |
|---|---|---|---|---|
| **no shear** | **1927** | **1953** | **363** | **382** |
| **shear**<br>**% rel. no shear** | **1869**<br>**-3.0%** | **1942**<br>**-0.6%** | **351**<br>**-3.3%** | **373**<br>**-2.4%** |
| **shear and ground – 90m**<br>**% rel. to shear** | **1916**<br>**2.5%** | **2078**<br>**7.0%** | **355**<br>**1.1%** | **386**<br>**3.5%** |
| **shear and ground – 75m**<br>**% rel. to shear** | **-**<br>**-** | **2188**<br>**12.7%** | **-**<br>**-** | **390**<br>**4.6%** |

both the GENUVP model and the AWSM model. Both models show a decrease in both power and thrust for the shear case without ground. However, the decrease in power computed with the GENUVP model (-3.0%) is much higher than with the AWSM model (-0.6%). When the ground now is present in combination with a tower height of 90m the GENUVP model shows an increase in power of 2.5% relative to the shear case without ground and the AWSM model predicts a considerable increase of 7.0%, also relative to the shear case without ground. This is even higher for the 75 m tower height where the increase is 12.7%. A closer analysis of the GENUVP results indicates that the speed up effect is mainly seen on the lower 20-30m (vertical height) of the rotor swept area.

# 5. Summary

Considerable shear in the inflow is a common operational condition for MW turbines. This can be either due to shear, particularly in the stable atmospheric boundary layer or it can be due to partial wake condition from an upstream turbine.

Analysis of simulation results from advanced flow models of the shear flow case shows that two flow mechanisms are important; 1) the non uniform induction over the rotor swept area and 2) a speed up effect on the lower part of the rotor amplified by the high thrust coefficient in this region. Although the available power over the rotor swept area is about 6% higher for the inflow with shear compared with the uniform flow case, three of the advanced models compute a reduction in rotor power for this flow case. However, the speed up effect on the lower part of the rotor counteracts this reduction and can even be stronger than the shear effect.

The engineering BEM type models show considerable deviation in the results for the shear flow case. Two of the models compute a considerable reduction in power for this case compared with the uniform flow case. Testing different BEM implementations in the same code shows that the rotor power can vary considerably from one implementation to another.

Analysis of the induced velocities from the advanced models shows that the induction is different for the blade pointing upwards compared with the downward position. This gives a guidance to an implementation of the BEM model in a version where the induction will vary as function of azimuth position within an annular stream tube. Such BEM type version is present in two of the BEM models used in the present study. Modeling the speed up effect in combination with shear seems also to be important for an accurate computation of the rotor power.

# 6. Acknowledgement

The work presented has been carried out within work package 2 of the UPWIND project

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