**The Main Errors of the Ultrasonic Sensor in Measuring Water Flow**

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**Abstract.** This article analyzes the use of ultrasonic sensors in measuring water flow and the main errors that may occur in this process. In the conducted scientific research, a time-pulse ultrasonic sensor was tested. The absolute, relative and repeatability errors of the sensor during water flow measurement were studied. The absolute error represents the largest difference between the value recorded by the sensor and the real value, affecting the overall accuracy of the measurement system. This error can vary depending on environmental factors, the design and operating principle of the sensor. During the experiment, the performance of this sensor was evaluated in a special test environment and the absolute and relative errors were measured. Based on the results obtained, graphs of the dependence of water flow on errors were drawn and it was determined what factors affect the increase in errors.

**Key words:** ultrasonic sensor, water flow measurement, absolute error, relative error, time pulse sensor, measurement accuracy, measured value, real value, uncertainty, experiment

**INTRODUCTION**

Water flow is one of the important quantities in hydromelioration systems, and in many cases its direct measurement is one of the complex issues [1, 2]. In times of water scarcity, special attention should be paid to the development and creation of new information measurement sensors with high sensitivity and accuracy for measuring water flow in open channels and pipelines [3]. Currently, the use of ultrasonic flowmeters is widespread in both industry and medicine. There are many other methods for measuring water flow, such as turbines, Venturi tubes, and others, but using an ultrasonic sensor has many advantages. Such a system has no moving parts, no additional pressure, and allows for two-way measurement [4].

Therefore, in this article, we used an ultrasonic sensor to measure water flow in an open channel and focused on its errors. Quality characteristic of measurement - accuracy of measurement describes the closeness of the measured quantity obtained as a result of measurement to the real value. The closer the measurement result is to the real value, the more accurate the measurements are and vice versa [12].

Sensor error, like error in other measuring instruments, is classified according to different criteria.

When analyzing the sources of errors that have a negative impact on the signal conversion process it is necessary to divide them into the main and additional sources of errors depending on the situation of determining the level of accuracy of the sensor. It is known that the main sources of errors are determined under normal conditions of use of primary measuring-converting sensors [12].

Normal conditions for an ultrasonic sensor for measuring water flow in an open channel are the following: normal ambient temperature, absence of external noise and reflected signals, absence of electromagnetic and mechanical interference [12, 15, 16].

**RESEARCH METHODS**

According to the method of expression, the main error is divided into absolute, relative and quoted errors.

A distinctive feature of determining the absolute error of sensors is that the real value of a physical quantity (input or output) is taken as the value of this quantity according to the nominal static change function (calibration characteristic).

Absolute error does not give a complete picture of the quality of measurements. In this case, relative error is used to quantitatively characterize the quality of measurements.

There are several categories of uncertainty, which differ depending on the method of determination. The most common standard uncertainty is denoted by U(x). This is the uncertainty of the result expressed as a standard deviation. U2(x) can also be expressed in terms of the standard uncertainty squared in the form of a variance.

Type A standard uncertainty is found by statistical processing of a series of observation results (1) [5, 6, 11, 13]:

(1)

here xi is the i-th observation result, and - is the average value of n observations.

For the determination of the standard uncertainty of type B in measurements using an analog measuring instrument, accuracy class γ and a normalization value called XN are considered (2).

For analog (as well as digital) devices, it is often equal to the measurement limit Xk (the maximum value of the device scale): XN=Xk. Considering a single distribution density model, the standard uncertainty of an analog measuring instrument with a measurement limit Xk is found as follows [7, 8, 13].

(2)

The accuracy class of digital measuring instruments is usually standardized by the binomial formula (3): c/d. In this case, the standard uncertainty of the readings of digital instruments is determined as follows [11, 13]:

(3)

Depending on the level of uncertainty (or the characteristics of its manifestation), errors are systematic and random.

Systematic error is an error that remains constant in repeated measurements. Systematic error is, for example, an error that arises from the nonlinearity of the approximation of the real calibration characteristic by a linear relationship.

