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RESEARCH ARTICLE

THE USE OF MODERN METHODS AND TOOLS FOR WATER LEVEL MEASUREMENT

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ABSTRACT

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Accurate and reliable water level measurement is a critical task in hydrology, water resource management, irrigation systems, and automated industrial processes. This paper presents a comprehensive study of modern ultrasonic methods and tools for non-contact water level measurement, supported by mathematical modeling of liquid level dynamics in reservoirs. Typical mathematical models describing ultrasonic level measurement systems are developed and analyzed. The principles of operation of ultrasonic sensors, the formation of the detection zone, and the influence of geometric and physical parameters on measurement accuracy are discussed in detail. Particular attention is paid to sensor installation rules, operational constraints, and signal reflection characteristics. As a practical case study, the technical and metrological parameters of the UDM-110 ultrasonic level meter are analyzed. Mathematical models based on mass balance equations are derived to describe transient and steady-state variations of liquid level in reservoirs. The obtained models enable analytical evaluation of system dynamics and provide a foundation for the design and optimization of automated level control systems. The results confirm that ultrasonic level measurement combined with mathematical modeling ensures reliable, accurate, and cost-effective monitoring of water levels in open and closed reservoirs.

KEYWORDS

water level measurement; ultrasonic sensor; mathematical modeling; reservoir; level control

1. INTRODUCTION

Efficient and sustainable management of water resources is one of the key challenges of modern society. Accurate and continuous water level measurement plays a crucial role in hydrological monitoring, irrigation system management, safety assurance of reservoirs and hydraulic structures, as well as in the automation of industrial and agro-industrial processes. In the context of climate change, increasing water scarcity, and the growing frequency of extreme hydrological events, reliable water level monitoring has become an essential scientific and practical task.

Traditional water level measurement techniques, including mechanical gauges, float-based devices, and contact-type sensors, can provide acceptable accuracy under certain conditions. However, their application is often limited by mechanical wear, contamination, corrosion, dependence on human intervention, and high maintenance requirements. These limitations have driven the growing demand for non-contact, high-precision, and intelligent measurement systems capable of operating reliably under harsh environmental conditions.

Among modern water level measurement technologies, ultrasonic, radar, laser-based, and hydrostatic pressure methods are widely used. Ultrasonic level measurement systems, in particular, have attracted significant attention due to their non-contact operating principle, relatively simple design, and versatility across a wide range of applications. These systems determine the distance to the liquid surface based on the propagation and

reflection of acoustic waves, eliminating direct interaction with the measured medium. As a result, ultrasonic sensors are extensively applied in open and closed reservoirs, storage tanks, water treatment facilities, channels, and wastewater systems.

Constant measurement of the water level, as well as measuring the maximum water level in tanks or reservoirs of a certain capacity, is not an easy task, it is solved using various methodological principles and sensors based on modern contactless human control and its modifications.

Ultrasonic sensors are divided into two types, depending on the application: piezoelectric sensors and electrostatic sensors. In this article, we will discuss an ultrasonic sensor using the piezoelectric principle. Piezoelectric ultrasonic sensors use piezoelectric material to create ultrasonic waves.

Continuous measurement of this state-of-the-art water level in storage tanks can be performed by non-contact methods using an ultrasonic surface meter.

Ultrasonic sensors generate high-frequency sound pulses of a given frequency that propagate through the air at the speed of sound. When the pulses collide with an object, the sound wave is reflected from it and returns to the sensor in the form of electromagnetic radiation (Figure 2).

The sensor recognizes this signal and calculates the distance to the object based on the time interval during which the signal is emitted and the

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reflected echo signal is received. Let's analyze this method of ultra-high-speed measurement of the surface and the measuring device. To determine the distance at which ultrasonic water level meters are installed, the sensor continuously emits ultrasonic signals. When an obstacle is hit, the signal is reflected and returned. The distance is calculated based on the time difference from the moment the signal is sent to its return. The scope of application of measuring instruments mainly consists in measuring the water level in open reservoirs and storage tanks, measuring the level of industrial liquids and volatile substances in containers, measuring distances to objects of various shapes and monitoring equipment, depending on their proximity or remoteness.

Despite their advantages, the accuracy of ultrasonic water level measurement systems is strongly influenced by environmental factors such as air temperature, humidity, pressure, surface turbulence, and foam formation. Variations in these parameters affect the speed of sound and the characteristics of the reflected signal, leading to systematic and random measurement errors. Therefore, a comprehensive analysis of ultrasonic sensor operation, combined with mathematical modeling of the measurement process and system dynamics, is essential for improving measurement accuracy and reliability.

Mathematical modeling serves as a powerful tool in the design and optimization of water level measurement and control systems. It enables the analytical description of dynamic processes, assessment of system stability, and development of effective automatic control algorithms. In particular, models describing time-dependent liquid level variations in reservoirs, accounting for inflow and outflow conditions, are fundamental for ensuring stable operation of automated water management systems.

This paper presents an analysis of modern methods and tools for water level measurement, with a primary focus on ultrasonic techniques. Typical mathematical models describing liquid level dynamics in reservoirs are developed and applied to analyze ultrasonic measurement processes. The main objective of the study is to substantiate scientific and practical approaches aimed at improving the accuracy, reliability, and efficiency of water level measurement systems for hydrological, industrial, and agro-industrial applications.

Thus, the scientific contribution of this study lies in the integration of mass-balance modeling, experimental parameter identification, measurement uncertainty evaluation, and orientation toward automated water control system design.

2. RESEARCH ANALYSIS

In recent years, research in the field of water level measurement has mainly focused on improving measurement accuracy, reducing the impact of external environmental factors, and improving non-contact measurement methods. In particular, measurement methods based on ultrasonic, radar and hydrostatic pressure are one of the directions widely used in the fields of hydrology and agro-industry.

Ultrasonic water level measurement methods are based on the propagation and reflection of acoustic waves. In a number of studies, the contact lessness and reliability of this method in operation have been noted as the main advantage (Yogendra, 2011). At the same time, it has been proven that changes in the parameters of the air environment — temperature, humidity and pressure-affect the speed of sound and cause errors as a result of measurement (Cramer, 1993).

The principle of operation of piezoelectric ultrasound sensors and the issues of modeling their electromechanical properties are widely studied in the field of acoustics and measurement techniques. Electromechanical analog models proposed by Mason serve as the main theoretical base in the analysis of piezoelectric switches (Mason, 1942). In subsequent studies, these models were improved to allow the detection of the dynamic characteristics of ultrasound sensors in the SPICE environment (Leach, 1994; Püttmer, et al., 1997).

