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Characterization of the SUMO turbulence measurement system for wind turbine wake assessment

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Abstract

The remotely piloted aircraft system (RPAS) SUMO (Small Unmanned Meteorological Observer) has been equipped with a miniaturized 5-hole probe sensor system for measurement of the 3-dimensional flow vector with a temporal resolution of 100 Hz. Due to its' weight and size this system is particularly well suited for operations in the vicinity of wind turbines. To qualify for full scale measurements in turbine wakes the system has been characterized by several laboratory and field tests described in this study.

A wind tunnel test against a hot-wire anemometer shows the capability of the 5-hole probe to react to turbulence in the same manner as the hot-wire system. The resulting spectra from the two platforms show in general good agreement for both laminar and turbulent flows. The 5-hole probe system is able to resolve turbulence up to frequencies around 20 – 30 Hz when using a tubing length of 15 cm between the probe and the pressure transducers.

In addition, an environmental parallel test against to two sonic anemometers mounted on the roof-top of a car was performed at Bergen airport Flesland. Despite several issues with the self-made and low-cost experimental setup, important system characteristics could be tested and verified. In particular the velocity spectral components of the sonic anemometer system and the 5-hole probe are in close resemblance to each other. This is at least a strong indication that the 5-hole probe is suitable for atmospheric turbulence measurements onboard the RPAS SUMO platform.

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Keywords: atmospheric boundary layer (ABL); turbulence; remotely piloted aircraft system (RPAS); wind turbine wake; wind energy;

1. Introduction

The interaction between wind turbines and the atmospheric boundary layer is highly complex. The resulting wind turbine wakes are characterized by high temporal and spatial variability. Their extension and dynamics strongly depend on atmospheric stability, which is the crucial factor controlling the interplay between the relevant flow conditions given by the profiles of wind speed, i.e. wind shear, and turbulence intensity. A turbine wake is mainly characterized by a reduction of the average wind speed and the increase of the turbulence level that negatively effects the productivity and fatigue load of downstream turbines in a wind farm. The proper understanding of the development and structure

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of a single turbine wake is therefore of uttermost importance. The detailed investigation of the dynamical behavior of such wakes, e.g. meandering or the dispersion of the wake zone with the downstream distance, requires both modeling and full scale observations. During the last years, corresponding CFD simulations have been performed with varying but in general increasing complexity (e.g. [1]). Required full scale data sets for the improved understanding of the underlying physical processes and the initialization, test and validation of such simulations are sparse at the best. One of the main reasons is the instrumental and infrastructural demand connected to corresponding observations. With the development and application of ground based scanning lidar systems and nacelle based static units looking backwards in the turbine wake, the observational basis is however expected to improve in the future (e.g. [2], [3]).

Most of the existing knowledge is based on records from in-situ measurements at meteorological masts and towers or on ground based remote sensing (e.g.[4]) by lidar [5–7], sodar [8] [9] and lately also radar [10]. Static masts and towers mainly lack positioning flexibility with respect to the high temporal and spatial variability of the wake and are in addition rather expensive, at least when completely covering the relevant altitude level of state-of-the-art wind turbines extending 150 m. Moreover, the interpretation of spatial structures based on point measurements requires the validity of Taylor's hypothesis of frozen turbulence [11] [12] which cannot be guaranteed in such a highly turbulent environment. The remote sensing sensors can only provide volume averages of the wind speed distribution and the spatial resolution of the systems nowadays in use, typically in the order of several tens of meters, is not sufficient for a detailed structural investigation of the wake.

In-situ airborne measurements can provide novel and highly relevant data sets in this field. Manned aircraft operations in a wind farm or in the vicinity of a single wind turbine are out of question due to safety considerations. Small and light-weight Remotely Piloted Aircraft Systems (RPAS) however can operate safely in such an environment [13] [14]. The miniaturization of electronics and sensors in the last years has now allowed to equip even very light RPAS with a take-off weight clearly below 1 kg with sensors for the measurement of the turbulent flow vector [15] [16]. Systems of this size and weight will not jeopardize the tower or the turbine blades even in the unlikely event of a collision of the RPAS with the structure. However, appropriate strategies for the used flight patterns and the after-flight data processing and interpretation have to be developed, keeping in mind that a single RPAS will only be able to provide a snapshot of the actual situation. The potential of simultaneous operation of several RPAS in the future would also be of invaluable benefit in this context.

The determination of reliable turbulence data sets from airborne platforms requires on one hand a careful characterization of the spectral response of the system to ensure that structures in the relevant scale can be resolved appropriately. On the other hand, adequate motion correction algorithms have to be applied to correct for the aircraft's attitude and motion during the turbulence measurements [17–20].

