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CALIBRATION AND OPTIMIZATION OF AN AUTONOMOUS SENSOR CAPSULE

Analysis of durability, dimensional parameters, autonomous operation, and an extended pH measurement range

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Calibration and Optimization of an Autonomous Sensor Capsule
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The book addresses the calibration, testing, and technical optimization of an autonomous experimental sensor capsule designed for long-term operation in chemically aggressive environments. Particular attention is given to the analysis of key technical requirements affecting the system's operational stability, durability, dimensional characteristics, and measurement accuracy.

The publication describes the use of chemically resistant materials, planar solenoids implemented as flat coils on printed circuit boards, and autonomous power-supply systems intended to ensure the prolonged and stable operation of the sensor capsule in physiological solutions, blood, gastric juice, and water with varying salt concentrations.

Special emphasis is placed on optimizing the geometric parameters of the sensor capsule, including the possibility of reducing its external dimensions while preserving functionality and measurement stability. The book also examines the system's extended calibration capabilities for measuring acidity levels across a broad pH range from 1 to 14, with experimental confirmation of its operability in both acidic and alkaline environments.

The presented results demonstrate the technological potential of the proposed sensor platform for the development of compact autonomous monitoring systems intended for biomedical, industrial, and scientific research applications requiring long-term, non-contact analytical monitoring.

Keywords: *Autonomous sensor capsule; electromagnetic resonance spectroscopy; non-contact monitoring; planar solenoid; sensor technologies; calibration testing; real-time monitoring; pH measurement; chemically resistant materials; autonomous power supply; intelligent sensor systems; experimental sensor platform; analytical monitoring; monitoring systems; artificial intelligence; artificial neural networks*

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Contents

LIFETIME – MORE THAN 10 YEARS (Power Consumption)

System Durability and Energy Supply

The prototype of the experimental sensor capsule was constructed exclusively from specialized materials capable of prolonged operation in chemically aggressive environments, including physiological saline solution, blood, gastric juice and its various analogues and equivalents, as well as water with different salt concentrations and equivalent aqueous media.

The use of planar solenoids manufactured as printed circuit boards (PCBs) with a specialized chemically resistant protective coating also ensures the absence of destructive degradation processes for a service life exceeding ten years.

The primary component affecting the long-term autonomous operation of the sensor capsule is the battery providing the electrical energy required for continuous operation.

The long-term reliability of the power supply can only be fully evaluated through realistic simulation and long-duration testing of the capsule operating under autonomous conditions.

SIZE OF THE CAPSULE

Physical Dimensions of the Sensor Capsule

According to the technical specification, the required dimensions of the sensor capsule are:

- Diameter: **30 mm;**
- Length: **100 mm.**

Following computer modeling and experimental testing, the engineering team concluded that the external dimensions could be reduced, if required, to:

- Diameter: **25 mm;**
- Length: **80 mm.**

A key factor enabling this reduction is the use of a planar solenoid implemented as a flat spiral coil on a single-layer printed circuit board.

The PCB dimensions of **16 mm in diameter** and **1.5 mm in thickness** significantly increase the available internal space within the sensor capsule, allowing further miniaturization without compromising system functionality.

Measurement pH Range (3–10)

Extended Acidity Measurement Range

The calibration testing range was expanded to include samples with pH values from **2 to 10**.

From a technological standpoint, the proposed measurement principle does not impose any fundamental limitations on the acidity values that can be measured.

Experimental studies confirmed successful measurements at:

- **pH 1**, using hydrochloric acid for sample preparation;

- **pH 14**, using alkaline household chemical solutions.

These results demonstrate that the specified measurement range is fully achievable in practical applications.

Operational Temperature Range (20–45 °C)

According to the technical specification, measurement accuracy was evaluated using samples maintained at **10 °C, 25 °C, and 40 °C** with a pH value of **6**.

Additional measurements were performed on samples with pH values of **3, 4, 5, 6, and 7** at temperatures of **23 °C** and **39 °C**.

The experimental results demonstrated that the prototype maintained sufficient measurement sensitivity and stability across the entire investigated temperature range for all tested acidity levels.

Measurement Resolution (pH 0.01)

During calibration of the experimental equipment, software capable of adjusting the excitation signal with a frequency resolution of approximately **0.001 MHz** and an amplitude resolution of **1 mV** was employed.

Consequently, the critical factor governing measurement resolution is the amount of electrical energy available for generating the excitation signal.

