A Low-Cost Ultrasonic Wind Speed and Direction Measurement System

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***Abstract*—The paper deals with a low-cost transducer that implements an improved technique for wind speed measurement in open air. The instrument is a 2-axis ultrasonic anemometer, capable of monitoring both wind speed and direction. Its main advantage is that using the ultrasonic technique it has no moving parts, allowing for the utilization in a variety of applications requiring low maintenance and fast response to rapid wind gusts. Wind speed measurement for power turbine control can be considered as a reference application of it. The proposed instrument presents a simple design and is constructed using commercially available components, to reduce development costs. In the paper the proposed architecture is presented, discussing the algorithm applied to process the transduced ultrasonic signals. Some results obtained during the first tests are also presented and discussed, suggesting for successive improvements.**

Keywords— wind energy; ultrasonic transducer; wind speed measurement; ultrasonic variables measurement.

I. Introduction

In recent years renewable sources of power are being increasingly exploited to address the challenges of climate change and fossil fuel depletion [1, 2]. Wind power is one of the few renewable energy sources capable of rapidly satisfying a reasonable proportion of future energy requirements. Wind turbines will be expected to significantly increase the power outputs with an improved efficiency and reliability.

The report on metrology related to the European FP6 project Upwind [3] in the Section 1.1 indicates that the development of wind energy is slow down by measurement problems. This is mainly because after a design enhancement of the wind generator, the better performance must be experimentally proved. Unfortunately the measurement uncertainties make impossible to confirm anticipated small performance improvements. One important problem in this field is related to the measurement of both wind speed and direction. These quantities are crucial for site assessment, turbine control and test of new turbine development.

As the turbine control is concerned, current practice in this sector is to use mast-mounted cup type anemometers for wind speed measurement, and a separate transducer for the wind direction. This anemometer consists of generally four hemispherical cups, each mounted on one end of four horizontal arms, which in turn are mounted at equal angles to each other on a vertical shaft [4, 5]. The air flow past the cups in any horizontal direction, turning them with an angular velocity proportional to the wind speed. Counting the turns over a fixed time period produces the average wind speed over this period.

Cup type anemometers have known functioning limitations, because they operate in one plane only and cannot measure two- or three-dimensional velocity and turbulence. Unfortunately, in operation they are exposed to both a wind velocity that fluctuates in magnitude and direction and to turbulences. These effects generate different types of errors, such as the overspeeding (faster response to an increase that to a decrease of wind magnitude), and lateral and vertical velocity fluctuations. The result is a positive bias of the measured mean wind speed [5-7]. Another disadvantage is the influence of rainfall, since the specific angular momentum produced by raindrops is different from that of the air [8].

The required enhancement for the wind speed anemometers can be satisfied with the help of new transducers, with a better response than cup type anemometers in challenging environmental conditions. We are conducting research activities oriented towards new approaches for this kind of measurement. This is because being able to measure wind speed and direction accurately from reliable equipment is more important than ever in competitive wind industry.

Main disadvantage of mechanical transducers is represented by moving parts; this is a physical limitation that prevents the device to reveal turbulence and gusts. Their transfer function can be assimilated to that of a first order system, operating as a mechanical integrator with a low-pass characteristic. Observed differences occur in measured wind speeds because of the time they take to physically start up or register a change in wind amplitude or direction. For example, if a storm blows through or the wind rapidly changes direction, the transducer reduces its speed, restarting again with the new wind direction, requiring up to several seconds to measure the new parameters.

An ultrasonic transducer, on the contrary, measures a change in wind direction or a high gust with a delay corresponding to the sampling period imposed by the signal processor. The transfer function can also be assimilated to a low-pass, but the cutting frequency for these devices is significantly greater, compared with mechanical anemometers.

When the ultrasonic output is averaged over time, the performance of mechanical and ultrasonic transducers is comparable.

Reliability is another advantage of ultrasonic devices, always for the absence of moving parts. When the mechanical transducer froze, it became inoperable or inaccurate; on the contrary the ultrasonic pulse is often sufficient to prevent the formation of ice, even if these devices are often heated to avoid this problem.

