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Preprosessering av meteorologiske data for atmosfæriske teoretisk/numeriske modeller

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Abstract

In order to investigate vertical wind profiles and deviations with respect to atmospheric stability in maritime environment a case study at the Skipheia measurement site on Frøya is presented.

In this study, vertical wind profiles including atmospheric stability such as the Monin-Obukhov similarity theory (MOST) are compared to non-stability corrected wind profiles which are commonly used in wind industry. For this purpose, the atmospheric stability at the Skipheia measurement site is investigated and five different extrapolation methods are tested and compared. Therefore, measurement data at 10 m are extrapolated to 70 m and compared to the actual measurement data at 70 m. This analysis focuses on the deviation of wind profiles due to atmospheric stability and the impact on power output calculations. Therein, the sensitivity of input parameters such as wind shear exponent, roughness length and measurement height is investigated.

It is found that models including atmospheric stability result in reduced deviations to the actual measurements; especially, in unstable and very unstable atmospheric stratification. Considering all stability classes the wind profile introduced by Peña [1] resulted in the highest accuracy. In addition, the lowest error on a power output calculation is found with the introduced wind profile by Peña as well as MOST. Both models achieve an error of 2.4%. The measurement height is found to have a significant influence on the accuracy of MOST in stable stratification whereas in unstable conditions its significance is negligible.

1 Introduction

Knowing mean wind speeds at hub-heights is necessary for the design process of wind turbines. Due to a lack of measurements at this height, wind measurements are often extrapolated to the necessary height. Current standards such as IEC 61400-3 [2] and DNV-OS-J101 [3] for designing offshore wind turbines are based on onshore experience [4] and show shortcomings in adaptation to maritime environment.

The behaviors of wind speed profiles in maritime environment have been studied before by several researchers like Lange [5] or Peña [1]. Lange investigated deviations due to extrapolating Monin-Obukhov similarity theory (MOST) from 10 m to 50 m in offshore environment whereas Peña presented a correction for MOST in maritime environment and tested it against wind measurements at 50 m.

In this study, however, these stability corrected wind profiles such as MOST are compared to non-stability corrected wind profiles which are commonly used in wind industry. The aim of this study is to identify deviations due to atmospheric stability and to investigate the impact on power output calculations for an example turbine. In addition, the influence of varying crucial input parameters such as roughness length and measurement height on MOST is investigated.

For this purpose, meteorological data from Skipheia measurement station on Frøya is used. The Skipheia measurement site is located on the south-west tip of Frøya at the west coast outside of Trondheim, Norway. This site is exposed to maritime wind conditions. In order to investigate the accuracy, 10 min-averages at 10 m are extrapolated to 70 m and compared to the actual wind speed.

In section 3 the investigated wind speed profiles are introduced; afterwards, the Skipheia measurement site is introduced. In section 5, the atmospheric stability is analyzed. Thereafter, the comparison of the wind speed profiles is presented in section 6. The last section gives conclusions and recommendations for future work.

2 Nomenclature

Abbreviations

BL	Boundary Layer
LL	Logarithmic Law
Log-BL	Logarithmic Linear Law with BL-correction
LogL	Logarithmic Linear Law
m	measured
MOST	Monin-Obukhov similarity theory
p	predicted
PL	Power Law
SH	Smedman-Högström and Högström
SL	Surface Layer

Variables

c_i	Stability constant of SH-α
f_C	Corriolis Parameter
g	Acceleration of gravity
k	Friction coefficient
L_O	Obukhov-length
P	Power output
u	Wind speed
$u*$	Friction velocity
z	Height
z_o	Roughness length
α	Wind shear exponent
ζ	Stability parameter
θ_v	Virtual potential temperature
κ	von Karman constant
ρ	Density
τ	Shear stress
ψ	Stability function

Statistical parameters

N	Number of Values
NRMS-error	Normalized root mean square error
$\bar{u}$	Mean wind speed
σ	Standard deviation

$$NRMS-error = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_{m,i}-u_{p,i})^2}}{\sqrt{\overline{u_m}\cdot\overline{u_p}}}$$

3 Methodology

3.1 Monin-Obukhov simalarity theory

Wind speed profiles inside the surface layer are commonly described by MOST, which predicts a log linear (LogL) form:

$$u = \frac{u^*}{\kappa}(\ln\frac{z}{z_0} - \psi(\frac{z}{L_O})) \tag{3.1}$$

Hence, wind speed u at height z depends on friction velocity u*, roughness length z_0, the von Karman constant (κ) given as 0.4 and the stability function (ψ). The friction velocity is a value which is defined by the shear stress τ and density ρ. u* is assumed to be constant inside the surface layer. The roughness length z_0, a terrain parameter, describes the theoretical height at which the wind speed equals zero. The stability function includes the Obukhov-length (L_O) as an index of atmospheric stability and describes how the heat and momentum exchange influences the vertical wind profile. According to Businger-Dyer [6] the stability function ψ is calculated depending on the non-dimensional stability parameter $\zeta = z/L_O$. In unstable conditions ($\zeta < 0$) the stability function is defined through equations (3.2) and (3.3). Unstable atmospheric conditions occur when there is a lot of surface heating.

