Final report

1.1 Project details

Project title	TrueWind
Project identification (program abbrev. and file)	Journalnr.: 64015-0635
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	DTU Wind Energy Frederiksborgvej 399, 4000 Roskilde
Project partners	Svend Ole Hansen ApS, Windsensor ApS, DantecDynamics A/S
CVR (central business register)	DK30060946
Date for submission	31-03-2020

1.2 Short description of project objective and results

TrueWind has addressed various sources of uncertainties of cup anemometry.

a) Uncertainty sources to cup calibration uncertainty:
   1) In order to improve the accuracy of the wind speed measurement in the wind tunnel, a series of tests were made with a LDA and a short-range lidar. Promising results were obtained with the lidar that could be used as a permanent installation for regular pitot tube calibration. This requires that the lidar to be traceably calibrated prior to being used as reference in the wind tunnel. A calibration procedure using a flywheel has been designed and fully tested, and the corresponding uncertainty model has been explicitly derived.
   2) DantecDynamics have designed and built a prototype for a combined LDA/lidar system that could measure the 3D wind speed vector in a wind tunnel.
   3) Small-scale turbulence in wind tunnels was shown to have a significant effect on the calibration results obtained for cup anemometers. At 10m/s the rotational speed seems to change by approx. 0.5-1%.

b) Uncertainty related to operational response of cup anemometer (classification):
   1) Full classification according to IEC 61400-12-1:2017 of 3 types of cup anemometers were completed. SOH tunnel has developed procedures for cup anemometer classification and is in the process of getting accreditation by Danak.
   2) The response of a Thies cup anemometer to open air flow has been analysed by comparison to the 3 dimensional lidar (static short range lidar WindScanner) measurement.
   3) The ACCUWIND model for cup anemometer classification has been tested through comparison of the model simulated response of the cup anemometer (to real 3D wind speed time series) to the actual cup anemometer measurement in the same wind conditions.
   4) WindSensor has designed a new cup anemometer with improved operational properties, thus expected to have a lower, and thereby improved, class number than the actual Windsensor cup anemometer.

1.3 Executive summary

TrueWind has addressed various sources of uncertainties of cup anemometry.

- Characterisation of the flow in the wind tunnel to be used for cup anemometer calibration:
    - A series of tests have been made in a wind tunnel used for cup anemometer calibration, with the aim of improving the accuracy of the reference pitot tube measurement. Two different optical measuring systems have been employed; a Lidar Doppler Anemometer (LDA) and a short-range, continuous wave lidar. Unfortunately, various technical issues encountered with the LDA system used for the tunnel experiments prevented to obtain satisfactory agreement between the two instruments. Nevertheless, the lidar was found to be generally suitable for reference wind speed service. In the test wind tunnel, a permanent installation for regular pitot tube calibration could be envisaged that would significantly enhance the real wind speed accuracy.
    - This requires the lidar to be traceably calibrated prior to being used as reference in the wind tunnel. A calibration procedure using a flywheel has been designed and fully tested, and the corresponding uncertainty model has been explicitly derived.
    - Dantec Dynamics A/S aims to integrate the Lidar and Laser Doppler Anemometry (LDA) technologies into a single, unique measurement solution with high market potential. A prototype has been made with all the components and beam paths that are expected in the final product, but with more adjustments and space between components.
    - Independently of the three previous results, small-scale turbulence was shown to have a significant effect on the calibration results obtained for cup anemometers. At 10m/s the rotational speed seems to change by approx. 0.5-1% due to different simulations of the small-scale turbulence. The effect of small-scale turbulence originates from changed forcing acting on the rotor, and it is not possible to take this effect into account by the present mathematical models of cup anemometer rotors, e.g. the models applied in cup anemometer IEC classifications [1].
- Characterisation of cup anemometer operational uncertainties (classification):
    - Full classification procedure (tests in wind tunnel on 5 samples and uncertainty evaluation through the ACCUWIND model) have been completed for three types of currently commercialized cup anemometers, according to IEC 61400-12-1:2017:
        - Windsensor;
        - Thies First Class Advanced;
        - Thies First Class Advanced II.
    - SOH has developed procedures for cup anemometer classification. Accreditation by Danak is under progress and expected within a trimester.
    - The response of a Thies cup anemometer to open air flow has been analysed by comparison to the 3 dimensional lidar (static short range lidar WindScanner) measurement.
    - The ACCUWIND model for cup anemometer classification has been tested through comparison of the model simulated response of the cup anemometer (to real 3D wind speed time series) to the actual cup anemometer measurement in the same wind conditions.
- WindSensor has designed a new cup anemometer with improved operational properties, thus expected to have a lower, and thereby improved, class number then the actual Windsensor cup anemometer.