Battery modeling and optimization of its operating parameters will be carried out during subsequent stages of the project. Nevertheless, the feasibility of achieving the required high measurement resolution has already been experimentally confirmed.

Accuracy of pH Measurement (±0.1 pH)

The required measurement accuracy was successfully achieved during system calibration.

Because calibration was performed using liquid samples with precisely characterized pH values while simultaneously conducting real-time reference measurements of temperature and colorimetric parameters, the transition to glucose concentration measurements demonstrated a comparable level of measurement accuracy.

Influence of Sample Content (Particles)

The influence of suspended particles was evaluated using coarse wheat flour at concentrations specified in the technical requirements:

- **100 g/L;**
- **200 g/L;**
- **400 g/L.**

The penetration depth of the electromagnetic field generated by the planar PCB-based coil into the liquid sample is approximately **1–1.5 mm**.

Since the flour particles gradually settled to the bottom of the container, their presence had virtually no influence on the measurement results.

Additional experiments were performed by introducing orange pulp into gastric juice samples with a pH value of **6** at a concentration of **10 g per 100 mL**.

The measurement results obtained from gastric juice samples with and without orange pulp were practically identical, demonstrating that suspended biological particles exerted no significant influence on the sensor system's measurement performance.

FEED CONTENT

Influence of Additional Components Introduced into the Test Samples

As required by the technical specification, the influence of various substances introduced into the test samples on measurement performance was evaluated. Since the test media included simulated gastric juice, hydrochloric acid, and tap water containing dissolved salts and hardness salts at a concentration of **400 mg/L**, the effects of the introduced additives varied depending on their concentration.

Additives at concentrations of **10 mg/L** and **60 mg/L** produced no measurable influence on the measurement results.

Similarly, additives at a concentration of **0.6 g/L** showed no significant effect on the measured parameters.

At a concentration of **1.2 g/L**, the additives produced frequency-dependent responses. However, at the operating measurement frequency of **25 MHz**, the obtained results were identical to those of reference samples with a pH value of **6** containing no additives.

The same behavior was observed for additives at a concentration of **6 g/L**. Although frequency-dependent variations were recorded, measurements performed at **25 MHz** remained identical to those obtained from reference pH 6 samples without additives.

Simulation of Capsule Orientation in Space, Including Contact Between the Sensor Surface and the Patient's Body

The influence of a **5 mm thick beef tissue sample** positioned **2 mm** from the planar sensor coil was investigated.

The penetration depth of the electromagnetic field generated by the impulse excitation system, when using a planar single-layer PCB coil, is approximately **1–1.5 mm**.

Under these conditions, the beef tissue sample located 2 mm from the face of the planar sensor coil produced **no measurable effect** on the accuracy or quality of the measurements.

The influence of direct contact between the beef tissue sample and the planar sensor coil was also investigated.

To compensate for complete contact between biological tissue and the sensor surface, the planar sensor coil should be structurally recessed by approximately **1.5 mm** beneath the outer surface of the sensor capsule.

Repeatability of Measurement Results

The repeatability test was conducted according to the following procedure:

- More than **1 gallon of distilled water** and **1 gallon of tap water** were prepared;
- The sample containers were hermetically sealed;
- Measurements were performed under the following operating conditions:

Frequency: 26.25 MHz

Signal amplitude:

- Distilled water: **9850 mV;**
- Tap water: **9590 mV.**

The identical comparative test was repeated **five times** at **three-day intervals** using the same water samples.

The measurement results obtained for samples having identical chemical compositions were **completely reproducible**,

demonstrating excellent repeatability and long-term measurement stability.

TECHNICAL REQUIREMENTS ANALYSIS

Preliminary Calibration of the Test Equipment

During the calibration procedure, the following verification activities were performed:

- Evaluation of compliance with the project technical requirements;
- Assessment of the feasibility of meeting the specified technical performance criteria;
- Verification of the expected operational lifetime of the device;
- Confirmation of the principal dimensions of the sensor capsule;
- Verification of the measurable acidity (pH) range;
- Evaluation of the operating and environmental temperature ranges;
- Verification of the required pH measurement accuracy;
- Assessment of the measurement limits and resolution for gastric acidity determination;
- Evaluation of the influence of food particles or other substances located on the patient's skin at the measurement site;
- Assessment of the influence of varying concentrations of chemical components present within the measurement zone.

Calibration demonstrated that all specified parameters fully satisfied the technical requirements and confirmed the readiness of the equipment, materials, and instrumentation for test-

ing in accordance with the first-stage experimental test program.