At present the main disadvantage of ultrasonic devices is the initial cost, generally greater than 2 k€.

In this paper we propose an anemometer that uses ultrasonic waves to measure wind speed, based on the time-of-flight of ultrasonic pulses between pairs of transducers. Specifically, we combined two transducer pairs to yield a measurement of velocity in two axes. In this kind of devices, the spatial resolution is given by the path length between the transducers, which is typically in the range from 10 cm to 40 cm. The transducer can take measurements with very fine temporal resolution, 80 Hz or better, which makes them well suited for turbulence measurements too. The absence of moving parts makes it suitable for long term use in exposed automated systems, where the reliability and accuracy of cup anemometers is adversely influenced by salty air or large amounts of dust.

The proposed instrument presents a simple design and is constructed using Commercial Off-the-Shelf (COTS) components, to reduce development costs. Ultrasonic transducers have been linked to analog signal conditioners to adapt signal levels and circuit impedances. A microcontroller device processes the signal and furnishes the result on a serial output port [9-12].

Our research project will extend in scope from laboratory activities through the real world application, in a manufacturing environment related to a wind turbine test site. The project is supported by the Italian Ministry for Education, University and Research, under the Grant PONa3_00308 (GELMinCAL).

In the paper the proposed architecture is presented, discussing the measurement procedure. Some experimental results obtained during the first lab tests are also included. Successive tests are planned to be executed in a wind chamber. Some idea for a successive improvement are also presented.

II. THE PROPOSED TRANSDUCER

A. Hardware architecture

The proposed transducer will be mounted on a horizontal axis wind turbine, to detect the horizontal components of wind speed and wind direction. In these turbines the yaw position control is used to orient the rotor, in such a way that it perpendicularly faces the wind stream [13]. The architecture of the overall system is shown in Fig.1.

The instrument embodies a microcontroller board (Fig. 2) , based on the PIC18F452, from Microchip, that generates the output signal, that is amplified (Fig. 3) and converted in an ultrasound wave [c,d,e,f] . The received wave is amplified by a two-stage amplifier, applied to a threshold voltage comparator and acquired by the PIC (Fig. 4). Transmission and reception multiplexers are also included; this is not a limitation, because the measurement along the two axes must be conducted at different times, to avoid interferences.

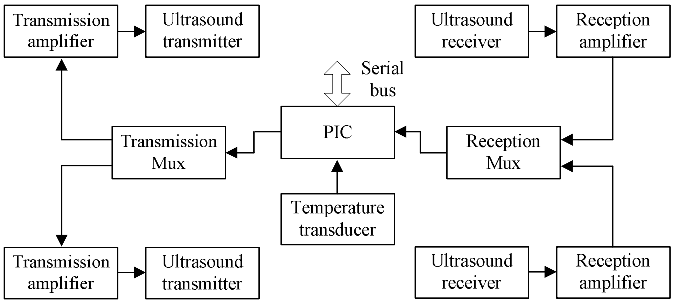

Figure 1. Block diagram for the proposed measurement system.

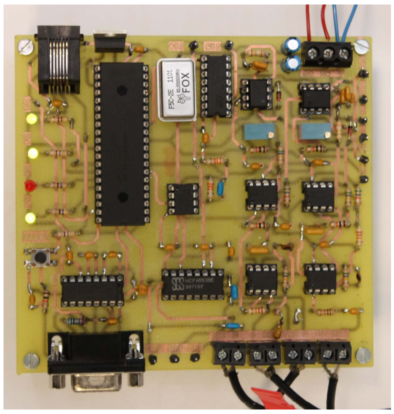

Figure 2. Developed board

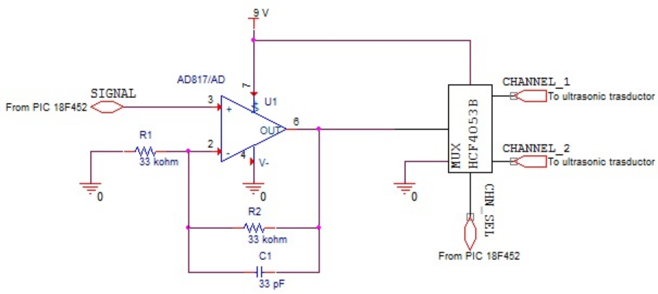

Figure 3. Transmission conditioning section.