1.4 Project objectives

TrueWind was an ambitious project aiming at improving the accuracy of cup anemometry by addressing all sources for measurement uncertainty: various effects affecting the cup anemometer calibration in the wind tunnel (wind tunnel wind speed calibration, wind tunnel blockage effect, small scale turbulence effect), design of a new-LDA-lidar measurement system providing an accurate 3D wind vector in the wind tunnel, cup anemometer classification tests in wind tunnel, comparison to cup anemometer response in free air, validation of the cup anemometer classification (ACCUWIND) model and design of a new improved cup anemometer.

The high ambition combined with the many different objectives and the commercial interest of each project partner has made it very difficult for the project team to clearly agree on which activities should be given priority in the project course. Furthermore, several serious technical issues were encountered (malfunctioning WindScanner to be used in the Open Air Test Rig, underperforming LDA system in wind tunnel experiments and issues in producing the new cup anemometer) and the project team had to revise the project objectives and plan several times throughout the project.

The project objectives have also adapted to the market development occurring in parallel to the project. In particular, as a new Thies cup anemometer was released on the market in 2017, classification according to IEC 61400-12-1:2017 has been included as new task in the project, to be carried out together with the classification of two previously existing cup anemometers (Thies First Class Advanced and Windsensor).

Finally, as the tests carried out in the wind tunnel for the classification of the 15 cup anemometers were found to be quite demanding, Svend Ole Hansen tunnel used as a process to prepare to possible commercialisation of such tests and have included as new objective to aquire accreditation from DANAK for cup classification.

1.5 Project results and dissemination of results

1.5.1 Wind tunnel Pitot tube accuracy

A series of tests have been made in a wind tunnel used for cup anemometer calibration, with the aim of improving the accuracy of the reference pitot tube measurement. The improvements are envisaged to come about through the use of optical measuring systems to provide improved pitot tube calibrations.

Two different optical measuring systems have been employed; a Lidar Doppler Anemometer (LDA) and a short-range, continuous wave lidar commonly referred to as a 'lidic'. Both these instruments have a claimed measurement uncertainty in the range 0.1%-0.2% and a major aim of the tests was to demonstrate simultaneous wind speed measurements using these two systems with results consistent within these uncertainties. Unfortunately, this was not possible to demonstrate, the LDA and lidic results differing by 0.7%. Comparison of both optical systems to the calibrated reference pitot tube strongly indicated that the LDA was measuring with the largest errors. Subsequent literature surveys and data analysis has uncovered three causes of LDA measurement error present in this campaign; the LDA beams were incorrectly aligned, the PlexiGlass wind tunnel window distorted the LDA fringe patterns and lastly the LDA flywheel calibration has been found to be somewhat dependent on the exact nature of the wheel surface.

Extra measurements were performed at the wind tunnel with the LDA after fixing those issues. The results of the measurements showed that adaptive record length gives more accurate results than fixed record length, especially for high wind speed. However, no conclusions on the calibrations on the pitot-static tubes could be drawn upon the true wind or if the measurements are corrected.

Whilst satisfactory (metrologically consistent) agreement between the LDA and lidic systems was not obtained, indirect consistency between the lidic and the LDA system used for the external pitot tube calibration was demonstrated, since the in-situ pitot tube calibrations performed on two pitot tubes gave results consistent with the external calibrations.

