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Abstract. This paper analyzes ultrasonic flow meters that provide stability of metrological characteristics during operation, low cost of meter maintenance, high reliability and sensitivity, and high performance in large diameter pipes and open channels. Based on the analysis, the requirements of the reclamation systems to the sensors, the causes of the error are formed. The difference between the speed of sound in the opposite direction of the flow direction or in the direction of flow in the ultrasonic sensors was studied. The measurement errors of ultrasonic sensors currently widely used in open canals are investigated graphically. Based on the analysis results, it is recommended to use an ultrasonic sensor suitable for the extreme conditions of our country.

1. Introduction

One of the urgent problems is the introduction of large-scale automated control systems in irrigation systems to determine the true value of water flow, equipping hydraulic structures of all hydro-ameliorative systems with sensors for measuring water level and flow, information-measuring systems. Nowadays taking into account these problems, theoretical and practical work is being carried out in our zone on the efficient use of existing water resources, improving the reclamation of lands, increasing productivity, reducing electricity consumption at pumping stations.

We know that the main part of the irrigation network in our country is open canals. Currently, the technical condition of water flow measuring and control devices at these facilities is not satisfactory. That is, in the current age of information technology, existing water flow meters in open canals do not meet many requirements. In order to effectively use the available water resources, it is necessary to create, develop and implement a general information system and a system of hydrological monitoring, accounting, storage and planning. It is necessary to pay special attention to the development and creation of new information sensors with high sensitivity and accuracy of water flow in open canals and pipes, the development of a new information and communication system in the irrigation system [2].
2. Methods
Currently, various types of measuring devices are being developed to measure water flow in open canals and unpressurized pipes. Different technological processes may place different requirements on these flow meters [1]. Therefore, we formulate the general technical requirements for the development of these flow meters.

The following requirements are set for modern flow meters:
- high reliability;
- high accuracy in measurement;
- minor error when changing the density of the liquid;
- high sensitivity in measurement;
- width of measurement range;
- adaptive adjustment;
- compactness;
- low cost.

In the article, we will look at modern ultrasound sensors.

The principle of operation of ultrasonic (acoustic) flow meters is based on the effect that occurs when acoustic vibrations pass through liquids or gases [7,8]. Most flow meters operate in the ultrasonic range. Ultrasonic flow meters are divided into the following types:
- flow meters based on the displacement of acoustic vibrations in a moving liquid medium;
- Doppler effect based flow meters.

The most common water flow meters are based on the principle of measuring the flow time and the transition time consumption of acoustic vibrations in the opposite direction [4,5]. In addition to the above-mentioned flow meters, long-wave acoustic flow meters have been developed that operate in the sound range of acoustic vibrations. Typically, ultrasonic flow meters measure the volumetric flow rate of liquids, but the flow rate can also be measured by placing a fluid-sensitive element in the structure [3,6]. The error of the ultrasonic flow meters available so far ranged from 0.5% to 2.5%.

Figures 1a and 1b below show an ultrasonic generator placed opposite the two sides of the unpressurized tube. As a rule, a piezoelectric crystal is used as the source of the ultrasound generator. Each crystal is used as an ultrasound generator (exciter) or receiver. In other words, a single crystal can act as an “amplifier” or a “microphone” if necessary.

The crystals are placed at a distance D from each other and at an angle $\phi$ relative to the direction of flow. In addition, a small crystal can be placed inside the tube in the direction of flow ($\phi=0^\circ$).

The time of sound propagation between two crystals A and B is related to the mean velocity of the current as follows [4,5]:

$$\frac{D}{c \pm v_{\text{average}} \cdot \cos \phi} \approx \Delta T \approx \frac{2D \cdot V_{\text{average}} \cdot \cos \phi}{c^2 + V_{\text{average}} \cdot \cos^2 \phi}$$

here $c$ - the speed of sound in the environment.

In this expression, the $\pm$ sign indicates the direction of sound propagation, i.e. along or against the stream. $V_{\text{average}}$ is the average flow rate in the direction of ultrasonic propagation.

