Ultrasonic level measuring
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Abstract – Today, in modern industrial plants, the usage of modern ultrasonic sensors for level measuring in container can be successfully integrated in automated plants and processes.

This paper describes the device for measuring the level with contactless method by an ultrasonic sensor. The advantages of the ultrasonic level measuring are low price of transducers, simplification of processing the information and the fact that changes in pressure, temperature or type of materials in container do not affect measuring.

The measuring transducer is designed for implementation in the established standard automation systems, i.e. for a connection with a programmable logic controller, and it has a local visual display of the measuring value.

The device was tested and used in laboratory exercises at Zagreb Polytechnic. The obtained results were statistically analyzed, as described in this paper, and it has been confirmed that the device meets the acceptance criteria.

I. INTRODUCTION

We define the measuring material level in container as the height column of liquid or tender material in container or reactor. The conventional symbol for level is the letter h and is measured by meter, h (m). There are several methods of level measuring. The generally used level transducers are: mechanical level transducers, electrical level transducers, pressure level meters, stretch level materials, and the ultrasonic level measuring method described in this paper. Applying the ultrasonic enables a contactless level measuring. This method is used for liquid and tender material level measuring.

An ultrasonic sensor sends a package of ultrasonic signals. There is a reflexion of ultrasonic signal on the edge of air and liquid or tender material. The device measures the time in which the emitted ultrasonic signal crosses a way from sensor to the container level and back. By using the acoustic velocity and the time measured, the device determines the container's filled-up state.

To understand better the ultrasonic method of the level measuring procedure, it's necessary to review certain physical characteristics of sound and ultrasound, which follows in the next chapter.

II. PHYSICAL BASICS OF ULTRASOUND

The ultrasound is made of the longitudinal waves area over 20 kHz, which is inaudible to human ear. The ultrasound can be generated in several ways, and it is also registered by the same principle as the one used in its generation. The best known methods for generating the ultrasound are: piezoelectric, magnetostrictive, electrostatic, electrodynamic methods, and generating it by mechanical and thermal stimulus. The most often used are piezoelectric ultrasonic sensors, described also in this paper. They work at frequencies from 40 kHz to 250 kHz. The ultrasonic sensor in this device works at 40 kHz.

1.) Acoustic velocity: The sound can spread through all media like a longitudinal wave. The speed of sound-wave depends on the characteristics of media in which it is spreading.

The wave equation for the longitudinal waves implies the following expression:
\[ v = \sqrt{\frac{E}{\rho}}, \]  
(1)

where \( E \) is Young's modulus of elasticity, and \( \rho \) material density. With that equation we can calculate acoustic velocity. Acoustic propagation through different media is described with the expression:
\[ v = \sqrt{\frac{B}{\rho}}, \]  
(2)

where \( B \) is volume modulus of elasticity, and \( \rho \) fluid density. Volume modulus of elasticity fluid is defined with:
\[ B = -V \frac{\Delta P}{\Delta V} = \rho \cdot \frac{\Delta P}{\Delta \rho}, \]  
(3)

and describes relative volume changes at a pressure variation. The modulus of elasticity depends on the type of thermodynamic process in gas. When sound spreads through the gases, pressure and volume change quite quickly, so the heat transfer is negligible. That's why we can suppose that gas compression and expansion are adiabatic processes. The relation between pressure and gas volume for adiabatic process is given with the expression:
\[ PV^\gamma = k \]  
(4)

or
\[ P = k \cdot \rho^\gamma, \]  
(4a)

where \( P, V, \rho \) are pressure, volume and gas density, and \( \gamma \) is a constant characteristic for individual gas, the so called adiabatic coefficient. \( \gamma \) is the proportion of gas specific capacity at constant pressure and constant volume, where
\[ \chi = \frac{C_p}{C_v} \] For atomic gases it is 1.67, for diatomic gases (and for air) it is 1.4, and for more atomic gases it is 1.3.

