Anemometer 3D Based on Ultrasound

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Abstract. The environmental variables influence in the development of plants and animals. One of these variables is the wind, which can be responsible to change the growing of plants and spread diseases. Therefore, the measure of wind speed is necessary to agriculture. Usually, such measuring is done by use of anemometers working with wind cocks which work in only two dimensions, measuring the wind speed and direction by a mechanical system. One disadvantage of this approach is the existence of mobile parts which does not render accurate speed measures, due to air friction and equipment inertia. In this work, an ultrasonic anemometer which measures the direction and speed of the air in three dimensions is presented. Such anemometer use only four piezoelectric sensors arranged in two orthogonal axes non-competitors. So that, joining together the points of each sensor it was get a structure in the form of a regular tetrahedron. The wind speed in three directions can be measured inferring the necessary time (transit time) so that a pulse of ultrasound, sent for one of the sensors, reaches the others three. Moreover, the tetrahedron-shaped structure allows to measure in four different coordinate systems. This adds redundancy to the system so that a better precision in the measures can be achieved. This measurement is performed by a microcontroller and is done to make the system immune to variations of temperature and air humidity. The microcontroller is also responsible for storage of data and later sending them to a microcomputer.

Keywords: 3D Anemometer, ultrasound, transit time, transducers.

Introduction

The wind influences the development of plants, may change its growth, reproduction and distribution in the field. For example, high wind speed brakes sheets tissues, branches, stem and may jeopardize a whole crop (MOTA, 1981). The wind can also spread plant diseases as asian rust, carrying spores and pollutants. Besides, one of the necessary cares in the moment of application of pesticides is to observe the wind speed, because such variable can be responsible to the pollution of neighbor crops and rivers, damaging the environment. Thereby, through the monitoring of wind direction and speed, it is possible to produce food healthier and cheaper, using pesticides intelligently so that the pollution of the environment can be reduced. This can be monitored through an ultrasonic anemometer. Such anemometer can measure wind speed with the aid of the transit time (ALMEIDA, 2004) which allows the measure of wind speed trough the measure of time which the ultrasonic pulse takes to be received after being transmitted. Such time varies depending on wind speed and sound. In this context, this work has a goal of projecting a 3D anemometer based on a technique which uses only four ultrasound piezoelectric sensors in order to measure wind speed. Such anemometer provides information about horizontal and vertical conditions of wind. This can be used to calculate the index of favorability to the appearance of plant diseases.

Methods and Materials

The majority part of the available anemometers in industry today measures wind speed in only two directions, parallel to Earth's plane. However, ultrasound transducer can also be arranged to measure wind speed in three dimensions. Such arrangement has a goal of measuring the upward and downward air currents, verifying if these measures favor the development of diseases. In a previously published work (QUARANTA et al., 1985), an arrangement of six transducers arranged in six competitors orthogonal axes in order to measure wind speed in three dimensions is used. In this work, a different arrangement of transducers in order to measure the wind speed in 3D is proposed. The adopted configuration, shown on figure 1, uses four transducers working sometimes as emitter and as receiver. Such transducers are arranged in two orthogonal axes, non-competitors, so that, joining together the points of each transducer was get a structure in the form of a regular tetrahedron. The tetrahedron edges form between them an angle of 60º, while the γ angle, formed between each edge of the tetrahedron and the opposite plane is 54,7356103º. Each edge of tetrahedron corresponds to a path where ultrasonic wave goes through. Besides, with this arrangement to measure wind speed in up to seven different coordinates systems is possible. One of those systems is obtained considering transducer T_1 as transmitter. Thereby, it is had that the $S_n(T_1/T_2,T_1/T_3,T_1/T_4)$ (non-orthogonal system with its origin in transducer T_1, formed by the paths of T_1 to T_2, of T_1 to T_3 and of T_1 to T_4) can be seen on figure 2.