If the stream is laminar $v_{\text{average}} = \frac{4v_a}{3}$, if the stream is turbulent, then $v_{\text{average}} = 1.07 \cdot v_a$. Here $v_a$ is the average velocity of the flow along the cross-sectional area. The difference between the speed of sound opposite to the direction of flow or in the direction of flow is determined as follows:

$$\Delta T = \frac{2D \cdot V_{\text{average}} \cdot \cos \phi}{c^2 + V_{\text{average}} \cdot \cos^2 \phi} = \frac{2DV_{\text{average}} \cdot \cos \phi}{c^2}$$
This expression is appropriate in most cases i.e. $c \gg v_{\text{average}} \cdot \cos \varphi$ cases. In order to improve the signal-to-noise relationship, the speed of propagation of the ultrasound signal is often measured in two directions [9,10]. In this case, both pesocrystals act alternately as receivers or transmitters (Figure 2).

![Figure 1](image1.png)

**Figure 1.** An ultrasound generator placed opposite the two sides of the tube.

The movement of the fluid causes a change in the propagation time of the ultrasonic signals along and against the flow (Figure 2).

The propagation velocity of an ultrasonic pulse in a liquid is the sum of the ultrasonic velocity and the fluid flow velocity $V$ and the fluid flow $V$ in a stationary fluid, which are considered to be a projection in the direction of the ultrasound. Thus, the propagation times of the ultrasound on and against the current are determined by the following formula [5]:

\[
\begin{align*}
    t_1 &= \frac{L_a - L_s}{c_o} + \frac{L_s}{c_o + V \cdot \cos \varphi} \\
    t_2 &= \frac{L_a - L_s}{c_o} + \frac{L_s}{c_o - V \cdot \cos \varphi}
\end{align*}
\]

(3) (4)

Here $t_1, t_2$ – the times of ultrasonic propagation along and against the current.

$L_a$ – is the length of the active part of the acoustic channel;

$L_s$ – is the distance between the membranes of PEs;

$c_o$ – is the ultrasonic velocity in stationary water;

$c_o$ – is the velocity of water in the pipe;

$\varphi$ – is the angle between the sensor and the pipe axes.

![Figure 2](image2.png)

**Figure 2.** The difference between the speed of sound in the opposite direction of flow or in the direction of flow.

The generating electronic unit and the ultrasonic transducer form the electronic unit of the secondary transducer (EB), where the data output is based on calculating the volume of water
consumption and measuring the propagation time of ultrasonic pulses. Calculation of consumption in the electronic unit $Q$ is calculated according to the following formulas, taking into account formulas (3) and (4) above [5,6]:

$$V = \frac{(t_2 - t_1) \cdot c_0^2}{2L_a \cdot \cos \varphi} \quad (5)$$

$$Q = \frac{\pi D^2 \cdot K}{4} \cdot \frac{(t_2 - t_1) \cdot c_0^2}{2L_a \cdot \cos \varphi} \quad (6)$$

Here: $D$ is the inner diameter of the ultrasonic flow meter at the place of installation of piezoelectric element 1 and piezoelectric element 2.

The $K$-correction factor takes into account the hydrodynamic properties of the fluid and the nature of its flow.

Ultrasonic sensors type AVFM 6.1 and Beluga operate according to the velocity-area method [3] when calculating the water flow.

$$Q = S \cdot v \quad (7)$$

In this case, $S$ is the width of the channel area, m, $v$ – is the fluid flow rate, m/s.

The reasons for the error in liquid flow meters are as follows:
- uncertain calculation of the influence of the flow profile;
- asymmetry of electronic acoustic channels;
- different speed of ultrasound in the environment;
- parasitic acoustic signals;
- an error introduced by the electronic circuit.

The influence of the uncertainty of the flow profile is due to the fact that the average speed and average speed of acoustic vibration are not equal.

