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**ВИЗНАЧЕННЯ ІНФОРМАТИВНИХ ПАРАМЕТРІВ ТА ОБҐРУНТУВАННЯ ПРАВИЛА ПОРОГОВОЇ ІДЕНТИФІКАЦІЇ ДЕФЕКТІВ У ТЕПЛОВОМУ НЕРУЙНІВНОМУ КОНТРОЛІ**

***О. Zivenko, A. Greshnov, Yu. Zhukov***

*Precision Instrumentation Department, , Admiral Makarov National University of Shipbuilding*

*208, Central Ave. 3, Mykolaiv, 3650, Ukraine; e-mail:* [*oleksii.zivenko@nuos.edu.ua*](mailto:oleksii.zivenko@nuos.edu.ua)

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**Ключові слова**: невизначеність вимірювань, калібрування, радарний датчик рівня направленої дії, діелектрична проникність.

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**Keywords:** measurement uncertainty, calibration, guided wave radar level sensor, dielectric permittivity.

**Introduction**

Accurate level measurement of liquids and solids is essential for standard industrial processes [1]: controlling storage tanks, ensuring precise filling in production lines, preventing overflows or dry running, and complying with stringent safety and environmental regulations. The reliability and precision of level sensors directly impact operational efficiency and product/process quality in industries such as oil and gas, food and beverage, chemical and energy, and manufacturing.

The quality of level sensing can be characterized by accuracy, repeatability, resolution, response time, and the influence of different environmental factors on the measurements. Measurement uncertainty or maximum permissible error (MPE) are critical concepts considered for several applications, such as warehouse monitoring, technological overfill protection, or any safety-related applications. Uncertainty represents the degree of confidence in a measurement result, often defined by statistical analysis, while MPE refers to the largest allowable deviation from the true value during operation. Understanding and minimizing uncertainties makes processes reliable and allows using results of such measurements for specific purposes, e.g., custody transfer applications. This article focuses on guided wave radar (GWR) sensors, which leverage electromagnetic energy for precise level measurement. GWR sensors can operate effectively in a variety of liquids and under extreme environmental conditions. While radar-based sensors are notable for their non-contact operation, which minimizes contamination risks, GWR sensors stand out for applications demanding high precision, such as monitoring liquids with low permittivity or in pressurized vessels. Another advantage of GWR sensors is their ability to work as a polymetric system, enabling simultaneous measurement of multiple parameters, such as level, temperature, and pressure, using a single device. However, achieving and sustaining such accuracy necessitates a meticulous calibration process and corresponding techniques. This process ensures traceability, enhances accuracy and provides consistent performance.

A calibration procedure aligns a sensor’s output to a known standard or reference. This involves adjusting measurements for level sensors to reflect true product levels under controlled conditions.

Calibration can establish/correct the measurement scale during manufacturing and test the accuracy and performance throughout the sensor's lifecycle. By using appropriate reference standards, calibration enables tuning of sensors during production and provides a means to verify the sensor's performance under standard or specific required conditions if a predefined calibration table is available.

This article addresses the calibration of GWR sensors, examining the impact of dielectric permittivity variations under reference and non-reference environmental conditions. It then makes recommendations to reduce measurement uncertainty, which is valuable for manufacturers, end-users, and regulators.

**The main objective** of this study is to analyze the influence of the environmental factors under reference and non-reference environmental conditions and to

1. evaluate the uncertainty in level estimation across extended environmental conditions for particular level sensor and calibration procedures;
2. propose recommendations for sensor manufacturers, end-users and independent evaluators on how to reduce measurement uncertainty.

**Literature review and analysis.** It’s essential to consider a measurement model and corresponding calibration scheme to highlight possible sources of uncertainties.A typical GWR level sensor uses a widely known time domain reflectometry principle [3-9]; the simplified measurement model is described by Eq. (1):

. (1)

where *L* – distance from generator/receiver of electromagnetic pulses; *c* – speed of light in vacuum; ε – dielectric constant of the vapor phase of a product through which the electromagnetic pulse propagates; *t* – time delay between moments of sounding and receiving the reflected pulse; the coefficient of ½ stands for the fact that the electromagnetic pulse propagates along double the length of the probe (forward and backward).

In this case, the main feature used to estimate distance *L* is the time delay *t* (if the vapor's dielectric constant is considered a constant).

However, sources [10-13] show significant variability in the dielectric constant of air (or correlated parameters under changing environmental conditions). Limited focus has been given to how these variations propagate into measurement uncertainty as this influence is traditionally considered as t. This leads to a need for appropriate corrections both for calibration and measurement stages to reduce the overall uncertainty. For example, some known correction techniques consider changes in the dielectric constant of the media, especially when working with vessels under high pressures [14-16]. It’s worth noting that some of these techniques use dynamic or online correction, which is based on some reference knowledge about distances or time-of-flight, while others require direct use of provided correction coefficients and uncertainty measures. Independent of the technique applied, understanding the reference uncertainty after initial calibration is crucial for calculating total uncertainty for a specific application.