Using the method of transit time, the orthogonal projection, υ_{12}^{m}, of the wind speed vector, $\mathbf{v}_V$, in the axes formed by transducers T_1 and T_2 is given by (PINTO, 2006),

$$\upsilon_{12}^{m} = \frac{d}{2}\left(\frac{1}{t_{12}} - \frac{1}{t_{21}}\right), \tag{1}$$

Where d is the distance between the transducers, t_{12} is the time to ultrasonic wave goes through the path from T_1 to T_2 and t_{21} is the time to ultrasonic wave goes through the path from T_2 to T_1. So, the accuracy in the measure of wind speed depends on the measure of t_{12} and t_{21}. However, in majority of cases, there is an error in measuring these times. It is because, at the beginning, the signal arrives on the receptor very attenuated. So, by providing the exact time which the signal arrives electronically, there must be a difference between the arrival of the signal, t_{12}, and the time where the signal is detected, $\hat{t}_{12}$. Such difference of time is titled of t_E. Considering t_E, the time of arrival of the ultrasonic wave (t_{12}) is given by

$$t_{12} = \hat{t}_{12} - t_E \tag{2}$$

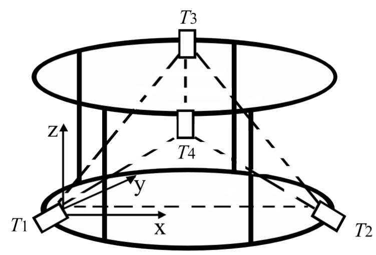

Figure 1: 3D Anemometer with transducers arranged in a tetrahedron shape.

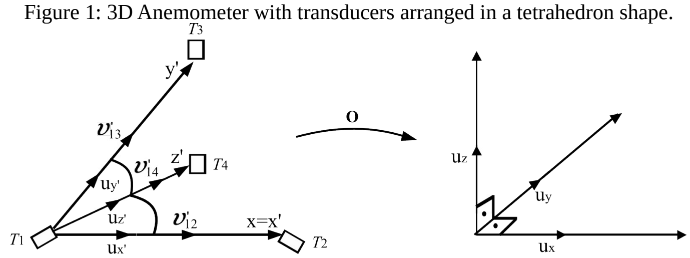

Figure 2: Coordinates system of the 3D Anemometer with transducers arranged in a tetrahedron shape.

In practice, the electronic delay can be calculated by a relation between the temperatures and wind speed (HALLYDAY, 2002). Considering zero wind speed, it is had the time to ultrasonic wave goes through the path between T_1 and T_2 is affected only by the sound speed (υ_S). So, t_E can be given by,

$$t_E = \hat{t}_{12} - d / \upsilon_S . \tag{3}$$

Due to this, to estimate the time of electronic delay, it is necessary to measure the environment temperature, besides to submit the ultrasonic anemometer into a zero wind speed.

It is known that, in the system $S_n(T_1/T_2, T_1/T_3, T_1/T_4)$ of figure 2, $\mathbf{v}_V$ is given by $\mathbf{v}_V = \begin{bmatrix} \upsilon'_{12} & \upsilon'_{13} & \upsilon'_{14} \end{bmatrix}^T$, where υ'_{12}, υ'_{13} and υ'_{14} are the parallel projections of the vector $\mathbf{v}_V$ on the x', y' and z' axes. On the other hand υ'_{12}, υ'_{13} and υ'_{14} can be obtained by the orthogonal projections measured, in other words,

$$\begin{bmatrix} \upsilon'_{12} \\ \upsilon'_{13} \end{bmatrix} = \mathrm{A}^{-1} \begin{bmatrix} \upsilon^m_{12} \\ \upsilon^m_{13} \end{bmatrix}, \tag{4}$$

Where υ^m_{12} and υ^m_{13} are the parallel projections of the vector $\mathbf{v}_V$ on x' and y' axes, obtained by (1), and

$$\mathbf{A} = \begin{bmatrix} 1 & \cos\theta \\ \cos\theta & 1 \end{bmatrix}. \tag{5}$$

So, by equation (4), we can calculate υ'_{14} .