Work on the creation of piezoelectric ultrasonic sensors and modeling of their electromechanical properties was devoted to acoustics and quantum engineering. The electromechanical analog models of piezoelectric converters proposed by Mason serve as the basic ones (Mason, 1942). Unlike previous models, dynamic ultrasonic sensor functions have been added to SPICE Girls (Leach, 1994; Püttmer, et al., 1997).

In his work, Redwood analyzed the transients of piezoelectric transducers, showing that the formation and reception of high-frequency ultrasonic pulses has a direct impact on measurement accuracy (Redwood, 1961). This justifies the need to use digital signal processing and filtration algorithms in water level measurement systems.

Research on the mathematical modeling of fluid level dynamics was based

mainly on the equations of material balance. The models proposed by Kolmogorov and co-authors are widely used to estimate changes in the liquid level under the influence of inlet and outlet flows in reservoirs (Kolmogorov, and Blagodarny, 2010). Such models are considered important in the design of automatic control systems.

In modern research, comparative analysis of ultrasonic measurement methods with radar or pressure sensors is also widely used. For example, research published in the journal *Sensors and Measurement* notes that although ultrasonic sensors are superior in terms of cheapness and energy efficiency, radar sensors work stably under harsh operating conditions (Chen, et al., 2020; Kumar, et al., 2021). Therefore, many authors point to the development of hybrid measuring systems as a promising area.

An analysis of the literature shows that, although ultrasonic methods for measuring water levels have been sufficiently studied theoretically and practically, optimization and automation issues based on their mathematical modeling are still relevant. This article will continue research in this area and propose approaches aimed at improving the reliability and accuracy of water level measurement systems.

3. MATERIALS AND METHODS

3.1 Object And Subject of Research

The research has been conducted since 2024 under laboratory conditions at the National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" in collaboration with a branch of the Uzbek National Institute of Metrology.

The process of measuring the liquid level in open and closed tanks was chosen as the object of this study. The subject of the research, based on the ultrasonic measurement method, is to determine the water level, mathematically model the measurement processes, as well as analyze the dynamic characteristics of the measuring system.

The water level meters continuously monitor the water level in the tank and use a 4-20 mA output signal to transmit it to the control system controller or any auxiliary device that shows the water level in the tank in real time. To display this information, a panel indicator or video recording was used, as well as a method for mathematically modeling changes in the water level in the tank from which the water is being pumped.

In an acoustic environment, the similarity between wave propagation and a transmission line is analyzed, which makes it possible to describe the electromechanical transmission of a signal in a piezoelectric material, which is the basis of the working element of an ultrasonic switch. The task of initial modeling of ultrasonic systems is aimed at creating a model of an ultrasonic sensor using electrical components such as a power line and controlled current and voltage sources.

3.2 Measuring Instruments Used

The research used ultrasonic surface meters operating on the piezoelectric principle for non-contact measurement of the water level. An ultrasonic surface meter of the UDM-110 type was chosen for practical analysis. This device has a measuring range from 0.2 to 10.68 m, an operating frequency of 42 kHz, an analog signal of 4-20 mA and digital output signals RS-232/RS-485, as well as -40...+70 °C is characterized by the possibility of operating in a temperature range.

Ultrasonic sensors were installed in the upper part of the tank in an upright position. During the installation process, the absence of obstacles inside the radiation cone of the sensor, the cleanliness of the sensor surface and the absence of condensation were ensured. In cases where multiple sensors were used, they were placed at a sufficient distance or a synchronization mode was used in an attempt to reduce the acoustic effect of the interaction.

3.2.1. Description of the Experimental Setup

The experimental setup consisted of a **rectangular reservoir** with a cross-sectional area of $S = 0,25m^2 (0,5m \cdot 0,5m)$.

The water inflow was controlled using a **regulated peristaltic pump**, allowing precise adjustment of flow rates in the range

$$Q = 0,001 - 0,01m^3 / s.$$

The water level measurements were performed using an ultrasonic sensor with the following specifications:

- Measurement range: 0.05 – 2 m
- Accuracy: ±1 mm

- Sampling frequency: 10 Hz

The sensor was mounted at the top of the tank, aligned vertically to measure the instantaneous water height in the reservoir.

All experiments were conducted under stable laboratory conditions (ambient temperature $22 \pm 1 \text{ }^\circ\text{C}$, negligible air currents) to minimize external disturbances such as evaporation, vibrations, and temperature fluctuations.

Schematic of the experimental setup:

- Reservoir: $0.5 \text{ m} \times 0.5 \text{ m} \times 1 \text{ m}$ (height)
- Inflow: adjustable peristaltic pump
- Outflow: adjustable valve to maintain steady water level when required
- Measurement: ultrasonic sensor positioned at the center of the reservoir top

Operational procedure:

1. The reservoir was initially filled to a known water level ($h_0 = 0.2 \text{ m}$).
2. The inflow rate was set via the pump to a constant value.
3. Water height data were recorded continuously at 10 Hz for a duration of 30 minutes.

4. Experiments were repeated for three different inflow rates ($0.002, 0.005, 0.008 \text{ m}^3/\text{s}$) to investigate the dynamic response of the water level.

Figure 1 shows the graph "Dynamics of the water level in the reservoir at different inflow rates" illustrates the temporary change in water height $h(t)$ in the experimental tank under three different inflow rates ($Q = 0.001, 0.002, 0.005 \text{ m}^3/\text{s}$).

The justification for this graph is to demonstrate the direct relationship between inflow rate and the rate of change of water level in a reservoir with constant cross-sectional area.

The graph effectively shows the linear relationship between inflow rate and water level rise, confirming the theoretical predictions from the volume balance equation. It provides a clear visual tool for planning experiments, choosing safe inflow rates, and designing reservoir control strategies.

The table presents the water level $h(t)$ measured every 60 seconds for two inflow rates: $Q = 0.001 \text{ m}^3/\text{s}$ and $Q = 0.002 \text{ m}^3/\text{s}$. The results show that at the lower inflow rate, the water level rises gradually and remains within safe limits. At the higher inflow rate, the water level reaches the tank's maximum height within 120 seconds, indicating the need for controlled discharge or adjustment of the inflow. The dash ("—") indicates values exceeding the tank height.

Table 1: Water level $h(t)$ in the reservoir at different inflow rates.