This paper is structured as follows. Section 2 shortly presents the recent, improved version of the SUMO system for turbulence measurement based on a 5-hole flow probe. The results of laboratory wind tunnel tests of the spectral response in comparison with a hot-wire anemometer are described in section 3. The potential effect of the tubing length between the probe and the pressure transducers has also been addressed in this part. Section 4 shows the results of an environmental test of the system by parallel measurements with a sonic anemometer mounted on a car. Finally a short summary and outlook is given in section 5.

2. The SUMO turbulence measurement system

The atmospheric turbulence measurement system developed for the future in-situ investigation of single turbine wakes presented here consists of the micro RPAS SUMO [15] [16] as sensor carrier and a commercially available 5-hole probe system for the measurement of the 3-dimensional turbulent wind vector. The fixed-wing model aircraft FunJet from Multiplex works as the basis for the SUMO airframe. The system has been developed and continuously improved over the last 7 years in close cooperation between the Geophysical Institute, University of Bergen, Norway and Lindenberg und Müller GmbH & Co. KG, Germany. SUMO is driven by a single propeller in the rear, electrically powered by a LiPo battery pack, enabling flight times of up to 40 min. With its take-off weight of around 600 g, a wingspan of 0.80 m and a length 0.75 m, SUMO provides a small and flexible measurement platform. It operates at cruise speeds of 12 - 25 $\mathrm{m\,s^{-1}}$. For navigation and automatic flight, SUMO uses the open source autopilot system Paparazzi [21] developed and maintained by the École National de l'Aviation Civile (ENAC) in Toulouse, France.

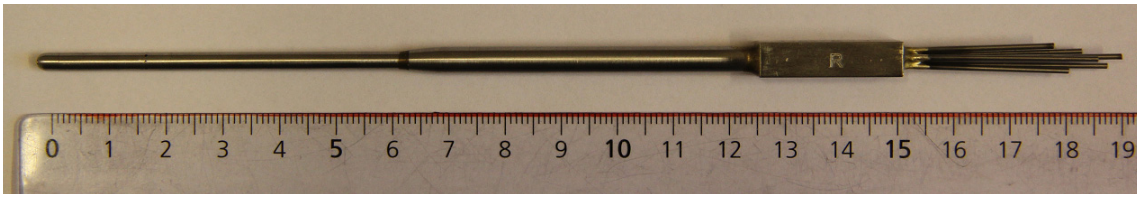

Fig. 1: The 5-hole probe from Aeroprobe Cooperations.

Continuously updated software and detailed description of hardware are freely available from the project website. Predefined flight plans can be flown autonomously and changes can be made at any time during a flight mission.

The SUMO airframe is operationally equipped with meteorological sensors for measurement of temperature and relative humidity (Sensirion SHT 75), pressure (M55611), and an downward directed IR sensor (MLX90247) for the estimation of the surface temperature. For the measurement of the 3-dimensional turbulent flow vector with a temporal resolution of 100 Hz the SUMO system can be extended by the Air Data System (ADS) from Aeroprobe Corporation. It consists of an air data computer and a miniaturized 5-hole probe with corresponding pressure transducers [22]. A soft plastic tubing (TYGON R-3603 [23]) connects the probe to the air data computer, which is placed inside the front compartment of the SUMO fuselage. The 5-hole probe itself is placed at the nose of the aircraft, with the sensing area about 10 cm in front of the nose tip, to minimize the effects of flow distortion induced by the airframe.

Fig. 1 shows the 5-hole probe. It is constructed in stainless steel and has a length of 15 cm and a diameter of 3 mm. The probe measures static and dynamic pressures through small holes at its side and tip. The resulting ADS output parameters, based on these differential pressure measurements, are the true airspeed (TAS), angle of attack (α), angle of sideslip (β) and altitude. The output can either be stored on a Micro-SD card on board or streamed directly to a PC through a serial RS-232 connection. The first option is used for SUMO flight missions while the latter is ideal for online monitoring, e.g. during system tests and laboratory calibrations.

The latest version of SUMO can store both the 5-hole probe turbulence measurements and the attitude information, i.e. the aircraft's pitch, roll and yaw as well as the linear and angular accelerations from the autopilots inertial measurement unit (IMU), on one common data logger. This avoids previously needed work and challenges in connection with motion correction based on two unsynchronized data sets [16] [13]. The sampling frequency of the aircraft attitude is now in addition increased from 10 Hz to 60 Hz.