The four ultrasonic transducers form two measuring directions, orthogonal to each other. The ultrasonic transmitters are the MULTICOMP SQ-40-T-10b, the receivers the SQ-40-R-10b. The transmitted signal is a square wave at 40 kHz, emitted with a beam angle of 30°. The operating temperature for the transducers ranges from -20 °C to 60 °C. A small and low-cost temperature transducer is also included, to measure the air temperature; this is the Microchip TC74, a digital 8-bit transducer operating from -40 °C to +125 °C. The system can supply both the instantaneous measurement of speed and direction, or the value averaged over a fixed period of time (normally 20 measures are averaged).

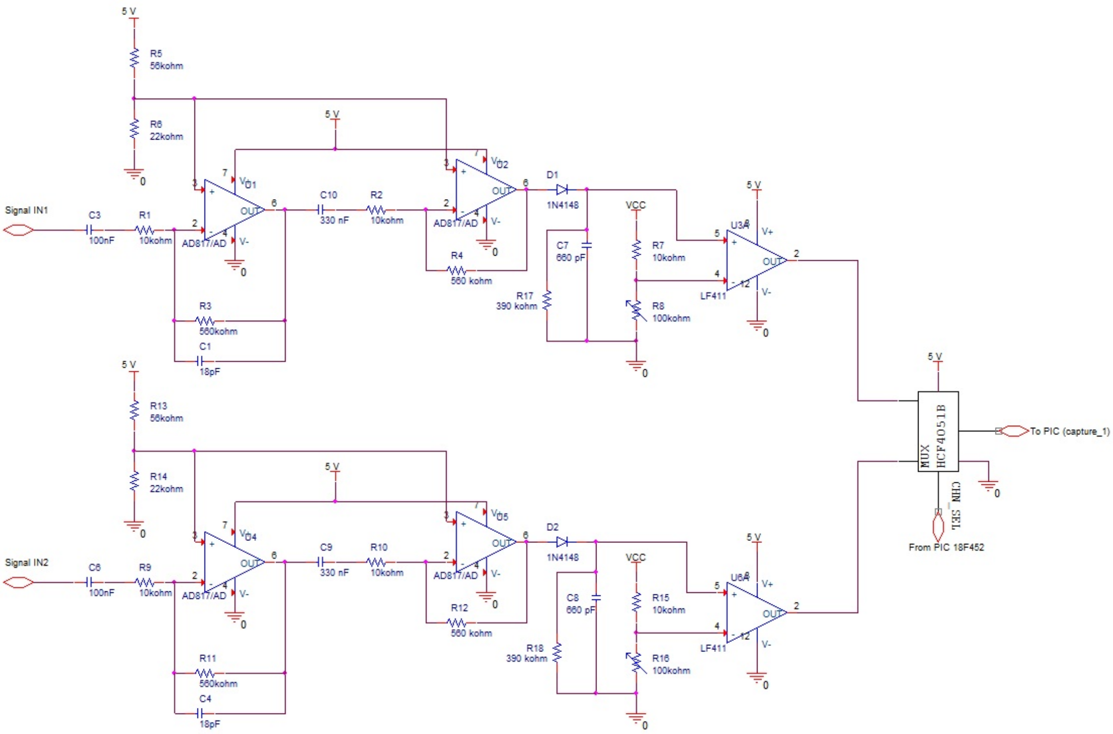

Figure 4. Reception conditioning section.