3. Results and Discussion
Based on the above requirements, we analyze several types of ultrasonic sensors for measuring water flow in open canals.

| Ultrasonic sensor type | Construction | Measurement error | Advantages and disadvantages |
|------------------------|--------------|-------------------|-----------------------------|
| AVFM 6.1               |              | ± 2%              | **Advantages:**
|                        |              |                   | - water flow can be measured in open trapezoidal, rectangular, elliptical canals;
|                        |              |                   | - simulates the output current signal in proportion to the selected parameters;
|                        |              |                   | - has a data logger (128 MB of memory);
|                        |              |                   | - transmits data via Modbus® RTU or HART protocols via RS-485 interface.
|                        |              |                   | **Disadvantages:**
|                        |              |                   | - price is expensive;
|                        |              |                   | - small memory;
|                        |              |                   | - big mistake in polluted water. |
| Ultrasonic Sensor Type          | ± 1.5%  | Advantages:                                                                                     | Disadvantages:                              |
|--------------------------------|---------|-----------------------------------------------------------------------------------------------|---------------------------------------------|
| Beluga                        |         | - high measurement accuracy;                                                                  | - the price is expensive;                    |
|                               |         | - has an intelligent system for spectral analysis of the flow distribution in real time.       |                                              |
|                               |         | - has the ability to measure the speed of a liquid in both leaky and water-filled pipes;       |                                              |
|                               |         | - Rugged case that meets the IP68 standard;                                                    |                                              |
|                               |         | - Ability to connect to SCADA and other telemetry systems;                                     |                                              |
|                               |         | - the sensor is connected directly to the system via the RS485 interface;                      |                                              |
|                               |         | - has an automatic diagnostic system.                                                           |                                              |
| Flo-sonic OCFM (Open Channel Flowmeter) | ± 1%    | - high accuracy of measurements in clean and polluted water;                                  | - measurement error depends on the canal size.|
|                               |         | - sensor can be used in open channels up to 150 meters wide;                                   |                                              |
|                               |         | - the flow can be measured in two directions;                                                  |                                              |
|                               |         | - echo shape control.                                                                         |                                              |
|                               |         | - rugged case that meets the IP68 standard;                                                    |                                              |
|                               |         | - has a programmable 4-20 mA output.                                                           |                                              |
|                               |         | - the sensor is connected directly to the system via the RS485 interface;                      |                                              |

Let's analyze the measurement errors of the above mentioned sensors.

![Figure 3. Dependence of the measurement error on the water flow.](image)

The ultrasonic flow sensors analyzed above have been tested under various extreme conditions in our facility. In this case, a model of the object was prepared, in which the water flow was diverted from open canals in a closed cycle. The flow rate was also monitored at various points in the canal.
cross-section during the test experiment. The velocity of the tested flowmeters differed by 0.1 ÷ 0.5% from the mathematically required nominal velocities, that is, the actual profile of the velocity distribution across the cross section of the liquid flow. Watercourses with varying degrees of pollution and temperatures were also discharged from the open canal. Under these conditions, it was noticed that the measurement error of the ultrasonic sensors of the AVFM 6.1 and Beluga types was increased in comparison with the ultrasonic sensor of the Flo- sonic ocfm type (Figure 3).

Based on these results, we recommend using the Flo- sonic ocfm sensor in water systems in our country.

4. Conclusions
1. Analysis of technological processes of irrigation systems shows that the technical characteristics of ultrasonic sensors largely meet the requirements of irrigation and drainage systems.
2. Accuracy of measurement is the main metrological characteristic and is mainly important when measuring the mass or volume of a passing liquid, and not the instantaneous value of the liquid flow rate. Currently, depending on the development of technical means, the rate is 0.2 ÷ 0.5%. In the last 90 years, this figure was 1.5-2%.
3. The use of ultrasonic sensors in hydro-reclamation systems allows continuous monitoring and remote automatic control of scattered irrigation structures.
4. The use of high-precision ultrasonic sensors in open canals can save water resources and electricity by 10-15%.

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