3. Wind tunnel tests of the 5-hole probe system

3.1. Measurement setup

A laboratory experiment took place in April 2013 in a wind tunnel at the University of Applied Sciences Regensburg, Germany, in order to validate the performance of the 5-hole probe ADS. The system was first tested in a parallel experiment together with a hot-wire anemometer (HW) for a comparison of the spectral response of the two systems. Thereafter the effect of varying tubing length between the probe and the air data computer was tested to investigate potential effects of spectral damping induced by the tubing. All tests were first conducted in laminar and then turbulent conditions, both with a background flow of 18 $\mathrm{m\,s^{-1}}$. This flow speed was chosen since SUMO usually operates in the range of 12 to 25 $\mathrm{m\,s^{-1}}$ during scientific flight missions. The turbulence was created by a horizontal stick in the flow ($\sim$ 3 cm diameter) upstream of the sensors. The simple mechanism used to create turbulence in these tests cannot be expected to fully reproduce atmospheric turbulence. However, the intention of the experiments was a general characterization of the spectral response of the 5-hole probe ADS compared to a well established measurement platform.

(a) (b)

Fig. 2: The mounting of the 5-hole probe in the wind tunnel (a) and the experimental setup for the turbulent flow, with a horizontal stick upstream of the probe (b). Pictures by Sebastian Wein.

The HW system (model StreamLine from Dantec) and the 5-hole probe ADS have been deployed alongside in the wind tunnel and placed straight in the flow direction, i.e. the probe angle of attack and angle of sideslip had no offset from the horizontal plane and the centerline respectively. All experiments had a duration of 5 min. With an original temporal resolution of 5 kHz, the HW measurements have been averaged to 100 Hz which corresponds to the sampling frequency of the 5-hole probe ADS. The ADS used the original tubing length of 15 cm for all parallel experiments. The HW system measured the airspeed and the ADS measured airspeed (TAS), angle of attack (α) and angle of sideslip (β).

The soft plastic tubing between the probe and the air data computer is responsible for transferring the incoming pressure signal to the pressure transducers. In a second test, the system was deployed alone in the wind tunnel and tested for the three tubing lengths of 15 cm (short tubing), 30 cm (medium tubing) and 90 cm (long tubing). The short tubing of 15 cm resembles the length already being used by SUMO for the first field campaigns. A longer tubing would be required if the positioning of the probe has to be changed, e.g. in case future wind tunnel tests reveal a considerable effect of flow distortion for the recent mounting at the aircraft nose.

3.2. Results of wind tunnel tests

Fig. 3 shows the averaged spectra of the airspeed component from the hot-wire anemometer (HW) and the 5-hole probe ADS under laminar (left) and turbulent (right) conditions. A marked difference in spectral energy density (S(f)) is visible between the laminar and turbulent case for both measurement systems. In the higher frequency range the non-turbulent spectra have an energy level of about 10^{-4} m^2 s^{-2} while the turbulent spectra reach values around 10^{-1} m^2 s^{-2}, namely three orders of magnitude higher.

The spectra from the two platforms show in general good agreement in the relevant frequency range (> 0.02 Hz). The 5-hole probe ADS reacts to the turbulence in the same manner as the HW system. The small difference between the ADS and HW spectra in both cases is nearly constant, suggesting a similar response to the turbulence, but with a difference in variability. The slightly higher energy level of the 5-hole probe ADS compared to the HW for laminar test conditions could indicate an enhanced basic noise level of the ADS compared to the HW. Under turbulent conditions, it is the HW system that has the highest energy level. Here the higher variability in the HW measurements can be explained by the higher temporal resolution of the system, when picking out instantaneous samples from 5 kHz data every 0.01 s to have directly comparable measurements to the 100 Hz ADS.

Fig. 4 presents the spectra of TAS, α and β for three different tubing lengths under laminar (left panels) and turbulent (right panels) conditions. The tubing lengths are indicated by the colors red (short), black (medium) and green (long). All parameters experience again the energy shift of 3 orders of magnitude between laminar and turbulent conditions. Variation of the tubing length has little effect under laminar conditions. All spectra lie approximately at the same energy level and keep this level throughout the high frequency range. Under turbulent conditions, the spectra vary more for the different tubing lengths. For the shortest tubing length of 15 cm, already being used when operating the ADS in SUMO, the TAS, α and β all experience a weak energy loss above 20 – 30 Hz. The use of medium or long tubing results in a bigger energy loss, which also starts at lower frequencies (around 10 Hz). The increase in spectral damping for the longer tubing lengths suggests that the shortest one is the best of the three options. A wave- or resonance effect can probably explain the observed energy loss. The ADS manual states that the tubing should be kept as short as possible in order to not limit the response between the probe and the air data computer [22], and our experiments seem to agree.