It is also necessary to orthogonalize the coordinates of the axes of the triangle (υ'_{12} , υ'_{13} and υ'_{14}) because, it is known the transducers are arranged on not orthogonal axes. Moreover, to orthogonalize the system $S_n(T_1/T_2,T_1/T_3,T_1/T_4)$, it is necessary a matrix **O** of change from basis ($u_{x'}, u_{y'}, u_{z'}$) to basis (u_x, u_y, u_z) as seen on figure 2, in other words,

$$\mathbf{O} = \begin{bmatrix} 1 & \cos\langle u_{x'}, u_{y'} \rangle & \cos\langle u_{z'}, u_{x'} \rangle \\ 0 & \sin\langle u_{x'}, u_{y'} \rangle & \alpha \\ 0 & 0 & \sqrt{1 - \cos^2\langle u_{x'}, u_{z'} \rangle - \alpha^2} \end{bmatrix}, \tag{6}$$

Where the basis vectors ($u_{x'}, u_{y'}, u_{z'}$) and (u_x, u_y, u_z) are unitary and,

$$\alpha = \frac{-\cos\langle u_{x'}, u_{y'} \rangle \cos\langle u_{x'}, u_{z'} \rangle + \cos\langle u_{y'}, u_{z'} \rangle}{\sin\langle u_{x'}, u_{y'} \rangle}. \tag{7}$$

So, to obtain a system of orthogonal coordinates, matrix **O** is multiplied by the non-orthogonal axis of anemometer.

After orthogonalization of $S_n(T_1/T_2,T_1/T_3,T_1/T_4)$, an orthogonal system $S_O(T_1/T_2,T_1/T_3,T_1/T_4)$ is obtained. However, this system is not aligned as the orientation of the Cartesian axes *x*, *y* and *z*. Thereby, to obtain correct measurements of wind speed, it is necessary to rotate the axes of this system. The rotation process is obtained by multiplication of the coordinates of a rotation matrix, represented by a sequence of Euler angles (KUIPER, 1999).

The system $S_O(T_1/T_2,T_1/T_3,T_1/T_4)$ must be rotated over the *x* axis (competitor with the axis formed by transducers T_1 and T_2) until the axis formed by the transducers T_1 and T_3 coincide with *y* axis. To do this, it is necessary rotation angles $\xi = 2\pi - \gamma$ (angle to be rotated clockwise over *x* axis), $\varsigma = 0$ (angle to be rotated clockwise over *y* axis) and $\psi = 0$ (angle to be rotated clockwise over *z* axis). So, the rotation matrix of the system is given by,

$$\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix}. \tag{8}$$

Experimental Results

<u>Results with the Simulated Anemometer</u>

By the proposed method, equation (1) and the matrix **O**, defined by equation (6), are used in order to measure 3D speed. In these equations, the angles and the length of the edges of the tetrahedron structure are used. Thereby, the exactness of the measure depends on the accuracy in the construction of this structure. Nevertheless, in practice, non-accuracy problems might happen in this process. In this section, it is wanted to analyze how such deficiencies influence in the final measured value. In order to do this, it was constructed a model of a tetrahedron in MATLAB software with the standard values of 11cm and 60^o to edges and angles of the tetrahedron, respectively. In this model, it is possible to insert error on some angles and edges. Evidently, the change in an angle or in a dimension changes all the tetrahedron structure, and, consequently, it causes some error of different magnitudes in each of the coordinates system.

In each test, the error inserted in the edges and in the angles of the tetrahedron followed Gaussian distribution of zero average. The standard deviation of such distributions was made equal to 0,55cm (5% of the distance between the transducers) and to 3º to edges and angles, respectively. Moreover, in the simulation, it was considered winds with speeds from 0,5 to 20m/s.

In the analysis of results, the Cartesians coordinates obtained in tests were converted to polar coordinates, in other words, the speed vector was given by the modulus and the orientation by azimuth and zenith angles. It was performed 200 tests with different values of error. In the tests, the average error inserted on tetrahedron edges was 2,49%, while the maximum error was 5%. In the angles between the edges, the average error inserted was 1,5º, with a maximum error of 3º. After the simulation, the error inserted generated an average error in speed modulus of only 1,85%, while the maximum error reached 5,6%. About zenith and azimuth angles of wind speed, the average error was only 0,34º, while the maximum error reached 3,45º. By these simulation results, errors in the measurements change proportionally to errors in construction of anemometer were verified.

Results with the Real Anemometer

The prototype of the proposed anemometer can be observed on figure 3. In such prototype, the distance between each transducer is 11cm. Moreover, the transducers which were chosen for the construction of the anemometer oscillate in a fundamental frequency of 40 kHz.