The lidic system was found to be generally more suitable for reference wind speed service due to its 'absolute' nature where the calibration is essentially a check of correct application of the physical parameters and algorithm. Furthermore, optical imperfections in the wind tunnel will only diffract the beam slightly but not cause errors in the measured speed as is the case for the LDA. In the test wind tunnel, a permanent installation for regular pitot tube calibration could be envisaged that would significantly enhance the real wind speed accuracy.

1.5.2 Lidar calibration using a fly-wheel

A rig for calibrating a continuous-wave coherent Doppler wind lidar has been constructed. The rig consists of a rotating flywheel on a frame together with an adjustable lidar telescope. The laser beam points toward the rim of the wheel in a plane perpendicular to the wheel's rotation axis, and it can be tilted up and down along the wheel periphery and thereby measure different projections of the tangential speed. The angular speed of the wheel is measured using a high-precision measuring ring fitted to the periphery of the wheel and synchronously logged together with the lidar speed. A simple, geometrical model5 shows that there is a linear relationship between the measured line-of-sight speed and the beam tilt angle and this is utilised to extrapolate to the tangential speed as measured by the lidar. An analysis of the uncertainties based on the model shows that a standard uncertainty on the measurement of about 0.1% can be achieved, but also that the main source of uncertainty is the width of the laser beam and its associated uncertainty. Measurements performed with different beam widths confirms this. Other measurements with a minimised beam radius shows that the method in this case performs about equally well for all the 10 tested reference speeds ranging from about 3 m/s to 18 m/s.

1.5.3 Lidic-LDA system

The objective of Dantec Dynamics A/S is to commercialize the Lidar technology for wind tunnel instrumentation. Specifically, Dantec Dynamics A/S aims to integrate the Lidar and Laser Doppler Anemometry (LDA) technologies into a single, unique measurement solution with high market potential. Further objectives are to demonstrate and validate the commercial solution in the SOH wind tunnel and to transfer DTU experience on Lidar technology to Dantec Dynamics A/S for development of future products.

A market analysis has been conducted. It concluded that there is a market potential for the combined LDA/Lidar product large enough to justify the development.

A prototype has been made with all the components and beam paths that are expected in the final product, but with more adjustments and space between components.

Changes to the Dantec Dynamics BSA Flow Software has been made, which makes it possible to use the same program for Lidar and LDA measurements.

Calibration of Lidar and LDA is done on a calibration wheel with a known diameter. The calibration of LDA is done to an uncertainty of 0.07% with the setup as seen on the below figure.

The traceable calibration of Lidar is documented in the article Flywheel calibration of a continuous wave coherent Doppler wind Lidar by Anders Tegtmeier Pedersen og Mike Courtney, which has been sent to Atmospheric Measurement Techniques for publication.

The main issues with the Lidar prototype are false 0m/s signal from any surfaces outside the measurement volume, and that the measurement volume is not definite, but large particles outside the defined measurement volume will give as strong signals as particles in the measurement volume. These issues need to be very well known and workarounds need to be in place for Lidar to replace a 3rd component in an LDA system, as LDA systems are used to measure flow velocities and turbulence in small areas. Several different methods to resolve these problems are being tested, but no conclusive results are made yet. Since the definition of measurement volume and which seedings can be used are very important factors to determine which costumers can use the product. There is no marketing plan, as resources have been used to resolve the above-mentioned problems before finalizing the product.

The Dantec Lidar prototype does sometimes give false 0m/s, and there has been issues with the type of seeding that SOH will accept in their wind tunnel (DEHS seeding). Therefore, the prototype has not been demonstrated in the SOH wind tunnel, but instead, it has been demonstrated in different set-ups at Dantec Dynamics. 1. Measurement on water vapour;2. with DEHS seeding; 3. Measurements on flying wire wheel.

1.5.4 Influence of small-scale turbulence on cup anemometer calibration

Small-scale turbulence is known to govern the curvature of shear layers around structures and is not related to the traditional under and over speeding of cup anemometers originating from large-scale turbulence components. The paper has shown that the small-scale turbulence has a significant effect on the calibration results obtained for cup anemometers. At 10m/s the rotational speed seems to change by approx. 0.5-1% due to different simulations of the small-scale turbulence.