$$\psi = 2\ln\frac{(1+x^2)}{2} - 2\tan^{-1}(x) + \frac{\pi}{2} \tag{3.2}$$

$$x = \left(1 - 19.3\frac{z}{L_O}\right)^{1/4} \tag{3.3}$$

Stable conditions, which are characterized through a positive Obukhov-length, often occur at night times. For stable conditions ($\zeta > 0$) the stability function is negative:

$$\psi = -4.8\frac{z}{L_O} \tag{3.4}$$

In neutral conditions the stability parameter equals zero; therefore, the stability function is also 0. Atmospheric neutral conditions occur regularly at high wind speeds when the turbulence caused by the ground roughness causes sufficient mixing of the boundary layer.

$$\psi \approx 0 \tag{3.5}$$

By transforming equation (3.1) wind speeds u_2 at height z_2 can be estimated:

$$u_2 = u_1 \frac{\ln(\frac{z_2}{z_0}) - \psi(\frac{z_2}{L_O})}{\ln(\frac{z_1}{z_0}) - \psi(\frac{z_1}{L_O})} \tag{3.6}$$

3.2 Power Law

In wind energy industry, however, the power law (PL) (3.7) is widely used for calculating wind profiles. IEC 61400-3 [2] and DNV-OS-J101 [3] suggest the power law to extrapolate wind speeds to a certain height. The power law is a mathematical approach to describe wind shear and has no explicit physical basis.

$$u_2 = u_1 \left(\frac{z_2}{z_1}\right)^{\alpha} \tag{3.7}$$

According to IEC 61400-3 and DNV-OS-J101 for offshore locations the wind shear exponent (α) of 0.14 is recommended.

3.3 Logarithmic Law

The logarithmic law is based on MOST for neutral conditions (ψ=0) and is another commonly used wind speed profile. The logarithmic law (LL) depends on the roughness length. DNV-RP-C205 [7] suggests different z_0 depending of the ground's topography and vegetation. In coastal areas with onshore wind the roughness length is between 0.01 and 0.001.

$$u_2 = u_1 \frac{\ln(z_2 / z_0)}{\ln(z_1 / z_0)} \tag{3.8}$$

3.4 Stability corrected logarithmic law including boundary layer height

In maritime environment deviations from MOST, especially in stable conditions, have been identified by several researchers, such as Peña [1] and Lange [8]. Based on the assumption that the boundary layer is lower in stable stratification, Peña [1] introduced a correction method for MOST depending on the boundary layer height (Log-BL).

$$u_2 = u_1 \frac{\ln(\frac{z_2}{z_0}) - \psi(\frac{z_2}{L_O})(1 - \frac{z_2}{2z_{BL}})}{\ln(\frac{z_1}{z_0}) - \psi(\frac{z_1}{L_O})(1 - \frac{z_1}{2z_{BL}})} \tag{3.9}$$

Therefore, the changes on the wind speed profile due to the correction are negligible, when the boundary layer height (z_{BL}) is high. For stable conditions Peña [1] found that equation (3.9) improves the concurrence of predicted and measured values.

3.5 Wind shear exponent depending on stability and roughness length

Gualtieri [9] found through a case study at a coastal site in Italy that the wind shear exponent introduced by Smedman-Högström and Högström [10] gave, especially, in unstable and neutral conditions good results for predicting wind from 10 m to 50 m. The wind shear exponent (PL-SH) depends on roughness length and stability. α was empirically determined through three measurement campaigns in different terrains in Sweden.

$$\alpha = c_0 + c_1 \log(z_0) + c_2 (\log(z_0))^2 \tag{3.10}$$

In the following Table 3.1 the stability dependent constants c_0, c_1 and c_2 are listed.

Stability class	c_0	c_1	c_2
very Unstable/Unstable	0.18	0.13	0.03
Neutral	0.30	0.17	0.03
weakly Stable	0.52	0.20	0.03
Stable	0.80	0.25	0.03
very Stable	1.03	0.31	0.03

Table 3.1: Values for c_0, c_1 and c_2 depending on atmospheric stability [10]

4 Skipheia Measurement Site

For a detailed description of the measurement program and the Skipheia measurement site the reader is referred to the wind site analysis by Øistad [11]. Here, only the most important points are mentioned. The measurements took place on the south-west tip of Frøya an island off the coast of mid-Norway. The Skipheia measurement site is located close to the village of Titran and exposed to maritime wind conditions. The site has three met masts. Mast-2 and Mast-4 are 100 m high and Mast-3 is 45 m high. For this study only data of Mast-2 is regarded. In UTM-coordinates Mast-2 is located at 8.34251 E and 63.66638 N, approximately 20 m above sea level. Depending on the direction the distance to the shoreline varies. From SE to SW (135°N to 225°N) the distance is less than 500 m from SE to W (225°N to 90°N) the distance to the shoreline is more than 1 km. In general, the topography is flat and homogenous. Based on linear least square regression the best-fit is calculated from the data set and solved for the roughness length. Figure 4.1 shows mean roughness lengths for four different sectors.

Met-Mast 2 is equipped with six pairs of 2D ultrasonic wind sensors (Type: Gill WindObserver II) and seven temperature sensors (Campbell Scientific 109 temperature probes). The wind and temperature sensors are installed at 10 m, 16 m, 25 m, 40 m, 70 m and 100 m. In addition, one temperature sensor is located close to the ground at 2 m. At each height two wind sensors are installed, one is facing 131°N and the other one is facing 311°N. Records from situations of direct mast shade have been omitted.

A detailed description of the overall meteorological data is also given by Øistad [11]. In general, the mean wind speed is 8.24 m/s and the main wind direction is SW. According to wind power classifications the site is class 6 (Outstanding).

