PRACTICAL APPLICATIONS OF ULTRASONIC WIND SENSORS FOR RESOURCE ASSESSMENT

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ABSTRACT

Making accurate wind measurements in difficult site conditions is a challenge for the meteorological community. Wind energy development has especially increased the importance of high quality wind data. Multi-million investment decisions are being based on bankable datasets. Over the years mechanical anemometers have become the industry standard for wind speed measurement despite their non-ideal performance in difficult conditions.

In this paper, we provide a better understanding of the state-of-the-art ultrasonic wind sensor functionality, trade-offs, and advantages in demanding wind measurement campaigns like wind energy resource assessment. Results are shared from MEASNET wind tunnel tests to characterize performance against traditional mechanical anemometers and older generation ultrasonic wind sensors. Experiences from Vaisala deployed meteorological towers in Europe with heated mechanical and ultrasonic wind sensors will also be presented, along with recommendations for best practices to maximize data availability and quality in the most demanding conditions.

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INTRODUCTION

The IEC 61400-12-1 revision draft currently under review by the IEC-TC88-12-1 maintenance team recognizes the use of ultrasonic wind sensor technology [1-2]. This will increase the adoption rate and use of ultrasonic wind sensors in the wind energy industry quickly once approved. Vaisala has a lot of practical experience using ultrasonic technology, including over three years of experience in the application of the wind energy resource assessment. This paper addresses some of the misconceptions about ultrasonic technology, and how the current generations of sensors provide measurement and diagnostic capabilities that outperform traditional mechanical anemometers and can support the reduction of uncertainty in energy yield assessment.

In the past, the main concern about ultrasonic wind sensor performance has been azimuth response of the sensor to wind. Previous studies have shown unacceptable variability in the wind speed measurement performance per given wind direction. State-of-the-art digital ultrasonic wind sensor technology [3] provides significant improvements to the past results and lifts the performance of the ultrasonic wind sensors to same level or even above its mechanical counterparts.

Extensive wind tunnel tests and data from three meteorological wind towers prove that the data provided by ultrasonic wind sensors is not only more consistent, but also higher quality. MEASNET calibrated wind tunnel tests show that issues with poor azimuth response are no longer valid with modern design of the ultrasonic wind sensors. Overall measurement accuracy of the Vaisala WMT700 series for direct or tilted flow is superior to mechanical anemometers. Measurement data from the wind towers confirm the results recorded in the wind tunnel. Not only is the better measurement performance of the ultrasonic wind sensor producing high quality data for analysis, but the data availability improvements, particularly, in cold climate and turbulent environments reduces uncertainty of the dataset.

WIND TUNNEL TESTS

AZIMUTH RESPONSE

Azimuth rotation tests are done to test the wind sensor's sensitivity to wind flows from different directions. As ultrasonic wind sensors measure wind speed and direction from the same measurement volume, it is crucial that both measurements are stable across the 360 degree circle.

During the test, the anemometer is rotated around its vertical axis. The stepping rotation is 5 degrees. The starting point is either defined with respect to the North marker of the sensor, or with reference to the sensor cable if it is not inside the supporting tube. The tests have been conducted at three wind speeds of 5, 10 and 15 m/s that are typical for wind energy use. The ratio of the wind speed at the assessed azimuth angle and the reference position has been calculated and plotted over direction. More test method details are presented in the IEC 61400-12-1 standard draft that is nowadays inline with the MEASNET test arrangements [2,4].

The scientific literature provides excellent sets of the azimuth responses both for the ultrasonic wind sensors and for the mechanical anemometers [5-6]. It can be observed that the azimuth variation of Vaisala 2D ultrasonic wind sensor, WMT700 series, is random and at appropriate level. With other words, the relative deviation to zero degree azimuth angle is less than +/- 0.010. That indicates that performance is independent from geometrical factors and stable across all wind directions. It is interesting that a 3D ultrasonic wind sensor used as the reference had the spike pattern due to the sensor's array structure.

Further it can be noticed that the ultrasonic wind sensor can even perform over it's mechanical counterpart when azimuth variations are compared. Same relative deviation varies from +/-0.05 to

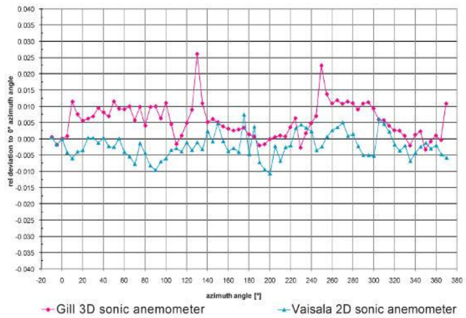

Figure 1. Ultrasonic wind sensor azimuth rotations [5].

