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Deviations between wind speed data measured with nacelle-mounted anemometers on small wind turbines and anemometers mounted on measuring masts

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Abstract: This article focuses on the readings received from two different types of nacelle-mounted anemometers and their comparison with reference measurements on-site. The aim of the article was to evaluate the influence of the wind turbine rotors on the wind data measured with the nacelle-mounted anemometers. The measurements were made during a case study of two existing small wind turbines. The framework conditions in the analysed cases were similar: both analysed anemometers were mounted on small, 10 kW horizontal axis type wind turbines (HAWT-s) with active yaw and pitch control, and although the wind turbines were situated at different locations, the wind conditions of the measurement sites were relatively similar. The comparative wind speed data for the analysis was acquired in both cases from measurement masts that were installed in the proximity of the analysed anemometers on the basis of the standard EN 61400-12-1:2006. The anemometer readings were logged during measuring periods of two months and saved as 10 minute averages. Three anemometers and a wind direction sensor were used for the reference measurements on both sites. It was found that in both cases the operating state of the wind turbines (presumably the rotation of the rotor blades of the turbine) influenced the readings received from the nacelle-mounted anemometers to a statistically significant extent. The 10 minute average wind speeds of the nacelle-mounted anemometers were significantly lower than the means of the data acquired from the measuring mast anemometers. Despite the fact that the means did not coincide the correlations between the reference wind data and the nacelle-mounted anemometer readings were strong. In the analysed cases the readings from the ultrasonic anemometer were more similar to the reference measurements than the readings from the mechanical cup-anemometer.

Key words: wind measurements, anemometers, accuracy, wind turbines.

INTRODUCTION

Modern wind turbines with active yaw and pitch control rely in their operation on real-time wind speed data, which is used for the automatic control operations. This requires constant wind speed measurements in the proximity of the wind turbine. Normally anemometers that are mounted on the nacelle of the wind turbine are used for acquisition of the necessary data. This occurs due to the fact that the anemometer has to be approximately on the same height with the wind turbine hub and installing a separate mast just for measurements is not reasonable. The problem lies in the fact that the wind turbine and especially the rotating rotor blades of the turbine influence the air flow that has to be measured. And thereby influence the results of the measurements.

Precise measuring results about weather conditions are especially important when evaluating the performance of autonomous or semi-autonomous renewable energy systems (Osadcuks et al., 2013).

MATERIALS AND METHODS

This analysis was based on two small (P_n = 10 kW) wind turbines. Wind Turbine 1 (WT 1) has a hub height of 18 meters and a rotor diameter of 7.2 meters. Wind Turbine 2 (WT 2) has a hub height of 16 meters and a rotor diameter of 8 meters.

Two measuring masts were installed in order to collect data about the wind conditions on the site of each wind turbine. The placement of the measuring masts was chosen on the basis of the standard EN 61400-12-1:2006. The main factors for the correct placement of the measuring mast were:

1) distance from the wind turbine;
2) direction in relation to the main wind direction and wind turbine.

The positioning of the mast is illustrated on Fig. 1.

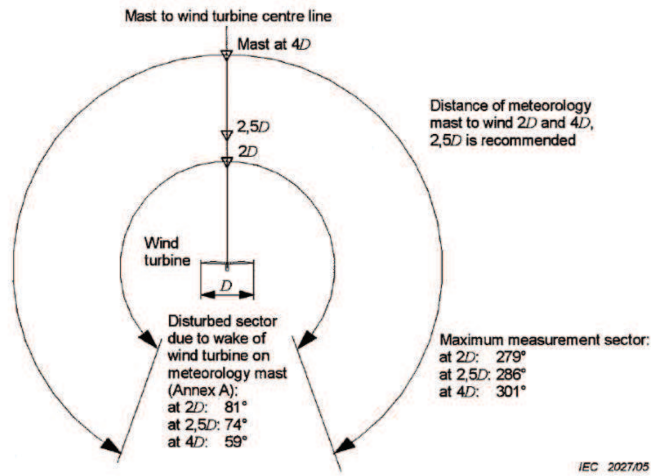

Figure 1. Placement of the measuring mast in relation to the wind turbine (European Committee for Standardisation, 2006).