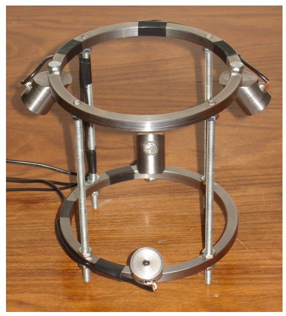

Figure 3: 3D Anemometer.

The tests in the laboratory were performed to validate the proposed instrumentation circuit by the method of time difference. The measurement was only performed over one of the axes of the anemometer, in other words, it was only considered a pair of transducers T_1 and T_2. The anemometer was installed in a closed environment where the wind speed was considered to be zero. Thereby, the anemometer was only exposed to the influence of sound speed. With this, t_E was estimated using equation (3).

In order to excite the transducer with one pulse, it is necessary a relatively high voltage (JOHANSSON et al, 2006), (MAIA, 2001), (NASCIMENTO, 2003). So, the circuit of figure 4 was used to obtain a pulse of 30V approximately on T_1.

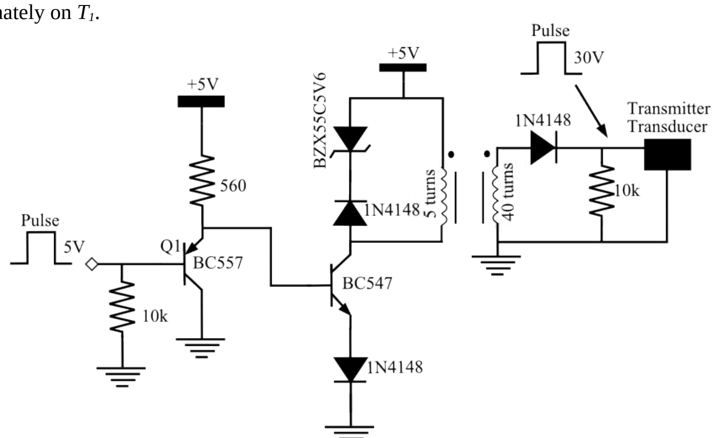

Figure 4: Schematic diagram of the circuit to excite transducer T_1.

It was used one zener diode to demagnetize the coil of transformer T1 (as shown on figure 4), in other words, the coil is magnetized with 5V and demagnetized with 5,6V which results to 52,83% of the maximum duty cycle allowed in order not to saturate the coil. In circuit of figure 4, it was used an EE 25/10/6 of IP6 material without gap, into the transformer's nucleus. The primary coil has five turns while the secondary has forty turns.

After the excitation, ultrasonic signal goes through the path until it reaches the receptor transducer. One way to instrument the reception of ultrasonic signal can be observed on figure 5. The circuit of this figure was implemented to transducer T_2. So, after excitation of T_1, it sends ultrasonic signal to T_2.

The pulse, applied on transistor Q1 (figure 4), is generated by the microcontroller PIC18F4550 with a duration of 1μs and a magnitude of 5V (in order not to saturate the coil, it is necessary this time of pulse). In order to measure the transit time of ultrasonic wave, it is necessary firstly to store the value of the PIC's timer (16 bit with a resolution of 83,3ns) at the same time which a pulse of 5V is emitted by microcontroller. This can be done with PIC's output compare pin. Besides, the microcontroller also needs to be responsible to monitor the arrival of the pulse emitted. This can be done with PIC's capture pin with the help of a instrumentation circuit of figure 5. It is stored again another value of timer when this happen. With these two values, the transit time of ultrasonic wave can be calculated. Unfortunately, PIC18F4550 has only three pins which are possible to work as output compare and input compare. However, to perform an implementation of a 3D system it is necessary at least four pins with these capabilities.

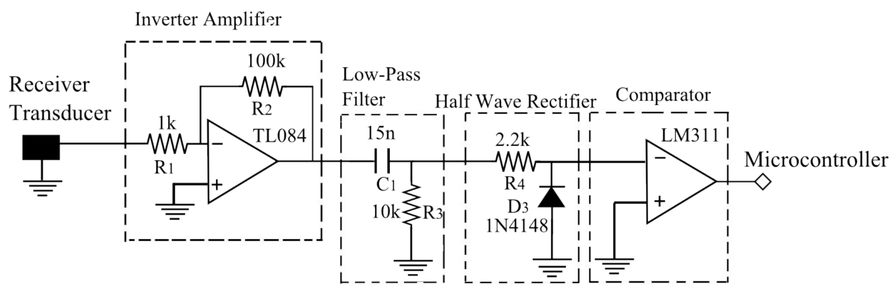

Figure 5: Schematic diagram of the circuit to instrument the reception of the ultrasonic wave.