Figure 4.1: Map of Norway, Skipheia and Mast-2 [12]

5 Data Analysis

The measurement campaign started on the 18th of November 2009 and is still ongoing. Here only data gathered until the 30th of September 2014 are analyzed. Technical problems, however, occurred during that time period; therefore, the dataset covers about 3 years. The wind and temperature sensors are sampling with a sampling rate of 1 Hz. For this analysis 10 min-averages are used. The Skipheia measurement site doesn't provide data about air humidity and barometric pressure. Therefore, the data from Sula meteorological measurement station are used to provide values at 10 m height. The Sula weather station is located on the island Sula about 20 km north of Skipheia measurement site. The barometric pressure data from Sula are corrected depending on height and temperature with the hydrostatic equation [13].

The data set covers overall 162 848 data points for each height. MOST is only valid for stationary conditions and within the surface layer. So, non-stationary conditions are filtered according to the following rules:

- A variation in u of more than 10%,
- a change in temperature of more than 0.5 °C
- and a variation of wind direction more than 10° between consecutive values. [4]

In order to secure that the measurements are within the surface layer, the surface layer height (z_{SL}) is computed and only data with z_{SL}>70 m is analyzed. Therefore, z_{SL} is calculated according to equation (5.1) [8]. Equation (5.1) is only valid for near-neutral conditions [14], hence mainly very stable and very unstable atmospheric conditions are filtered out. The equation contains the Corriolis Parameter (f_C) of 0.0001:

$$z_{SL} = 0.1 \cdot 0.25 \cdot \frac{u^*}{f_C} \tag{5.1}$$

The friction velocity [7] is estimated through the friction coefficient k and 10-min mean wind speeds u_{10} at 10 m.

$$u^* = \sqrt{k} \cdot u_{10} \tag{5.2}$$

The friction coefficient [7] is computed through the von Karman constant, the roughness length, and z=10 m. In favor of an accurate friction coefficient, four different mean roughness lengths are used (cf. Figure 4.1Figure 4.1)

$$k = \frac{\kappa^2}{(\ln \frac{z}{z_0})^2} \tag{5.3}$$

The applied filters reduce the data set to 37 712 data points.

5.1 Atmospheric Stability

The atmospheric stability and the Obukhov-length are calculated with the Richardson Gradient Method. First, the gradient Richardson number (5.4) is computed. For this purpose, temperature and wind speed at two different heights are needed. The gradient Richardson number is calculated with equation (5.4) [6] between z_1=40 m and z_2=100 m.

$$\Delta Ri(z_{ref}) = \frac{g(\frac{\Delta\theta_v}{\Delta z})}{\overline{\theta_v}(\frac{\Delta u}{\Delta z})^2} \tag{5.4}$$

In this equation, θ_v is the virtual potential temperature [13] and g is the acceleration of gravity. All the differences are taken with the lower value first as it is expressed in equation (5.5).

$$\Delta z = z_1 - z_2 \tag{5.5}$$

The following empirical relationship between the gradient Richardson number and the Obukhov-length is used to convert the gradient Richardson number. With values higher than 0.2 this method loses accuracy [6]:

$$L_O = \begin{cases} \frac{z_{ref}}{\Delta Ri}, \Delta Ri \leq 0 \\ \frac{z_{ref}(1-5\Delta Ri)}{\Delta Ri}, 0 < \Delta \mathrm{Ri} < 0.2 \end{cases} \tag{5.6}$$

The reference height [15] for the Obukhov-length is given by equation (5.7)

$$z_{ref} = \frac{z_1 - z_2}{\ln(\frac{z_1}{z_2})} \tag{5.7}$$

Table 5.1 shows stability classifications according to the Obukhov-length [16]:

Obukhov-length	**Atmospheric Stability**
-200 m $< L_O <$ 0 m	very Unstable
-1000 m $< L_O <$ -200 m	Unstable
$\lvert L_O \rvert >$ 1000 m	Neutral
200 m $< L_O <$ 1000 m	Stable
0 m $< L_O <$ 200 m	very Stable

Table 5.1: Stability classification

The generated data through the stability classifications shown in Figure 5.1 are illustrated in normalized mean wind speed profiles for each stability class. At the Skipheia measurement site very unstable conditions (38%) dominate. Only 20% of the data are classified as neutral conditions.

Figure 5.1 shows that the mean wind speed profile deviates due to different atmospheric stratification which has a significant impact on the shape of the wind profile. It can be seen that the slopes from stable to unstable conditions decreases. In unstable stratification the shear profile is vertically stretched; therefore, the gradient is low. Contrarily, in stable stratification the shear profile is stretched horizontally. In other words, measurements at low heights in stable stratification are significantly higher at hub height (70 m to 100 m).