B. Software architecture

The microcontroller adopts a serial bus to communicate with the PC host. The communication protocol has been developed in order to avoid measurement and communication fault. The PC host can: i) Open the serial communication with the measurement system; ii) Put the measurement system in sleep or normal mode; iii) request a single measurement; iv) request a averaged measurement; v) request a free running measurement state; vi) detect measurement or communication fault and re-send measurement command in case of measurement fault. The technique adopted to manage the fault is a timeout – blocking – thread software programming mode. The Pc host user interface has been developed in order to open a different thread on the interrupt routine serial communication. In this way, the interrupt service routine has been instantiated in thread different form the main thread that manages the whole user interface. The thread performs a timeout implementation of serial communication: for every request the timeout has been reset from other thread that manages the communication. If during a single request the interrupt service routine does not receive a response from the microcontroller, this means that the communication system or measurement system have some problem, so a new request has been performed for a maximum of three re-transmissions. If no response has been received from the microcontroller, the user interface closes and opens the serial communication port and waits for a certain time in order that the measurement system has been reset by the microcontroller watchdog. When the microcontroller is again operative, the user interface begins to resend the measurement request for a maximum of three times. Although in this case the measurement system does not response, the user interface notifies to the user the problem (communication fault). If during an averaged over a fixed period of time the user interface does not receive any response it: i) first of all the user interface try to resend the request and waits for the response (measurement fault); if no response has been given by the microcontroller ii) the user interface perform a single request in order to check if the problem depends on the serial communication or the measurement system. In this phase, the user interface performs all the steps explained for a single measurement in order to check the communication system and in order to reset the Pc host serial communication port and the microcontroller by the watchdog.

It is important underline that the serial communication protocol that interface the measurement system and the Pc host (reported in Fig. 5) has been developed for the following reasons: i) it uses a CRC field in order to check if the communication packet is correct; ii) the request and the response lengths are fixed, so the high level software can check if there are some fault during the communication; iii) the communication protocol can be adopted in sensors network because the sender and receiver fields are presents (for example using a RS 485 or a IEEE 488 physical layer); iv) every request is mapped using a univocal id, so the receiver can perform the requested action; v) the response packet data is 2x8-bit length in order to reduce the delay time introduced by the communication packet length.

The measurement technique adopted (showed in next section) require some processing task that produced floating point results. In order to send to the Pc host these results, a 2x32-bit registers are necessary to transmit. Since hardware comparators have been adopted to perform the measure, only the value of each hardware comparator has been send to the Pc host and not all the processing result.

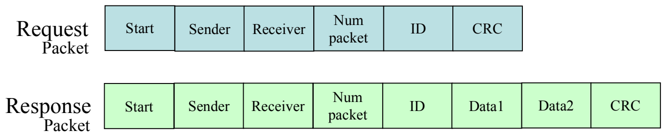

Figure 5. Communication protocol

C. The Measurement Method: Time-of-Flight Approach

The speed of ultrasound propagation in calm-air is superposed by the velocity components of the air-flow in wind direction. When a wind velocity component operates in the same direction, the propagation speed increases. On the contrary, when a wind velocity component is opposite to the propagation direction, the propagation speed decreases. The resulting different propagation times (time-of-flight) over the measurement path reveals the specific wind velocity and direction.

Numerous techniques have been developed for time-of-flight measurement which can be summarized as measurement in frequency domain or in time domain. The first technique often presents the problem of an insufficient frequency resolution, to increase which high sampling rate and memory size are required. But, in this way, the signal processing is heavier.

The second technique requires the use of a high-performance counter, but the result can be affected by signal noise and unwanted multiple echoes. This is the solution implemented in the prototype, also because it can be easily carried out in hardware, using a microcontroller internal timer. A better solution is under study.

As previously stated, the wind speed is measured using the two couples of ultrasonic transducers, that supply the time-of-flights needed for the ultrasonic wave to travel from the transmitters to the receivers tof1 and tof2 . By combining two times, measured along paths which are at right angles to each other, we obtain the instantaneous wind velocity vector in the form of rectangular components (Fig.6):

$$v_x = \frac{D}{t_{ofx}} - v_u \qquad (1)$$

$$v_y = \frac{D}{t_{ofy}} - v_u \qquad (2)$$

where D is the measurement path length.