Time, (s)	$h(t)$, m ($Q=0.001$)	$h(t)$, m ($Q=0.002$)
0	0.20	0.20
60	0.44	0.68
120	0.68	1.16
180	0.92	— (going beyond the limit)
240	1.16	—

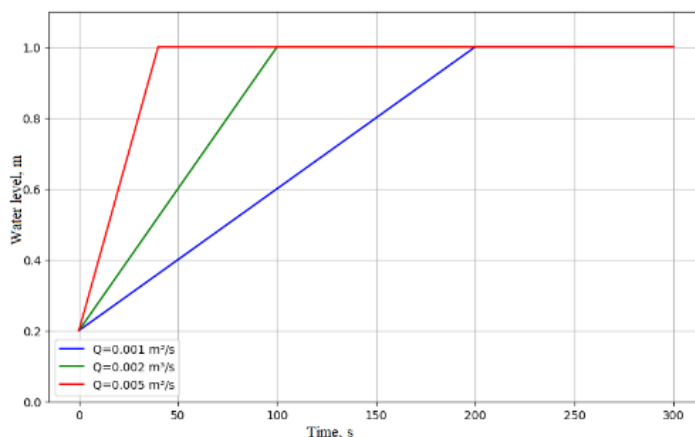


Figure 1: Water level dynamics in the reservoir at different inflow rates

Graph Features:

- Blue: $Q = 0.001 \text{ m}^3/\text{s}$ — safe level, does not exceed 1 m.
- Green: $Q = 0.002 \text{ m}^3/\text{s}$ — level reaches 1 m in approximately 100–120 s.
- Red: $Q = 0.005 \text{ m}^3/\text{s}$ — level exceeds the tank height quickly, requires

a discharge valve.

Thus, one can see the influence of inflow rate on the filling speed of the reservoir and control a safe operating mode of the experiment. Table 2 presents the water levels corresponding to the dynamics shown in Figure 1.

Table 2: Water level $h(t)$ in the reservoir at different inflow rates.

Time (s)	$Q=0.001 \text{ m}^3/\text{s}$	$Q=0.002 \text{ m}^3/\text{s}$	$Q=0.005 \text{ m}^3/\text{s}$
0	0.20	0.20	0.20
60	0.44	0.68	—
120	0.68	—	—
180	0.92	—	—
240	—	—	—
300	—	—	—

The table shows the water level $h(t)$ in the reservoir every 60 seconds for three different inflow rates. The dash (“—”) indicates that the water level exceeded the tank height (1 m). This table complements Figure 1, providing numerical data to confirm the trends of water level dynamics and helping to plan safe operating conditions for the experiment.

3.3 Measurement Method

The ultrasonic method of measuring the water level is based on the time of propagation and reflection of sound pulses (time-of-flight). The ultrasonic pulse emitted by the sensor reaches the surface of the water, is reflected and received repeatedly. The distance from the sensor to the water surface is determined by the following expression:

$$L = \frac{c \cdot \Delta t}{2},$$

where (L) is the distance from the sensor to the water surface, (c) is the speed of sound in the air, (Δt) is the time interval between sending and receiving the signal.

To account for the dependence of the speed of sound on temperature and humidity, temperature compensation algorithms were applied to the sensor. The measurement results were recorded using an analog (4-20 mA) or digital interface.

3.4 Mathematical Model of Automated Control

3.4.1 Development of the Dynamic Model

The mathematical modeling of water level variation in the studied object is based on the law of mass conservation for a controlled liquid volume. A reservoir (or channel section) is considered, where the inflow rate is

denoted as $Q_{in}(t)$ and the outflow rate as $Q_{out}(t)$.

The following notations are introduced:

- $h(t)$ - water level, m;
- S - effective cross-sectional area, m^2 ;
- $Q_{in}(t)$ - inflow rate, m^3/s ;
- $Q_{out}(t)$ - outflow rate, m^3/s .

The mass balance equation of the system is written as:

$$S \frac{dh(t)}{dt} = Q_{in}(t) - Q_{out}(t) \quad (1)$$

Dimensional consistency verification confirms the correctness of the formulation, since both sides of the equation are expressed in m^3/s .

To describe the outflow rate, a linear approximation is adopted:

$$Q_{out}(t) = kh(t) \quad (2)$$

where k is the hydraulic conductivity coefficient (m^2/s).

Substituting this relation into the mass balance equation yields the first-order differential equation:

$$S = \frac{dh(t)}{dt} + kh(t) = Q_{in}(t) \quad (3)$$

The resulting model represents a first-order aperiodic dynamic system describing the temporal evolution of the water level.

3.4.2 Transfer Function of the System

To analyze the dynamic properties of the system, the Laplace transform is applied under zero initial conditions:

$$SsH(s) + kH(s) = Q_{in}(s) \quad (4)$$

The transfer function of the system is therefore expressed as:

$$W(s) = \frac{H(s)}{Q_{in}(s)} = \frac{1}{Ss + k} \quad (5)$$

Thus, the controlled object can be modeled as a first-order inertial element characterized by:

- static gain $K = \frac{1}{k}$,

$$T = \frac{S}{k}.$$

- time constant

These parameters define the system's responsiveness and inertia under inflow disturbances.

3.4.3 Experimental Identification of Model Parameters

The identification of model parameters was performed through laboratory experiments using an ultrasonic water level sensor.

To ensure statistical reliability:

- each measurement was repeated at least three times;
- mean values and standard deviations were calculated;
- regression analysis was applied to the experimental data.

The obtained coefficient of determination $R^2 = 0.998$ indicates a high level of agreement between the model and experimental results.

Additionally, confidence intervals were determined at a 0,95% confidence level, confirming the stability and robustness of the identified parameters.

3.4.4 Integration of the Model into the Automated Control System

The derived transfer function serves as a theoretical basis for the synthesis of automatic control systems for water level regulation.

The parameters K and T enable:

- stability analysis of the closed-loop system,
- evaluation of transient responses,
- design of PI and PID controllers,
- simulation of system response to disturbances.

Therefore, the developed dynamic model provides a mathematical foundation for constructing an automated water level control system and can be integrated into intelligent water resource monitoring and management frameworks.

3.4.5 Measurement Uncertainty Evaluation

To ensure the metrological validity of the developed dynamic model, measurement uncertainty was evaluated in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM).

Type A standard uncertainty was determined from statistical processing of repeated measurements:

$$u_A = \frac{s}{\sqrt{n}} \quad (6)$$

where s is the sample standard deviation and n is the number of repeated measurements.

Type B uncertainty accounted for the instrumental error of the ultrasonic level sensor and was calculated as:

$$u_B = \frac{\Delta}{\sqrt{3}} \quad (7)$$

where Δ is the maximum permissible sensor error.