Figure 2. Mechanical anemometer azimuth rotations [6].

+/-0.035 for presented mechanical anemometers. This comparison becomes visible in figures 1 and figure 2, when same scaling is used for the diagram of the ultrasonic wind sensors and the diagram of the mechanical anemometers.

TILT RESPONSE

Tilt angle response tests are done to test the sensor immunity to angled flows or vertical vectors in the wind. An ideal sensor should only report the in-plane horizontal wind speed. If flow direction deviates from this, then reading should follow COS-function.

To test sensor's tilt response, anemometers are exposed to the flow in the wind tunnel at three different wind speeds. In these tests the angle of inflow e.g. tilt angle has been varied in the range from -30 to +30 degrees with increments of 2 degrees, while maintaining the sensor's center position fixed. More test method details are presented in the IEC 61400-12-1 standard draft that is in line with the MEASNET test arrangements [2,4].

Again the scientific literature provides excellent sets of the tilt responses both for the ultrasonic wind sensors and for the mechanical anemometers [5-6]. The Vaisala ultrasonic wind sensor WMT700 series, for instance, shows excellent agreement with the theoretical COS-function over full test range from -30 to +30 degrees as seen in the figure 3. For negative tilt angles, the relative deviation is negligible, while for positive tilt angles the relative deviation is -0.02. The 3D ultrasonic wind sensor used as the reference had in practice same measurement results.

The ACCUWIND project [6] demonstrated that mechanical anemometers have significant difficulties with angled flow conditions when flow angle exceeds 15 degrees either negative or positive direction as seen in figure 4. When compared to theoretical COS-function at the tilt angle

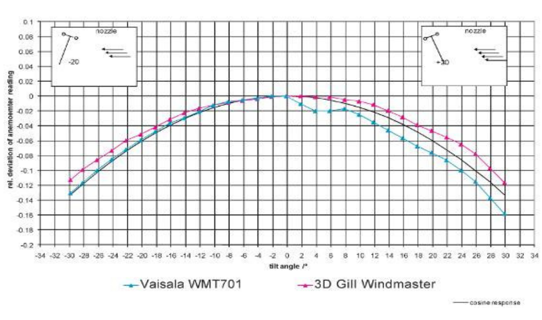

Figure 3. Ultrasonic wind sensor tilt responses [5].

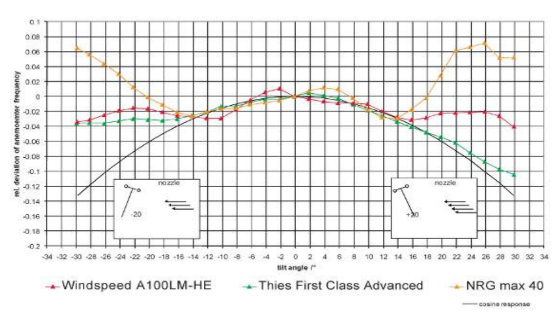

Figure 4. Mechanical anemometer tilt responses [6].

Table 1. Comparison between ultrasonic wind sensor and mechanical anemometer and wind vane.

Feature	Ultrasonic wind sensor	Mechanical sensor	
		Anemometer	Wind vane
1. Azimuth response	Good	Poor … Excellent	Excellent
2. Tilt response	Excellent	Limited	Limited
3. Analog signals	Available	Available	Available
4. Digital signals	Available	-	-
5. Self diagnostics	Available	-	-
6. Calibration	MEASNET	MEASNET	MEASNET
7. Acceptance	IEC 61400-12-1; 2011 draft	IEC 61400-12-1	IEC 61400-12-1

of the -30 degrees as worst scenario, the difference is from +0.10 to +0.20. This is 5 times more when compared to the ultrasonic wind sensor. In the Table 1, the generic features of the different wind sensors have been listed with qualitative measures.

WIND TOWER CAMPAIGN DATA AVAILABILITY AND CORRELATION

The data used for analyzing the sensor performance has been collected from three wind towers installed in Scandinavia. The three measurement sites are different in their geography and local climate.

