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3D Ultrasonic Anemometer with tetrahedral arrangement of sensors

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3D Ultrasonic Anemometer with tetrahedral arrangement of sensors

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Abstract. The paper describes the structure, operating principle and software of the ultrasonic velocity and air flow meter with the arrangement of sensors at the vertices of the tetrahedron. This design, with a minimum of sensors, makes it possible to measure the velocity components in three directions at once. The influence of dimensions of the construction on the metrological characteristics of the device is evaluated.

1. Introduction

The fast monitoring of airflow rates taking into account the direction of their movement in three-dimensional space is relevant in the study of climate control systems, in meteorological observation and environmental monitoring systems, climate change research, in the development of forced and exhaust ventilation systems and in a number of other areas of science and technology [1-4].

To solve such problems, ultrasonic anemometers are becoming increasingly widespread [5], because, in comparison with popular anemometers and vane anemometers, they have such undeniable advantages as:

- the simplicity of the design for the implementation of 3D-measurements;
- increased reliability due to the lack of moving mechanical parts;
- Low measurement error and high sensitivity.

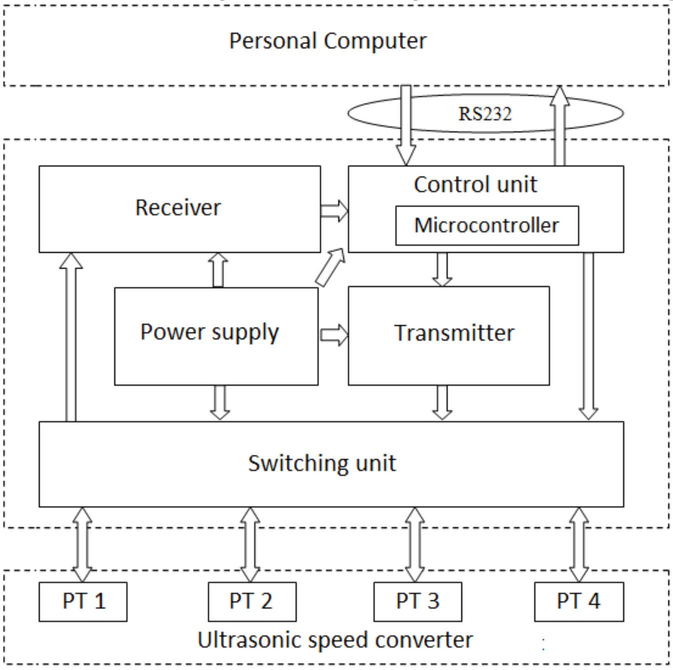
At the same time, the influence on the speed of sound of such factors as temperature, gas composition, the presence of impurities in the form of aerosols and dust, as well as the possibility of the appearance of precipitation in the form of rain and snow on the way of ultrasound propagation leads to the need to take appropriate measures for minimization of their influence. Next, we consider one of the possible options for the practical implementation of an ultrasonic anemometer, which is distinguished by its simple design and good metrological characteristics.

2. Structure, composition and operating principle of the device

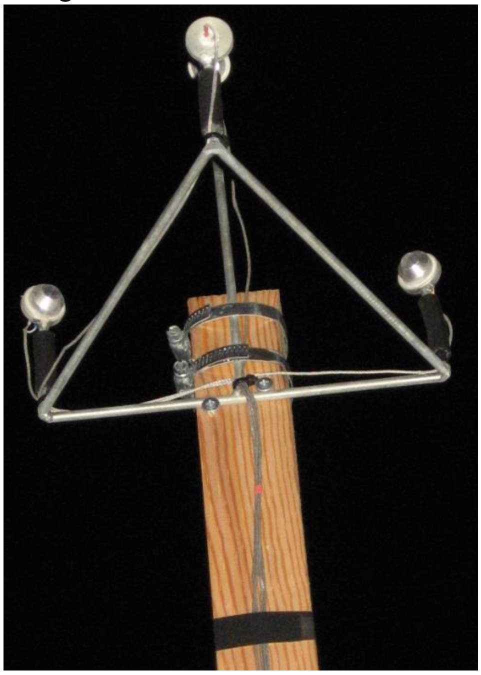
The proposed acoustic anemometer differs from the distributed six- and eight-point circuits [6-9] by the tetrahedral arrangement of the sensors, first described in the French patent [10]. From the prototype, it is differ by the use of other circuitry solutions. But the main difference is that it uses the same ultrasonic piezoelectric sensors operating as the emitter and receiver. Since such sensors operate both in the generation mode and in the reception of ultrasonic waves, we will call them piezoelectric transducers (PT).

