## Static Characteristics of the Ultrasonic Sensor

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## Abstract. In this article, the changes in the output signal of the ultrasonic sensor with respect to the pulse propagation distance were analyzed through practical tests. During the experiment, the relationship between the input signal (distance) and the output signal (voltage) was studied, and the character of the sensor was determined. In the course of the analysis, nonlinearity of the output signal was observed in some parts of the range of 0-20 m of the spread of sensor pulses. In order to make it linear, 1st-level (linear) and 2nd-level (quadratic) approximation methods were used. According to the research results, the correlation coefficients for both approximation methods were calculated and the validity level of the model was evaluated. It was recommended to use the quadratic approximation method to linearize the static characteristic of the sensor.

## Key words: Ultrasound sensor, signal, approximation, correlation coefficient, linearization, range, accuracy, distance, voltage, model

**INTRODUCTION**

In the process of supplying water to agricultural crops, water resources are transferred through pipes and open channels. In these facilities, various measurement methods and tools are used to measure quantities such as water flow and water level [1]. Currently, the Department of Electrical Engineering and Mechatronics is conducting research on the development and creation of a new class of sensors for hydro-reclamation systems [2]. Classified as a non-contact measuring instrument, the ultrasonic flow meter is capable of detecting both velocity and area of an object. In addition, it facilitates real-time measurement and is inexpensive to manufacture [3, 4, 5, 6, 7, 8, 9]. Static characteristics of a time-pulse ultrasound sensor reflect its characteristics under constant conditions. These characteristics are important for assessing the reliability and accuracy of the sensor [10]. Follow are the basic static characteristics of a time-pulsed ultrasonic sensor [11, 12, 13, 14, 15]:

Measurement Range: This refers to the minimum and maximum values of the water flow velocity and the distance between the sensors that the sensor can measure. This range depends on the physical characteristics of the sensor and the microelectronic devices used in it.

Accuracy: The difference between the measured water flow velocity and distance and the true value. Usually expressed as a percentage (%) or millimeters (mm). High accuracy ensures the reliability of the sensor.

Linearity: Linearity is determined by the characteristic of the dependence of the input signal on the output signal. If the graph is linear, the accuracy of the measurements increases. The linearity deviation is expressed as a percentage (%).

Repeatability: The closeness of the results of measurements obtained when measuring water flow velocity, distance between sensors, etc., multiple times under the same conditions. Usually expressed as standard deviation (standard error) or standard uncertainty.

Signal-to-noise ratio (SNR): The ratio of the useful signal to the noise received by a sensor. A higher SNR value increases the sensitivity of the sensor and reduces uncertainties; a lower SNR value decreases it. This value is expressed in decibels (dB).

Sensitivity: A measure of how quickly and accurately a sensor responds to very small changes in water flow velocity and distance. Typically expressed in Volts/second (V/s), Volts/meter (V/m), or milliseconds/Volt (ms/V).

Angle of Measurement: This refers to the maximum angular range that the sensor can measure. This is largely dependent on the design of the sensor.

Operating Temperature Range: This refers to the minimum and maximum temperatures that the sensor can operate at for proper operation.

Power Supply Requirements: Indicates the voltage and current required for the sensor to operate.

Output Signal: Indicates the type of signal (e.g., analog, digital) and its parameters (e.g., voltage level, digital code) provided by the sensor.

**RESEARCH METHODS**

We analyze the static characteristics of the sensor (by changing the distance of the sensors installed in the channel) according to the above. The static characteristic shows the relationship between the sensor output signal (U) and the measured parameter (L – distance). This relationship can be found experimentally and is expressed by the following formula (1) [15]:

(1)

here: Umax=5 V – maximum output voltage; L=20 m – distance; k – sensitivity coefficient of the sensor (determined by experiment).

If we take the coefficient k to be 0.1, then:

In order to increase the accuracy of water flow measurement, it is necessary to linearize (linearize) the static characteristic of the sensor of the intelligent system. There are several ways to do this [15]:

**1. Linearization using Taylor series.**

If the static characteristic is an analytic function (for example, exponential or logarithmic), its first-order Taylor series can be taken and expressed as a linear equation (2):

(2)

here: X0 – linearization point (average value); Y0 – the output value of the sensor at the base point;

– gradient (the slope of a straight line).

This method is used to analyze the characteristics of the sensor at small distances.

**2. Linearization by taking logarithms.**

If the output signal is in exponential form, then it can be linearized using (1) by taking its logarithm.

we change this function (3):

ln(1−Uout⋅Umax)=−kL (3)

Using this formula, we obtain a linear relationship between L and ln(1 - Uout/Umax) (4).

Y=aln(X)+b (4)

**3. Approximation by experimental points (linear regression).**

If sensor measurement results are available, they can be fitted to a linear function using the linear regression method. Here:

Uout=aL+b (5)

The coefficients a and b are determined according to the equation in the form.