The wind speed module is obtained from the relation:

$$|v| = \sqrt{v_x^2 + v_y^2} \qquad (3)$$

and the wind direction is:

$$\varphi = arctg\frac{v_y}{v_x} \qquad (4)$$

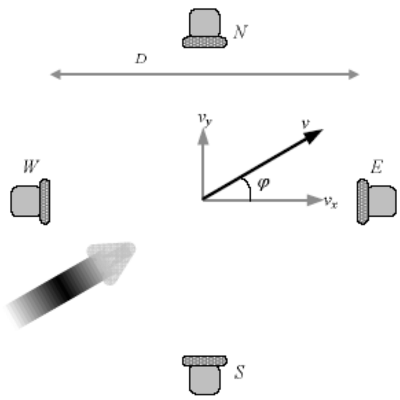

Figure 6. Wind speed components

The speed of ultrasound v_u in the steady air depends on air temperature T_a as follows:

$$v_u = 331.4 + 0.62\ T_a \qquad (5)$$

where 331.4 m/s is the ultrasound speed in air, at freezing temperatures. The system measures T_a using the temperature sensor (Fig.1), in order to correctly identify the actual ultrasound speed v_u .

The transducer can calculate the mean value of the wind speed and direction, averaging 20 successive measurements for each couple of transducers, obtaining a measurement frequency of 4 Hz.

The user interface shown in Fig. 7 has been implemented on a PC, to remotely operate the transducer and display the measurement data.

III. EXPERIMENTAL TESTS

As part of the development phase, the implemented prototype has been tested in the laboratory. The first tests were conducted to verify the signal amplitude and to calibrate the amplifier gains. Fig. 8 shows the signal generated by the microcontroller at the transmitter input, after the conditioner; it has a frequency of 40 kHz, an amplitude of 2.5 V and an offset of 1.25 V. The signal at the receiver output is depicted in Fig. 9

The transducer interdistance was made modifiable, to investigate about the influence of this parameter on the measurement accuracy; the better performance was obtained with a distance of approximately 40 cm.

Tests were conducted to verify the correctness of the wind direction measurements. An air flow was simulated by means of a fan, rotating its position around the transducer. The wind direction, read on the user interface, indicated the right operation of the device. Successively we conducted and planned a series of laboratory tests to document the transducer specifications and quantify its characteristics. (3)

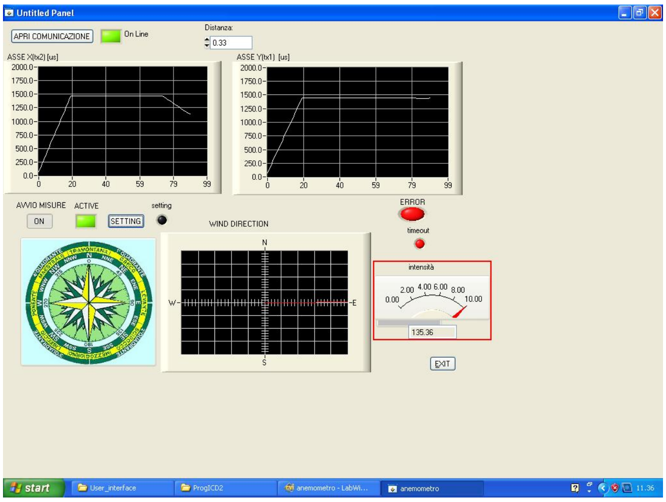

Figure 7. User interface.

As the wind speed is concerned, the planned tests will relate the anemometer signal output to a reference wind speed. These tests are planned to be carried out on a wind chamber, as required by international standards that define procedures for testing these anemometers, e.g. the ISO 16622 [14].

The base calibration will be performed in a zero-wind condition, which involves the measurement of the acoustic path length and transient times; tests will be conducted at different temperature and pressure environments. Other tests will be performed in a steady state wind tunnel, where controlled conditions isolate the transducer performance from disturbances such as vibrations and off angle winds.