- Site A is a coastal site on an island with very small changes in the elevation
- Site B is an inland site where the tower is located on top of a hill
- Site C is a forested inland site with small changes in elevation

All towers are lattice style equipped with MEASNET calibrated mechanical wind sensors and ultrasonic sensors (Figure 5). The mechanical anemometers used in the campaigns were Vaisala WAA151 type with shaft heating, and the ultrasonic sensors were Vaisala WMT702 with heated transducer heads. Installation practices used in the towers were according to IEC 61400-12-1

Figure 5. Installation of a mechanical anemometer Vaisala WAA151 and an ultrasonic anemometer Vaisala WS425 to same measurement boom at Site A. Other sites applied the WMT702 ultrasonic wind sensor.

recommendations. Nominal measurement height of the towers is 100 meters, but there is small deviation in the real installations.

The datasets have been collected during the years 2010-2012. For this analysis and comparison from each tower, two datasets have been created and analyzed. One collected during two summer months and a second collected during two winter months. Both summer and winter datasets have been measured with the same sensors without changes to the system settings. Wind data was measured at a rate of 1Hz and 10 minute averages were calculated. This means that each dataset consists of more than 7,000 data points. Wind speed data less than 4 ms^{-1} have been filtered out because it is not significant for the wind energy industry.

The criteria for evaluating mechanical anemometer performance against ultrasonic were:

- Consistency of the measurement data, wind speed and standard deviation of wind speed
- Data availability, technical delivery of data from the logger to database and availability of uncontaminated data
- Occurrence of icing and speed-up effects on mechanical anemometers, effect of different validation limits
- Seasonal variability of the data

Based on these data sets the technical data availability from the systems is very close to 100%. However, the amount of data from the sensors, which has better than 3% agreement is considerably less. From the winter data sets it is clear that the main cause of slower mechanical

Table 2. Average values for data collected at the three towers during the analysis period. The validation limit is the difference in measurement threshold applied when comparing mechanical and ultrasonic wind speed data at each 10 min average interval. The validation level reference is the ultrasonic wind sensor data. Temperature is in ºC and wind speed in m/s.

Site A, Class A terrain, island	Average Air Temperature	Average WS uSonic 96m	Std Deviation uSonic 96m	Turbulent Intensity uSonic	Technical Data Availability	Average WS anemo 96m	Std Deviation anemo 96m	Turbulent Intensity anemo	Technical Data Availability	Validation limit	Readings below the validation level	Readings above the validation limit	Readings in agreement
Dec 2010 - Jan 2011	-6.06	8.62	0.56	0.06	99.1 %	7.95	0.44	0.06	100.0 %	3 %	29.0 %	17.1 %	54.0 %
										5 %	26.1 %	8.4 %	65.4 %
										10 %	21.7 %	3.5 %	74.8 %
June-Jul 2010	14.45	8.13	0.95	0.12	100.0 %	8.26	0.69	0.08	100.0 %	3 %	17.1 %	39.4 %	43.4 %
										5 %	13.3 %	29.7 %	57.0 %
										10 %	8.2 %	14.4 %	77.5 %
Site B, Class S, top of a hill													
Nov-Dec 2011	-2.95	9.34	0.87	0.09	100.0 %	9.10	0.81	0.09	100.0 %	3 %	14.9 %	17.9 %	67.2 %
										5 %	14.2 %	6.0 %	79.8 %
										10 %	11.9 %	2.1 %	86.0 %
June-Jul 2011	14.28	7.60	0.77	0.10	100.0 %	7.73	0.80	0.10	100.0 %	3 %	0.3 %	16.6 %	83.1 %
										5 %	0.0 %	4.9 %	95.1 %
										10 %	0.0 %	0.1 %	99.9 %
Site C, Class A terrain, Forest													
Dec 2011 - Jan 2012	-1.91	8.54	0.82	0.10	100.0 %	8.47	0.75	0.09	100.0 %	3 %	8.6 %	23.1 %	68.3 %
										5 %	6.1 %	1.8 %	92.0 %
										10 %	4.6 %	0.1 %	95.4 %
June-Jul 2011	16.18	6.97	0.71	0.10	100.0 %	6.79	0.65	0.10	100.0 %	3 %	0.8 %	38.1 %	61.1 %
										5 %	0.6 %	9.2 %	90.2 %
										10 %	0.2 %	1.0 %	98.8 %

anemometer wind speed averages is icing. Naturally, this phenomenon is not as evident in the summer dataset. Both summer and winter datasets have significant amounts of mechanical anemometer data, which shows higher readings than ultrasonic sensor data. The amount of over-speed data seems to be related to the turbulent intensity of the wind, instead of the local site geography.