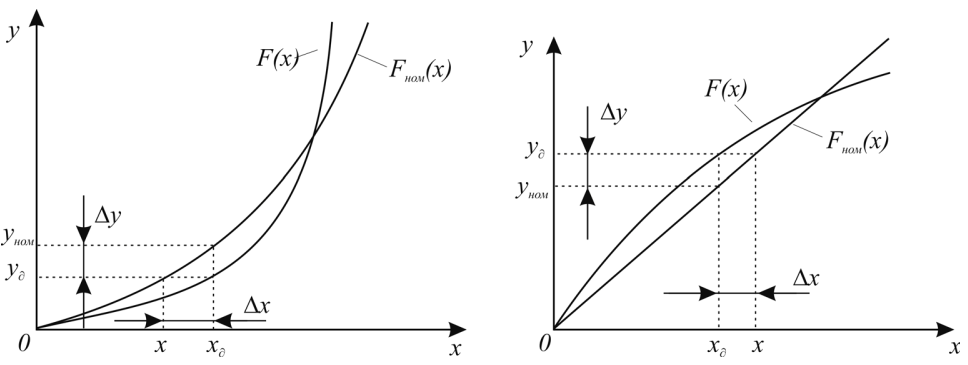
Random error is a component of the general measurement (transducer) error, the value of which changes randomly during repeated changes of an unchanged quantity.

Therefore, depending on the level of uncertainty, the error of a sensor (transducer) reduced to an input or output can be expressed as follows (4), (5) [11, 13].

(4)

(5)

Here , , , - are systematic and random errors, respectively.



**FIGURE 1**. Detection of errors occurring in the input and output of the sensor [13]

However, it should be noted that the problem of generalization of errors is more complicated than it seems at first glance and requires study in each case [7, 10, 14].

Random errors are described using the methods of mathematical statistics and probability theory [15]. To determine the random error, it is necessary to make several measurements for each (or selected) point in the range, and then construct a histogram of the error distribution based on the experimental data.

If the distribution of errors is normal, the random error is estimated to have a standard deviation of δ (6) [13].

(6)

Here n is the number of measurements; *хі* — *і* – is the measurement result; — n is the mathematical expectation (average value) for n measurements.

Based on the above information, we will analyze the errors that occur in the improved time pulse ultrasound sensor in the thesis work.

During the measurement of water flow in an open channel, various errors may appear in the sensor. Errors that occur during the operation of the water flow measurement sensor are divided into 3 main types:

1. Systematic errors;

2. Random errors;

3. Group errors.

**Systematic errors** are errors that are constantly repeated during the operation of the sensor, and they can be eliminated through calibration and correction methods.

We can include errors such as linearity, temperature effect, source voltage change in this error.

A time-pulsed ultrasonic sensor detects the velocity of a liquid flow by measuring the time it takes the ultrasonic pulses to travel in and against the direction of the liquid. The difference between the measured times is proportional to the average speed of the fluid movement in the open channel. If the internal calibration coefficient of the sensor is incorrect, the following linear error (7) will occur [12, 13]:

Elin=k⋅Δt−Δt (7)

here: k is the calibration coefficient, Δt – is the difference between the travel times of ultrasound pulses along and against the direction of liquid movement, s.

If k>1, the value of the measurement results increases, and if k<1, the opposite is observed.

In ultrasonic sensors, the air temperature affects the signal velocity. The velocity of ultrasonic waves in air, V, is determined by the following formula (8):

V=331,4+0,6T (8)

here: T - is the air temperature, °C.

From this formula, we can see that as the temperature increases, the ultrasonic velocity increases and the water flow value changes accordingly.

If the source voltage changes, the operation of the sensor's electronic circuits may change. Errors due to source voltage are usually estimated by the following formula (9) [13]:

(9)

here: ΔU – source voltage change, V, Un – nominal voltage, V.

A decrease in voltage reduces the sensitivity and accuracy of the ultrasonic sensor in operation.

## Random errors are unpredictable errors that occur for various reasons during the operation of the sensor. For example, the process by which the results differ when several measurements are taken with a sensor is the effect of random error.

## They include:

## **change in the direction of wave propagation;**

## **various fluctuations in the water level (turbulence);**

## **change of the signal due to external influences (electromagnetic and mechanical influences).**

Random errors (10) are usually analyzed by statistical methods and accuracy is evaluated [13]:

(10)

here: Xi – individual measurements, – average value of measurements, n – number of measurements.

**Group errors** are errors caused by a specialist or equipment. These errors include incorrect installation of the sensor on the object, errors in calibration, etc.

**RESULTS AND DISCUSSION**

In order to confirm the theoretically obtained data, we conduct the following experiment figure 2 and figure 3. The following measuring instruments were used for the experiment.