Results of Equipment and Monitoring Device Preparation for Testing and the Influence of the Obtained Experimental Results on the Design Principles of the Autonomous Sensor Device

The calibration and experimental testing program confirmed the operational readiness of the monitoring equipment and validated the fundamental engineering principles adopted for the design of the autonomous sensor capsule.

The obtained experimental data provided essential information for optimizing the structural design, material selection, sensor configuration, and operating parameters of the autonomous monitoring device.

Furthermore, the calibration results confirmed the capability of the proposed measurement methodology to reliably identify acidity (pH) levels and other target analytical parameters, thereby supporting the feasibility of implementing the sensor capsule in long-term biomedical, industrial, and scientific monitoring applications.

Selection and Experimental Validation of Structural Materials

- Selection and experimental validation of structural materials;
- Selection and experimental validation of protective coatings;
- Selection and experimental validation of the sensor design configuration, including a comparative analysis of alternative sensor designs;

- Selection and experimental validation of the test setup;
- Preparation of liquid samples for testing;
- Procedure for measuring acidity levels before and after testing;
- Influence of temperature on acidity levels;
- Influence of time on the stability of acidity levels;
- Influence of the chemical composition of the samples on acidity levels;
- Influence of organic materials or fruit juices present in the samples on acidity levels.

The influence of coarse-ground wheat flour present in the sample was assessed at the concentrations specified in the technical requirements table:

- **100 g/L**
- **200 g/L**
- **400 g/L**

The penetration depth of the signal generated by the pulse generator into the liquid sample, when the planar coil is implemented as a single-layer printed circuit board, is approximately **1–1.5 mm**.

For the subsequent stages of measurement calibration and experimental testing, the following potential evaluation procedure should be considered.

Influence of Biological Tissue Positioned Near the Sensor

The influence of a **5 mm thick beef tissue sample** positioned within the test medium at a distance of **2 mm** from the planar sensor coil should be evaluated.

The penetration depth of the signal generated by the pulse generator into the liquid sample, when the planar coil is manu-

factured as a single-layer printed circuit board, is approximately **1–1.5 mm**.

A beef tissue sample positioned at a distance of 2 mm from the face of the planar coil should not affect the quality or accuracy of the measurements.

The influence of a beef tissue sample placed in direct contact with the planar sensor coil should also be assessed.

Considering that the signal penetration depth is approximately **1–1.5 mm**, compensation for full contact between the biological tissue and the planar sensor coil requires the coil to be structurally recessed by approximately **1.5 mm** below the outer surface of the sensor assembly.

Calibration of the Primary Test Equipment for Assessing the Fundamental Feasibility of the Technology

The principal tasks addressed during the evaluation of the technology's fundamental operability included determining differences in measurement responses and carrying out a comparative assessment of controlled liquid samples with the following characteristics:

- distilled-water-based samples with pH values ranging from **4 to 7**, adjusted by adding hydrochloric acid;
- tap-water-based samples with pH values ranging from **4 to 7**, adjusted by adding hydrochloric acid;
- distilled-water-based samples with pH values ranging from **2 to 7**, adjusted by adding hydrochloric acid;
- tap-water-based samples with pH values ranging from **2 to 7**, adjusted by adding hydrochloric acid;

- distilled-water-based samples with pH values ranging from **4 to 7**, adjusted by adding hydrochloric acid and tested at **25 °C**;
- tap-water-based samples with pH values ranging from **4 to 7**, adjusted by adding hydrochloric acid and tested at **25 °C**;
- distilled-water-based samples with pH values ranging from **4 to 7**, adjusted by adding hydrochloric acid and tested at **39 °C**;
- tap-water-based samples with pH values ranging from **4 to 7**, adjusted by adding hydrochloric acid and tested at **39 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **25 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **25 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **40 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **40 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **25 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **25 °C**;

- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **10 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and tested at **10 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and fruit juice and tested at **25 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and fruit juice and tested at **25 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and sodium chloride and tested at **25 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and sodium chloride and tested at **25 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and sodium bicarbonate and tested at **25 °C**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water and sodium bicarbonate and tested at **25 °C**;
- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water, maintained at **25 °C**, and tested **1 hour after preparation**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water, maintained at **25 °C**, and tested **1 hour after preparation**;

- hydrochloric-acid-based samples with pH values ranging from **2 to 7**, adjusted by adding distilled water, maintained at **25 °C**, and tested **24 hours after preparation**;
- simulated gastric juice samples with pH values ranging from **2 to 7**, adjusted by adding distilled water, maintained at **25 °C**, and tested **24 hours after preparation**;
- simulated gastric juice samples with a pH value of **6**, containing **10% fruit juice with pulp**;
- simulated gastric juice samples with a pH value of **6**, containing **1% sodium chloride**;
- simulated gastric juice samples with a pH value of **6**, containing **2% sodium chloride**;
- simulated gastric juice samples with a pH value of **6**, containing **1% sodium bicarbonate**;
- simulated gastric juice samples with a pH value of **6**, containing **2% sodium bicarbonate**.