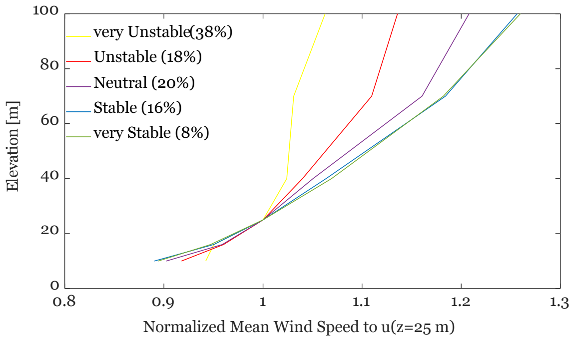

Figure 5.1: Normalized mean wind speed profiles for each stability class

Figure 5.2 shows the distribution for each wind speed bin at the Skipheia measurement site according to atmospheric stability. At lower wind speeds, from 6 m/s to 10 m/s, very unstable conditions dominate the observed wind velocities. From 6 m/s to 8 m/s more than 50% of the observed values are measured at very unstable stratification. At high wind speeds unstable conditions barely occur and neutral conditions dominate. Stable and very stable conditions occur mainly between 8 m/s and 15 m/s. In Figure 5.3 it is recognizable that unstable and very unstable conditions mainly occur from SW to W, which is also the direction closest to the shoreline. Neutral conditions also mainly occur from SW.

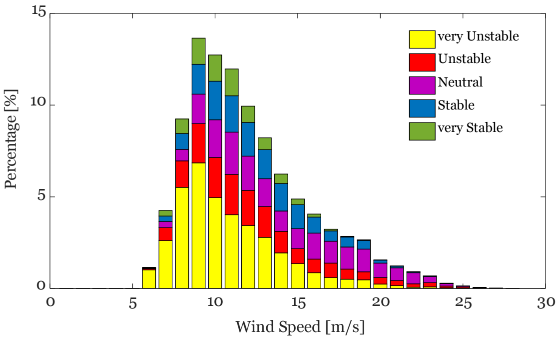

Figure 5.2: Histogram for each stability class

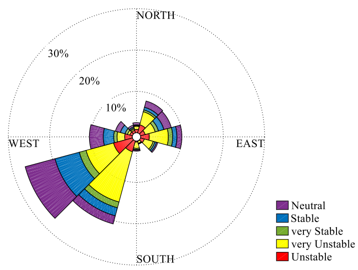

Figure 5.3: Atmospheric stability rose

5.2 Wind shear exponent

In order to estimate the variation of the wind shear exponent according to atmospheric stability and directional changes, α is calculated with equation (5.8) between z_1=10 m and z_2=70 m. The topography and vegetation at the Skipheia measurement site is flat and homogenous [11]. Hence, direction bins are defined by the approximate distance to the shoreline [12] since there is a significant change in roughness. Each bin has at least 25 data points.

$$\alpha = \frac{\ln(u_2) - \ln(u_1)}{\ln(z_2) - \ln(z_1)} \quad (5.8)$$

In Table 5.2 mean wind shear exponents and corresponding standard deviations (σ) are presented. In general, the gathered data shows that the mean wind shear exponent increases from very unstable to very stable conditions. Accordingly, the lowest wind shear exponent is achieved at very unstable conditions with α=0.05 whereas the highest wind shear exponent is found at very stable conditions as α=0.16. Additionally, the standard deviation increases as well. As stated before IEC-61400-1 recommends an α=0.14 for offshore sites which corresponds to stable and very stable conditions at the Skipheia measurement site. The direction-dependant variation of α is lower in very unstable conditions than in very stable conditions. Overall, the gathered data shows that the deviations of α caused by atmospheric stability are bigger than the variations due to wind directional changes at the Skipheia measurement site. Nevertheless, in order to conclude further about the directional variations of α and the impact of the coastline on the wind shear exponent further investigations are necessary.

Direction	Distance to shoreline	very Unstable		Unstable		Neutral		Stable		very Stable	
		α	σ	α	σ	α	σ	α	σ	α	σ
250°-47°	1 km-4 km	**0.06**	0.034	**0.11**	0.024	**0.13**	0.029	**0.15**	0.041	**0.14**	0.043
47°-110°	>4 km	**0.05**	0.025	**0.08**	0.031	**0.12**	0.036	**0.13**	0.044	**0.12**	0.051
110°-125°	1 km-4 km	**0.05**	0.023	**0.07**	0.022	**0.11**	0.042	**0.13**	0.041	**0.14**	0.056
125°-250°	<1 km	**0.05**	0.027	**0.08**	0.026	**0.11**	0.025	**0.14**	0.036	**0.16**	0.052

Table 5.2:Wind shear exponent depending on atmospheric stability and direction

6 Results

6.1 Comparison of predicted and measured wind speed profiles

In order to assess the accuracy of the introduced wind speed profiles, the profiles are investigated regarding errors with respect to different atmospheric stabilities. Furthermore, the accuracy of these extrapolation methods is analyzed depending on different wind speeds.

In this analysis 10 min-averages at 10 m are extrapolated to 70 m. In accordance to international standards it is assumed that the wind shear exponent is 0.14 [2] and the roughness length is 0.001 [7].

Figure 6.1 shows the wind speed ratio between the measured and predicted wind speeds (u_m/u_p) against the thermal stratification of the atmosphere. The thermal stratification is expressed by the non-dimensional stability parameter z_1/L_O. Therefore, $z_1/L_O<0$ refers to unstable, $z_1/L_O\approx0$ to neutral and $z_1/L_O>0$ to stable conditions. The error bars represent the standard deviations of each bin and only bins with at least 25 values are shown. According to Webb [17], MOST is only valid in a range of $-1\leq z_{ref}/L_O\leq1$ which corresponds to $|L_O|\geq65$. All graphs are shown within this interval. In addition, the mean ratio, the standard deviation of the ratio and the NRMS-error are calculated for each stability class. Those statistical values are presented in section 8.