**4. Linearization using Python.**

Linear regression is the most reliable method for finding the linear characteristic of a sensor according to the data obtained as a result of an experiment. Linear regression is used to analyze the results of the experiment and ensure the linearity of the static characteristic.

We assume that the sensor output varies from 0 V to 5 V, depending on the given range.

It is expressed by the following equation (6) [16, 17]:

y=ax+b (6)

here: y — output voltage (V); x — value measured by the sensor (distance, m); a — regression coefficient (gradient); b — initial offset (for example, the output voltage is 0 V);

If the sensor output is truly linear, this equation represents an accurate model. If the sensor output is partially nonlinear, it can be linearized using a linear regression method.

**RESULTS AND DISCUSSION**

The source voltage of the sensor in scientific research work is 5 V, the measuring range is 0 - 10 m/s. The output voltage varies between 0 and 5 V. This means that the output can be 0 V in still water, and 5 V when the maximum measuring distance between the sensors is reached, i.e. 20 m.

(6) we determine the regression coefficients in the expression [16, 17]:

(7)

(8)

Here: n – number of measurements, xi - the distance measured by the sensor (L, м), yi – sensor output voltage   
(Ui, V).

The experiment was carried out at different distances between the sensors. The results of this experiment are presented in the following table:

**TABLE 1**. Experiment and calculation results

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| № | distance (L), m  *xi* | Output signal (Uout), V  theoretical, *yi* | Output signal (Uout), V  experiment, *yi* |  | *xi yi* | Uout=a⋅x+b  linear |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2.11 | 0.949 | 1.019 | 4.4521 | 2.15009 | 0.593465031 |
| 3 | 4.21 | 1.718 | 1.818 | 17.7241 | 7.65378 | 1.184117432 |
| 4 | 6.32 | 2.341 | 2.431 | 39.9424 | 15.36392 | 1.777582463 |
| 5 | 8.42 | 2.846 | 2.936 | 70.8964 | 24.72112 | 2.368234864 |
| 6 | 10.53 | 3.255 | 3.305 | 110.881 | 34.80165 | 2.961699896 |
| 7 | 12.63 | 3.586 | 3.656 | 159.517 | 46.17528 | 3.552352296 |
| 8 | 14.74 | 3.855 | 3.925 | 217.268 | 57.8545 | 4.145817328 |
| 9 | 16.84 | 4.072 | 4.142 | 283.586 | 69.75128 | 4.736469729 |
| 10 | 20 | 4.323 | 4.393 | 400 | 87.86 | 5.62526096 |
| ∑ | **95.8** | **26.945** | **27.625** | **1304.27** | **346.33162** |  |

Based on the determined values, we write the regression equation as follows:

y=ax+b; Uout=aL+b=0.2115L+0.7363

Based on this expression, we construct a graph of the static characteristic of the sensor versus *Uout*=*f*(*L*). This graph is shown in Figure 1 follow. In this graph, we analyze the results obtained as a result of approximation and as a result of experiment, as well as the error.

We know that this error is calculated by the sum of the squares of the errors (9) [16, 17].

(9)

here – yi – sensor output voltage (V), xi - value measured by the sensor (distance, m).

This formula (6) is the most important indicator of the degree of approximation and the degree of error between experimentally obtained results or a mathematical model.

Another indicator that determines the quality of approximation and experimental characteristics in the developed mathematical model is called the *R2* value, which is determined by the following expression (10) [16, 17]:

, (10)

where D-deviation (deviation).

The graph in Figure 1 shows that the developed model is consistent with the experimental results and confirms the linear relationship between the sensor output power and distance.

The sum of squares of the deviation in formula (10) is calculated by the following formula [16, 17]:

. (11)

Usually the value of R2 is between 0 and 1. From the formula (10) above, it is clear that if ∑δ2=0, then R2=1, and as a result, the error is very small and the approximation and experimental graph almost coincide.

**FIGURE 1**. Static characteristics of the developed ultrasonic sensor

Using the experimental results (Table 2) and the graph obtained by approximation, the errors present in each measurement can be calculated as follows:

;

 and so on.

We present the calculation results in table 2 follow.

