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A calibration procedure to correct the shadow effect in ultrasonic wind sensors

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ABSTRACT

Ultrasonic anemometers have a wide variety of applications in wind engineering and industrial aerodynamics. A general and easy-to-use theoretical model for predicting their measurements certainly in the transducer's shadow zones still remains a gap in the existing knowledge and a proper calibration should be performed to take the transducer shadow effect into account. In this paper, several wind-tunnel tests have been undertaken on a single-axis ultrasonic anemometer to propose a procedure to calibrate the sensor outputs. The signal path of the anemometer was placed at various azimuthal angles with respect to the wind direction. It has been observed that at each angular position, different wake and vortices depending on the sensor blockage area and magnitude of the wind speed are shed into the measurement path. These wakes make the signal path deviate from its straight line inducing a phase shift into the signal path which is calculated by a fourth order polynomial function for the tested sensor. Then, the obtained phase angle is used to construct a calibration model which can be used not only to correct the sensor outputs but also to study the transducer wake behavior and effect on the measurements. This approach has been shown to work satisfactorily for the circumstances where the anemometer is rotating continuously around its vertical axis.

1. Introduction

The Ultrasonic Anemometer, UA, output is based on the time of flight of the ultrasound pulses between two transducers. Each transducer acts alternatively as a transmitter and a receiver, sending ultrasonic pulses between themselves. The wind speed measured by the UA is determined from the difference between the inverse of the times of flight during the send and receive processes (Cuerva and Sanz-Andres, 2000).

This type of anemometer is widely used in several wind engineering applications such as atmospheric, meteorological, civil aerodynamics and wind turbines (Kato et al., 1992; Martínez et al., 2008). Since there are no moving parts in UAs, they need less maintenance and calibration comparing to cup anemometers. Also, they are suitable for outdoor applications and adverse weather conditions and are able to work even in icing temperatures, turbulent flows and dusty air conditions (Wyngaard, 1981; Cuerva et al., 1998).

Due to UAs capabilities in wind energy, they are popular choices for wind resource assessment on met towers, nacelle and spinner anemometry. Their output signals are used to determine accurate power performances of wind turbines which is a vital need for proper monitoring and adjustment of the blades and for shutting down turbines in adverse and strong winds to avoid any probable mechanical failure (IEC61400-12-2, 2013).

Indeed, wind turbine power output is proportional to the third power of the mean wind speed, so wind speed plays a significant role in the output energy of a wind turbine (Kristensen, 2000). Hence, the accuracy of the magnitude and direction of wind speed measurements is crucial as they are used to adjust the orientation of the wind turbine spinner to the direction of the maximum wind velocity, and change the blade angle of attack. This highlights the importance of the calibration of ultrasonic wind sensors, used in met tower, nacelle and spinner anemometry for optimization of wind turbine power output.

In wind turbine nacelle anemometry, 2-D sonic sensors are installed over the nacelle chamber of a wind turbine for wind speed measurements. In spinner anemometry, on the other hand, three 1-D sonic sensors are placed symmetrically on the wind turbine spinner to measure both wind speed and direction in front of the wind turbine (Pedersen et al., 2007). The locations of the UAs installed over the nacelle and spinner of the wind turbines are schematically drawn in Fig. 1. The measurements with UAs on the nacelle are affected by flow distortions and wakes of the

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Nomenclature

U_∞	Free stream wind speed, [m/s]
U_s	Velocity measured by ultrasonic anemometer, [m/s]
U_r	Reference velocity, [m/s]
U_c	Calibrated measurements, [m/s]
θ	Azimuthal angle between transducers' signal path and the wind direction, [rad]
ϕ	Phase angle because of transducer wake effect, [rad]
ω	Angular velocity, [rad/s]
ΔU	Velocity deficit, [m/s]
σ	Standard deviation, [m/s]

rotor and blades (Zahle and Sorensen, 2011). However, on the spinner as a newer technique, although there are still some distortions in front of the wind turbine which affect the UA measurements, they are less pronounced than those that exist over the nacelle chamber. With proper calibration at the UAs used in the nacelle and spinner anemometry, they should exhibit higher accuracy in the measurement process for a wind turbine (IEC61400-12-2, 2013; Demurtas et al., 2016).