When measuring the speed of air streams, the operating frequency range of such PES must lie within of 15-100 kHz, since the sound waves at these frequencies have minimal attenuation in the air [11]. To use the anemometer in outdoor conditions, the PT must have a hermetic design and a wide range of operating temperatures. In addition, because of the use of the tetrahedron layout, they must have a wide directional angle. These requirements are completely satisfied by the T / R40-18U sensors developed by Audiowell for parking sensors [12]. They have an operating frequency 40 kHz, and the temperature range from -40 to + 85 ° C.

The functional diagram of the device and the appearance of the converter of a speed to an electrical signal are shown in Figure 1, and in Figure 2 the scheme for placing the PT



a)



b)

Figure 1. Functional diagram of the device (a) and the appearance of the measuring transducer of the air speed converter to the electrical signal (b).

Excitation of ultrasonic oscillations is carried out by a PT placed at the vertices of a tetrahedron, each facet of which is an equilateral triangle. The axis of symmetry of all the PTs are directed to the center of the tetrahedron. The PTs operate in pairs alternately in the receiver / emitter mode and provide the emission or reception of ultrasonic acoustic pulses. Formation of pulses and measurement of the time of their passage between the PES occurs in the electronic unit, that includes receiver, transmitter, control unit, switch unit and power supply.

Controlling the operation of the electronic unit, collecting and processing information coming from it is carried out by a personal computer or other means of computing technique.

The device operates according to the following algorithm (Figure 3): after power is applied to the device circuit, the microcontroller starts. It forms the basis

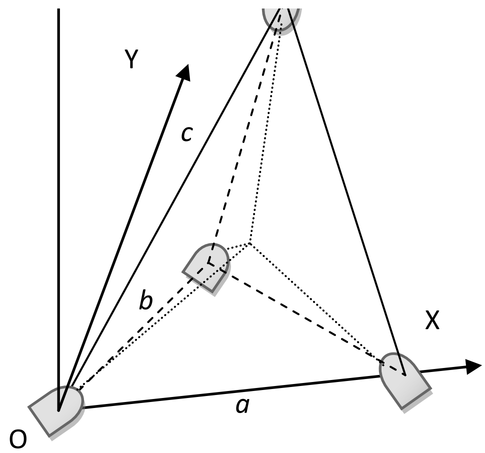


Figure 2. Diagram of the spatial location of the PTs in the measuring transducer.

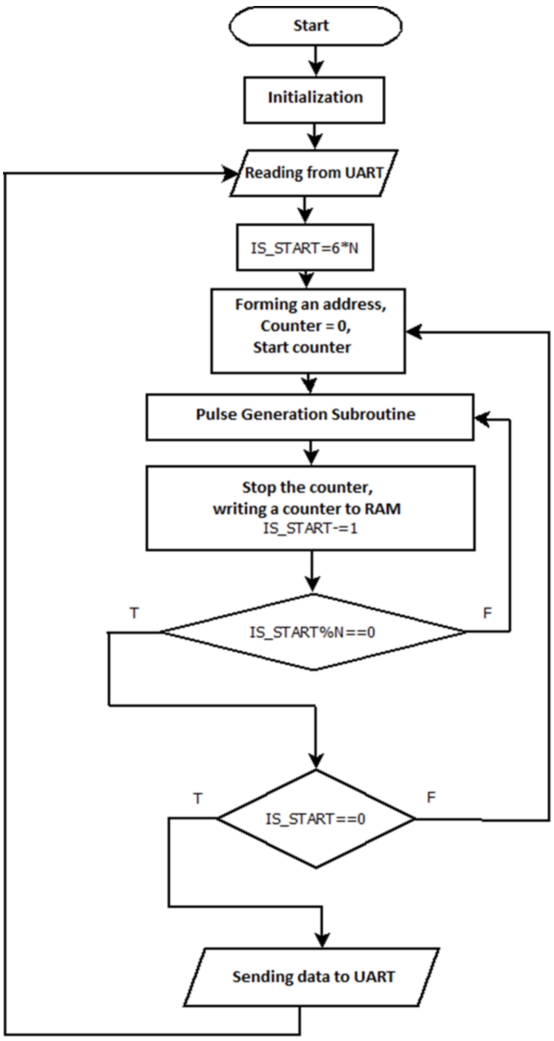


Figure 3. The algorithm of the control unit.