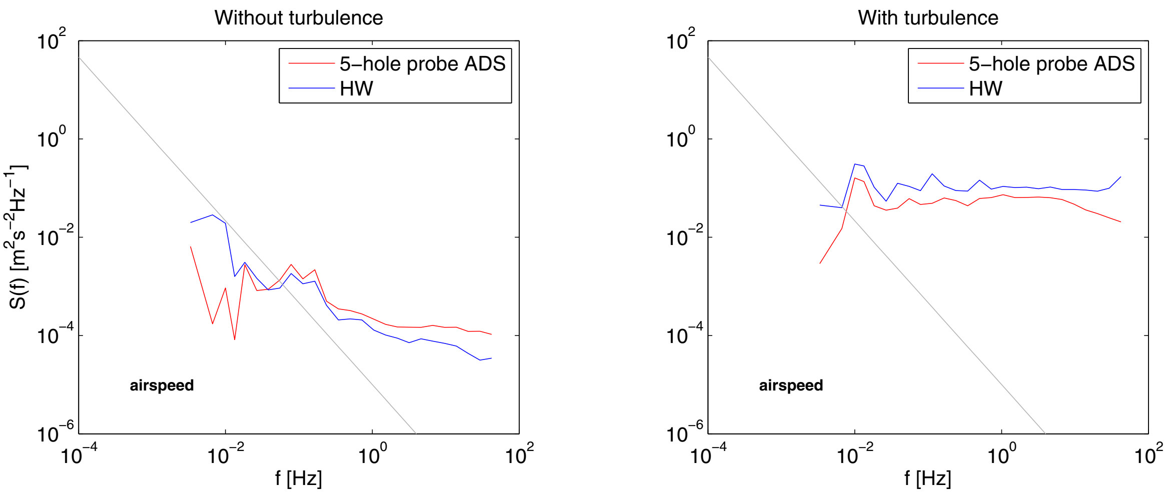

Fig. 3: Averaged power spectra of airspeed measured by the ADS (red) and the HW (blue) systems for the parallel setup, with frequency (f) on the x-axis and spectral energy density (S(f)) on the y-axis. The laminar case to the left and the turbulent case to the right. The grey line represents the −5/3 slope expected for the inertial subrange of a Kolmogorov spectrum.