**TABLE 2.** Calculation results

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Individual experiment number (*i*) | Each result on the measurement distance (*L*) or abscissa axis *xi*, *m* | Output power (Uout, experimental) or each result on the ordinate axis, *yi, V* | Expression obtained as a result of approximation,  *Uout=a⋅x+b* | *δi* |  |
| 1 | 0 | 0 | 0.737843285 | -0.7363 | 0.54213769 |
| 2 | 2.11 | 1.019 | 1.183774983 | -0.16356 | 0.02675350 |
| 3 | 4.21 | 1.818 | 1.627593261 | 0.191285 | 0.03658995 |
| 4 | 6.32 | 2.431 | 2.073524959 | 0.35802 | 0.12817832 |
| 5 | 8.42 | 2.936 | 2.517343237 | 0.41887 | 0.17545207 |
| 6 | 10.53 | 3.305 | 2.963274935 | 0.341605 | 0.11669397 |
| 7 | 12.63 | 3.656 | 3.407093213 | 0.248455 | 0.06172988 |
| 8 | 14.74 | 3.925 | 3.853024911 | 0.07119 | 0.00506801 |
| 9 | 16.84 | 4.142 | 4.296843189 | -0.15596 | 0.02432352 |
| 10 | 20 | 4.393 | 4.964684026 | -0.5733 | 0.32867289 |
| **∑** | **95.8** | **27.625** | **27.625** | **0.0003** | **1.44559984** |

from this table, the sum of squared errors is 1.44559984.

But it is difficult to understand any content from this number. If we calculated the errors of several curves in this way, we could make a conclusion by comparing them.

Therefore, we use ∑Uout to find its average value as follows.

(12)

Then we calculate the sum of squares of the deviation based on formula (11).

.

We calculate the R2 value using formula (10) as follows.

So the number R2=0,9227 is approaching 1. From this we can conclude that the graph obtained as a result of the approximation is satisfactory.

We will use the second-order approximation method to determine the degree of agreement between experimental results or a mathematical model.

The polynomial regression (level 2) equation is expressed as follows [16, 17]:

y=ax2+bx+c (13)

Here: a — quadratic coefficient; b — first order (linear) coefficient; c — free will.

Based on the experimental data, we find a second-order polynomial function that represents the relationship between the distance between the sensors (L) and the sensor output voltage (U):

U(L)=a⋅L2+b⋅L+c (14)

Here: a,b,c — coefficients to be determined; L — independent variable (distance between sensors, m); U — output voltage, V.

We construct a system of equations with three unknowns for this equation:

(15)

So, the coefficients a,b,c in the equation create an approximate function that best represents your experimental data.

Follow we present the mathematical basis of the Least Squares Method for a second-degree polynomial.

To determine the coefficients, we perform some calculations in this table.

**TABLE 3**. Determination of coefficients.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| ***i*** | ***Li*** | ***Ui*** | **Li2** | **Li3** | **Li4** | **Li⋅Ui** | **Li2Ui** |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2.11 | 0.949 | 4.4521 | 9.393931 | 19.82119441 | 2.0024 | 4.225 |
| 3 | 4.21 | 1.718 | 17,7241 | 74.618461 | 314.1437208 | 7.2328 | 30.45 |
| 4 | 6.32 | 2.414 | 39.9424 | 252.43597 | 1595.395318 | 15.256 | 96.421 |
| 5 | 8.42 | 2.856 | 70.8964 | 596.94769 | 5026.299533 | 24.048 | 202.48 |
| 6 | 10.53 | 3.356 | 110.881 | 1167.5759 | 12294.57398 | 35.339 | 372.12 |
| 7 | 12.63 | 3.856 | 159.517 | 2014.6984 | 25445.64139 | 48.701 | 615.1 |
| 8 | 14.74 | 4.273 | 217.268 | 3202.5244 | 47205.21001 | 62.984 | 928.38 |
| 9 | 16.84 | 4.323 | 283.586 | 4775.5815 | 80420.79253 | 72.799 | 1225.9 |
| 10 | 20 | 4.2 | 400 | 8000 | 160000 | 84 | 1680 |
| **Σ** | **95.8** | **27.945** | **1304.27** | **20093.776** | **332321.8777** | **352.36** | **5155.1** |

We solve the system of equations using the values in the table:

By solving this system of equations, we determine the values of the coefficients a, b, c:

a=-0.01; b=0.4067; c=0.1011.

We substitute the found values into the polynomial representation of the function and form the following equation:

U(L)=aL2+bL+c=-0.01⋅L2+0.4067⋅L+0.1011

We determine the correlation coefficient:

(16)

Here: ; .

Calculation result: .

This model represented the data with 99.77% accuracy.

**CONCLUSION**

In this study, the relationship between the input and output signals depending on the pulse propagation distance of the ultrasonic sensor was analyzed through practical tests. Based on the obtained data, it was determined that the output signal of the sensor has a non-linear variation with respect to the distance.

In the analysis, linear (1st order) and quadratic (2nd order) approximation methods were used to model the relationship between distance and output signal. Correlation coefficients (R²) were determined for both models, proving that the 2nd order model has high accuracy.

Research has shown that accurate modeling and linearization of sensor signals is essential for accurate sensor control and calibration in digital systems.

The results of this work serve as a scientific and practical basis for the effective use of ultrasonic sensors in automated systems, robotics and control-measuring devices.

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