Design of the Container and Upper Flange for Installation of the Capsule Simulator Used for pH Measurement

The liquid-sample container was designed so that its upper flange fits tightly against the cylindrical body of the container without any gaps.

The capsule simulator used for pH measurement is also equipped with a support flange that fits tightly against the upper flange of the container without any gaps.

This design prevents direct contact between the sample and the surrounding atmosphere during measurement, thereby eliminating oxidation processes caused by exposure of the sample to atmospheric oxygen.

One group of samples included mixtures with pH values of **4, 5, 6, and 7**. During each measurement, up to **1,000 combinations of frequency and amplitude** of the directional pulse generated by the pulse generator were monitored.

Another group of samples included mixtures with pH values of **2, 3, 4, 5, 6, and 7**. During each measurement, up to **1,000 combinations of frequency and amplitude** of the directional pulse generated by the pulse generator were monitored.

Additional Chemical Component Used for Sample Preparation

High-purity hydrochloric acid, certified by leading chemical laboratories in California, was used as an additional chemical component in the preparation of measurement samples.

A precision dropper was used to introduce the acid into the sample volume.

After each addition, the resulting pH level was measured using a laboratory instrument and subsequently verified using a reference instrument. Before each use, the reference instrument was calibrated using standard buffer solutions with pH values of **4 and 7**.

Simulated Gastric Fluid Used as the Primary Sample Component

Pepsin-free simulated gastric fluid was used as the principal component for preparing the test and measurement samples.

A precision dropper was used to introduce the pepsin-free simulated gastric fluid into the sample volume.

After each addition, the resulting pH level was measured using a laboratory instrument and subsequently verified using

a reference instrument. Before each use, the reference instrument was calibrated using standard buffer solutions with pH values of **4 and 7**.

Prototype Sensor Capsule with a Conventional Solenoid Coil

A system incorporating a conventional solenoid coil was designed as the prototype measurement and testing device.

The solenoid coil was wound around an internal sleeve. All electrical conductors were routed through the axial channel of the sleeve to the external measuring instruments.

Several coil configurations were tested, using different wire diameters and different numbers of turns.

Selection of the Planar Coil Sensor Configuration

Based on the combined results of testing and measurement, the most effective sensor configuration was found to be a planar coil implemented as a single-layer or multilayer printed circuit board.

For the tested configuration, the printed circuit board had the following dimensions:

- **Outer diameter:** 16 mm;
- **Thickness:** 1.5 mm.

The PCB topology incorporates two spiral systems:

- a single-turn spiral;
- a concentric planar solenoid consisting of **29 spiral turns**.

Two installation configurations were evaluated for the PCB-based sensor:

1) installation of the printed circuit board inside the prototype capsule housing with an intermediate membrane;

2) installation of the printed circuit board inside the cylindrical housing without an intermediate membrane.

Testing demonstrated that the best measurement results were obtained when the printed circuit board was installed directly in the cylindrical housing without an intermediate membrane.

Recommended Method for Installing the Planar Solenoid

The test and measurement results showed that the most sensitive and stable configuration involved installing the planar solenoid, protected by a specialized chemically resistant coating, within an external recess formed in the capsule housing.

Considering the anticipated capsule dimensions – **30 mm in diameter and 80 mm in length** – this installation method is expected to preserve the entire internal cylindrical volume of the capsule body, approximately:

- **22 mm in diameter;**
- **72 mm in length.**

This internal volume remains available for installation of the capsule's other components while retaining the simplest possible external geometry.

The simple geometric form of the capsule also makes it possible to apply various innovative protective coatings over its entire external surface, including an **artificial diamond film coating**.

Preparation of Liquid Samples for Testing and Measurement

The following source materials were used to prepare the liquid samples.