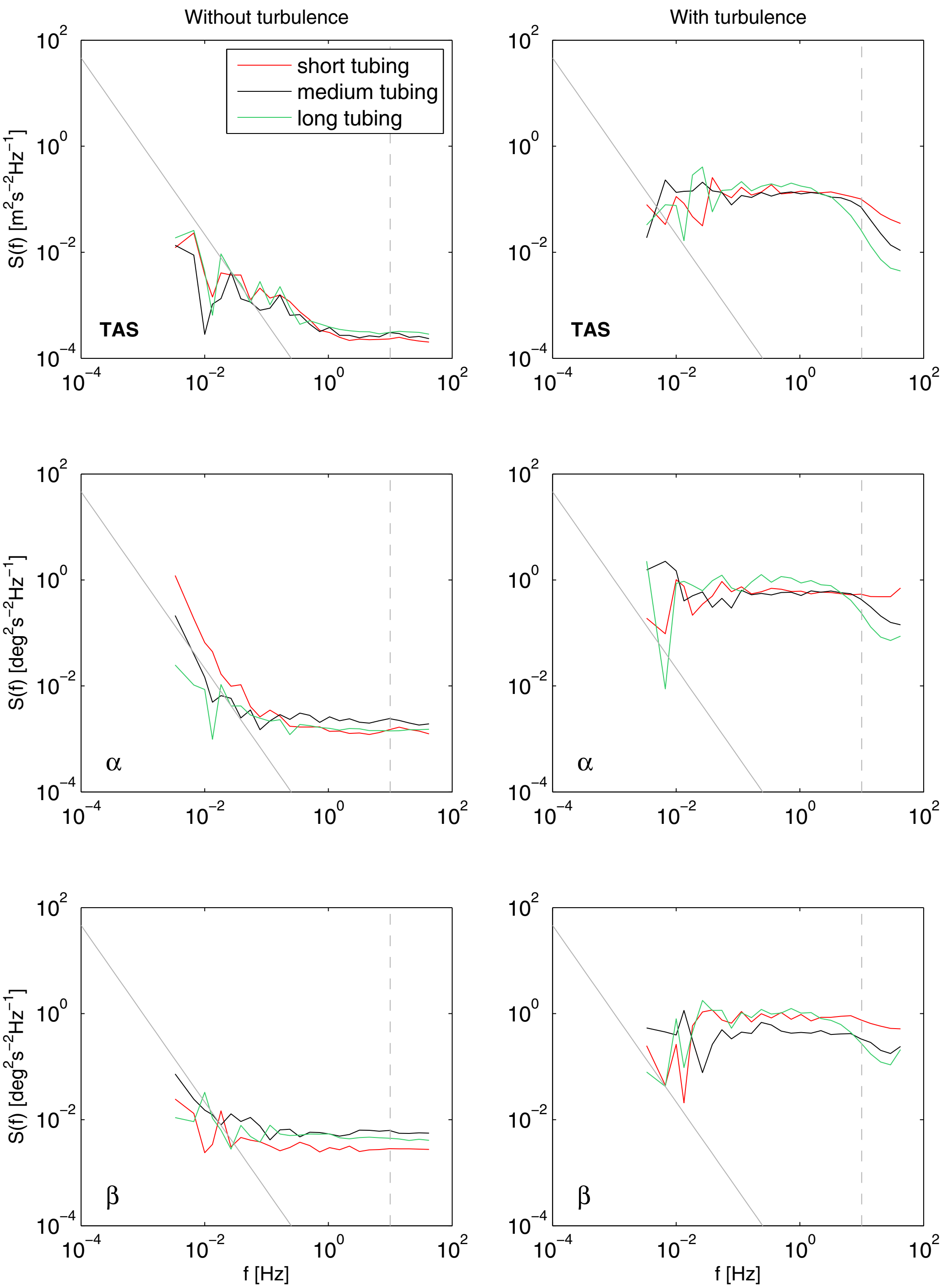

Fig. 4: Averaged power spectra of airspeed (top panel), angle of attack (middle panel) and angle of sideslip (bottom panel) from the 5-hole probe ADS. Again with the frequency (f) on the x-axis and spectral energy density (S(f)) on the y-axis. Tubing length is indicated by the colors, red (short tubing - 15 cm), black (medium tubing - 30 cm) and green (long tubing - 90 cm). The laminar case is shown to the left and the turbulent case to the ringht. The frequency of 10 Hz is indicated by the dashed grey line, while the solid grey line represents the −5/3 slope expected for the inertial subrange of a Kolmogorov spectrum.

4. Environmental test of the 5-hole probe system

4.1. Measurement setup

As a next step after the laboratory experiments at only very low turbulence levels, the 5-hole probe system was tested under real atmospheric turbulence conditions. The 5-hole probe ADS mounted on a SUMO dummy airframe was deployed together with two different sonic anemometer systems, one Campbell CSAT 3 and one Gill R3-100, on the roof-top of the institute car, a Ford Transit model 1995. The R3-100, hereafter referred to as the DCF (Direct Covariance Flux) system, is originally part of an offshore based turbulence measurement system and therefore also equipped with an inertial measurement unit (IMU) for motion correction purposes [24]. The test was performed in the early morning of October 25, 2013, on the runway of Bergen airport Flesland.

Fig. 5 shows the instrument placement on an extension arm slightly in front of the vehicle. Two ladders secured to the roof racks of the car served as the basis for the extension arm. A customized frame in aluminium and wood was mounted on top as sensor platform. All three measurement systems were placed at the same height level, with a horizontal separation of 48 cm. The SUMO dummy with the 5-hole probe ADS on board was mounted in the center, with the CSAT3 to its right and the DCF system to the left. The tip of the 5-hole probe was aligned with the center of the measurement volumes of both sonic anemometers. The mobile laboratory of Gordon et al. [25], used for turbulence measurements behind trucks on highways in Canada, provided the inspiration for the selected experimental setup.

The car was operated for 12 straight legs each of ca. 3 km length. Consecutive legs were run in opposite directions down the runway (runway heading 17/35) using the constant car speeds of 20 and 25 m s^{-1}. The test was performed in a window of no precipitation, with weak winds of about 1-2 m s^{-1}, and a temperature of around 7.5 °C. Unfortunately, the CSAT3 did not work properly and only data from the DCF system will be compared to the SUMO measurements.