Overall non-stability corrected functions like PL and LL overestimate in unstable and underestimate in stable conditions the wind speed depending on the input parameters (wind shear exponent or roughness length). As shown in section 5.2 the wind shear exponent deviates depending on direction and atmospheric stability. Accordingly, using a wind shear exponent of 0.14 leads especially in very unstable conditions to over-estimations and a NRMS-error of 15%. The LL has an NRMS-error of 12% in very unstable conditions. The predictions through stability corrected equations such as LogL, Log-BL and PL-SH show small deviations in very unstable stratification.

In neutral stratification the stability function equals zero, therefore LogL, LL and Log-BL are equal and deviations of 6% are found. The predicted wind speeds with the PL show deviations of 8%. The PL-SH shows even higher deviations of 11.6%.

In stable up to very stable conditions, the predicted wind speeds with stability corrected equations are overestimated. It can be seen that LogL and Log-BL have shortcomings in describing wind speed profiles in stable conditions. The large deviations are based on the estimations of the Obukhov-length through the Richardson Gradient Method. Similar results for the Richardson Gradient Method in stable stratification have been observed by Lange [8] and Venora [18]. This leads to the conclusion that other effects play an important role in stable conditions which are not described sufficiently. Nevertheless, an explicit explanation is not found yet and further research is necessary [5]. The lowest deviations in stable conditions are achieved with non-stability corrected profiles like PL (10%) and LL (12%) in stable conditions. The PL-SH over predicts wind speeds in stable and very stable conditions. PL-SH predicts with z_0=0.001 in stable conditions a wind shear exponent of 0.32. As shown in section 5.2 the average wind shear exponent in stable conditions is much lower (0.13-0.15); therefore, a wind shear exponent of 0.32 leads to an overestimated wind speed.

In consideration of all stability classes the prediction of wind speeds based on MOST, so LL, LogL and Log-BL, show the smallest deviations (7%-8%). The prediction through PL shows a NRMS-error of 10%. The wind shear exponent through equation (5.8) by Smedman-Högström and Högström over-predicts α especially in stable and very stable conditions which leads to an NRMS-error overall of 27%.

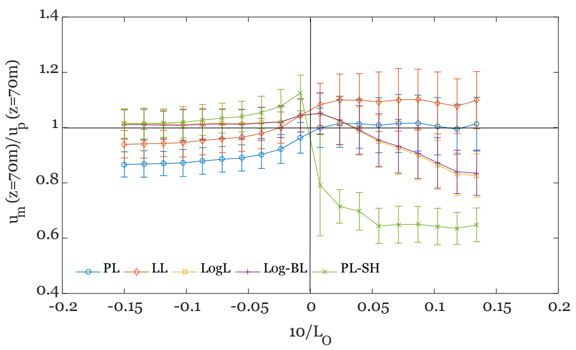

Figure 6.1: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus stability parameter at 10 m

	NRMS-error				
	PL	**LL**	**LogL**	**Log-BL**	**PL-SH**
all Data	10%	8%	8%	7%	27%
very Unstable	15%	8%	5%	5%	5 %
Unstable	12%	6%	5%	5%	7%
Neutral	8%	6%	6%	6%	12%
Stable	7%	10%	8%	8%	38%
very Stable	10%	12%	17%	17%	49%

Table 6.1: NRMS-error of prediction through PL, LL, LogL, Log-BL, PL-SH according to atmospheric stability

In the interest of investigating the impact of different wind speeds on the prediction, the bin-mean averages are shown versus the wind speed at 10 m (cf. Figure 6.2, Figure 6.3 and Figure 6.4).

In general, it can be seen that all profiles show the same tendency in all stability classes: The extrapolation methods over-predict in low wind speeds and under-predict at high wind speeds.

The curve progression is the same for each stability class. In addition, all wind speed profiles show lower standard deviations for each bin towards high wind speeds. Especially, in unstable and neutral stratification LogL and Log-BL achieve low deviations at high wind speeds. In stable atmospheric conditions, especially, the PL-SH over-predicts wind speeds.

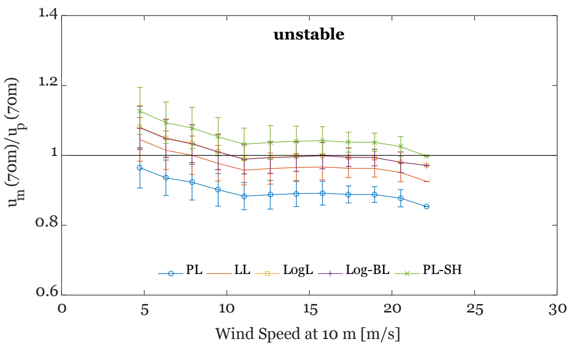

Figure 6.2: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus wind speeds at 10 m for unstable conditions

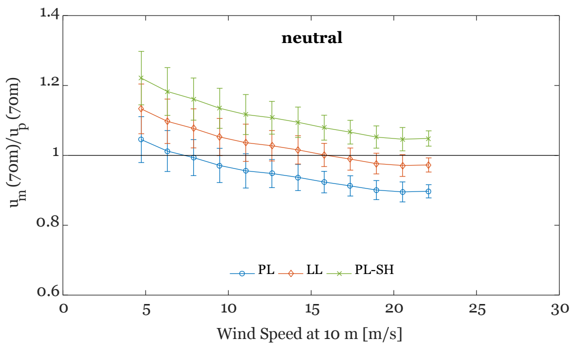

Figure 6.3: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus wind speeds at 10 m for neutral conditions