The volume modulus of gas elasticity, taking into consideration the adiabatic process, amounts:

\[ B = -V \cdot \frac{dP}{dV} = \rho \cdot \frac{dP}{d\rho} = \chi \cdot P, \] (5)

By inserting expression for modulus of elasticity into the expression for acoustic velocity, we get the expression for phase velocity of acoustic waves in gas:

\[ v = \sqrt{\frac{\chi}{\rho} P}, \] (1a)

By using the gas equation:

\[ PV = \frac{m}{M} \cdot RT, \] (6)

i.e.

\[ P = \frac{\rho}{M} \cdot RT, \] (6a)

we get the correlation of acoustic velocity of temperature and gas type:

\[ v = \sqrt{\frac{RT}{\chi M}}, \] (1b)

where \( R = 8.314 \, \text{J/mol} \, \text{K} \) (gas constant), \( T \) absolute temperature (in Kelvin's), and \( M \) molar mass of gas (kg/mol).

By inserting constants and setting the equation we get the following equation:

\[ v = v_0 \sqrt{1 + \frac{t}{273.15}} \] (1c)

where \( v_0 \) is acoustic velocity at 0°C (331 m/s), and \( t \) air temperature at °C.

The acoustic velocity of air, at temperature of 20°C and pressure of 1.013 bar, gets 345 m/s.

2.) Volume: The volume or acoustic intensity is determined by the transmitted average power of sound wave per area density vertical on wave spreading direction.

The wave average power \( P \) is proportional with square of amplitude and frequency, and wave velocity.

\[ \overline{P} \propto f^2 A^2 v, \] (7)

The longitudinal oscillating wave with angular frequency \( \omega \) is determined with the expression:

\[ \xi = A \sin(kx - \omega t), \] (8)

where \( k \) is wave number. The pressure changes by the law:

\[ dp = -d p_m \cos(kx - \omega t), \] (9)

With \( dp \) being the pressure fluctuating component, i.e. a pressure variation at certain average value of pressure (i.e. steady state) \( p_m, dp_m \) is maximum value of that change. Therefore we get the effective force:

\[ F = dp S = -d p_m S \cos(kx - \omega t), \] (10)

where \( S \) is the area affected by the pressure. Since the particles vibration rate is

\[ \nu = \frac{d\xi}{dt} = -\omega A \cos (kx - \omega t), \] (11)

there is an instantaneous power transferred by the wave to the area \( S \):

\[ P = F \nu = S \omega \delta p_m A \cos^2(kx - \omega t). \] (12)

The average value of power transferred by the wave through the area \( S \) is:

\[ P = \frac{1}{2} S \omega \delta p_m A = \frac{1}{2} S \frac{(dp_m)^2}{\sigma_0 v}. \] (12a)

The volume is defined as energy transferred in a time unit by a sound-wave thorough the unit area which is vertical on the wave spreading direction (average power):

\[ I = \frac{1}{2} \left( \frac{dp_m}{\sigma_0 v} \right)^2, \] (13)

where \( dp_m \) indicates changes of pressure maximum amplitude in media, while \( \sigma_0 \) and \( v \) indicate media density and wave velocity in media.

The volume is proportional to the sound-wave amplitude squared. The unit for measuring the volume is \( \text{W/m}^2 \). Due to the bandwidth in which the volume is measured and instead of the volume itself the level of loudness (and noise) is often defined as follows:

\[ L = 10 \log \frac{I}{I_0} \, [\text{dB}], \] (14)

where \( I_0 \) is reference volume taken as audibility limit (quieter than foliage rustle): \( I_0 = 10^{12} \, \text{W/m}^2 \).

The acoustic level \( L \) is measured in decibels (dB). The sound audibility threshold is at 0 dB, while the sound at 130 to 140 dB starts to cause pain in the ear.