It is emphasized that the effect of small-scale turbulence originates from changed forcing acting on the rotor, and it is not possible to take this effect into account by the present mathematical models of cup anemometer rotors, e.g. the models applied in cup anemometer IEC classifications [1].

In the short term it is recommended that the Measnet approved calibration wind tunnels quantify their small-scale turbulence, and this information may in the long term lead to requirements for small-scale turbulence in Measnet and subsequently IEC specifications. On long term manufactures of cup anemometers may use a small sensitivity to small-scale turbulence as a competitive advantage.

A thorough understanding of all aspects influencing calibrations of cup anemometers is the first step towards increasing the accuracy of wind speed measurements in field. The work-presented in the paper regarding the small-scale turbulence influence on the calibrations is a breakthrough in regards to using wind tunnel calibrations results to interpret wind speed field measurements as well as reducing the bias between calibration results obtained in the individual anemometer calibration institutes. This is of great importance in order to meet the demands from the wind energy industry on a reduction of uncertainty regarding the wind speed measurements.

The outcome of the presented work is firstly of great relevance for the anemometer calibration institutes, creating an awareness of the influence of turbulence on the calibration results. The turbulence influence is an aspect well known in other parts of wind tunnel testing experiments but is yet to be recognized within the cup anemometer calibration industry. The present guidelines for cup anemometer calibrations refer alone to the turbulence intensity of the flow not handling the influence of small-scale turbulence and this contributes to the present well known bias between the individual anemometer calibration institutes. The paper aims to spread the achieved knowledge of small-scale turbulence influence for the general benefit of reduction of uncertainties on cup anemometer calibrations.

Tests with various turbulence in the wind tunnels have uncovered the influence of small-scale turbulence on the response of the cup anemometers. This is new knowledge in the calibration industry and may lead to explain the +/-1% deviation within MEASNET calibration institutes. A presentation of the influence of this work has been prepared and sent to the MEASNET Expert Group for Anemometer Calibrations and presented at the Wind Europe 2017 conference. As the small-scale turbulence influence the calibration of cup anemometers, this parameter must be included in inter comparison tests of different wind tunnels. Thus, the initial planned activities of investigating the influence of blockage/boundary effects on calibration results were combined with investigations of the turbulence influence. The mapping of turbulence influence and comparisons between calibrations made in different sized tunnel cross sections with different tunnel boundary effects have led to a greater understanding of the deviations between wind tunnels. Three different tunnel cross section sizes have been evaluated in regards of blockage/boundary effects. It has been concluded that the turbulence spectra must be mapped in greater detail when comparing calibration results, than described in the current IEC standard.

1.5.5 Classification of 3 types of cup anemometers

- Full classification procedure (tests in wind tunnel on 5 samples and uncertainty evaluation though the ACCUWIND model) have been completed for three types of currently commercialized cup anemometer, according to IEC 61400-12-1:2017:

  - Windsensor P2546A-OPR:

Class A	Class B	Class C	Class D
1.04	3.76	1.32	3.80

  - Thies First Class Advanced 4.3351.10.000
    - The classification according to IEC 61400-12-1:2017 that requires tests on 5 samples was obtained by combining:
      - Two complete tests performed previously;
      - Two tests performed according to IEC 61400-12-1:2005, completed by friction tests at low temperature (to comply to the new requirements of IEC 61400-12-1:2017) in February 2020.
      - Full test according to IEC 61400-12-1:2017 for one cup anemometer (the cup anemometer used in the open air test rig, the tests were performed after the measurement campaign).
    - Final class numbers remain to be compiled in a public summary report.
  - Thies First Class Advanced II 4.3352.10.000