The measuring masts were placed according to the wind measurement standard (European Committee for Standardisation, 2006) at a distance of 2…4 times the diameter of the wind turbine. The preferred distance is 2.5 times the diameter.The anemometers used for the measurements are described in Table 1.

A 40 meter high wind measurement mast was used for mounting the Thies Clima anemometers. Three anemometers were used on both masts: one on the height equal to respective wind turbine nacelle, one on 26 meters and another on 40 meters height. Also a Thies Clima wind direction sensor on height 40 m was installed on both measuring masts. Wilmers Messtechnik GmbH Wilog 306 loggers were installed on the foot of the mast for the data acquisition.The validity of the reference data from the measuring masts was verified using measurements made on multiple heights. The wind speeds on different heights may be different, because of the ground roughness (Bañuelos-Ruedas et al., 2010; Sen et al., 2012), but nevertheless there should be strong correlations between the data.

Table 1. The main parameters of used anemometers

Anemometer	Thies Clima cup-anemometer, type 4.3303.22.000 (measuring mast)	AirMar 150WX (Wind turbine 1)	SMA Wind Sensor (Wind turbine 2)
Measuring range	0.3 – 50 m s^{-1}	0–40 m s^{-1}	0.8–40 m s^{-1}
Accuracy	± 0.3 m s^{-1} / ± 2 % of m.v.	0 m s^{-1} to 5 m s^{-1}; 0.5 m s^{-1} + 10 % of reading 5 m s^{-1} to 40 m s^{-1}; 1 m s^{-1} or 5 %, dependant which is greater	± 5%
Electrical output	3–1042 Hz 4–18 V DC	9 – 40 V DC	n a^{-1}

The data was at first compared with a T-test, to test the similarity of the results from the nacelle anemometers with the reference data. The following hypotheses were made:

1. H1: The means of the data from the wind turbine anemometer and the reference anemometer on the same height are significantly different (but there may be a correlation between the data).
2. H0: The means of the data are similar.

For the initial comparison a T-test was applied to the data from the wind turbine anemometer and the reference data. The pairwise comparison was used because the time of each measurement was important (Kaart, 2012). The software package R was used for the statistical analysis.

The time steps where the nacelle anemometer or reference anemometer data was not available were neglected. Also the data from time steps when the wind direction was from the disturbed sector was neglected.

The T-test analyses the data on the hypothesis whether the mean nacelle anemometer results and reference anemometer results are significantly different, but it does not give an estimation about the correlation of the results.

Pearson and Spearman correlation coefficients were calculated in order to analyse the strength of relations between the nacelle-anemometer data and reference anemometer data. The Pearson correlation analyses the linear correlation of the results and the Spearman correlation analyses the rank correlation of the named parameters. The rank correlation describes the monotony of the relation.

The categorisation between the correlation coefficients can vary to some extent by approach. For the present analysis the approach shown in Table 2 is used (Dancey & Reidy, 2004).

Table 2. Strength of Correlation (Dancey & Reidy, 2004)

Value of the Correlation Coefficient	Strength of Correlation
$\lvert r \rvert = 1$	Perfect
$0.7 < \lvert r \rvert \leq 0.9$	Strong
$0.3 < \lvert r \rvert < 0.7$	Moderate
$0.1 < \lvert r \rvert \leq 0.3$	Weak
$r = 0$	Zero

As the number of measurements was relatively high (8000+ measurements at WT 1 and 4000+ measurements at WT 2), some of the graphic illustrations (Figs 3 and 7) of the data were compiled using the method of bins described in the standard EN 61400-12-1:2006 in annex K: In situ comparison of anemometer. The data sets were averaged using 1 m s^{-1} bins. (European Committee for Standardisation, 2006).