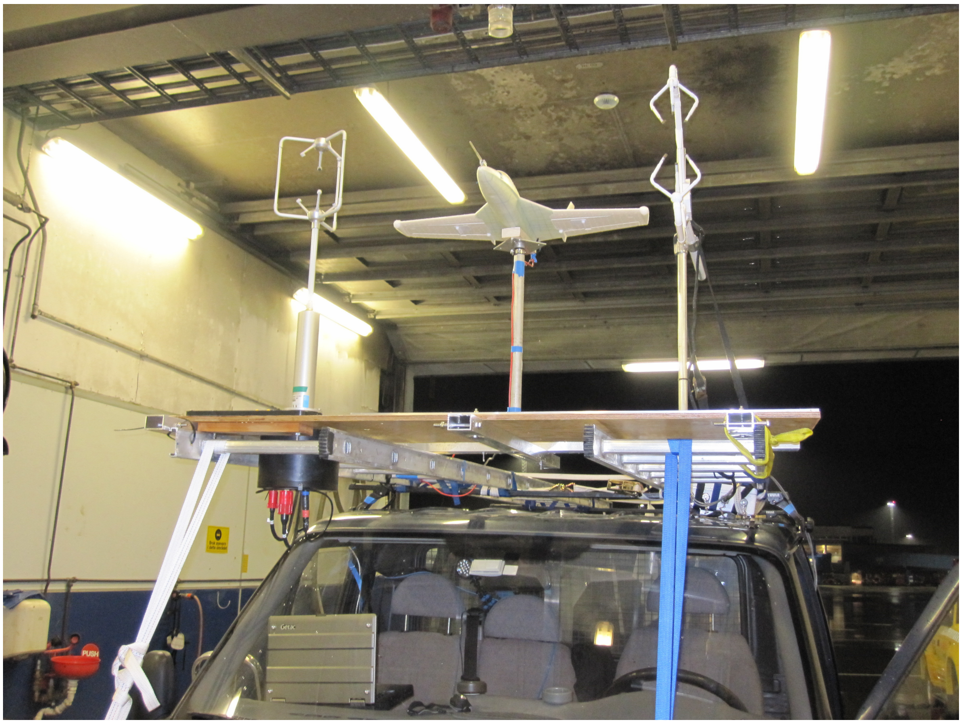

Fig. 5: The experimental setup for the test campaign at Flesland airport in Bergen. From left to right: Gill R3-100 sonic anemometer, SUMO dummy with the 5-hole turbulence probe, Campbell CSAT3 sonic anemometer

Uncorrected measurements of the longitudinal (U), lateral (V) and vertical (W) velocity components are shown in Fig. 6. A motion correction is necessary as the measurements have been performed from a moving platform. While the vibrations caused by the diesel engine of the car should be negligible, the mounting frame of the instrumentation on the roof-top might have been exposed to surge and sway motions when driving over uneven parts of the runway. In addition, we expected the mounting frame to be slightly lifted as a function of the incoming airflow when driving the car. The anemometer and the 5-hole probe also have to be corrected for instrumentation tilt offsets (e.g. [26]) so that all measurements can be compared in the same reference plane.

For simplicity, we chose to rotate the local coordinate systems of the SUMO and the DCF into the car's right-handed frame of reference which is defined as: x-axis pointing forward, y-axis pointing to the left and z-axis pointing upward. The tilt angles (e.g. pitch and roll) of the instruments coordinate systems are given from the respective IMU's and can be directly used in the transformation matrix **T** ([27]) which rotates the wind speeds recorded in the instrument coordinate systems into the car coordinate system. The IMU's accelerometers and angular rate sensors also recorded surge and sway motions of the DCF and the SUMO dummy. These oscillating motions induce an additional velocity component ($\mathbf{U}_{plat}$) which has to be added to the rotated wind measurements of the 5-hole probe ADS and the sonic anemometer respectively. This velocity component is assessed by rotation of the accelerometer outputs into the car's reference frame, followed by subsequent integration and high-pass filtering. The recorded longitudinal velocity component of both systems is finally corrected by subtraction of the car's velocity. The complete motion correction procedure can be found elsewhere in the literature (e.g. [18,28,29]).

Application of the motion correction procedure showed that the surge and sway motions of the both instrument platforms are small ($O\left(\mathbf{U}_{plat}\right) = 10^2$) compared to the recorded wind speeds, which was to be expected as the car was operated on a straight airport runway. This simplifies the correction procedure to

$$\mathbf{U}^{car}_{true} = \mathbf{T}(\mathbf{U}_{rec}) - Lp[\mathbf{V}_{GPS}] \quad (1)$$

where $\mathbf{U}^{car}_{true}$ is the corrected wind vector in the car reference frame, **T** denotes the transformation matrix for coordinate system rotation, $\mathbf{U}_{rec}$ the recorded wind velocity vector in the instrument frame, $\mathbf{V}_{GPS}$ is the car's velocity vector over ground given by the instrument platform's GPS systems and Lp denotes a low-pass filter operator.