WIND TOWER CAMPAIGN DATA QUALITY

The data used for analyzing sensor data quality and characteristics has been collected from a wind measurement system installed on an existing GSM tower in Scandinavia. The measurement site has the following characteristics.

- Site D is an island site with small changes in elevation and some surrounding forest

The tower is lattice style equipped with MEASNET calibrated mechanical wind sensors and ultrasonic sensors (Figure 6). The mechanical anemometers used in the campaigns were Vaisala WAA252 type with shaft and cup heating and Thies First Class Advanced with shaft heating. The ultrasonic sensor was Vaisala WMT702 with heated transducer heads. Installation practices used in the towers were according to IEC 61400-12-1 recommendations. Nominal measurement height of the tower is 75 meters, but there is small deviation in the real installations.

The dataset was collected in February and March 2012. For this analysis wind data was measured at a rate of 1Hz and 10 minute averages were calculated, with more than 4,000 data points. Once again, wind speed data less than 4 m/s has been filtered out because it is not significant for the wind energy industry.

The criteria for evaluating mechanical anemometer performance against ultrasonic were:

- Consistency of the measurement data, wind speed and standard deviation of wind speed
- Data availability, technical delivery of data from logger to database and availability of uncontaminated data
- Occurrence of tower shadowing turbulence and overspeeding on mechanical anemometers, effect of different validation limits

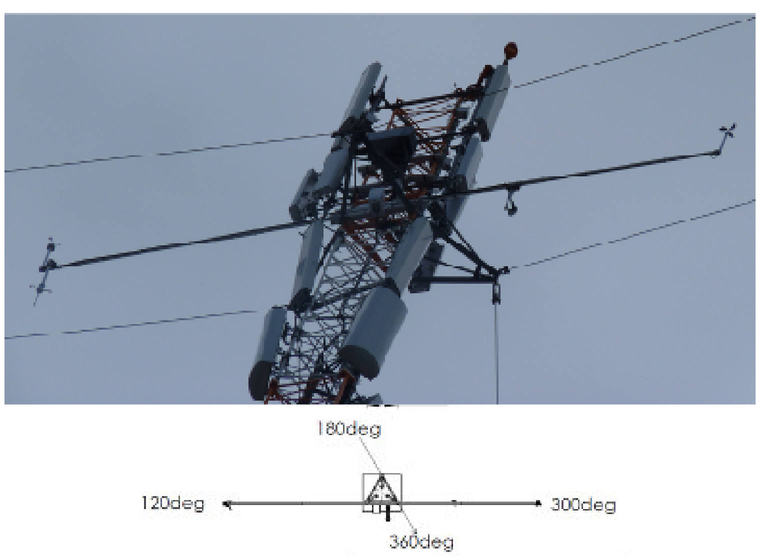

Figure 6. Installation at Site D of the mechanical anemometer Vaisala WAA252 and sonic anemometer to the same boom on the left (120 deg orientation) and the Thies First Class Advanced on the right (300 deg orientation) at nominal height of 75 meters.

Table 3. Average values for data collected at the tower during the analysis period of 20 February – 26 March 2012 for wind originating from the 90-150 degree and 270-330 degree sectors. The validation limit is the difference in measurement threshold applied when comparing mechanical and ultrasonic wind speed data at each 10 min average interval. Temperature is in ºC and wind speed in ms^{-1}. The validation level reference is the ultrasonic wind sensor data (Data courtesy of our cooperating partner, efe – egentliga finlands energy Ab).