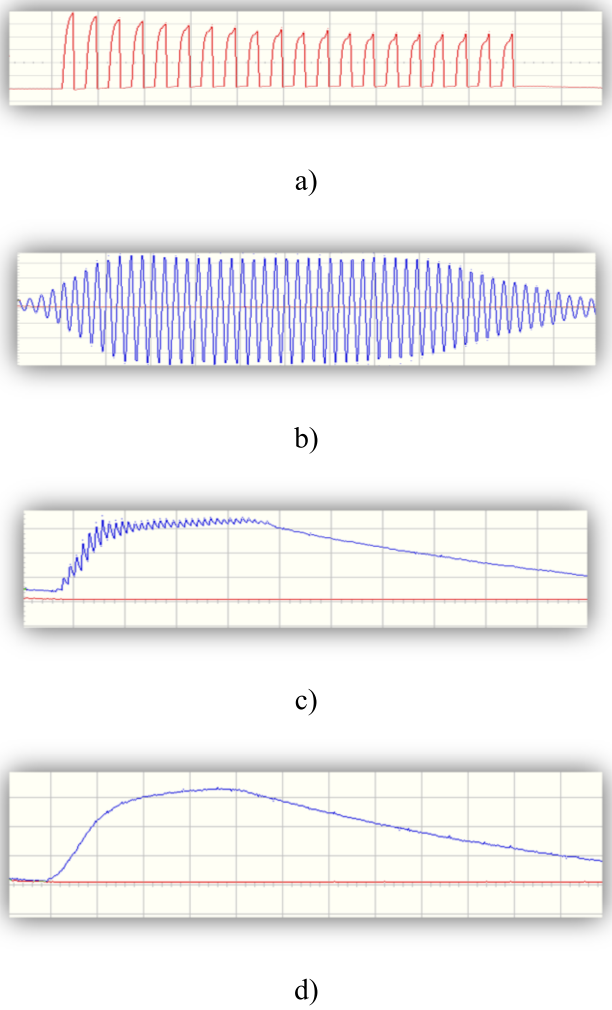


Figure 4. Timing diagrams of anemometer signals.

of the control unit. During the controller start, its peripherals are initialized: analog comparator, timer / counter, I / O ports, UART. Having received from the PC via UART the control start byte, the controller begins to generate bursts of pulses with a frequency of 40kHz (Figure 4a), which are input to the transmitter, amplified, and through the switching unit they are fed to a PT emitter. The number of pulses in the stack is N, and the total number of packets in the measuring cycle is 6 to determine the propagation time of the acoustic wave between the three pairs of PTs in the forward and backward directions. The pulse duration in the stack is set by the controller. At the beginning of each packet, the controller starts a timer-counter and generates a new address to be sent to the switch for changing the PTs pair and / or the direction of transmission of the acoustic wave. The order of the alternation of pairs and the direction of ultrasound transmission is shown in Figure 5.

Converted by one of the PTs into an ultrasonic wave, this wave through the air reaches another PEP working with it in a pair. This PT performs the inverse transformation of ultrasonic pulses into an electrical signal whose amplitude is about 20 mV and the shape of which is shown in Figure 4b.

This signal, passing through the switching unit, goes to the input of the receiver, where it amplifies, detected by the amplitude detector (Figure 4c), filtered (Figure 4d) and enters to the analog comparator input. At a time when the signal level at the input of the comparator exceeds the threshold voltage, a hardware interrupt is triggered, the processor of which stops the counter. The accumulated value in it, proportional to the time of passage of an acoustic wave between a pair of PETs, is stored in the controller's memory in a special buffer, and the counter itself is reset. By storing the counter values for all sensor pairs, the controller generates a transmission for transferring data to the computer via the serial port.