RESULTS AND DISCUSSION

Wind Turbine 1

Measurements at the location of WT 1 were made from 20.10.2013 to 21.12.2013. The readings were registered as 10 minute averages in 8811 time steps. From this data set 8,345 time steps were used for the further analysis, the other time steps had to be neglected because of the criterion that were described in the previous chapter.

The location of wind WT 1 is in North-Estonia, 42 kilometres away from the coast. The wind roses that were created on the basis of the data measured at different heights of the measuring mast are shown on the following Fig. 2.

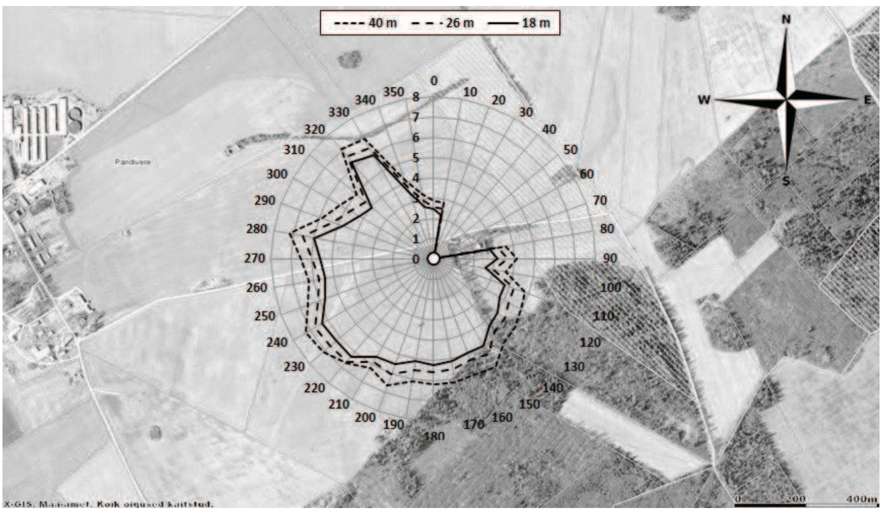

Figure 2. Wind roses on three different heights at the location of WT 1 (Estonian Land Board, 2014).

Fig. 2 shows, that as expected, the main wind direction is from the south-west, as it is common for this part of Estonia (Kull, 1996). The similarity of the wind roses on different heights indicates a strong correlation of the measuring mast anemometer readings and the validity of the reference anemometer measurement results. The excision in the north-east sector of the wind roses (Fig. 2) is caused by the positioning of the measuring mast in relation to the wind turbine (Fig. 1). The wind roses on different height give also indication about the ground roughness of different directions. The lines representing the average wind speed are more away from each other on the directions were the ground roughness is higher – like the forest area to the south of the measuring location (Fig. 2).

The parameters of the wind speed measured at the location of WT 1 are summarized in Table 3.

Table 3. Summary of measurement results at the location of WT 1

Parameter	WT anemometer 18 m	Measuring mast anemometers 18 m	26 m	40 m
Mean wind speed, m s^{-1}	3.72	5.17	5.58	6.01
Median wind speed, m s^{-1}	3.40	5.02	5.41	5.94

The T-test results of the collected data on Wind Turbine 1 (WT 1) showed that the mean difference of the nacelle anemometer reading and the reference anemometer is 1.455 m s^{-1}. The p-value found in the test is smaller than 0.05%, this gives a basis for the assumption that the wind turbine had a statistically significant influence on the results measured with the nacelle-anemometer.

It was found that the wind turbines (presumably the transient rotor blades of the turbine) influence the measuring results of the nacelle-mounted anemometers to a significant extent in both cases.

The test results showed also, that the confidence interval on a 95% significance level is 1.426 to 1.484 m s^{-1}. It means, that with a 95% confidence can be said that the mean difference between the nacelle anemometer and reference anemometer readings is in the range of 1.426 to 1.484 m s^{-1}, when the framework conditions remain the same.

The linear and rank correlation coefficients of the data from wind turbine 1 are shown in Table 4 and Table 5 respectively.