Since the principal measurements were intended to be performed using gastric fluid or its synthetic equivalents, simulated gastric fluid was used as the base material representing natural gastric juice. Its initial pH was approximately **1.0–1.4**.

According to the technical specification and the known biological characteristics of gastric fluid, the most significant pH changes occur within the range of **pH 3 to pH 7**. The material was therefore used to prepare measurement samples according to two different procedures.

First preparation procedure

Distilled water with an initial pH of approximately **7** was used as the base liquid. Simulated gastric fluid was then added to obtain samples with pH values of:

- 6;
- 5;
- 4;
- 3;

Second preparation procedure

Simulated gastric fluid was used as the base liquid. Distilled water was then added to increase the pH from the initial value of approximately **1.0–1.4** to:

- 2;
- 3;
- 4;
- 5;
- 6;

A similar procedure was used to prepare distilled-water-based and tap-water-based samples. The tap water had an

electrical conductivity of approximately **240 µS**, and hydrochloric acid with a pH of approximately **1** was added to the mixture.

First hydrochloric-acid preparation procedure

Distilled water with an initial pH of approximately **7** was used as the base liquid. Hydrochloric acid was then added to obtain samples with pH values of:

- 6;
- 5;
- 4;
- 3;

Second hydrochloric-acid preparation procedure

Hydrochloric acid was used as the base liquid. Distilled water was then added to increase the pH from approximately **1.0–1.4** to:

- 2;
- 3;
- 4;
- 5;
- 6;
- 7.

RESULTS OF PREPARING THE EQUIPMENT AND MONITORING DEVICE FOR TESTING

The preparation stage evaluated the influence of the obtained measurement and test results on:

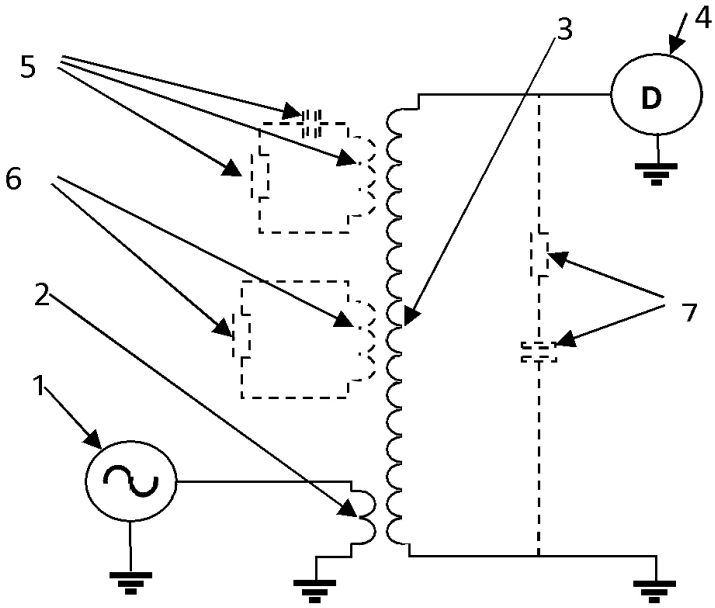
- the design principles of the autonomous device, namely the sensor capsule;
- the interpretation of the measurement results;
- identification of sample parameters, including the pH of simulated gastric fluid.

The following activities were carried out:

- selection and experimental validation of structural materials;
- selection and experimental validation of protective coatings;
- selection and experimental validation of the sensor design configuration;
- comparative analysis of alternative sensor designs;
- selection and experimental validation of the test setup;
- preparation of liquid samples for testing;
- development of the procedure for measuring pH before and after testing;
- evaluation of the influence of temperature on pH;
- evaluation of the influence of time on pH stability;
- evaluation of the influence of sample chemical composition on pH;
- evaluation of the influence of organic materials or fruit juices present in the sample on pH.

All matters and tasks specified in the technical requirements and the technical specification will be addressed in detail in the subsequent sections of the final report.