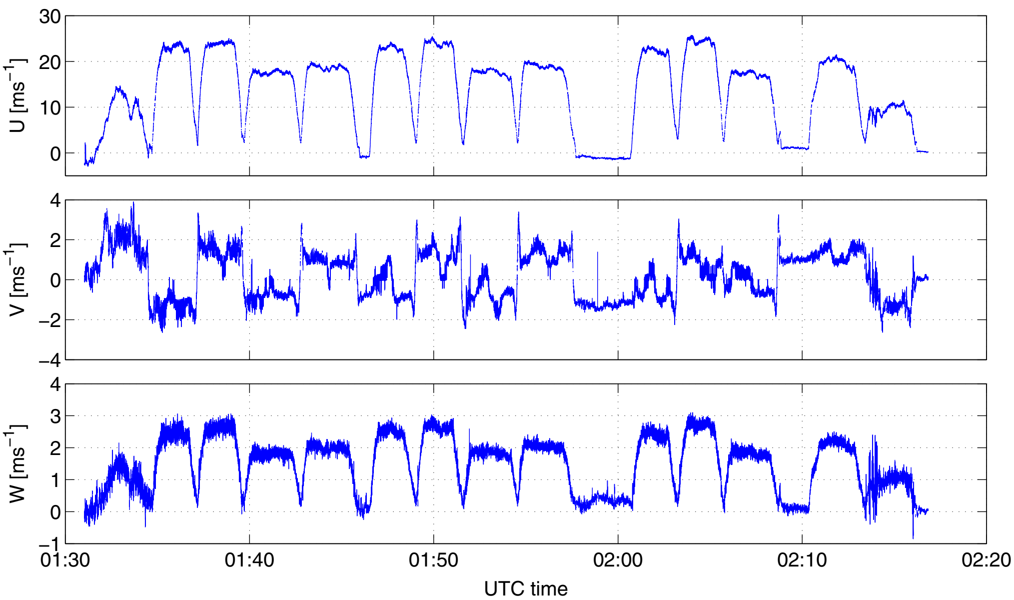

Fig. 6: Time-series of the longitudinal (U - in direction of the moving car), lateral (V - crosswind) and vertical (W) components of the measured flow vector from the DCF system.

4.2. Results of environmental test

To investigate the behavior of the 5-hole probe ADS under real atmospheric conditions, the spectral response of U, V and W components from SUMO are compared to those obtained from the Gill sonic anemometer (DCF system) when driving with both instruments on the roof-top of the institute car (Fig. 7).

The 100 Hz TAS data of the 5-hole probe ADS and the 60 Hz attitude information of the SUMO aircraft have been re-sampled to 50 Hz to match the frequency of the DCF system. Vibrations of the instrument mounting result in several spectral peaks which are removed by the motion correction procedure. Unfortunately, the accelerometers of the SUMO system were only running with a low frequency resolution due to technical limitations at the time of the field test. As a consequence, the frequency peaks, which are clearly seen in the 5-hole probe ADS spectra between 1 and 10 Hz, could not be removed at this instance. Nevertheless, we emphasize that the measured velocity components introduced by the mounting vibrations are small compared to the measured wind speeds.

Both panels of Fig. 7 show enhanced spectral energy (fS(f)) for all velocity components at the low- and high-frequency end. Higher spectral energy at the low-frequency end ($f < 10^{-1}$) of the horizontal spectra is likely due to the low-frequency oscillations of the car speed which was varying around the target velocity of 20 and 25 m s^{-1} (see upper panel of Fig. 6). The enhanced spectral energy at the low-frequency end of the vertical velocity spectra is likely due to the low-frequency oscillations of the mounting frame. Analysis of both systems pitch angles revealed that the frame was slightly lifted upward by the incoming air-flow as a function of the car speed.

The increased spectral energy at the high-frequency end of the DCF-spectra is likely to be a result of flow distortion from the straps used to fix the ladders (see Fig. 5). The horizontal velocity spectra of the 5-hole probe ADS roughly follow the theoretically expected −2/3 slope of the inertial subrange for both velocity intervals. However, the vertical spectra of the 5-hole probe ADS is not following the expected slope for the car speed of 20 m s^{-1}, indicating to be affected by flow distortion. This might be a consequence of the increase of vertical velocity with car speed (see lower panel of Fig. 6). Together with the slight variations in the pitch angle during the experiment lead us to conclude that the mounting frame decelerate and deflect the horizontal airflow in front of the car, introducing an vertical velocity