Table 4. Pearson correlations between the data measured on WT 1 and the reference data

-		WT anemometer 18 m	Measuring mast anemometers 18 m	26 m	40 m
WT anemometer	18 m	1.000	0.874	0.874	0.871
Measuring tower anemometers	18 m	0.874	1.000	0.996	0.985
	26 m	0.875	0.996	1.000	0.993
	40 m	0.871	0.985	0.993	1.000

From Table 5 it can be concluded that the linear correlation between the nacelle anemometer and reference anemometer on the same height is strong (the correlation coefficient is 0.874).

The coefficients between the different heights of the measuring mast were in the range of 0.985 to 0.993, which refers to an almost ideal relation. This gives ground to conclude that the reference anemometers were calibrated correctly and there were only little wind turbulences at the measuring site.

The Spearman rank correlation coefficients in Table 5 show the monotony of the relation. The monotone relation shows, that if the reading of one anemometer grows, then also the reading of the other compared anemometer increases, and this relation is relevant for the entire measuring range.

Table 5. Spearman rank correlations between the data measured on WT 1 and the reference data

-		WT anemometer 18 m	Measuring mast anemometers		
			18 m	26 m	40 m
WT anemometer 18 m		1.000	0.906	0.905	0.900
Measuring tower anemometers	18 m	0.906	1.000	0.997	0.986
	26 m	0.905	0.997	1.000	0.993
	40 m	0.900	0.986	0.993	1.000

The Spearman rank correlations are slightly higher than the linear correlation coefficients. This gives ground to conclude that the differences between the nacelle anemometer and reference anemometer are not even during the entire measuring range. The relation of nacelle anemometer and reference anemometer readings in the most relevant range for the wind turbine (from 3 to 12 m s^{-1}) is shown in Fig. 3.

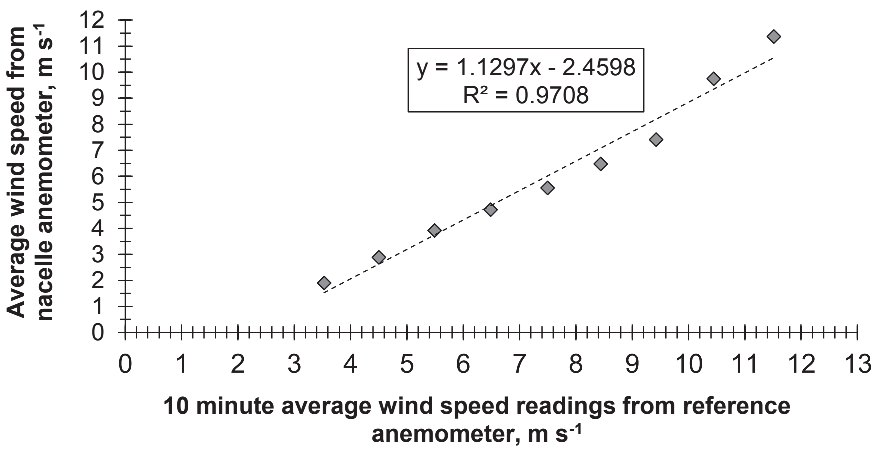

Figure 3. Relation of WT 1 nacelle anemometer and reference anemometer readings.

Fig. 3 shows 10 minute averages, which can be used to assess the real wind speed on the basis of the nacelle anemometer speed. It has to be noted that this figure can only be used for assessing the actual wind speed when the specific wind turbine is working. The measurement range of 3 to 12 m s^{-1} is given due to the fact that a simple dependence could not be given outside this range. Most of the measured wind speeds fell in that range as well (Fig. 4).

The frequency distribution and Weibull function of the reference anemometer of WT 1 are shown in Fig. 4.

A Weibull distribution curve with a shape parameter of k = 2.24 and a scale parameter of λ = 5.87 was fitted to the frequency distribution. A shape parameter of 2 (which results in a Rayleigh distribution) is considered as the most common value for a wind speed distribution in the Baltic area (Bisenieks et al., 2013).