3.) Spreading of ultrasound through the media: Transmitter of ultrasonic sensor, which is used in this device, has a cylindric form (picture 1.).
Though its dimensions are small in relation to the measured distance, which, in further elaboration will be considered as the point source of the ultrasound. In case of a point source the ultrasound is spreading radially and its intensity $I$ is declining along with the radial distance squared from the transmitter.

$$I = \frac{k}{d^2}. \quad (13a)$$

The ultrasonic wave level at the distance $d_1$ from the transmitters is $L_1 = 10 \log(I_1/I_0)$, and at the distance $d_2$ is $L_2 = 10 \log(I_2/I_0)$. The level is declining along with the increase of radial distance.

$$L_1 - L_2 = 10 \log \frac{I_1}{I_0} = 10 \log \frac{I_2}{I_0} = -20 \log \frac{d_1}{d_2} \quad [dB], \quad (14a)$$

while at a doubled distance the weakening is $6 \, dB$. The weakening of ultrasonic wave due to the absorption in the air is proportional to the frequency squared. Therefore, the sensor’s measuring span becomes smaller as the ultrasonic frequency increases and it is limited to $10 \, m$ at the frequency of $100 \, kHz$.

4.) Ultrasound direction: A typical diagram of ultrasound spreading consists of the main and side lobes. The angle $\alpha$ is taken as a unit for direction measuring.

The beam angle $\alpha$ is defined as the angle which closes circular sector between points where ultrasonic level is lower by $6 \, dB$ in relation to the maximum value. The beam angle $\alpha$ depends on the proportion between the wavelength $\lambda$ and the effective diameter of the transmitter’s $D$ membrane. The results therefore show that shorter wavelength and longer diameter of membrane produce better direction focus. The beam angle $\alpha$ of the used ultrasonic sensor is $35^\circ$, and Fig 1. presents its direction diagram.

### III. DEVICE FOR LEVEL MEASURING

The device consists of a transmitter, a receiver, a counter, a display, a D/A converter, an amplifier, a switch, control electronics and an oscillator.

![Schematic diagram of ultrasonic level gauge](image)

The control electronics generate a package of voltage impulses at the frequency of $40 \, Hz$. The transmitter transforms the voltage impulses into the ultrasound of the same frequency. The transmitted package of ultrasonic impulses reflects from the surface of liquid or tender material in the container back to the receiver. The receiver transforms the reflected ultrasonic signal to a voltage signal which after processing in amplifier changes position of switch, and thus aborts impulse delivery from the oscillator to the counter. The oscillator’s frequency amounts to $7 \, kHz$. That frequency corresponds with a half of acoustic velocity, which, at air temperature of $20^\circ C$, amounts to $343.8 \, m/s$. Since the sound must cross a double distance from transmitter to receiver, the actual length is obtained by dividing acoustic velocity value by two, which amounts to $171.9 \, m/s$. If the oscillator is adjusted to the frequency of $17 \, kHz$, it will create one impulse in the time in which the sound covers distance of $0.01 \, m$. The number of impulses arriving from the oscillator to the counter is proportional with the distance between the device and the level in container.
Before transmitting each package of ultrasonic impulses, i.e. before new measuring, control electronics restart the counter. The duration of measuring is short due to the acoustic velocity, and to obtain real values, the measuring is frequent. A problem arises because the counter keeps the measured value for very short time, and therefore it is impossible to display measured value by way of designator or analog output. In order to solve that problem the D/A converter circuit and designator have possibility to memorise the counters output position. With the D/A converter it is made possible by the circuits IC2 i IC3. They are D-bistable circuits the inputs of which are connected to the counter outputs, receiving rhythmic impulses from the control electronics before the counter resets. Consequently, the counter output position before resetting remains in the circuits in circuits IC2 and IC3. Their outputs are connected to the output of the D/A converter which transforms binary number from the counter to continuous analog current signal. Current output signal is applied for control systems.

The device uses a piezoceramic ultrasonic sensor 400ST/R Pro-wave electronics [9] which has a physically separated transmitter and receiver. The measured distance is shown by seven-segmental displays. The electronic component of the device is arranged on three printed circuit boards and together with the ultrasonic sensor is built into a plastic box.

IV. FUNCTIONAL INSPECTION OF DEVICE

During the device inspection four measurements have been performed. Each measurement has been performed in another room. Measuring has been conducted by changing of set up distance starting at 30 cm to 250 cm.