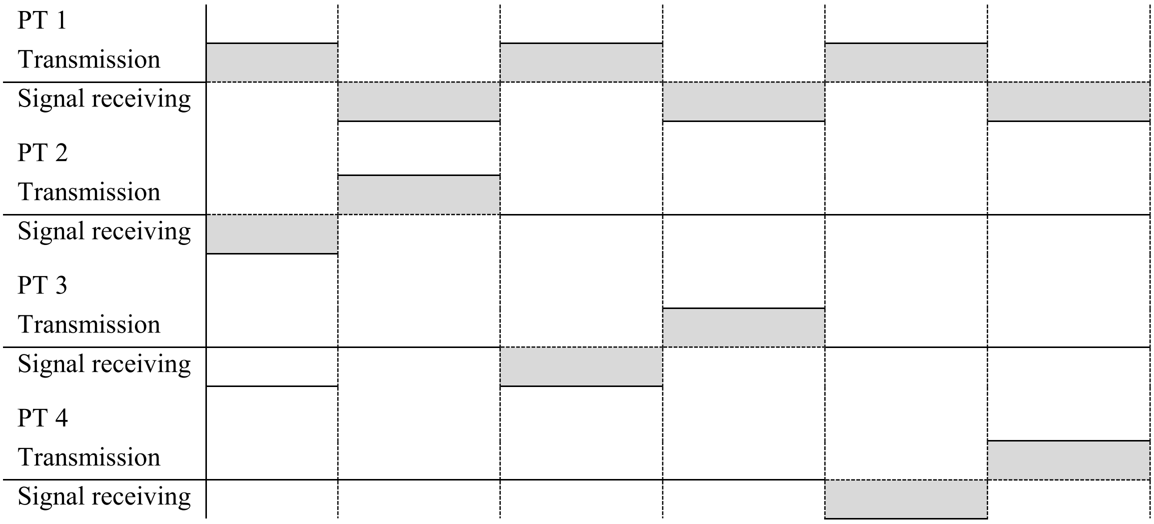


Figure 5. Time Diagram of the PEP Operation.

3. Software-algorithmic support

Further processing of data arriving from the anemometer takes place using a PC. The airflow velocity ***V*** between each of the three pairs of PET is calculated in it by the formula:

$$V = \frac{L(t_2 - t_1)}{2t_1 t_2},$$

where L is the distance between the PT pair;

t_1 – time of ultrasonic wave propagation along the stream;

t_2 – the propagation time of the ultrasonic wave against the flow.

As can be seen from the formula, the value of the velocity depends only on the distance between the PES pairs and the propagation times of the ultrasonic wave between the PTs in the forward and backward directions and does not depend on the propagation velocity of the ultrasonic waves.

Having obtained the values of the velocities ***Va***, ***Vb*** and ***Vc*** between the three sensor pairs located on the vertexes of the edges of the tetrahedron ***a***, ***b*** and ***c*** (Figure 2), the program first averages the obtained results for ***K*** measurements to reduce random errors and then translates the obtained results from the oblique coordinate system in the Cartesian one. As can be seen from Figure 2, if the x axis is directed along the edge ***a***, then we get that ***Vx = Va***. When using an anemometer in climatic measurements to determine the wind speed, this axis can be immediately oriented to the north. The velocities for the other two coordinates, ***Y*** and ***Z***, can be found from expressions:

$$V_y = \frac{2V_b - V_a}{\sqrt{3}}$$

$$V_z = V_c\sqrt{\frac{3}{2}} - \frac{(V_a + V_b)}{\sqrt{6}}$$

Or, in the matrix form, ***V = AV '***, where ***V'*** is the vector column consisting of the components ***Va***, ***Vb*** and ***Vc***, and the transformation matrix **A** is

$$A = \begin{matrix} 1 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{6}} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{1}{\sqrt{6}} \\ 0 & 0 & \sqrt{\frac{3}{2}} \end{matrix}$$

The screen form of the main window of a demo program written in C ++, which controls the work of the anemometer and performs the described calculations, is shown in Figure 6. To averaging the readings, 20 samples were used. The number of pulses in the package was set to 50. Along with the components of the velocity vector, the program displays the azimuth of the vector and its ballistic angle, finds the velocity vector and its value according to the Beaufort scale. On the basis of this program, a software module was developed in the Java language that performed similar calculations and transmitted data to the main program of the information and measurement system for operational control of energy resources and climate monitoring of the Altai State Technical University [13-15], which transmits data to the web server.