Class A	Class B	Class C	Class D
1.50	2.98	6.50	7.05

1.5.6 Open air cup anemometer test rig

The verification of the cup anemometer (Accuwind) model, used for classification, requires that the 3D wind field is accurately known in detail at the cup anemometer position. In practice the cup anemometer measurements are compared to simultaneous measurements from a co-located instrument. In most cases a sonic anemometer is used as reference, since another cup would not enable us to distinguish the specific response of the tested cup anemometer. However, sonic anemometers are not ideal references for this type of comparison since their measurements are disturbed by the flow distortion of their own supporting rods. The DTU short range WindScanners (SRWS) system is offering a solution. The system is made of three continuous wave lidars with their beam focused and crossing in the same position thus providing a measurement of the 3D wind vector and the flow is not disturbed. For this specific study the WindScanner system was set up to measure at 10 m above the ground. The telescopes in the WindScanners are designed to have a probe volume of each of the scanner is 10 cm at this distance, which is comparable to a sonic anemometer (without the inconvenient of the flow distortion due to the rods). Before their deployment, the line of sight (LOS) wind speed of each lidar was verified against a flywheel . During the deployment, the WindScanner beams were carefully oriented to the same measurement position. The WindScanner measurement were compared to simultaneous measurements using a Metek sonic anemometer in order to validate the algorithm applied to calculate the three components of the wind vector (u,v,w) from the three LOS wind speeds. Finally the WindScanner was used as reference to estimate the response of the Thies First Class cup anemometer. The data quality was thoroughly checked. The sensitivity of the ratio between the cup anemometer and the WindScanner wind speed measurements to various conditions of speed, turbulence and temperature were investigated.

This experiment demonstrated the ability of the SRWS system to provide measurement of the undisturbed flow. In this experiment, the SRWS wind data were streamed directly to the DTU data acquisition system DAQwin for the first time. Thus data from all instruments (especially the test anemometer and the SRWS) were recorded simultaneously by the same data acquisition system which enabled an easy and accurate time synchronization of the different systems. This is a first step towards a stable and user friendly set up for this kind of cup testing.

The current location of the OATR is however not suitable for cup anemometer calibration, if the purpose is to provide a calibration for conditions in which the cup anemometer is to be used (e.g. mounted on a mast at wind turbine hub height); especially because the turbulence intensity is too high due to the terrain relative complexity and the proximity of the ground.

The cup anemometer wind speed was larger than that measured by the SRWS by 0.88%. A sensitivity analysis has been carried out in order to identify if some of the deviation could be explained by the cup anemometer response to the open air wind conditions. Only small sensitivities to the wind speed and the turbulence intensity could be shown, but they were almost insignificant compared to the large scatter in the data. As the SRWS uncertainty mainly includes biases and no random uncertainty, those scatter are expected to be due variations in the cup anemometer response.

1.5.7 Verification of the cup classification model

Cup anemometer models simulate cup anemometers: a) tilt angular response characteristics; b) temperature induced effects on the anemometer performance and c) dynamic effects due to rotor torque characteristics. These models are used in classification schemes (ref IEC 12-1) that use artificial three-dimensional wind datasets.

The ACCUWIND cup anemometer model has been evaluated by using the Open Air Test rig data and comparing the model simulated cup anemometer response to the actual cup anemometer reported wind speed. The response characteristics of the Thies FCA cup anemometer used in the open air test rig have been quantified though wind tunnel measurements lab test at SOH facilities. The model as been configured with the parameter values specific to this cup anemometer. Times series of the 3D wind vector measured by the staring short range WindScanner were used as input. The cup anemometer response was simulated for each of these time series. The simulated results (10 min statistics of the rotational frequency and wind speed) were compared to the actual measurements from the cup anemometer.

About 1% difference was found on average between the simulations and the actual measurements. The simulated cup anemometer wind speed were actually very similar to the input wind speeds. According to those results, the cup anemometer response to the wind conditions (especially high TI) during the measurement with OATR, does not explain the 1% difference between the wind speed measured by the WindScanner and the cup anemometer. Possible explanantions are:

a. The WindScanner measurements, used as reference and considered as the "true wind speed" in this exercise, are somehow erroneous (in spite of the thorough quality control performed on the data – see report by Rolighed Thorsen et al.);

b. The cup anemometer model is not perfectly modeling the cup anemometer response; e.g. the instantaneous horizontal shear is not taken into acount.