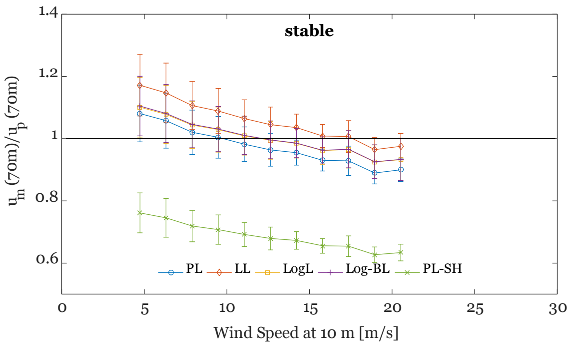

Figure 6.4: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus wind speeds at 10 m for stable conditions

6.2 Prediction of power output and comparison of different methods

In order to investigate the influence of the deviations on power output calculations, the power output for a Vestas V100 1.8 MW is computed with measured and predicted wind speeds at 70 m. Corresponding to section 6.1, the measured wind speeds at 10 m are extrapolated to 70 m. In addition, the error between the predicted and measured power output, so $(P_m-P_p)/P_m$, is calculated and illustrated in Table 6.2.

The power output calculated from measured wind speeds at hub height is 1316 kW. The estimated power output calculated from predicted wind speeds is in all cases lower than the power output derived from measured wind speeds. The error is between 2.4% and 12.1% as shown in Table 6.2. The smallest error of 2.4% is found with Log-BL and LogL.

It must be noted that only small deviations for the actual power output are found, even though large deviations between the measured and predicted wind speeds are shown in section 6.1. As shown in section 6.1 depending on the atmospheric stability the wind speed is over- or underestimate. The data set for the power output calculation contains all stability classes. Hence, it is concluded that these over- and under-predictions compensate each other which leads to low errors in the power output calculation.

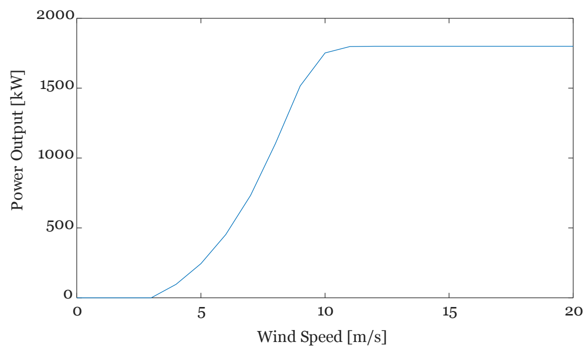

Figure 6.5: Power curve of Vestas V100 1.8 MW

	Power output [kW]	Error [%]
u(z=70 m)	1316	
PL	1245	5.4%
LL	1279	2.8%
LogL	1284	2.4%
Log-BL	1285	2.4%
PL-SH	1156	12.1%

Table 6.2: Power output at 70 m calculated with PL, LL, LogL, Log-BL and PL-SH

6.3 Sensitivity to input parameters

In order to investigate the stability dependent impact on MOST of crucial input parameters, two different cases are regarded: First, the influence of the measurement height is assessed. Thereafter, different roughness lengths are tested in different atmospheric stabilities.

In Figure 6.6 three different heights for u_1 are compared in different atmospheric stabilities. In general, the gathered data shows that with an increasing height of u_1 the standard deviation for each bin can be reduced. Furthermore, in neutral, unstable and very unstable conditions the bin-mean averages are similar for all heights. On the other hand, in stable and very stable conditions significant deviations between the different measurement heights are found. In other words, the measurement height is found to have a significant influence on the accuracy of MOST in stable stratification whereas in unstable conditions its significance is negligible.

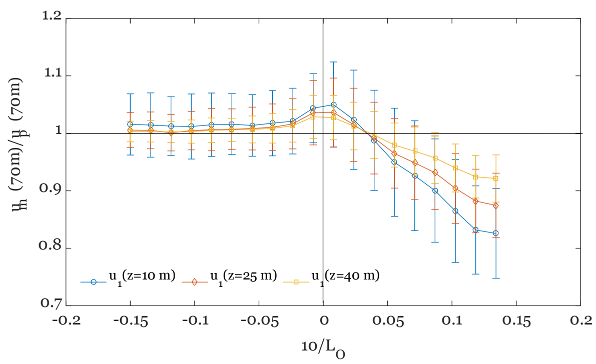

Figure 6.6: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus stability parameter for $u_1(z=10\text{ m})$, $u_1(z=25\text{ m})$ and $u_1(z=40\text{ m})$

In coastal areas with onshore wind DNV-RP-C205 [7] recommends a roughness length between 0.001 and 0.01. These roughness lengths are compared to a partitioned mean roughness length calculated from the dataset which deviates according to the direction as shown in Figure 4.1.

The partitioned roughness length leads to low deviations especially in unstable and very unstable conditions. In stable conditions, however, the prediction through z_0=0.001 shows the lowest deviations. Furthermore, the gathered data shows that the change of the roughness length does not have a significant impact on the scatteredness of the bins. Considering all data points z_0=0.001 achieves the lowest deviation.