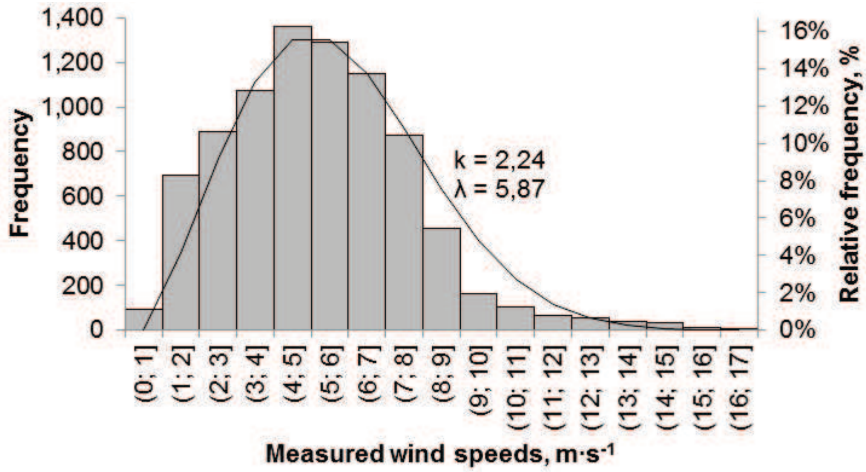

Figure 4. Frequency distribution and approximated Weibull distribution of the wind speed measurement results from the reference anemometer of WT 1.

For comparison, the nacelle anemometer results of WT 1 are presented on the following Fig. 5.

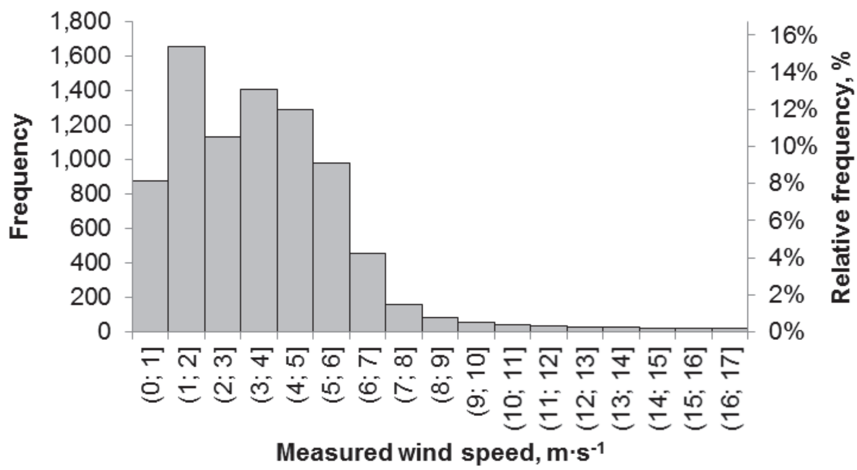

Figure 5. Frequency distribution of the wind speed measurement results from the nacelle anemometer of WT 1.

From Fig. 5 can be seen, that the nacelle anemometer results do not follow a Weibull distribution and their frequency distribution is significantly different from the frequency distribution of the reference anemometer results. The distribution is shifted to lower wind speeds. The discrepancies are especially in the range of the lowest wind speeds. The cut-in speed of WT 1 is in the range of 3 m s^{-1} and this causes that many of the nacelle anemometer results fall into the ranges of 0 to 1 and 1 to 2 m s^{-1} in time steps where the reference (actual) wind speed is from 3 to 5 m s^{-1}.

Wind Turbine 2

The location of wind WT 2 is on the Estonian island of Saaremaa, 5 kilometres away from the sea. For the Wind Turbine 2 (WT 2) the measurement period was also 2 months long. The measurements were made from 09.11.2013 to 11.01.2014. The readings were registered as 10 minute averages in 9060 time steps.

For the current analysis only the data from time steps was used, when the wind direction was not from the disturbed sector (Fig 1) and the data from wind turbine and measuring mast both were available. There were 4,872 time steps, were the data met those criterion.

