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# A procedure for calibrating the spinning ultrasonic wind sensors

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## ABSTRACT

The accuracy of wind speed and direction measurements with spinning ultrasonic wind sensors is important than ever in today's wind industry in which, they are usually installed on the hub of the wind turbines to measure the wind speed and direction for optimized power. In this paper, extensive wind-tunnel tests have been performed to calibrate the wind speed and direction measured by a spinning single-axis ultrasonic anemometer for both static and spinning conditions. This has been carried out with static measures at various stationary angles of transducers signal path with wind direction, and with dynamic measures in which the anemometer is rotating with various rotational speeds. The velocity measured by ultrasonic anemometer in static tests is calibrated with pitot-tube data, and the interpolation of obtained calibration coefficients is used to correct the ultrasonic velocity measured in dynamic tests. It is observed that the calibrated ultrasonic wind speed measurements in dynamic tests are in a good agreement with the reference velocity. According to the results, the ultrasonic velocity measurements in both static and dynamic tests are affected by the transducers head distortions, and the shifting in acoustic pulse trajectory due to the rotational motion does not affect the anemometer measurements. The uncertainty of the calibration process for the spinning tests was found to be about 0.3%.

## 1. Introduction

Ultrasonic anemometer, UA, is an instrument to measure the wind speed vector based on the detection of the influence of the flow field on the transmission of ultrasonic signals between a pair of facing transducers which defines its measurement path length, $L$ [1]. Each transducer emits an ultrasound signal that travels towards the opposite transducer and therefore the flow velocity field has a different effect on the propagation of signals in each direction.

By measuring the differences between the forward and backward travelling times, the wind speed component along the measurement path can be determined as:

$$U_s = \frac{L}{2}\left(\frac{1}{t_+}-\frac{1}{t_-}\right) \tag{1}$$

This is the well-known transit-time algorithm, being used by most ultrasonic anemometers, regardless of the flow velocity field where $L$ is the length of the acoustic path, and $t_\pm$ is the time required by the pulse to cover the distance between transducers in sense of forward, the $+$ subscript, and backward, the $-$ subscript, directions [2]. This expression, however, is valid only if the velocity field is uniform.

These devices are capable of measuring multiple components of the velocity at a point. Furthermore, since there are no moving parts inside them, the ultrasonic anemometers are robust and also very suitable to use when exposed to severe weather conditions. They require very little maintenance compared to other techniques of anemometry, like hot-wire, cup and propeller anemometers [3].

Altogether, the characteristics of these anemometers have made them very attractive for an extensive application range including wind energy [4], flow metering [5,6,7,8,9], and urban boundary layer and atmospheric turbulent research [10,11].

Recently, many investigations have raised new applications with ultrasonic anemometers installed on mobile platforms such as UAVs [12,13], ships [14], atmospheric probes [15,16] or wind turbines [17,18]. These new applications have brought the issue of studying their behaviors during motion and rotation, into forefront of the recent surveys.

In wind turbine applications, a fixed 2D sonic anemometer along with cup anemometer and wind vane, are commonly used to measure the wind speed and direction, known as nacelle anemometry. The measurements by these anemometers in nacelle anemometry are affected by the wakes and flow distortion generated by the blades and nacelle chamber [19]. A previous research by Zahle et al. [20], has shown a remarkable influence of flow distortions on the nacelle anemometers.

A recent developed technique to nacelle anemometry is spinner

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**Nomenclature**

| | |
|---|---|
| $L$ | acoustic path length between two transducers [m] |
| $D$ | diameter of ultrasonic transducers [m] |
| $t_+$, $t_-$ | travelling time of the acoustic pulses in forward and backward directions [sec] |
| $f$ | sampling frequency [Hz] |
| $\omega$ | angular velocity [rad/s] |
| $U_\infty$ | free stream wind speed [m/s] |
| $U_s$ | velocity measured by ultrasonic anemometer [m/s] |
| $U_c$ | calibrated velocity measured by ultrasonic anemometer [m/s] |
| $U_r$ | reference velocity [m/s] |
| $\theta$ | azimuthal angle between transducers' signal path with flow direction [rad] |
| $\sigma$ | standard deviation |
| $C$, $a$ | transducer shadow effect parameters |
| $U_m$ | theoretical model [m/s] |

anemometry, which uses three single-axis ultrasonic anemometers to measure wind speed and direction over the wind turbine spinner. Therefore, the UAs in spinner anemometry are not affected by such flow distortions experienced by nacelle anemometry [21]. There are still some distortions in front of the wind turbine; of course they are less pronounced, but they still influence the measurement results and a proper calibration process to take this into account should be performed.

In a wind turbine, accurate information about the incoming wind speed and direction is important in yaw and pitch regulations for optimized wind turbine power. Furthermore, since the wind energy is directly proportional to the third power of the wind speed [22], an accurate wind speed measurement, as performed by a properly calibrated anemometer, would be extremely needed to achieve the maximum performance from energy saving viewpoint.