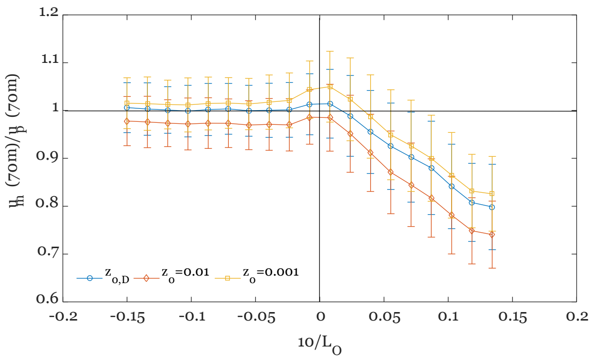

Figure 6.7: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus stability parameter with different z_0

7 Conclusion

It can be concluded that including atmospheric stability in wind profiles significantly improves the prediction especially in unstable and very unstable conditions. In stable conditions, however, large over-estimations have been found. Therefore, further research in maritime environment on wind profiles in stable conditions is necessary before it can be recommended to include atmospheric stability in the extrapolation. Nevertheless, in consideration of all data points the Log-BL (3.9) model achieves the lowest NRMS-error.

In more detail it can be concluded:

- The wind shear exponent deviates from 0.05 to 0.16 according to atmospheric stability. In addition, the gathered data shows that deviations of the wind shear exponent due to different stabilities are bigger than deviation caused through wind directional changes. These strong variations in α discloses the need for more accurate models taking atmospheric stability into account
- The error on a power output calculation is between 2.4% and 12.1%. The lowest error in the power output calculation is achieved by LogL (3.6) and Log-BL (3.9)
- In stable atmospheric conditions a higher measurement height leads to smaller deviations while in unstable stratification the measurement height is not as relevant
- In consideration of all atmospheric stabilities a roughness length of 0.001 leads to the lowest deviation to the actual measurements

These findings underline the necessity for further development on wind profile models in maritime environment, especially for stable stratification as this could significantly improve power output predictions of wind turbines.

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8 Appendix

Statistical values of the comparison and sensitivity analysis

Table 8.1: Statistical values of PL, LL, LogL, Log-BL, Pl-SH

	Mean ratio (u_m/u_p)					**Standard Deviation of ratio**					**NRMS-error**				
	PL	**LL**	**LogL**	**Log-BL**	**PL-SH**	**PL**	**LL**	**LogL**	**Log-BL**	**PL-SH**	**PL**	**LL**	**LogL**	**Log-BL**	**PL-SH**
all Data	0.95	1.03	1.02	1.02	0.95	0.081	0.088	0.077	0.077	0.195	10%	8%	8%	7%	27%
very Unstable	0.88	0.95	1.01	1.01	1.02	0.047	0.051	0.054	0.054	0.055	15%	8%	5%	5%	5%
Unstable	0.91	0.99	1.02	1.02	1.06	0.052	0.056	0.056	0.056	0.060	12%	6%	5%	5%	7%
Neutral	0.96	1.04	1.04	1.04	1.12	0.057	0.062	0.062	0.062	0.067	8%	6%	6%	6%	12%
Stable	1.01	1.09	1.03	1.03	0.71	0.079	0.086	0.082	0.083	0.056	7%	10%	8%	8%	38%
very Stable	1.01	1.09	0.91	0.92	0.65	0.098	0.106	0.101	0.102	0.063	10%	12%	17%	17%	49%

Table 8.2: Statistical values of comparison between $z_{0,D}$, z_0=0.01 and z_0=0.001

	Mean ratio (u_m/u_p)			**Standard Deviation of ratio**			**NRMS-error**		
	$z_{0,D}$	**z_0=0.01**	**z_0=0.001**	**$z_{0,D}$**	**z_0=0.01**	**z_0=0.001**	**$z_{0,D}$**	**z_0=0.01**	**z_0=0.001**
all Data	1.00	0.96	1.02	0.076	0.077	0.077	8%	10%	8%
very Unstable	1.00	0.97	1.01	0.053	0.052	0.054	5%	6%	5%
Unstable	1.00	0.97	1.02	0.056	0.054	0.056	6%	7%	5%
Neutral	1.01	0.99	1.04	0.065	0.059	0.062	6%	7%	6%
Stable	1.00	0.96	1.03	0.079	0.078	0.082	8%	10%	8%
very Stable	0.89	0.83	0.91	0.102	0.096	0.101	19%	25%	17%

Table 8.3: Statistical values of comparison between u_1(z=10 m), u_1(z=25 m) and u_1(z=40 m)

	Mean ratio (u_m/u_p)			**Standard Deviation of ratio**			**NRMS-error**		
	u_1(z=10 m)	**u_1(z=25 m)**	**u_1(z=40 m)**	**u_1(z=10 m)**	**u_1(z=25 m)**	**u_1(z=40 m)**	**u_1(z=10 m)**	**u_1(z=25 m)**	**u_1(z=40 m)**
all Data	1.02	1.02	1.01	0.077	0.059	0.039	8%	5%	4%
very Unstable	1.01	1.01	1.00	0.053	0.034	0.020	5%	3%	2%
Unstable	1.02	1.01	1.01	0.057	0.042	0.027	5%	4%	2%
Neutral	1.04	1.03	1.03	0.062	0.055	0.037	6%	5%	4%
Stable	1.03	1.02	1.02	0.083	0.063	0.041	8%	6%	4%
very Stable	0.91	0.94	0.96	0.101	0.069	0.045	17%	11%	7%