The wind roses from different heights of the measuring mast at the location of WT 2 are shown on the following Fig. 6.

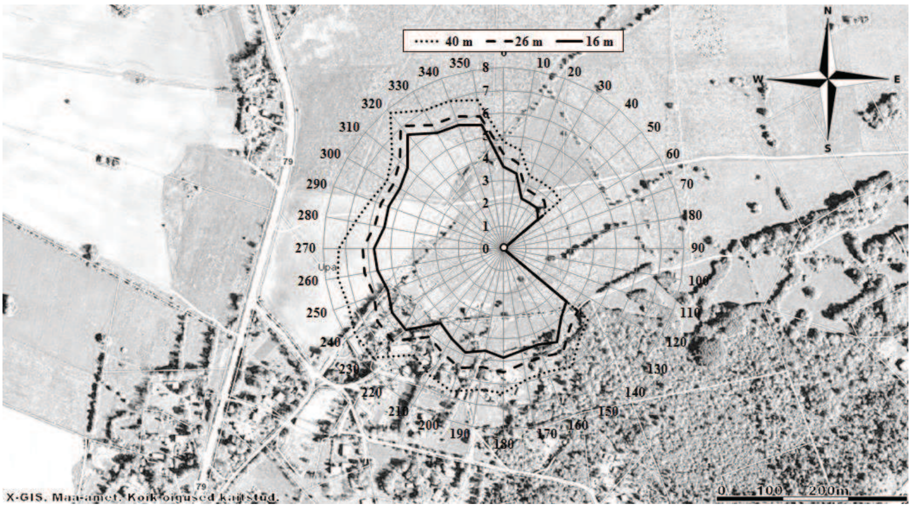

Figure 6. Wind roses on three different heights at the location of WT 2 (Estonian Land Board, 2014).

On Fig. 6 can be seen that the main wind direction on the site of WT 2 is from south-west. The influence of nearby buildings can also be seen on the wind roses. It can be said that the wind conditions at the site of WT 2 are because of the surrounding landscape more turbulent than on the site of WT1. The excision in the eastern side of the wind roses is caused by the positioning of the measuring mast in relation to the wind turbine.

The summary of the wind data described above is shown in Table 6.

Table 6. Summary of measuring results in the proximity of WT 2

Parameter	WT anemometer 16 m	Measuring mast anemometers 16 m	26 m	40 m
Mean wind speed, m s^{-1}	2.96	5.21	5.84	6.83
Median wind speed, m s^{-1}	2.70	5.02	5.63	6.58

The T-test, which was made on the basis of the data from the nacelle anemometer of WT 2 and the reference anemometer in the proximity of wind turbine, showed that the mean difference of the comparable data pairs was 2.25 m s^{-1}.

The p-value found in the T-test was under 0.05, this means that the wind turbine influenced the nacelle anemometer results to a statistically significant amount. The test showed also that on the confidence interval on a 95% significance level was 2.22 to 2.28 m s^{-1}, which means that with a 95% confidence can be said that the mean difference between the readings on the nacelle anemometer and reference anemometer would remain in this range if the other framework conditions would remain the same.

The correlation coefficients for the data measured at WT 2 are shown in the following tables (Table 7 and Table).

Table 7. Pearson correlations between the data measured on WT 2 and the reference data

-		WT anemometer	Measuring mast anemometers		
		16 m	16 m	26 m	40 m
WT anemometer	16 m	1.000	0.812	0.797	0.772
Measuring mast anemometers	16 m	0.812	1.000	0.982	0.949
	26 m	0.797	0.982	1.000	0.979
	40 m	0.772	0.949	0.979	1.000

From Table 7 can be concluded, that the correlation coefficient between the nacelle anemometer and reference anemometer is strong, but not very strong, the correlation coefficient is 0.812. The linear correlations between the anemometers were in the range from 0.949 to 0.982, which lets conclude, that the correlation between the anemometers on the measurement mast was very strong.