IV. Conclusions and Discussions

In this paper the design of an ultrasonic anemometer has been presented. It provides both speed and direction of the wind, whilst compensating for errors that occur due to ambient temperature. This ultrasonic anemometer provides the two instantaneous components, or the averaged values.

The implemented prototype showed two main advantages: its reduced complexity and cost. The first tests showed a relatively high noise sensitivity. Two were the possible reasons: a reflection of the waves produced by the mechanical support adopted in the lab tests or the transducer itself.

We tested the system putting sound-absorbent material in the area under the ultrasonic transducers (Fig. 10), obtaining similar results. Successively we conducted other investigations concluding that better performance, in terms of noise, can be obtained using transmitters with a reduced beam angle, in order to concentrate the ultrasound power in a smaller area. The obtained greater power density can help the receiver for a better signal detection. To implement these changes a different and more accurate mechanical assembly is required, for two reasons. The first is related to the reduced transmission area, that requires a more precise positioning of the receiver.

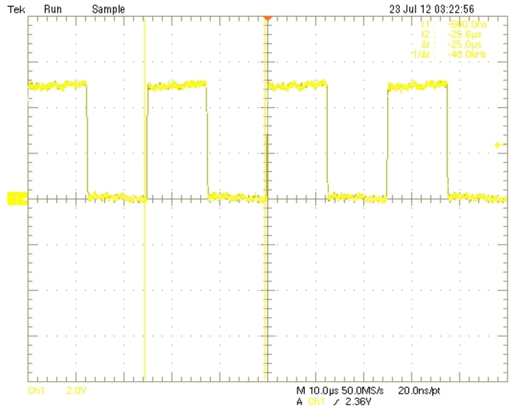

Figure 8. Signal at the transmitter input.

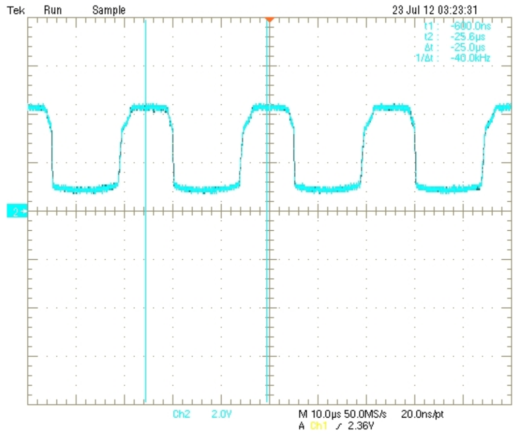

Figure 9. Signal at the receiver output.

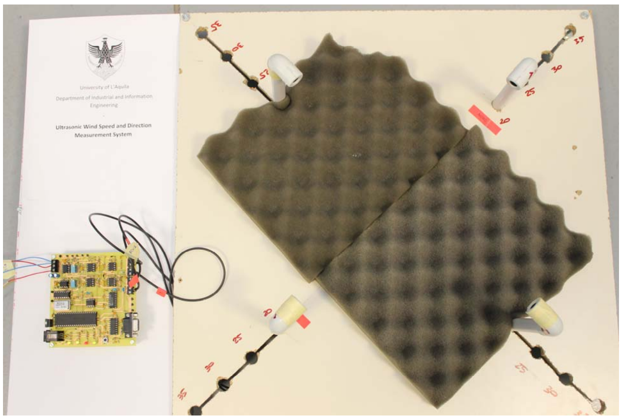

Figure 10. The first laboratory tests.

The second one is that the transducer mechanical supports must be designed in order to avoid the formation of turbulence, distortion, scattering and echoes of the ultrasound signal. A reduced size for the transducers appears to be a positive feature, but the overall shape must be studied accurately. On the same time, a better numerical algorithm for processing the ultrasonic based on the log-power spectrum, is under study, to improve the performance also in presence of signal noise and secondary echoes.

Another improvement refers to effects on the ultrasound speed of other factors such as humidity and air pressure, that influence the local atmospheric density. Two transducers for these quantities can be included, correcting also for these error components.

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