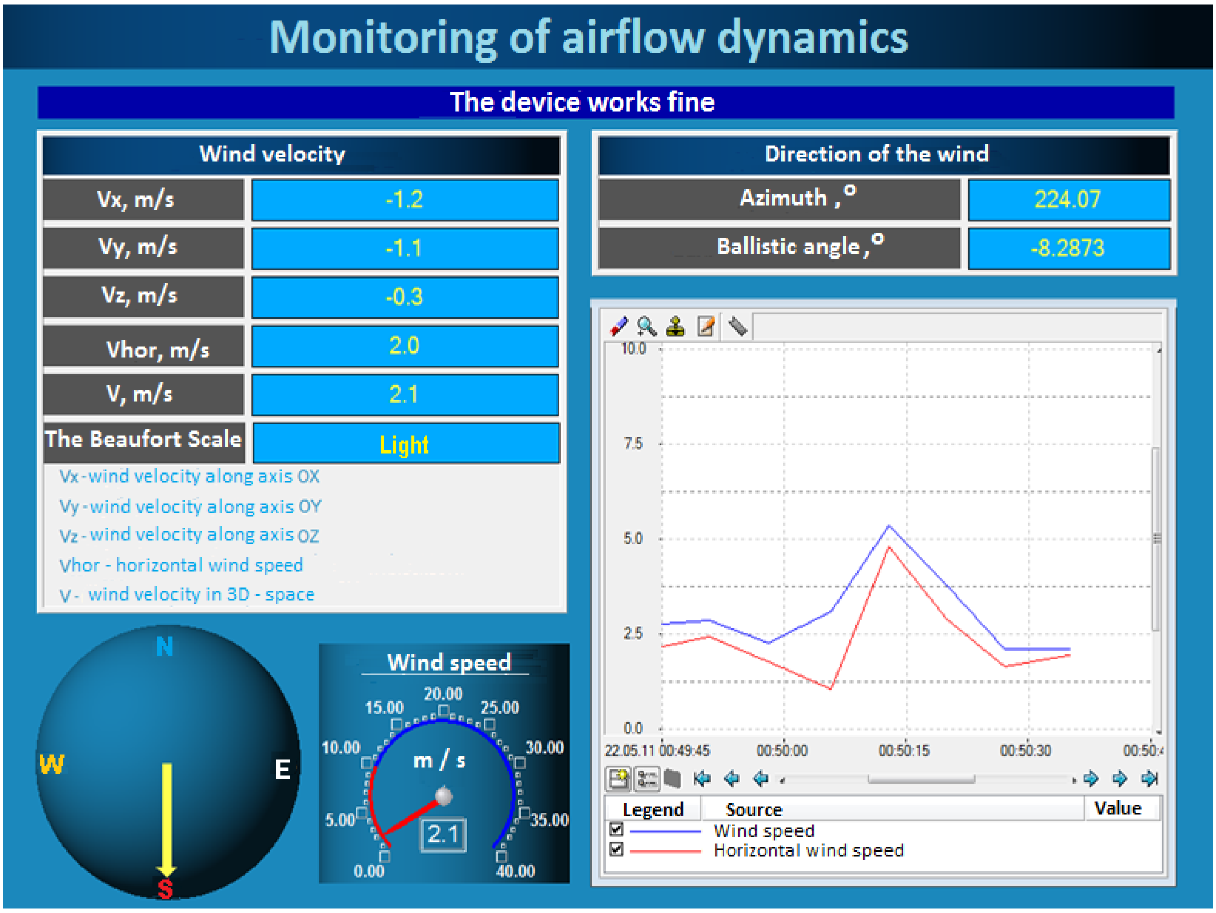


Figure 6. The main window of the wind speed direction monitoring program.