**Methodology.** The calibration process for level sensors is typically performed under reference conditions, as defined for accurate sensors in [17]. For the most precise calibrations, national reference standards are employed, such as the Ukrainian National Standard of the Unit of Length for the Liquid Level (DETU 03-02-15) [18]. This standard reproduces the unit of length based on the global constant—the speed of light in a vacuum—and achieves an extended uncertainty of *UNS*=±0.3 mm over a range of 0 to 20 meters. Using interferometers enables highly accurate distance measurements, with the transfer of the unit of length to high-precision level meters conducted via direct comparison.

However, due to the costliness of the full calibration cycle with national standards, equipment manufacturers often employ their own calibration setups. These setups are optimized for their specific technological processes and are generally less accurate than national standards but more practical and cost-effective for routine operations. For instance, the calibration setup at AMICO Group is an example of such an approach. Fig. 1 illustrates the calibration setup used in this study, along with its simplified design and working scheme.

Diagram of a diagram of a flowchart

Description automatically generated

**Figure 1 – Structural Diagram of a Calibration Stand for Evaluation and Tuning of Level Sensors**

Figure 1 illustrates the components of the calibration setup for level sensors:

* Level Sensors Calibration Complex (LSCC): control system managing the calibration process.
* Reference Measurement (RM) Instruments: Equipment responsible for the reference level estimation: laser rangefinder + magnetic encoders-based system to measure the position of the reference plate or reflector;
* Reference Plate (RP): reference plate or reflector.
* Additional Reference Instruments (ARI): temperature, pressure, and humidity sensors distributed in the measurement zone. They allow measuring temperature and humidity at multiple points along the sensing axis of level sensors and the temperature of liquids additionally.
* Pumps and Valves Control Subsystem (PVCS): This subsystem regulates the flow and level of the liquid in the calibration setup;
* Level Sensors under test (LS1..LSn): The sensors are being calibrated.
* Vessels with controllable liquid (V1, V2): These reservoirs store liquid and set a specific liquid level during calibration.

The reference measurement instrument (RM) relies on a precision reflector for accurate operation. During a single calibration cycle, multiple level sensors can be calibrated simultaneously. The procedure involves repeated measurements, capturing the readings from the level sensors under test and those from the reference instrument RM. At the same time, all the environmental parameters are monitored to satisfy the requirements of the particular procedure.

Uncertainties of the reference instruments. The distance (level) measurement reference instrument has an extended uncertainty of ΔLRM= 0.4 mm. Temperature sensors in the calibration complex have extended uncertainty ΔT = 0.5 °C, ΔP = 1 kPa for pressure and ΔRH = 2.5 % for relative humidity.

**Environmental Influence.** The study considers the following reference conditions:

* Temperature (T) in [15, 25] °C.
* Relative Humidity (RH) in [40, 80]%.
* Pressure (P) in [90, 100] kPa.

Values for dielectric permittivity can be interpolated using experimental tabular data [12] or applying known equation [13]:

(2)

where *ε*0 is the permittivity of vacuum, *T* is the absolute temperature (K), RH is the relative humidity (%), *P* (mm Hg) is the pressure of the air, and *PS* (mm Hg) is the pressure of saturated water vapor at the temperature *T*.

**Uncertainty Propagation.** The effect of the changes in *ε*air on the distance estimation ΔLε can be roughly assessed by substituting (2) into the relation for the level estimation (1).

(3)

where ΔLε is the contribution of the uncertainty in distance estimation due to uncertainty in the dielectric permittivity value Δε. There are two main approaches to define Δε depending on the measurement mode used. The first mode is the most widely used, and it assumes no corrections if the measurements are performed within specified ranges of pressure, humidity, and temperature, without applying any corrections for environmental conditions. In this case, the maximum uncertainty in permittivity is defined by the maximum difference in dielectric permittivity values within the given ranges. This approach assumes a worst-case scenario where no compensations for environmental influences are applied, potentially leading to higher uncertainty in distance estimation.

The second approach assumes that the sensor is applying corrections depending on the data about the dielectric constant and uncertainty or based on the environmental conditions and model provided. In this case, for air, the dielectric constant is recalculated using Equation (2). The uncertainty in Δε then can be propagated through the uncertainties of the reference measurements. In this case, corrections are applied to account for the influencing factors, reducing the overall uncertainty in distance estimation and calibration. However, the resulting Δε depends on the accuracy and reliability of the reference instruments used.