In figure 6, a pulse which excites Q1 and ultrasonic wave received with the gain stage, can be seen. In this figure, it is also noticed the transit time (t_{12}), in other words, the time which the ultrasonic wave takes to be received.

It was acquired 500 measures of transit time of ultrasonic wave from T_1 to T_2. Calculating the average and the standard deviation of such values, it was obtained, respectively: 403,64μs and $9{,}0067\times10^{-8}$. Thereby, to consider that the noise present in the measuring follow a normal distribution, it is possible to infer the probability of the measured times being found in the interval from 403,39μs to 403,94μs is of 99,73%. With this interval and the determination of t_E, the uncertainty of the anemometer can be estimated.

As seen, to estimate t_E, it is necessary to measure υ_S that is determined by the measure of the environment temperature. In order to get a higher precision in the measures, it was used two thermometers. In one of these thermometers, the temperature measured was of 24°C, while the other was 25°C. So, it was considered an average of the temperatures measured (24,5°C). It is known that wind speed in these conditions was zero. With this, υ_S was calculated and the result obtained was 345,8m/s and t_E of $8{,}557\times10^{-5}$s. It is also possible to determine some uncertainty in the measure of wind speed considering transit time, defined by normal distribution, and t_E calculated. It is noticed, therefore, in the desired application, the uncertainty shown by the anemometer is not significant.

It is known to measure the wind speed by method of time's difference, it is necessary to set transducers as transmitters and as receivers. Thereby, for the proposed anemometer, four transmitter's circuits (as seen on figure 4) and four receivers' circuits (as seen on figure 5) to put into operation the reception of the ultrasonic wave have been used. Each transducer must be connected to one transmitter circuit and one receiver circuit. So, transducer will be able to work as transmitter as receiver.

Tests with four transducers to measure wind speed in all coordinates systems are necessary, so that a whole implementation of the system of this proposed anemometer can be achieved. Also, calibration of the proposed anemometer must take place in a suitable wind tunnel and with the aid of a commercial anemometer.

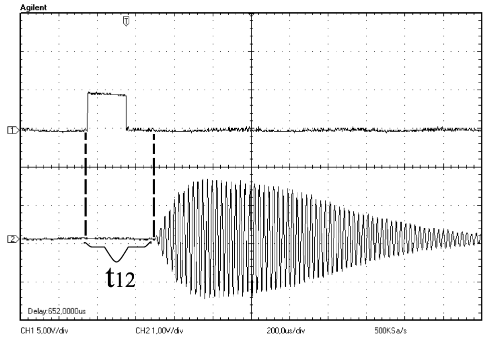

Figure 6: Pulse (channel 1 of oscilloscope) and the ultrasonic signal received (channel 2 of oscilloscope)

Conclusion

The wind is an important factor to agriculture, because it can affect since germination until maturation of plants. For instance, the wind speed can define the right moment to perform a chemical control, bringing benefits to farmers and consumers. Beyond such benefits, we can cite the intelligent usage of fungicides, production of healthier and cheaper food, optimization of production of food and reduction of pollution of the environment.

In this work, a 3D anemometer based on ultrasound was proposed. Such anemometer, with a three-dimensional arrangement proposed, is useful to measure wind speed with its vertical and horizontal direction. With these information, important decisions concerning controlling certain epidemics can be taken.

It was performed simulation to the proposed anemometer. In these simulations, it was verified that errors calculated varied proportionally with errors inserted in construction of anemometer. To the speed vector modulus, the average error calculated was less than the average error of distance. On this anemometer, it is possible to measure wind speed in up to four different coordinates systems. The error calculus of speed can be decreased by redundancy of these systems.

As seen, by practical experiments, it was possible to estimated t_E with the help of transit time method. It was had a high accuracy in the proposed project considering miscellaneous measures of transit time because the error found was up to 0,3m/s in the measured speeds.

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