4. Evaluation of metrological characteristics of ultrasonic anemometer

To determine the absolute error in measuring the projections of the velocity vector on the coordinate axis, the following formula was used:

$$\Delta v = \sqrt{\left(\frac{t_2 - t_1}{2t_1 t_2}\Delta x\right)^2 + \left(\frac{x}{2t_1^2}\Delta t\backslash_1\right)^2 + \left(\frac{x}{2t_2^2}\Delta t_2\right)^2}.$$

Figure 7 shows the dependence of the relative error on the wind speed for different sensor bases.

For experimental verification of the results obtained and simultaneously for the calibration of the anemometer, it was fixed in the immediate vicinity of the AMK-312 meteorological station [16], established for conducting meteorological observations on the territory of the Institute of Water and Environmental Problems of the Russian Academy of Sciences. When specifying the values of software scaling coefficients in three coordinates, they were averaged over 50 results of observations of a weather station in three sections of the measuring range for all three coordinates: for velocities of the order of 0.5-2 m/s, 5-7 m/s and 15-20 m/s. Measurements were made in the warm and cold season. The data of these measurements were subsequently used to estimate the measurement errors. In the course of the experiment, it was found that the differences in the indications of the developed and verification device were within the errors of the verification device itself, in which the relative error in measuring the velocity did not exceed ± (0.2 + 0.02 V) m / s, where V is the wind speed and the absolute error of measuring of the direction of the wind not exceed ± 4 °

5. Conclusion

The results of practical operation of the developed anemometer in the above-mentioned information and measuring system of operational control of energy resources and climate monitoring for six years showed its high reliability and stability of indications. However, this anemometer can be used not only in this system, but also at any weather stations.

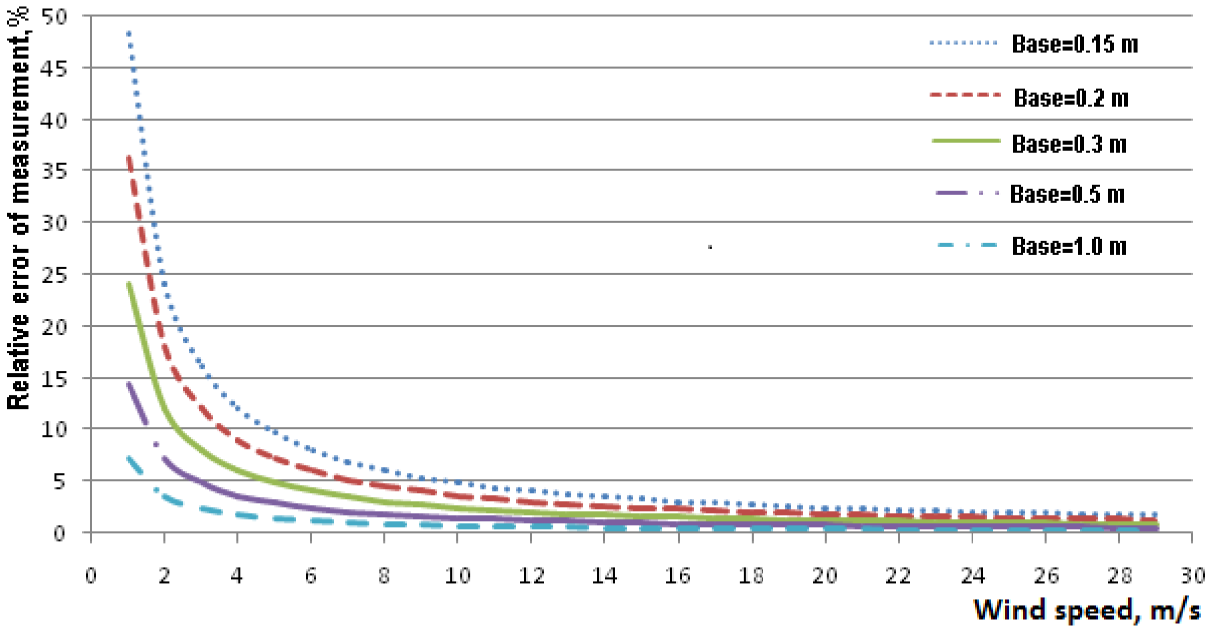


Figure 7. Graph of dependence of the relative error on the wind speed for different sensor bases.

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