The obtained measuring results are presented in table 1.
Table 1. Measured results

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</table>

From the measuring results the sensors statistical characteristic has been obtained. The obtained statistical characteristic is realistic, i.e. it deviates from the ideal linear characteristic. For calculation of some of the characteristic values it is necessary to have the ideal statistical characteristic. By application of the least square method on the obtained results the linear regression is determined and it is used as an ideal characteristic in calculation of characteristic values.

1.) The least squares method (linear regression)

In the measuring process pairs of measured values \((x_i, y_i)\) are obtained. Between values \(x\) and \(y\) there is linear dependence:

\[
y = aX + b.
\]  

Let us suppose that deviations of measuring values \((x_i, y_i)\) from the straight line \(y = aX + b\) are random. In that case, unknown parameters of the straight line can be calculated requesting for the sum

\[
\sum_i (y_i - (aX_i + b))^2,
\]  

to have a minimum. The sum will have a minimum if its partial derivative according to both parameters equal 0. By derivation and equilization with 0, and by execution of the system thus obtained, we get parameters of linear regression:

\[
a = \frac{xy - \bar{X}\bar{y}}{x^2 - \bar{x}^2},
\]

\[
b = y - ax.
\]

2.) Calculation of characteristic values

a) Range: Range of this device is defined by the group of data situated between two delimiters on the scale and it is \(0.3 – 2.5\ m\).

b) Span: Span of this device is defined as algebraic difference between two delimiters which correspond to minimum and maximum values on the scale and it is \(2.2\ m\).

c) Range accuracy: Precision of this device is characterised by its capability to produce, in reference operational conditions, indications close to realistic measuring value.

\[
T = \frac{\text{Max. error}}{\text{Span}} \cdot 100 = \frac{0.02}{2.3} \cdot 100 = \pm 0.86% \quad (19)
\]

d) Sensitivity: Sensitivity of this device is defined as relation between the increase output value and increase measuring value after the output value reaches the steady state:

\[
S = \lim_{\Delta x \to \infty} \frac{\Delta y}{\Delta x}. \quad (20)
\]

Considering that the sensors statistical characteristic is linear, sensitivity is constant through the entire span, and it can be presented as a relation between the span on output and scale span on input. Sensitivity is equal to slope of the statical characteristic.

\[
S = \frac{O}{T} = \frac{1.21\ mA}{2.5\ m} = 0.48\ mA/m. \quad (21)
\]

i) Threshold: Sensitivity threshold of this device is \(0.3\ m\). That value is obtained by measuring of minimal value on input which induces an indication change on output.

f) Resolution: Resolution of this device is \(0.01\ m\). Resolution is defined by measuring of the minimal
increase in measuring value inducing an indication change on output.

\( g \) **Nonlinearity**: Nonlinearity of this device is defined with maximal difference between his real and ideal statical characteristic.

\[
\frac{N[\%]}{O_{\text{MAX}} - O_{\text{MIN}}} = \frac{N}{0.01mA - 1.22mA} \cdot 100 = 0.925\%
\]

(22)

Where \( N, O_{\text{MAX}} \) and \( O_{\text{MIN}} \) are maximum nonlinearity, maximaum output value and minimum output value.

\( h \) **Repeatability**: That means that device gives each time the same output value at the measuring of the same input value. The repeatability error of this device is:

\[
\delta_r = \frac{\Delta \times 100\%}{FS} = \frac{2}{250} \times 100 = 0.8\%
\]

(23)

Where \( \delta_r, FS \) and \( \Delta \) are repeatability error, maximum input value and maximum difference between two measurements of the same input value.

V. CONCLUSION

The method of ultrasonic level measuring has many advantages. Some of the main characteristics of the ultrasonic level measuring method are: simplicity of installation, non-contact measuring, the material characteristics in container do not affect measuring, and low price of device. Due to its advantages the ultrasonic level measuring in container is even more often used in automated industrial plants.

The construction of ultrasonic level measuring converter is presented in this paper. The processing of the obtained results of measuring has shown that the device meets the requirements set, and that it is possible to incorporate it in the existing standard automation systems. Also, it is possible to be upgraded with a circuit which will increase the amount of its output current value.

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