Although there are investigations in which the performance of the spinner ultrasonic anemometer is evaluated on wind turbine, [18,23,24], it has not found a systematic study on the behavior of these devices in rotational conditions. According to the Standard: IEC 61400-12-2 [25], the calibration process that is used for spinner anemometry consists of three major phases including the wind tunnel calibration tests for each ultrasonic sensor, the calibration of each spinner UA installations, and the calibration of each wind turbine type.

Currently the calibration process for each UA, the first phase, is a series of wind-tunnel tests in which the anemometer is calibrated for various stationary inflow angles of attack such that wind direction is fixed and not changed during the test [26]. However, in the present paper, the wind speed measurements with a 1D sonic sensor, similar to ones used in spinner anemometry, are calibrated under both static and rotational conditions.

In the static tests, the anemometer's signal path was set in various stationary orientations with respect to the wind direction, and several wind speed has been examined for each test.

In the dynamic tests, the anemometer was rotating with various angular velocities, exposed to different wind speeds. Thus, a complex system was designed for supplying power and downloading the measurements from the spinning UA. The calculated correction factors from the static tests were used to correct the measurement data in the spinning cases.

Indeed, the objective of this article is to propose a calibration process for wind speed indicated by the spinning single-axis UA. The calibration process consists of two series of experiments in an accredited wind-tunnel. Firstly, the UA was placed in various angles of attack toward the inflow direction, and its measurements were calibrated with pitot-tube. The calculated calibration coefficients were then used for correcting the wind speed measured by the same anemometer in rotational motion.

## 2. Experimental setup

Experiments were performed in the S4 low turbulence wind tunnel of IDR institute in the Polytechnic University of Madrid, Spain. Fig. 1 shows the schematic side view of the wind tunnel which is of open circuit with a closed test section. The wind speed is controlled electronically by a variable frequency drive, and flow velocities can be attained up to 25 m/s with the flow uniformity in the test section better than 0.2% and the turbulence intensity less than 0.1%. This wind tunnel fulfills the requirements of the MEASNET and the ISO/IEC17025 standard which is mainly used for the calibration of anemometers.

A specially designed single-axis ultrasonic anemometer, which was a modification of the 'K style-probe' ultrasonic anemometer from Applied Technologies Inc., has been used for the experiments. The sonic path length ($L$) of this anemometer is 0.15 m, and it can measure wind speed in a range of ± 30 m/s with a resolution of 0.01 m/s. The sonic path has been mounted on a system that allowed to rotating at constant and controlled angular speed. Note that the designed system has a high complexity due to the necessity of supplying power and recover the signals measured by the UA while it is rotating.

Other than the UA itself, the main components of the installation were a DC motor and a controller for its speed, a contactless angular position sensor and a slip ring rotating connector that supplied current to the sonic path and downloaded the output signals, while the UA was rotating inside the wind tunnel test chamber. The free stream velocity was measured with a pitot tube and a pressure cap of DRUCK (model LPM 9481). Fig. 2 shows a photo of the modified UA installed in the S4 wind tunnel, and a schematic view of the installations in the test section. During the experiments, the measurements from UA and angular position sensor have been synchronized at the same time base. It is claimed that the structure is designed and constructed in a way that it has a negligible vibration during the rotational tests which cannot affect the measurements.

The static test was similar to the typical calibration procedures of an anemometer, i.e. it was subjected to the wind tunnel flow, varying the wind speed from 0 to 23 m/s, with a fixed orientation of the acoustic

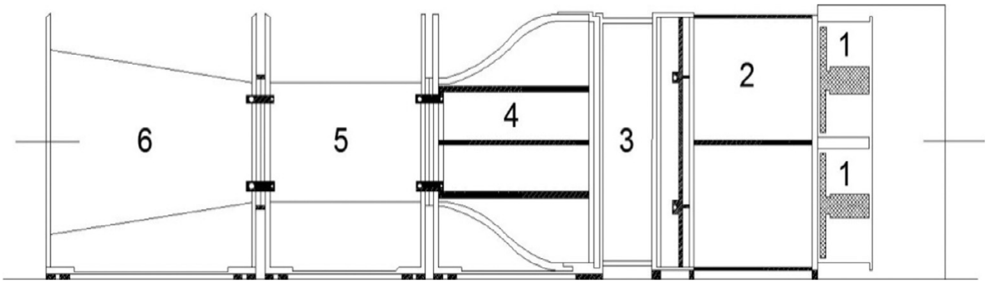

**Fig. 1.** Sketch of the S4 wind-tunnel: 1 = fans, 2 = plenum chamber, 3 = honeycomb and grids, 4 = contraction, 5 = test section, and 6 = diffuser.