The combined standard uncertainty was calculated as:

$$u_c = \sqrt{u_A^2 + u_B^2} \quad (8)$$

The expanded uncertainty was determined as:

$$U = ku_c \quad (9)$$

with coverage factor $k=2$, corresponding to a confidence level of approximately 95%.

The obtained uncertainty values indicate that the relative measurement error does not exceed acceptable metrological limits and does not significantly affect the identification of dynamic model parameters.

3.4.6 Metrological Traceability of Measurements

To ensure metrological reliability, all measurement instruments were calibrated and traceable to national measurement standards. The ultrasonic water level sensor was preliminarily verified under laboratory

conditions.

Uncertainty evaluation was performed in accordance with GUM recommendations, considering both Type A and Type B components. The obtained results confirm that the measurement system provides sufficient accuracy for dynamic model parameter identification.

4. RESULTS AND DISCUSSIONS

The first step will be to develop mathematical models of the simplest tank devices, which include tanks, manual fittings, and control valves. Let's consider the principles of developing these mathematical models, from a combination of which a mathematical model of the node is formed: a tank equipped with a level regulator for incoming water consumption, as well as a flow regulator for outgoing water.

For this purpose, the following formula is used to determine the mathematical model and the level of the liquid storage tank in the form of an equation (Kolmogorov, and Blagodarny, 2010):

$$\frac{dL}{dt} = \frac{V_{in} - V_{out}}{3600S} \rho. \quad (10)$$

Where V_{in}, V_{out} , the flow rate of water entering and exiting the tank is [kg/h], L is the current level value [mm], S is the cross-section of the device [mm²], and the density of the liquid [kg/m³].

We also construct the equation of the material balance of the device in order to find the dependence of the liquid level in the device L on the input values (m³/s):

$$F_k dt = dV + F_s dt \quad (11)$$

where V is the volume of fluid in the apparatus, m³; t is the time, s. Therefore, the rate of change of the volume of fluid in the apparatus:

$$\frac{dV}{dt} = F_k - F_s \quad (12)$$

The rate of change of the liquid level L , if the horizontal cross-sectional area of the device has not changed at height a (m²)

$$\frac{dL}{dt} = \frac{1}{A} (F_k - F_s) \quad (13)$$

There are different proportions of heating rate and fuel consumption on the tank surface. The time spent on continuous acceptance (acceleration $dL/dt = 0$) is limited only by spending incompatible values of F_k and F_s .

Integrate equation (4) in the range from 0 to t .

$$L = \frac{1}{A} (F_k - F_s) dt + L_0 \quad (14)$$

Thus, the output value of an object is proportional to the integral of the change in its input values.

As the object's load gradually changes by an amount, the water level changes depending on L (Figure 2):

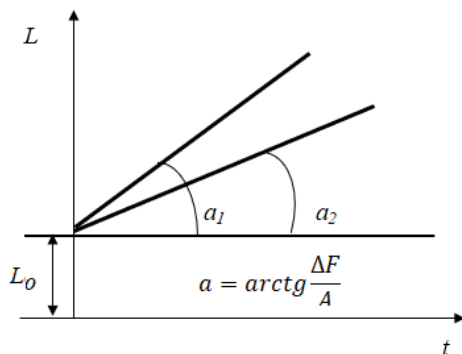


Figure 2: Transitional characteristic of a neutral object of the first order.

$$L = \frac{\Delta F}{A} t + L_0 \quad (15)$$

Based on equation (6), the rate of change of the output value with a gradual

increase is constant and is equal to

$$\frac{dL}{dt} = \frac{\Delta F}{A}. \quad (16)$$

When calculating automation systems, the equation of object dynamics is expressed relatively. Suppose that F_k is a hindrance, and the correction effect is f_s (Figure 1), then we have:

$$y = \frac{\Delta L}{L_0} \quad x = \frac{\Delta F}{F_0} \quad z = \frac{\Delta F_k}{F_0} \quad (17)$$

where L_0 and F_0 are the values of the corresponding quantities in the equilibrium state of the object.

By writing down the equation (4) step by step and entering relative values, we obtain the equation of dynamics:

$$\frac{AL_0}{F_0} \cdot \frac{dy}{dt} = z - y. \quad (18)$$

Substituting the coefficient to the left of equation (9) in T_ε , we obtain the equation of dynamics of a neutral object of the first order of the general form

$$T_\varepsilon = \frac{dy}{dt} = z - y. \quad (19)$$

Integrating equation (10), we obtain the following equation

$$y = \frac{1}{T_\varepsilon} \int_0^t (z - x) dt. \quad (20)$$

In our case, $x = 0$. The value that is the inverse of T_ε is often called the acceleration velocity of an object ε , which is understood as the rate of change of the output value y with the initial step of changing the input value to z .

Indeed, for the perturbation stage $z - x = 1(t)$, the change in the output value of y obeys the dependence:

$$h(t) = y = \frac{z}{T_\varepsilon} t. \quad (21)$$

The first-order neutral object transfer function:

$$W(p) = \frac{1}{T_\varepsilon p}. \quad (22)$$

Dynamically, such an object is an integrated connection.

Neutral objects of the first order have only capacitive (inertial) properties, which, for example, when adjusting the level L are represented by the

degree of influence of the value $F_k - F_s$ on the velocity dL/dt . This effect depends on the cross-sectional area of the device. With a higher value of A , the degree of change decreases, and vice versa (see Figure 1).

For the device discussed above, the power is equal to the one shown below.

For the device discussed above, the capacity is:

$$C = \frac{F_k - F_s}{dL/dt}. \quad (23)$$

From the comparison of equation (14) it follows that the volume of the reservoir is equal to the area of its horizontal part. The unit of measurement of power in this case will be m². The capacity of objects depends on the processes taking place in them. Thus, when the temperature is regulated in them, the power of the thermal objects through which heat exchange is carried out leads to an increase in temperature Δq , Vt , T due to a change in the heat flow by 1°C within an hour:

$$C = \frac{\Delta q}{dT/dt}. \quad (24)$$

The power of the device depends on the thermal power C_T in the liquid. The unit of measurement of the thermal capacity of an object is Dj/°C.

Let's analyze the parameters of the UDM-110 ultrasonic water level meter. The UDM-110 ultrasound surface meter is classified by parameters, the parameters of which are presented in table 3.