1. Multimeter Fluke 80-III (USA):

- measuring range - 0÷40 mOhm;

- permissible value is 4 mOm, ± 0.001 kOm

- measurement error ± 0,2 %;

2. Arduino Mega 2560 R3 platform;

3. LCD screen;

4. Time pulse-based ultrasound sensor - measurement error: ±1%;

5. Hydrostatic pressure sensor.

Initially, these devices were systematically assembled as an experimental stand. All devices were connected to each other via the Arduino Mega 2560 R3 platform. A time-pulse-based ultrasonic sensor measures the time when pulses generated by a piezoelectric crystal are transmitted from one piezoelectric element to another [9, 10, 15, 16]. In this case, the time of movement of pulses along the water flow and against the flow is measured. The pressure in the water flow is measured by a hydrostatic pressure sensor installed at the bottom of the open channel. After determining the necessary parameters, the water flow rate, water level and water flow are determined by the following formulas.

Expression (11) for calculating water flow in an open channel:

(11)

Here A is the area (12) of the water-filled part of the canal, m2.

(12)

V – water flow speed (13) in the channel, m/s.

(13)

h – the height (14) of the water level in the channel, m.

(14)

L is the distance between the ultrasonic sensors, m; b is the length of the lower part (base) of the channel, m;   
α=450 - the angle of inclination of the channel (degrees); t1 – the propagation time of the ultrasonic wave along the water flow, s; t2 – the propagation time of the ultrasonic wave against the water flow, s.

The mathematical expressions and parameters listed above are entered into the Arduino program, which is based on C++, and uploaded to the platform.

|  |  |
| --- | --- |
| **FIGURE 2.** Assembled experimental device for measuring water consumption in a canal | **FIGURE 3.** An experimental stand where experimental research was conducted |

In the scientific research work, we analyze the absolute, relative and repeatability errors in the measurement of water flow using a time-impulse ultrasound sensor.

Absolute error: ΔQ=∣Qm−Qr∣ (15)

here: Qm – measured value of water flow (experimental), m3/s; Qr – real measured value of water flow, m3/s.

Relative error: (16)

**Maximum error:** ΔQmax=max(ΔQ1,ΔQ2, …, ΔQn).

We include the experimental and calculation results in table 1 below:

**TABLE 1.** Experiment and calculation results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| No | Qr (m³/s) | Qeksp (m³/s) | ΔQᵢ (m³/s) | δᵢ (%) |
| 1 | 0.4 | 0.404 | 0.004 | 1 |
| 2 | 0.8 | 0.8076 | 0.0076 | 0.95 |
| 3 | 1.2 | 1.2109 | 0.0109 | 0.9083 |
| 4 | 1.6 | 1.614 | 0.014 | 0.875 |
| 5 | 2 | 2.017 | 0.017 | 0.85 |
| 6 | 2.4 | 2.42 | 0.02 | 0.8333 |
| 7 | 2.8 | 2.823 | 0.023 | 0.8214 |
| 8 | 3.2 | 3.2264 | 0.0264 | 0.825 |
| 9 | 3.6 | 3.63 | 0.03 | 0.8333 |
| 10 | 4 | 4.034 | 0.034 | 0.85 |

**Repetition error**:

(17)

here: average water flow,

(18)

Based on the results of the measurements, we determine the absolute error using (15):

ΔQ=∣Qm−Qr∣, Qm=Qeksp, Qr=Qeksp.

ΔQ1=∣Qm−Qr∣=∣0,404−0,4∣=0,004 m³/s;

All calculations continue in this way.

Based on the results of the measurements, we determine the relative error using (16):

All calculations continue in this way.

Based on the results of the measurements, we determine the repeatability error using (17):

; m³/s;