The correlation coefficients were slightly lower than the correlations on the measuring mast in the proximity of Wind Turbine 1. This could be caused by more turbulent wind conditions.

Table 8. Spearman correlations between the data measured on WT 2 and the reference data

-		WT anemometer	Measuring mast anemometers		
		16 m	16 m	26 m	40 m
WT anemometer	16 m	1.000	0.929	0.920	0.896
Measuring mast anemometers	16 m	0.929	1.000	0.985	0.954
	26 m	0.920	0.985	1.000	0.981
	40 m	0.896	0.954	0.981	1.000

The Spearman rank correlations are also at the WT 2 slightly higher than the linear correlation coefficients. This gives ground to conclude that the differences between the nacelle anemometer and reference anemometer are not even during the entire measuring range.

The relation of nacelle anemometer and reference anemometer readings in the most relevant range for the wind turbine (from 3 to 12 m s^{-1}) is shown in Fig. 7.

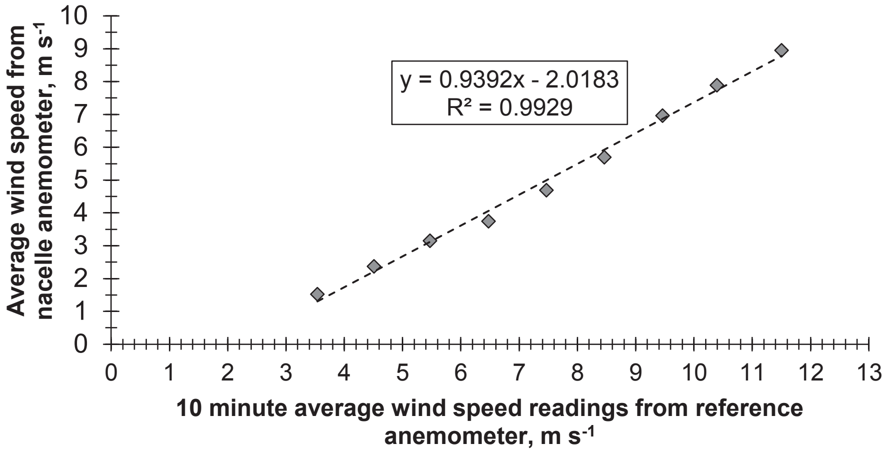

Figure 7. Relation of WT 2 nacelle anemometer and reference anemometer readings.

The frequency distribution and Weibull function of the reference anemometer of WT 2 are shown in Fig. 8. Weibull distribution curve with a shape parameter of $k = 2.24$ and a scale parameter of $\lambda = 5.87$ was fitted to the frequency distribution.

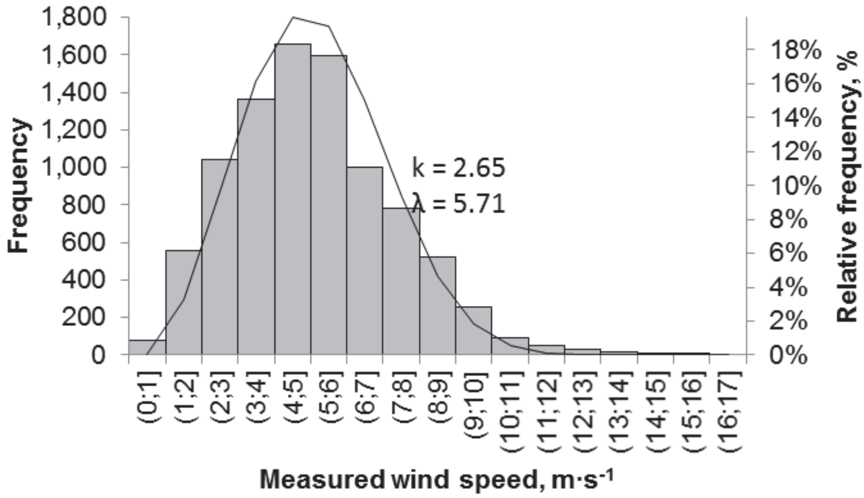

Figure 8. Frequency distribution and approximated Weibull distribution of the wind speed measurement results from the reference anemometer of WT 2.