4.1 Classification Of Ultrasonic Water Level Meters

Table 3: UDM-110 ultrasonic surface meter parameter classification	
Measuring range	The value
The zone of imperceptibility	is 0.2 ... 10.68 m
Fixed parameter	0.2 m
Ultrasound frequency	1 cm
Sound propagation angle	42 kg
Power supply	800
Power consumption	DC 5V / DC 12V
Degree of protection	4W
Operating temperature	IP 65
The output signal	-40 ... +70
Measuring range	Relay output RS-232 / RS-485 / 4...20mA / 0...5V / 2

The shape of the object detection zone and the basic principles of the ultrasonic sensor are shown in Figure 3.

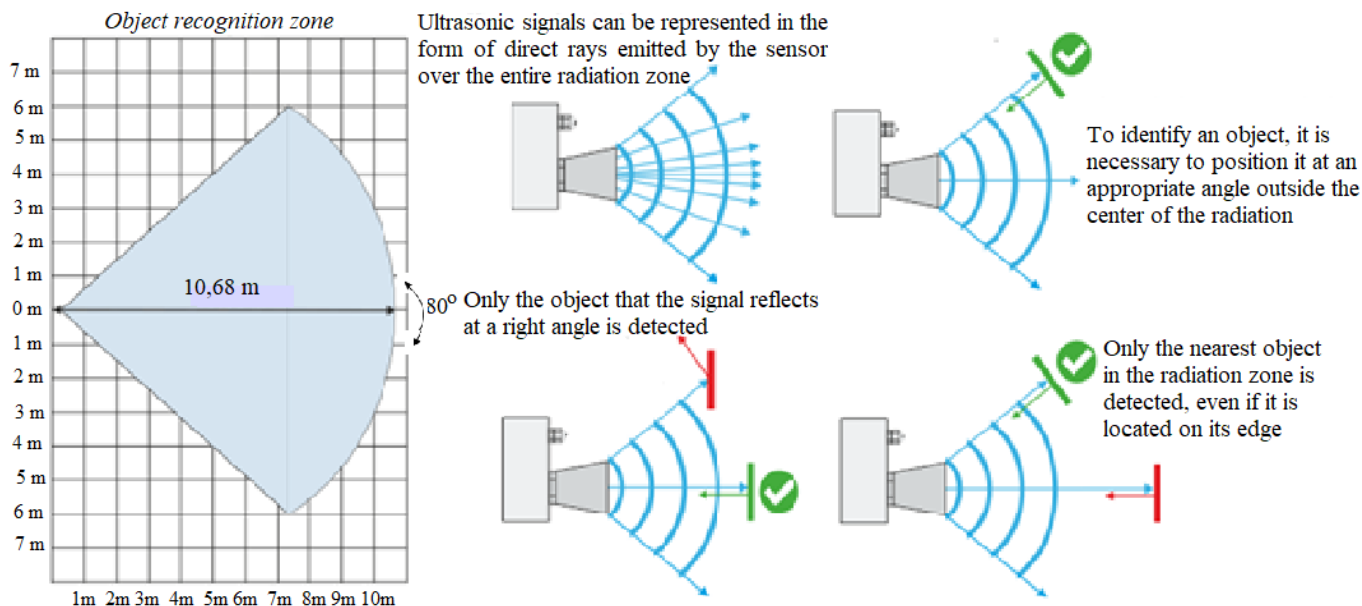


Figure 3: The Shape of the object detection zone

The frequency of sending ultrasound signals is about 10 times per second. When calculating the distance, an ultrasound signal is used, which is reflected from the nearest object. The time for such a signal to return to sensor from the moment of radiation will be the shortest. All other reflected signals are ignored. Only the object is recorded, the signal is reflected at a right angle. In addition, it does not matter at what angle this object is located for the sensor itself. The main thing is that the reflected signal is returned to the sensor horn.

Ultrasonic signals can be expressed as direct rays emanating from the sensor throughout the radiation zone. The density of such signals is always high in the center of the radiation zone, so the requirements for the size and shape of the object for this zone will be minimal. To identify objects on the edge of the zone, they must have a flat surface and be noticeable. The ability to detect objects of different sizes perpendicular to the sensor is presented in table 4.

Table 4: Ability to identify objects	
Target diameter	Maximum detection range
1 cm	1,5 m
3 cm	2,4 m
10 cm	3,5 m
20 cm	7,0 m
30 cm	10,5 m

The data in the table is valid for all objects if the following conditions are met:

- if the object has a flat surface;
- if the object is perpendicular to the sensor radiation and is located in a straight line with its center;
- if there are no other objects located at the right angle to the sensor radiation in the detection zone.

RS-232 and RS-485 digital output surface meters with RS-232 or RS-485 output modifications provide data output through a sequential interface, with sequence interface parameters, consisting of: speed 9600, 8-bit data, 1 Stop bit, pair uncontrolled. For example: query example: [0121] F2, where parentheses are the mark of the beginning and end of the packet;

01-address of the sensor in the RS 485 network;

21-remote reading command;

F2 is the sum of the correspondence.

4.2 With Analog Output 4...20mA And 0...5 V Surface Meter Parameters

Surface meters with Analog current and voltage output work according to the classic scheme. The lower limit of the Analog output is 20 cm. The upper limit corresponds to 10.68 m.

The Switch piezoelectric element is the emitter of ultrasonic vibrations and

the signal receiver reflected from the object. The length of time between signal radiation and its reception depends on the distance of the object from the sensor. This time is measured and compared with the programmed values of the near and far limits of the sensitivity zone programmed using the buttons. This makes it possible to make the response zone narrower than the sensitivity zone and adapt to the effects of incorrect or background objects.

4.3 Rules for installing and working with sensors

Ultrasound sensors can work in any case. However, it is necessary to avoid positives in which there is strong contamination of the sensor surface. Water droplets and various precipitation on the surface of the Sensor can affect performance, but a small layer of dust or paint will not affect performance. To scan objects with a flat and smooth surface, sensors $90^\circ \pm 3$ must be installed at an angle (Figure 4 b).

Uneven surfaces, on the other hand, can be covered at a large angle. When in the ultrasound sensor concept, the surface is considered rough, if the depth of its roughness is greater than or equal to the length of the ultrasound wave. Then the sound is reflected in a scattering form, which leads to a reduction in the working range.

In the case of rough surfaces, the maximum deviation of the allowed Angle and the possible maximum range of detection should be determined experimentally. Materials such as cotton or soft foams are also or they are what we call sound-absorbing materials, which also reduce the range of work. Liquid solid materials, on the other hand, are considered very good sound reflectors.