1.6 Utilization of project results

- SOH has in parallel with the continuous work of obtaining an accurate calibration of the reference wind measurements by two individual optical systems and investigating turbulence and blockage/boundary effects, developed procedures for classification of cup anemometers. The classification of cup anemometers has been included in the latest edition (2017) of the IEC standard. The work carried out under the True Wind project evaluates the consistency of classification methods and the uncertainties related to the classification. The knowledge and knowhow, regarding classification of anemometers, obtained by Svend Ole Hansen ApS is considered a valuable market asset crucial for being a worldwide state-of-the-art calibration and classification facility. SOH expect this to provide substantial business opportunities in the future. SOH has updated their calibration procedures to follow the newest IEC standard and achieved the accreditation by Danak for this service. Furthermore, an updated calibration certificate has been developed. This allows SOH to offer state-of-the-art services within anemometer calibrations.
  Accreditation by Danak of the SOH service: classification of anemometers, in progress. Expected approved within a trimester.

- Classification of three types of cup anemometers according to IEC 61400-12-1:2017 in SOH tunnel are seen as a major result of the project as well (yet to be published). First of all, classification of cup anemometers according to the newest edition of the IEC standard has been requested for more than 2 years by the cup anemometer users. Furthermore, very few classification results are produced and made publically available, and some are in conflict with the IEC standard. Therefore classification results are expected to generate discussion and improvement of the classification procedure by the measurement standardisation community.

- WindSensor is in the process of publishing the classification summaries of all classified anemometers as well as a comparison of the fixed range Class A, B, C, and D numbers on its web site. In addition, WindSensor has created an online Class S calculator, which allows for the calculation of the class number for any combination of the influence parameter ranges. This may significantly reduce the total classification and consequently the AEP uncertainty. The calculator provides Class S numbers for WindSensor anemometers only.

- WindSensor is also in the process of producing 5 samples of their new cup anemometer (new design), which are expected to go through a full classification procedure according to IEC 61400-12-1:2017. This will bring a new cup with low class number on the market.

- DantecDynamics expect to finalise and commercialise their combined LDA/lidar system.

- Based on the new calibration method developed for short range wind lidar using a fly-wheel, DTU Wind Energy has proposed a new development project (to EUDP in March 2020) to develop a new method for nacelle lidar calibration without using cup anemometer. Three short-range lidars would be used as reference instead of a cup anemometer (current reference wind speed measurement in lidar calibration). This could considerably reduce the uncertainty of the lidar measurements used in wind turbine power curve measurement for example.

1.7 Project conclusion and perspective

- Svend Ole Hansen ApS is getting accredited for cup anemometer calibration and classification according to IEC 61400-12-1:2017.
- WindSensor ApS is about to get a new cup anemometer characterized through full classification process, demonstrating the lower class number.
- DantecDynamics is finalizing a new combined LDA/lidar measurement system for wind tunnels (commercial product).
- DTU Wind Energy has fully developed a method to calibrate short range wind lidars with a fly-wheel.

Annex

Dissemination:

- Influence of small-scale turbulence on cup anemometer calibrations
M Marraccini et al 2017 J. Phys.: Conf. Ser. 926 012005
https://iopscience.iop.org/article/10.1088/1742-6596/926/1/012005
- Rolighed Thorsen, G., Wagner, R., Courtney, M., & Pedersen, A. T. (2019). TrueWind - Open Air Test Rig. DTU Wind Energy. DTU Wind Energy E, No. 0184
https://orbit.dtu.dk/en/publications/truewind-open-air-test-rig
- Flywheel calibration of a continuous-wave coherent Doppler wind lidar
Author(s): Anders Tegtmeier Pedersen and Michael Courtney MS No.: amt-2020-88 MS Type: Research article in Atmospheric Measurement Techniques (AMT)
Iteration: Initial Submission
- Michael Courtney. (2019, June). Cup-less lidar calibrations. Zenodo.
http://doi.org/10.5281/zenodo.3698634

Relevant links

https://www.windsensor.com/en/class_calculator_ed1