Transducer shadow effect is known as the main source of uncertainty in UA measurements, and is defined as the underestimation of the wind components measured along the ultrasound paths due to velocity deficits in the wake of the transducers (Kaimal, 1978; Mortensen, 1994). Wyngaard and Zhang (Wyngaard and Zhang, 1985) proposed an empirical model to correct for the transducer shadow effect in which two constants must be determined from the best fit of the model with experimental data. By careful aerodynamic design and with small dimensions of the transducers, the effects of the wakes on the signal path can be reduced, though it is impossible to completely eliminate the transducer shadow effect. On the other hand, since the wake behavior behind each transducer is actually complicated and unknown, the authors have found no general and accurate tool in the existing literature up to now, based on the nature of the wake region, to correct the transducer shadow effect on UA measurements.

Franchini et al. (2007), analyzed the wind speed measured using a dual sensor transit-time ultrasonic anemometer by considering the effect of the shift of the trajectory of the ultrasonic pulse from a straight line caused by the velocity field. The method was based on a mathematical model of the physical process of the ultrasound signal propagation between the transmitter and the receiver of the measurement path and in more advanced than the state-of-the-art models that consider just the straight line path propagation ((Kaimal et al., 1968), (Kristensen and Fitzjarrald, 1984)). Franchini et al. (2012), worked on the effect of the wake generated by the UA supports on its wind speed measurements. They combined Von Karman's vortex street model with a mathematical model of the measuring process carried out by UAs that already developed (Franchini et al., 2007). The obtained results were correction functions of the measured wind velocity, which depended on the geometry of the sonic anemometer and aerodynamic conditions.

Ghaemi-Nasab et al. (2018) proposed a calibration process to correct the wind speed measurements from a single-axis UA in static and rotating conditions. Their experimental results showed that the shift in acoustic pulse trajectories due to the rotational motion of the anemometer did not affect the transducer shadow in a spinning UA. It can thus be inferred that the UA measurements in both static and spinning conditions are mainly influenced by the wake of the transducer and a static shadow calibration works for the spinning case as well.

In the present paper, wind tunnel tests were performed to obtain a calibration model for correcting the velocity measured by an ultrasonic wind sensor. The process is similar to the usual static directional calibration tests in which the signal path of the UA is set to various stationary orientations with respect to the flow direction. The flow distortion and wake of the upstream transducer induce a phase angle in the resultant azimuthal orientation of the UA signal path with respect to the oncoming flow. A polynomial function was obtained from the experimental results to calculate this phase angle. The proposed calibration function is based on projection of the wind vector onto the corrected UA signal path in which phase angle, found by the fitted polynomial, was added to the geometric azimuthal angle.

The experimental results performed in the present paper have shown that the proposed calibration model can be used for the same transducer in both static and spinning cases with high accuracy. Ghaemi-Nasab et al. (2017), in a recent paper have proposed another correction for yaw misalignment in the signals measured by a UA during a continuous spin. The process to obtain this model in the present article can easily be followed and employed in the calibration of such single-axis ultrasonic wind sensors.

2. Experimental setup

The experiments were performed in a calibration wind-tunnel of IDR/UPM Institute at the Polytechnic University of Madrid, Spain. The institute is a member of the MEASNET organization in which all the members perform mutual and periodical quality assessments for their measurements. An individual MEASNET member passes the evaluation if its result deviates less than 1% from the mean value calculated from the results of all members. Also, the calibration wind-tunnel in IDR/UPM Institute is evaluated each year in accordance with the ISO/IEC 17025 standard. A wind speed of 25 m/s can be reached in the test section of the IDR/UPM wind-tunnel with a uniformity of 0.2% and a turbulence intensity under 0.1%.

A single-axis ultrasonic anemometer, K-probe from Applied

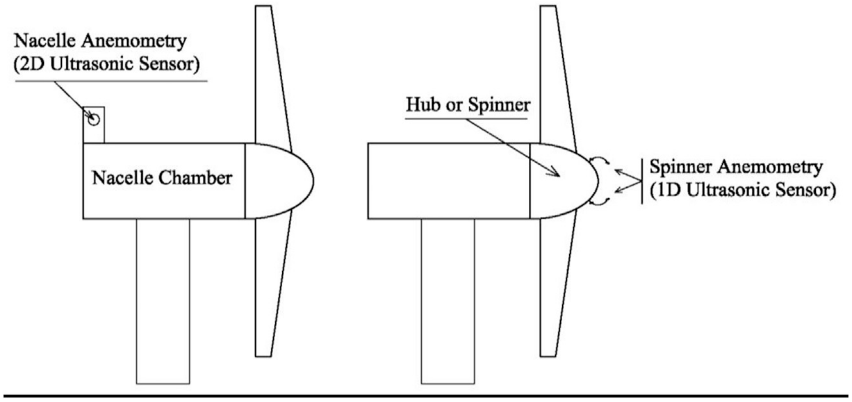

Fig. 1. Locations of the ultrasonic sensors on the nacelle and spinner.