Table 8.4: Statistical values of comparison of surface layer height

	Mean ratio (u_m/u_p)				**Standard Deviation of ratio**				**NRMS-error**			
	z_{SL}>0 m	**z_{SL}>50 m**	**z_{SL}>70 m**	**z_{SL}>100 m**	**z_{SL}>0 m**	**z_{SL}>50 m**	**z_{SL}>70 m**	**z_{SL}>100 m**	**z_{SL}>0 m**	**z_{SL}>50 m**	**z_{SL}>70 m**	**z_{SL}>100 m**
all Data	1.04	1.03	1.02	1.01	0.120	0.084	0.077	0.069	8%	8%	8%	7%
very Unstable	1.04	1.02	1.01	1.01	0.132	0.067	0.054	0.046	7%	6%	5%	5%
Unstable	1.04	1.03	1.02	1.01	0.102	0.067	0.056	0.048	6%	6%	5%	4%
Neutral	1.06	1.05	1.05	1.03	0.085	0.062	0.062	0.055	6%	6%	6%	5%
Stable	1.05	1.04	1.03	1.02	0.126	0.089	0.082	0.073	9%	8%	8%	7%
very Stable	0.87	0.84	0.83	0.80	0.151	0.104	0.096	0.087	25%	25%	17%	15%

Influence of surface layer filter on MOST

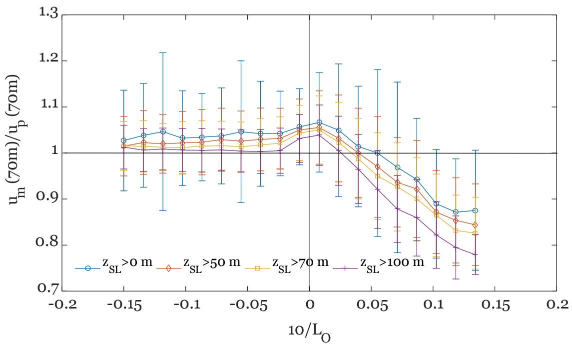

Figure 8.1: Bin-averaged ratio of measured and predicted wind speeds at 70 m versus stability parameter with different minimum surface layer heights

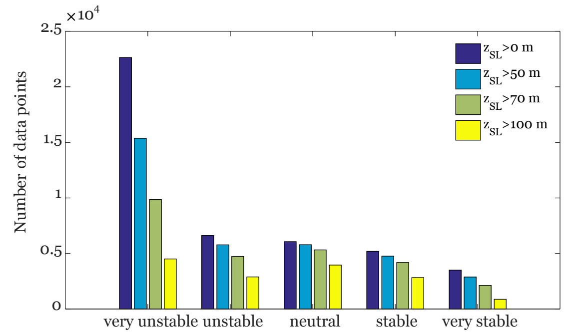

Figure 8.2: Number of data points for each stability class according to surface layer height

Accuracy of MOST in unstable, neutral and stable stratifications sorted according to direction

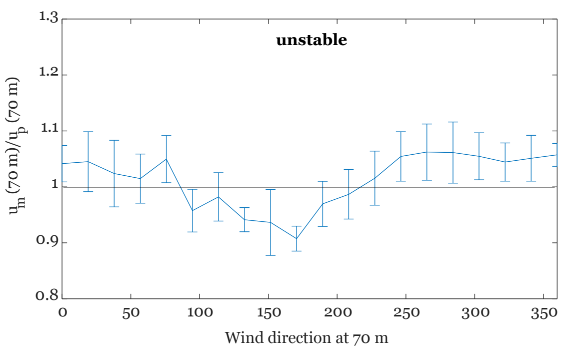

Figure 8.3: Bin-mean averaged ratio of measured and predicted wind speeds at 70 m vs. wind direction at 70 m in unstable stratification

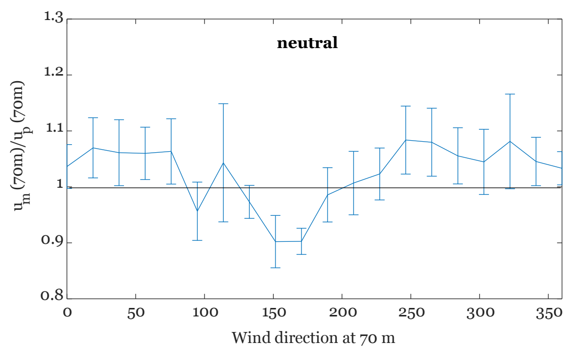

Figure 8.4: Bin-mean averaged ratio of measured and predicted wind speeds at 70 m vs. wind direction at 70 m in neutral stratification

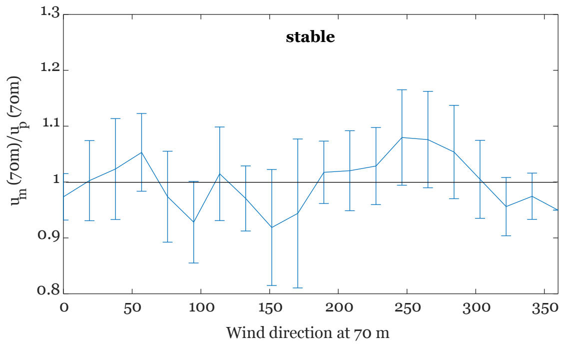

Figure 8.5: Bin-mean averaged ratio of measured and predicted wind speeds at 70 m vs. wind direction at 70 m in stable stratification