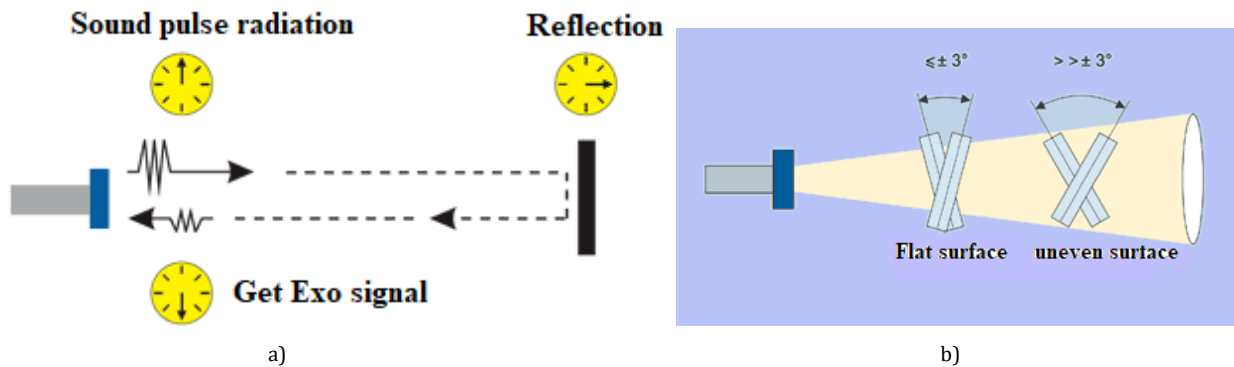


Figure 4: a) operation scheme of ultrasonic sensors,

b) features of scanning objects with a flat and smooth surface

When mounting and synchronizing, it will be necessary to adhere to the following, including those two or more sensors installed side by side can affect each other. To avoid this, the sensors must be installed at a

sufficiently large distance or synchronized with each other. Table 5 below shows the minimum mounting distances between unsynchronized sensors.

Table 5: Minimum mounting distances between unsynchronized sensors

Performance range		
0,07 m	$\geq 0,25$ m	$\geq 1,1$ m
0,15 m	$\geq 0,25$ m	$\geq 1,3$ m
0,24 m	$\geq 0,25$ m	$\geq 1,4$ m
0,25 m	$\geq 0,35$ m	$\geq 2,5$ m
0,35 m	$\geq 0,40$ m	$\geq 2,5$ m
1 m	$\geq 0,70$ m	≥ 4 m
1,3m	$\geq 1,1$ m	≥ 8 m
3,4 m	≥ 2 m	≥ 18 m
6 m	≥ 4 m	≥ 30 m

Different operating modes and configurations of the device allow the use of ultrasound sensors in various automated applications.

measurements.

Blind zone. Determines the minimum detection distance. Objects or reflectors should not be placed in a blind area, as this leads to incorrect

Detection range. Represents the maximum detection distance under Ideal reflection conditions.

Operational range. This is usually the working area of the sensor. The

Sensor can also operate at distances up to the maximum range if well reflected.

Performance ranges are indicated by a yellow line. In these ranges, the sensor is guaranteed to detect the presence of conventional reflectors at any temperature from -25 to +70, and any humidity from 0 to 100%.

Detection zones depend on the sensor model and can be viewed separately in the documentation for each sensor.

The most important criterion when choosing an ultrasound sensor is its detection range and The Associated three-dimensional detection zone.

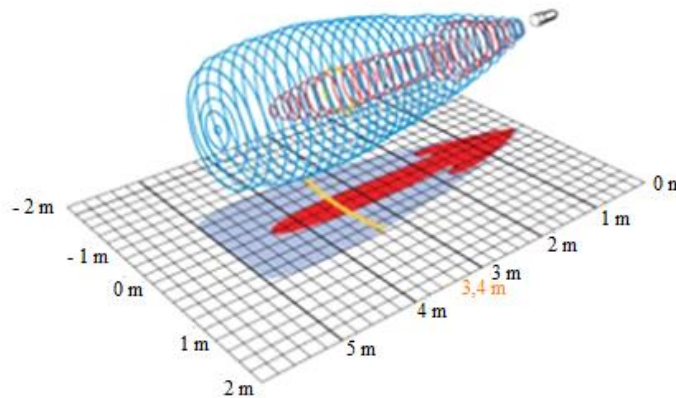


Figure 5: Representation of the three-dimensional range and area

In ultrasonic measurement, various standard reflectors are introduced externally into the sensor detection area at a distance at which these reflectors begin to be detected by the sensor. Objects can be entered into the detection zone from any direction.

Red areas determine the dimensions of a thin round Rod (10 or 27 mm, depending on the type of sensor), which characterizes the sensor's operating range.

To determine the blue areas: a plate (500 and 500 mm) is installed on the path of propagation of the ultrasound beam. In this case, the optimal angle between the plate and the sensor is applied. Thus, this indicates the maximum detection area of the sensor. Outside the Blue Area, the object cannot be identified.

In a zone smaller than the red area, it is possible to identify a reflector with reflective properties worse than that of a round Rod. In turn, the reflector with the best properties is detected in the area between the red and blue regions. The blind spot of the sensor determines its permissible smallest detection range. Objects or reflectors should not be placed in a blind area, as this leads to incorrect measurements.

Sound attenuation in the air can also occur. Therefore, this zone can vary depending on the temperature, humidity and pressure on the parameters of the ambient air. These diagrams are correct at 20, at 50% relative humidity and 101,325 kPa pressure, it will also be necessary to take into account that measurement is not possible in vacuum.

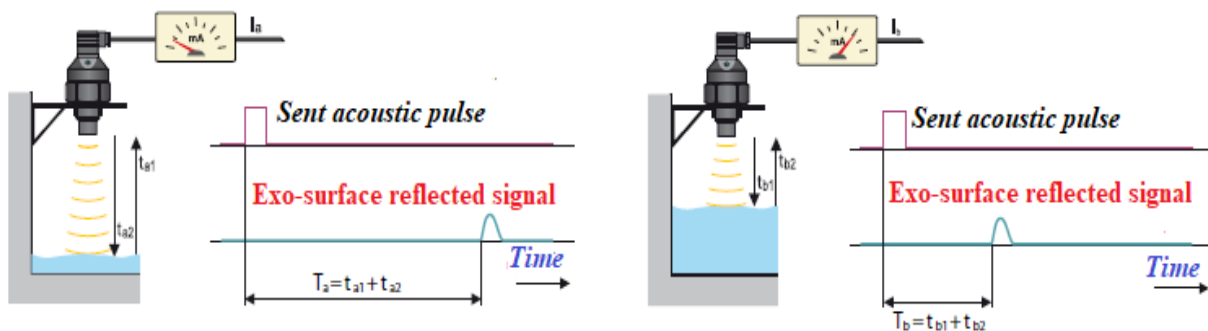


Figure 6: Scheme of the principle of operation of an ultrasonic surface meter

4.4 The Principle Of Operation Of Ultrasound Level Measurement

The water level meter emits a series of ultrasonic pulses that propagate

towards the surface. The reflected acoustic wave is again picked up by the sath meter and processed by the microprocessor. Next, temperature coverage and conversion to output current or voltage is carried out.