It is essential to assess the impact of these factors on the uncertainty in level estimation, considering the trade-off between simplicity, where measurements are taken without additional corrections, and improved accuracy, achieved by applying corrections. Based on the specified reference conditions within the given ranges, the variation analysis reveals the following results for the dielectric constant of air. The minimum value, 1.000543±0.000007, occurs under 45.00% relative humidity, a temperature of 15.0°C, and a pressure of 645 mmHg. The maximum value, 1.000766±0.000010, corresponds to conditions of 75.0% relative humidity, a temperature of 25.0°C, and a pressure of 795 mmHg. The Arden Buck equations were applied to calculate the saturation vapor pressure *Ps* to temperature for moist air [21].

The stated uncertainty interval is derived from uncertainty propagation using Equation (2), based on the uncertainties of the reference sensors for temperature, pressure, and humidity. It’s worth noting Figure 2 shows an example of the dielectric constant dependence for some fixed temperature values while varying the pressure and humidity of air as a media of wave propagation.

A graph of a number of different shades of gray

Description automatically generated with medium confidence

**Figure 2 – Dielectric constant of air depending on humidity value and pressure for a fixed temperature value**

Figure 2 also shows a point with the value of the dielectric constant corresponding to given reference conditions and a region where the dielectric constant lies within the calculated uncertainty region.

It’s necessary to consider additional sources of uncertainty to make a consistent analysis of the contribution to the measurement process. Related to simplified Equation (1) the uncertainty comes from uncertainty in time estimation ΔtR and uncertainty in distance measurement, which comes from the reference measurement instrument ΔLRM. Several factors, including the sounding pulse shape and the signal-to-noise ratio, influence uncertainty in time estimation. These characteristics vary for each specific sensor and play a critical role in determining the accuracy of time measurement.

In general, this uncertainty component depends on the distance between the sensor and the measured surface (or reflector). As the electromagnetic wave propagates, the shape of the reflected pulse changes with distance, introducing additional variability in the time measurement (the amplitude of the reflected signal decreases with the increase in distance decreasing signal-to-noise ratio). To model this dependency, the uncertainty in time estimation Δ*tR* can be expressed as a function of the distance *L*. A practical approach is to approximate this relationship using an exponential curve:

(4)

where *L* is the distance between the generator and interface air-liquid (or reflector), parameters *A* and *B* are determined during the calibration process based on the sensor's characteristics and its operating conditions.

The calibration function is usually stored in a tabular form, and level calculation is done according to Equation (5):

(5)

where – measured delay between sounding and reflected pulses; – corresponding data about distances saved in the calibration table.

The following factors were considered contributing to the total measurement uncertainty:

Nonlinearity between Calibration Points: Hardware tolerances in the guidewave system introduce a nonlinearity of up to ±0.2 mm, representing the maximum permissible deviation between two calibration points. This is a fixed contribution for each segment of the calibration table.

Random Error in Time Estimation Δ*tR*. The random error in time measurement, which varies with the distance L, is modeled using noise analysis and experimental data. The uncertainty in time estimation is calculated using Equation (4) and is distance-dependent, accounting for the degradation of the signal-to-noise ratio with increasing distance.

Uncertainty of the Reference Instrument: The accuracy of the reference device used during the calibration procedure directly impacts the calibration uncertainty. This contribution is considered fixed.

Uncertainty Due to Changes in Dielectric Constant: Variations in environmental conditions affect the propagation time of the electromagnetic pulse, introducing additional uncertainty, and this can be simulated using Equation (6), which propagates uncertainty in the dielectric constant into uncertainty in time estimation due to difference in dielectric constant:

(6)

Using Equations (2), (5), and (6) along with uncertainty propagation techniques, the contributions from each factor were analyzed. The results of these calculations are presented and discussed in the subsequent sections of this article, providing insights into the impact of each uncertainty component on the overall measurement reliability.

**Uncertaintu Calculation Results, Recomendations.**

Dielectric Variability

The analysis shows:

εmax=[Value]εmax​=[Value],

εmin=[Value]εmin​=[Value],

Δε=εmax−εminΔε=εmax​−εmin​.

6.2 Impact on Calibration

Short Distances (<1 m<1m):

Errors are dominated by ruler uncertainty.

Longer Distances (>10 m>10m):

Dielectric variability contributes significantly to uncertainty.

6.3 Recommendations

For Sensor Manufacturers:

Incorporate real-time environmental compensation in GWR devices.

For Metrological Regulators:

**Conclusions**

1. Подано аналіз сутності та наведено приклади застосування правила порогової ідентифікації дефектів у методах неруйнівного контролю при оцінці якості виробів та об‘єктів контролю.

2. Виконано порівняльний аналіз основних характеристик активної та пасивної термографій в тепловому неруйнівному контролі та визначено їх основні інформативні параметри при контролі виробів та об‘єктів тепловізійним методом.

3. Обгрунтовано підхід до побудови правила порогової ідентифікації дефектів при діагностуванні технічного стану промислових димових труб із застосуванням пасивного тепловізійного методу.

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