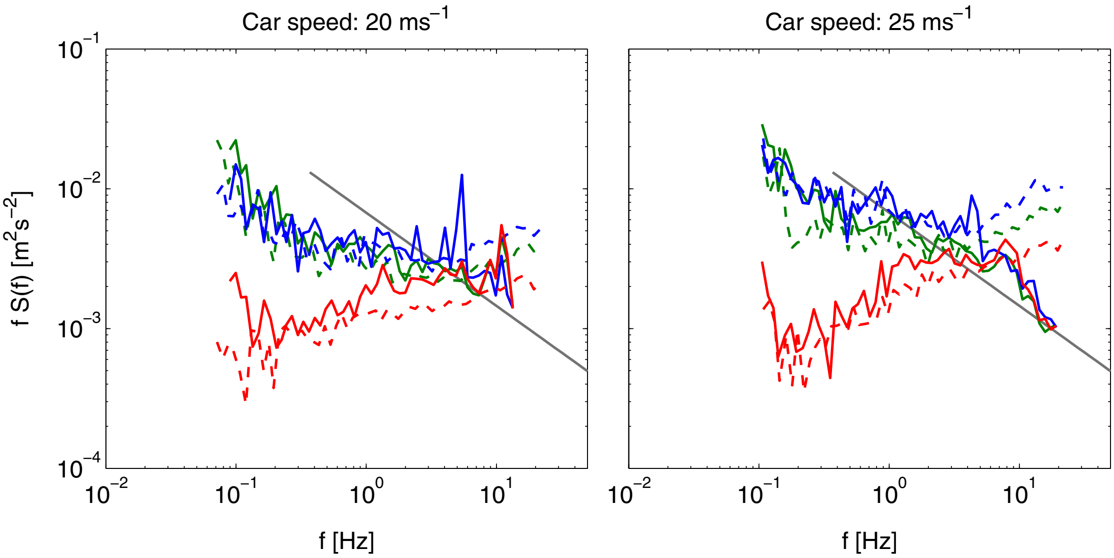

Fig. 7: Corrected power spectra of the longitudinal (green), lateral (blue) and vertical (red) velocity components from the SUMO 5-hole probe ADS (solid line) and the DCF system (dashed line), with frequency (f) on the x-axis and spectral energy (fS(f)) on the y-axis. The spectra are averaged for consecutive legs with car speeds of approximately 20 and 25 m s^{-1} to reduce the variability between the individual spectra induced by the low-frequency oscillations of the mounting frame. The theoretically expected −2/3 slope of the inertial subrange is shown by the grey line.

component as shown in the experiments by [30–32]. Nevertheless, the 5-hole probe ADS vertical velocity spectra for the car speed of $25\,\mathrm{m\,s^{-1}}$ follows the expected subrange slope. We speculate that this is a consequence of the higher velocity of the approaching airflow. For the car speed of $20\,\mathrm{m\,s^{-1}}$, the car is still slow enough for the streamlines to be deflected both horizontally and vertically. When driving with $25\,\mathrm{m\,s^{-1}}$, the streamlines are not able to be sufficient vertically deviated in front of the car, thus reducing the amount of vertical flow distortion.

Despite the flow distortion at the high-frequency end and the peaks introduced by vibrations of the SUMO dummy, Fig. 7 shows that the spectral components of both systems are in close agreement for both velocity ranges. This indicates that the 5-hole probe ADS is suitable for turbulence measurements from the RPAS SUMO platform.

5. Summary and outlook

The 5-hole probe ADS turbulence measurement sensor from Aeroprobe has been implemented and tested for the RPAS SUMO.

The 5-hole probe ADS was first tested in a wind tunnel. A parallel experiment together with a hot-wire anemometer (HW) shows the capability of the probe to react to turbulence in the same manner as the HW system. The resulting spectra from the two platforms show in general good agreement in the relevant frequency range (> 0.02 Hz), for both the laminar and the turbulent case.

Thereafter, the effect of varying tubing length between the probe and the air data computer was tested to investigate potential effects of spectral damping induced by the tubing. For the shortest tubing length of 15 cm, already being used when operating the ADS in SUMO, the system is proven to resolve turbulence satisfactory up to frequencies around $20 - 30$ Hz. The spectral damping increases for increasing tubing length.

Parallel to two sonic anemometers, the 5-hole probe ADS was mounted on a SUMO airframe at the roof-top of the institute car to investigate its behavior under real atmospheric conditions. The car was driven for 12 consecutive straight legs down the runway of Flesland airport, Bergen, Norway, with car speeds of 20 and $25\,\mathrm{m\,s^{-1}}$. The components of the velocity spectra show that the DCF system suffers from flow distortion, possibly introduced from the straps used to fix the ladders used as mounting frame and from corner deflection effects of the mounting frame. Do to technical limitations, the SUMO accelerometers and angular rate sensors were only running with low resolution during this experiment. Therefore, the peaks associated with vibrations of the SUMO dummy seen in the 5-hole probe spectra could not be removed. Nevertheless, the velocity spectral components of both the DCF system and the 5-hole probe ADS are in close resemblance to each other. This indicates that the 5-hole probe ADS is suitable for turbulence measurements from the RPAS SUMO platform. The environmental test in this study also shows that care must be taken to avoid flow distortion when constructing a "low-cost, self-made," instrument mounting frame on the roof-top of a car. To improve the quality of the turbulence measurements performed in this study, the authors plan a new test at Flesland airport with an improved mounting design causing less flow distortion, e.g. similar to that one presented by [33].

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