For comparison, the nacelle anemometer results of WT 2 are presented on the following Fig. 9.

From Fig. 9 can be seen, that the WT 2 nacelle anemometer results can also not be approximated with the Weibull distribution, but they are more similar to a Weibull distribution than the results from WT 1 (Fig. 5).

The comparison of Fig. 8 with Fig. 9 shows the slowing down effect of the rotor blades to the wind measured with the nacelle anemometer. The most frequent wind speed range at the nacelle anemometer is 2 to 3 m s^{-1}. This is 2 m s^{-1} less (which is consistent with the T-test results) than the most frequent wind speed range at the reference anemometer, 4 to 5 m s^{-1}.

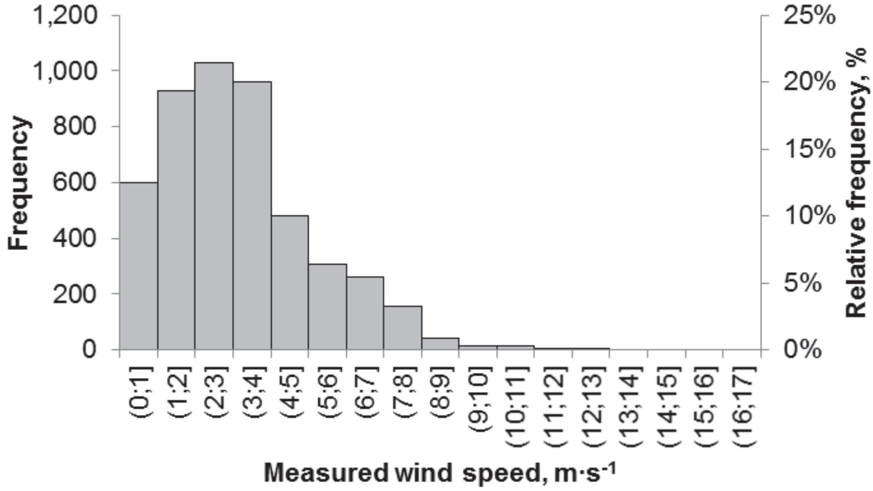

Figure 9. Frequency distribution of the wind speed measurement results from the nacelle anemometer of WT 2.

By comparing the results from WT 1 and WT 2 can be seen that the differences between the nacelle and reference anemometer readings were smaller on WT 1. This could be caused by less turbulent wind conditions, more advanced anemometer technology (ultrasonic anemometer) and more stable wind turbine operation.

CONCLUSIONS

It was found that, when the wind turbines are operational, the rotation of the rotor blades influences significantly the measurement results of the nacelle-mounted anemometers in both analysed cases. The wind roses compiled on the basis of the reference measurement data were as expected. The means of the 10 minute wind data from wind turbine nacelle´s anemometers were significantly lower than the means of the data acquired from the reference measuring mast anemometers. The average difference of nacelle and reference anemometer readings at Wind turbine 1 was 1.45 m s^{-1} and at Wind turbine 2 was 2.25 m s^{-1}. One of the reasons for the smaller difference at Wind turbine 1 can the less turbulent wind conditions on the site of Wind turbine 1.

Despite the fact that the means were different the correlations between the reference wind data and the nacelle-mounted anemometer readings were strong. In the analysed cases the reading from the ultrasonic anemometer was more accurate (smaller difference and stronger correlation) than the reading from the mechanical cup-anemometer. It has to be noted the numerical relations and specific findings are based on the specific cases where the measurements were done. In practice the results from nacelle anemometers can be used for indication. When the data has to be used for more exacting purposes, like for the automatic control of the turbine, then an individual correction algorithm should be found for the specific wind turbine and anemometer combination. Future work could concentrate on the differences between anemometer readings when the rotor is in the cut-out regime (the rotor stands still) and the situation right before the cut-out wind speed.

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