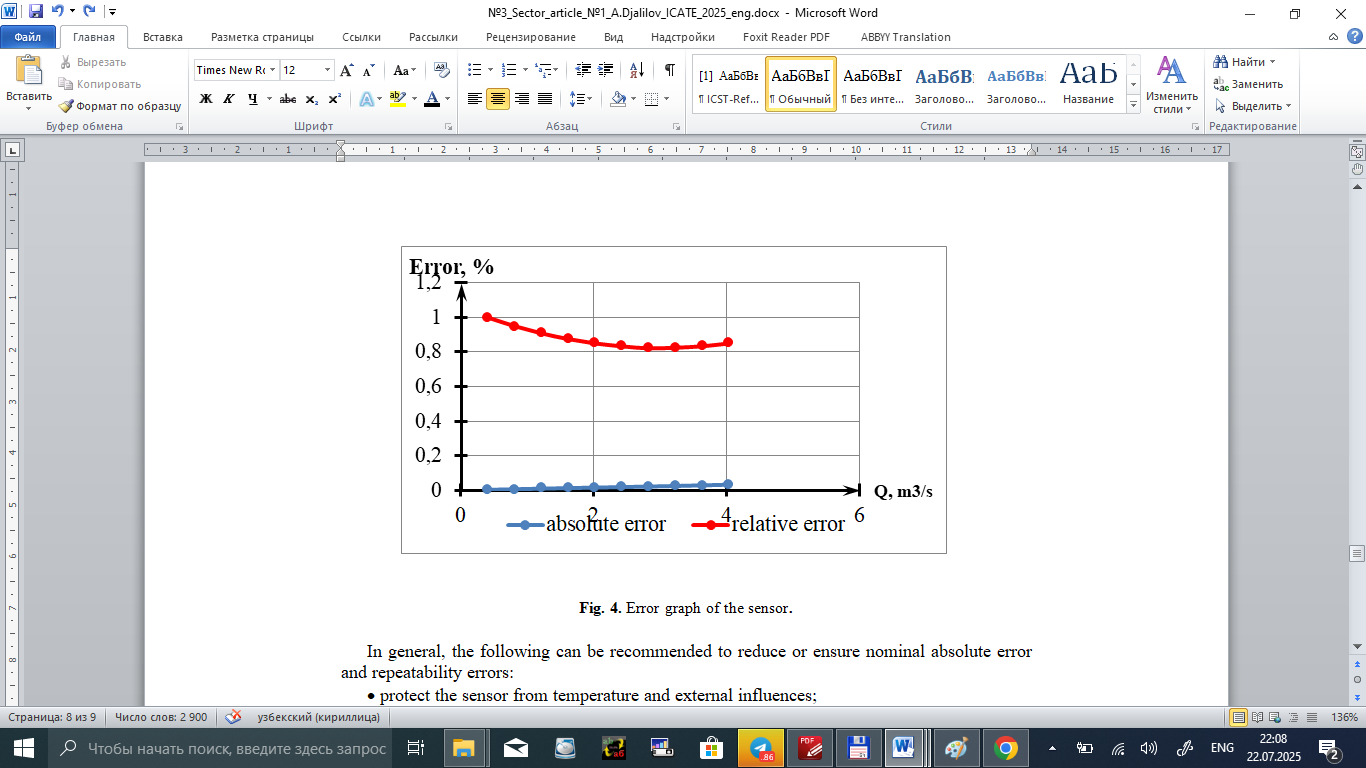
.

All calculations continue in this way.

Using the results of the experiment, we analyze the absolute and relative errors using a graph figure 4.

The measurement accuracy and reliability of sensors are assessed by their absolute and repeatability errors. Absolute error represents the largest difference between the value recorded by the sensor and the real value, and affects the overall accuracy of the measurement system. This error may vary depending on environmental factors, sensor design and operating principle. [17].

The repeatability error represents the variation between repeated measurements under the same conditions and plays an important role in evaluating the sensor's stable performance. A small repeatability error ensures continuous and reliable operation of the sensor.



**FIGURE 4.** Error graph of the sensor.

In general, the following can be recommended to reduce or ensure nominal absolute error and repeatability errors:

• protect the sensor from temperature and external influences;

• introduction of calibration and correction mechanisms;

• application of calibration and smart algorithms in programming;

• constructive improvement of sensors.

Computer programs are also important in measuring water flow in an open channel and analyzing, processing and, if necessary, calibrating the measured data.

**CONCLUSION**

It was found that changes in ambient temperature affect the propagation speed of pulses, leading to increased errors in the uncalibrated state;

It has been proven that the angle and location of the sensor on the object is also one of the factors affecting the measurement accuracy;

Taking into account all the requirements for the sensor, an experiment was conducted at the facility and it was graphically proven that the average value of the absolute and relative errors does not exceed 1%;

A sensor error of no more than 1% allows for up to 5-7% savings in water resources at the facility;

This scientific research work can serve as a scientific-methodical basis for the development and application of high-precision sensor systems in the future.

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