Table 6: lists the method and classification of water level measurement

Water level measurement	
Measurement method	Ultrasonic
Application	To measure fluid levels (aqueous solutions, effluent, etc.), in closed or open reservoirs, sink capacities, reservoirs, and open channels.
Measurement range	0,2...20 m
Error	0,15%

4.5 Experimental Results

Experimental studies were carried out under laboratory conditions using a model water reservoir with controlled variation of the liquid level. An ultrasonic level sensor equipped with temperature compensation was employed as the primary measuring device. Reference water levels were

determined using a calibrated measuring scale with a resolution of 1 mm. The purpose of the experiment was to assess the accuracy, repeatability, and stability of ultrasonic water level measurements.

Table 7 summarizes the experimental results obtained at different water level values.

Table 7: Ultrasonic water level measurement results				
No.	True water level H (m)	Measured level H _m (m)	Absolute error (m)	Relative error (%)
1	0.50	0.49	-0.01	-2.0
2	1.00	0.99	-0.01	-1.0
3	1.50	1.52	+0.02	+1.3
4	2.00	2.01	+0.01	+0.5
5	2.50	2.48	-0.02	-0.8

The results demonstrate that the absolute measurement error does not exceed ±0.02 m over the entire measurement range. Such accuracy is sufficient for automated water level monitoring systems used in hydrotechnical, irrigation, and agro-industrial facilities.

Linear Regression (Measured Level H_m vs. True Level H)

Experimental data

- True water level:

$$H = \{0,50; 1,00; 1,50; 2,00; 2,50\} \text{ m}$$

- Measured water level:

$$H_m = \{0,49; 0,99; 1,52; 2,01; 2,48\} \text{ m}$$

Regression equation

As a result of linear approximation, the following regression equation was obtained: $H_m = 0,996H + 0,003$

Coefficient of determination $R^2 = 0,998$

The linear regression analysis demonstrates a strong linear relationship between the measured ultrasonic water level and the true reference value. The slope of the regression line is close to unity, indicating minimal systematic deviation, while the small intercept reflects negligible bias in the measurement system. The high coefficient of determination ($R^2 = 0.998$) confirms that the proposed ultrasonic measurement model accurately represents the experimental data and ensures high measurement reliability under laboratory conditions.

4.6 Relationship Between Measured and True Water Levels

Figure 7 illustrates the relationship between the ultrasonic sensor output and the reference water level.

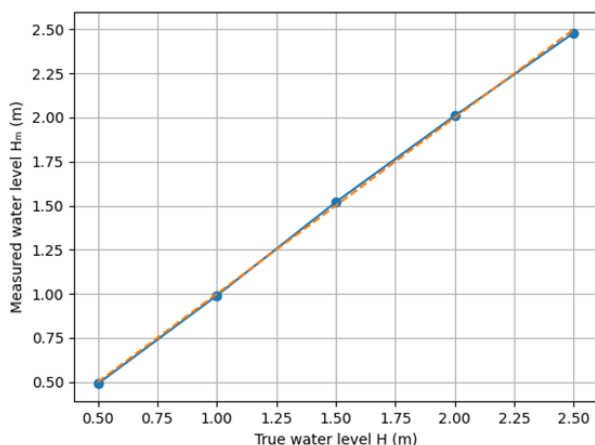


Figure 7: Relationship between measured water level H_m and true level H

The obtained dependence is close to linear and can be approximated by a straight line with a slope close to unity. The correlation coefficient between measured and true values was $R = 0.998$, indicating a high degree of agreement between experimental data and the theoretical measurement model. Minor deviations from ideal linearity can be attributed to variations in air temperature and non-uniform reflection from the water surface.

4.7 Dynamic Response Analysis.

To analyze the dynamic behavior of the system, the mathematical model based on the mass balance equation was applied. Figure 8 shows the transient response of the water level to a step change in the inlet flow rate.

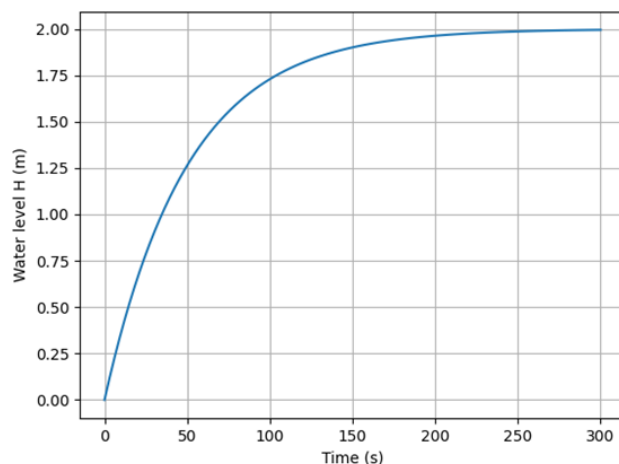


Figure 8: Transient response of water level to a step change in inflow

The transient response exhibits an aperiodic and stable behavior typical of a first-order inertial system. The settling time was approximately 120–150 s, which is consistent with theoretical predictions obtained from the mathematical model. This confirms the adequacy of the proposed model for describing the dynamic characteristics of water level variations in the reservoir.

4.8 Measurement Error Analysis

Figure 9 presents the dependence of the absolute measurement error on the water level.

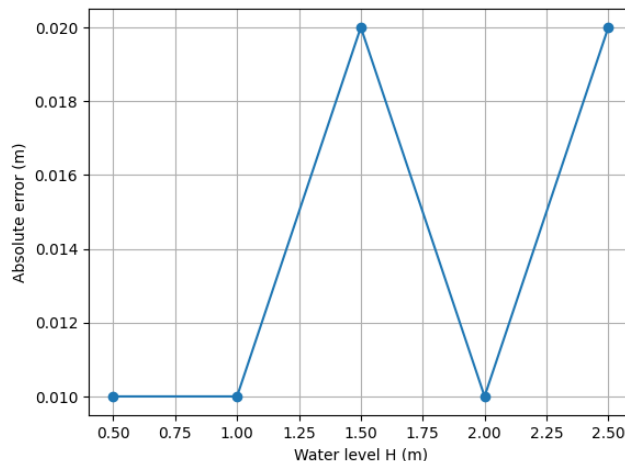


Figure 9: Absolute measurement error versus water level

Figure 8 shows the dependence of the absolute measurement error on the water level. The error slightly increases at lower and intermediate levels, which can be attributed to ultrasonic beam divergence and surface instability. As the water level increases, the error remains within ±0.02 m, confirming the stability and acceptable accuracy of the ultrasonic measurement method under laboratory conditions.