Site D, Class A terrain, island with forest **Wind Direction Sector 90-150 degrees** **20 Feb – 26 Mar 2012**	Average Air Temperature	Average WS uSonic 73m	Std Deviation uSonic 73m	Turbulent Intensity uSonic	Technical Data Availability	Average WS anemo 75m	Std Deviation anemo 75m	Turbulent Intensity anemo	Technical Data Availability	Validation limit	Readings below the validation level	Readings above the validation limit	Readings in agreement
Vaisala WAA252	0.12	5.66	1.01	0.18	100.0 %	5.85	1.04	0.18	100.0 %	3 %	0.0 %	63.6 %	36.4 %
						+3.3%		-0.4%		5 %	0.0 %	7.5 %	92.5 %
										10 %	0.0 %	0.0 %	100.0 %
Thies First Class Advanced	0.12	5.66	1.01	0.18	100.0 %	5.78	1.36	0.24	100.0 %	3 %	19.7 %	57.0 %	23.2 %
Tower Shadowing						+2.0%		+31.5%		5 %	17.5 %	48.7 %	33.8 %
										10 %	11.4 %	0.0 %	88.6 %
Site D, Class A terrain, island with forest **Wind Direction Sector 270-330 degrees** **20 Feb – 26 Mar 2012**													
Vaisala WAA252	0.12	6.77	1.86	0.28	100.0 %	6.83	2.05	0.30	100.0 %	3 %	27.1 %	53.9 %	19.0 %
Tower shadowing						+0.9%		+9.2%		5 %	24.1 %	18.8 %	57.1 %
										10 %	11.1 %	1.0 %	87.9 %
Thies First Class Advanced	0.12	6.77	1.86	0.28	100.0 %	7.40	1.74	0.23	100.0 %	3 %	22.2 %	45.8 %	32.1 %
						+9.4%		-14.8%		5 %	4.5 %	42.8 %	52.8 %
										10 %	0.1 %	36.5 %	63.3 %

Based on this data set the technical data availability from the system is maximized at 100%. Unlike the earlier datasets, there are no indications of icing slowing the mechanical anemometer readings. Instead, the negative effects of tower shadowing induced turbulence are evident. This phenomenon is likely magnified in this case given the additional equipment installed on the GSM tower as shown in Figure 6. The turbulence intensity for the Thies anemometer is 31.5% greater than the Vaisala WMT702 ultrasonic when winds come from the 90-150 degree sector. The effect is also seen in the Vaisala WAA252 anemometer when winds come from the 270-330 degree sector with a 9.2% increase in turbulence intensity, although this is muted since the reference ultrasonic measurement is also exposed to the tower shadowing.

The improved wind speed accuracy of ultrasonic sensors becomes evident when analyzing the data in more detail. For example, when winds originate from the 90-150 degree sector, 63.6% of the Vaisala WAA252 data shows more than a 3% over-speed bias relative to the ultrasonic sensor. The added weight of the heating elements in the cups and less favorable tilt-response increases the cup inertia, resulting in a 3-5% positive bias in wind speed measurement. The over-speed effects are even more apparent with the Thies anemometer. When winds originate from the 90-150 degree sector, inducing turbulence and lower average wind speeds on the Thies anemometer, it still has a 2.0% higher average wind speed than the ultrasonic. For 48.7% of the measurements the Thies anemometer measurements are 5-10% higher than the ultrasonic, demonstrating a significant over-speed bias in this turbulent environment. It is possible that the vertical inflow angle cosine response (Figure 3) and the lower 73 meter mounting height of the ultrasonic sensor (Figure 6) explain some of the mechanical anemometer bias. However, the results indicate that extreme caution should be used when analyzing mechanical anemometer data in turbulent environments and ultrasonic measurements should be used whenever possible as the primary measurement and validation tool.

CONCLUSIONS

The wind tunnel tests show that state-of-the-art ultrasonic wind sensors can be used as a benchmark for wind measurements in challenging conditions. Both mechanical and ultrasonic sensors can produce datasets with high data availability. However, linking high data availability to data quality can lead to large misconceptions. The real life tower data shows almost perfect data availability numbers, but well correlated data is halved when the two measurement datasets are tested against each other, with the effect magnified in turbulent environments. The question then arises, “Why this is the case?”

Some of the reasons why the datasets do not correlate can be easily recognized, like wind sensor icing. Others, such as wind sensor over-speed effects and tower shadowing are more difficult to recognize and estimate their influence on the data quality. Even when the phenomena are recognized, their identification from the dataset alone is difficult without reference data. Since most of these phenomena are linked to the operating principles of mechanical anemometers, use of complementary ultrasonic wind sensors makes the analysis fairly straightforward. Optionally, the identification of these phenomena can be conducted through analysis of various wind variables.

Ultimately, with state-of-the-art ultrasonic sensors and their built-in diagnostics, and digital communication between wind sensor and data acquisition system allow the data validation remotely every time it is collected and post-processing of data becomes gradually obsolete. This improvement in wind speed data quality and accuracy is the foundation for closing the gap seen in resource assessment energy yield estimates and wind farm underperformance today.

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