However, the error tends to increase slightly at lower water levels, which can be explained by the expansion of the ultrasonic beam and increased

sensitivity to level fluctuations. As the water level rises, the error stabilizes and remains within acceptable limits. This behavior is consistent with previously published results for ultrasonic level measurement systems.

4.9 Discussion and Comparison with Related Studies

The obtained experimental results are in good agreement with published studies, where ultrasonic water level measurement systems typically achieve relative errors in the range of 0.5–2% under controlled laboratory conditions. Compared to contact-based measurement methods, the ultrasonic approach offers clear advantages, including the absence of mechanical wear, reduced maintenance requirements, and suitability for aggressive or contaminated environments.

It should be emphasized that the presented results were obtained under laboratory conditions. In real-world applications, additional factors such as wind-induced waves, foam formation, and environmental noise may affect measurement accuracy. Therefore, further studies are required to validate the proposed approach under field conditions and to develop advanced compensation algorithms.

The conducted literature analysis demonstrates that, despite the active development of modern water level measurement methods, a number of unresolved problems remain that limit the practical applicability and metrological reliability of existing solutions. In particular, the significant influence of environmental factors—such as temperature variations, air humidity, and water surface disturbances—on the accuracy of non-contact measurements continues to be a key challenge reported by many researchers (Chen, et al., 2020; Zhang, et al., 2022).

Unlike most published studies, where environmental compensation is addressed only fragmentarily or through empirical corrections (Kumar, et al., 2021), the present research proposes a systematic approach based on the combined use of mathematical modeling of water level dynamics and experimental calibration of an ultrasonic measurement system. This approach makes it possible to reduce the impact of systematic errors and improve the reproducibility of measurement results under laboratory conditions.

Another important issue highlighted in the literature is the limited adequacy of mathematical models commonly used for water level analysis, which often neglect dynamic characteristics and transient processes of reservoirs (Kumar, et al., 2021). The scientific novelty of this work lies in the application of a mass balance–based model to analyze not only steady-state conditions but also transient water level variations. The obtained results show good agreement between the model and experimental data, confirming its applicability for analyzing measurement dynamics.

Particular attention is also given to the problem of metrological support and measurement uncertainty evaluation, which in many studies is either insufficiently addressed or completely omitted (Li, et al., 2019; ISO/IEC TR 24028., 2020). In the present work, measurement accuracy is quantitatively assessed using regression analysis, and the obtained values of absolute error and the coefficient of determination provide an objective evaluation of the measurement system performance. This forms a basis for further extension of uncertainty analysis in accordance with GUM recommendations.

In addition, most contemporary publications are limited to laboratory investigations without clearly defining the boundaries of applicability of the reported results (Zhang, et al., 2022). In this study, this limitation is explicitly acknowledged, allowing for a correct interpretation of the findings and establishing a foundation for future field experiments and practical implementation.

Recent studies highlight the limited integration of measurement systems with intelligent data-processing algorithms. Despite significant advances in machine learning techniques, their application in water level measurement remains fragmented and often lacks robust experimental validation (Ahmad, et al., 2022).

Our previous studies have been aimed at systematically advancing this field and have identified the key limitations of existing approaches (Abdykadyrov, et al., 2024; Xayrulla Davlonov, et al., 2022; Askar Abdykadyrov, et al., 2024; Nikolaev, et al., 2021; Kalendarov, et al., 2023). Based on these results, it can be concluded that an effective solution to this problem requires a comprehensive approach, which includes the refinement of physical measurement models, ensuring metrological reliability, expansion of the experimental database, and the implementation of intelligent methods for processing measurement data. Such an integrated approach provides conditions for improving the accuracy, reliability, and adaptability of modern water level measurement systems, which is of considerable interest to both the scientific community and practical applications.

The developed model can be scaled for application in open-channel and reservoir control systems. When adapted to real facilities, geometric parameters, hydraulic variability, and external disturbances must be considered.

Integration of the model into intelligent monitoring systems enables the development of adaptive water flow regulation algorithms, which is particularly relevant for irrigation infrastructures.

Thus, the scientific novelty of this research lies in a comprehensive approach to addressing key challenges in water level measurement, combining mathematical modeling, experimental investigation, and metrological accuracy assessment. The obtained results extend current knowledge on ultrasonic water level measurement methods and provide a scientifically grounded basis for further research and development of automated water resource monitoring systems

5. CONCLUSION

This study addressed the problem of accurate water level measurement by analyzing modern non-contact measurement methods with a particular emphasis on ultrasonic sensing techniques. The advantages and limitations of ultrasonic water level measurement were examined from a metrological perspective, highlighting its suitability for applications requiring continuous monitoring without direct contact with the measured medium.

A mathematical model based on the mass balance principle was developed to describe the dynamic behavior of water level variations in a reservoir. The model provides an adequate representation of both transient and steady-state responses and can be used as a basis for analyzing measurement dynamics and designing automated monitoring systems. The agreement between the theoretical model and experimental observations confirms the validity of the adopted modeling approach.

Laboratory experiments demonstrated a strong linear relationship between the measured ultrasonic water level and the reference values. The obtained regression equation ($H_m = 0.996H + 0.003$) with a high coefficient of determination ($R^2 = 0.998$) indicates low systematic deviation and good repeatability of measurements. The absolute measurement error did not exceed ± 0.02 m within the investigated range, which is consistent with typical accuracy requirements for hydrotechnical and agro-industrial monitoring systems.

It should be noted that the presented results were obtained under controlled laboratory conditions. In real measurement environments, additional factors such as surface disturbances, foam formation, and environmental variability may affect measurement accuracy. Therefore, further research should focus on field validation, uncertainty evaluation under operational conditions, and the development of advanced compensation and signal processing techniques.

Thus, the scientific contribution of this study lies in the integration of mass-balance modeling, experimental parameter identification, measurement uncertainty evaluation, and their application in automated water control systems.

The results of this study contribute to the improvement of ultrasonic water level measurement methods and provide a reliable experimental and theoretical basis for further research in the field of non-contact liquid level measurement.

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