Principle of measurement (electromagnetic coupling with object under test)



Equivalent circuitry of RIST-sensor illustrates an electromagnetic coupling with analyte

Schematic of RIST-sensor (depicted with solid line)

1 – source of an alternating electric field with frequency sweep (sweep generator)

2 – excitation coil

3 – sensing coil

4 – data acquisition system

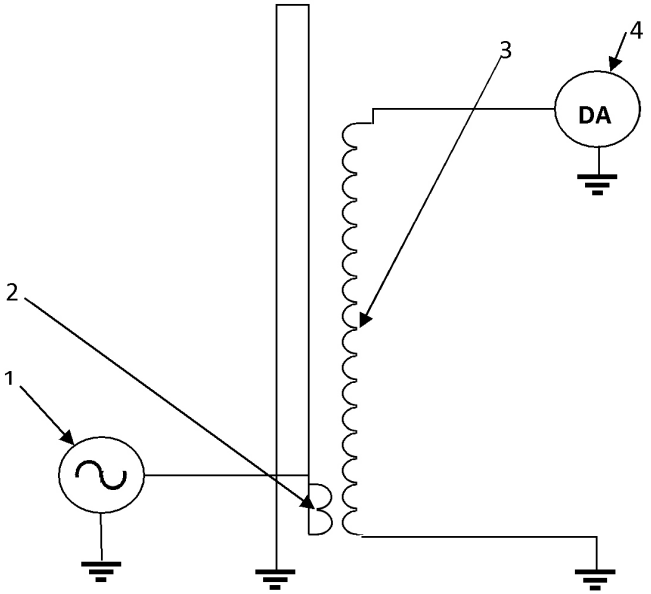
Electromagnetic response of object under test (depicted with dash line)

5 – vertical displacement currents (dielectric polarization)

6 – vertical ionic currents and eddy currents

7 – linear conductance, displacement and ionic currents caused by difference in electrical potential spread along of the sensing coil.

Schematic of the set-up



Schematic of RIST-sensor (depicted with solid line)

1 – source of an alternating electric field with frequency sweep (sweep generator)

2 – excitation coil

3 – sensing coil

4 – data acquisition system – checking the sensor's response to the temperature of the controlled liquid

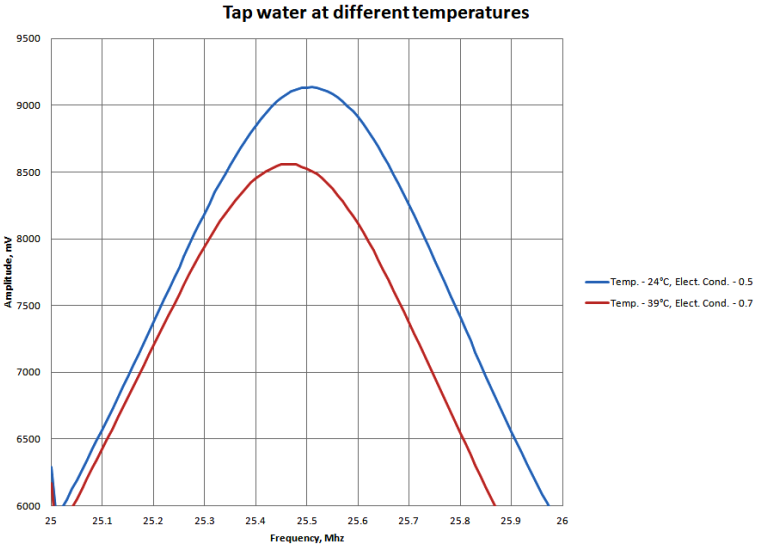
Effect of Temperature on Electrical Conductivity and Resonance Response

Since the normal human body temperature is approximately **36.5 °C**, it is essential during the calibration process to evaluate how the electrical conductivity and resonance response of ordinary drinking water change at this temperature.

Experimental results demonstrated that increasing the temperature of drinking water from **24 °C to 39 °C** increased its electrical conductivity from approximately **0.5** to **0.7** (as measured under the experimental conditions).

As the concentration of mobile ions in the water increases with temperature, the measurement process becomes more precise while requiring a lower level of excitation energy.

Accordingly, during the next stage of experimental testing, all water samples with different acidity (pH) levels should be heated to **36.5 °C** prior to measurement in order to simulate physiological operating conditions and ensure consistent calibration results.



Control and Adjustment of Initial Acidity

The initial acidity (pH) should be verified and adjusted **after heating the sample to 36.5 °C** and immediately before the start of each test.

If the pH changes as a result of temperature-induced effects, the required amount of hydrochloric acid should be added to the sample using a precision dropper. The pH should then be remeasured, followed by a verification measurement of the sample temperature before proceeding with the test.

Verification of the Influence of Sensor Immersion Depth

The response of the test equipment should be evaluated as a function of the depth of sensor immersion in the monitored liquid.

Calibration measurements demonstrated that the highest measurement quality and sensitivity are achieved when the sensor cylinder is immersed to the maximum practical depth within the test liquid.

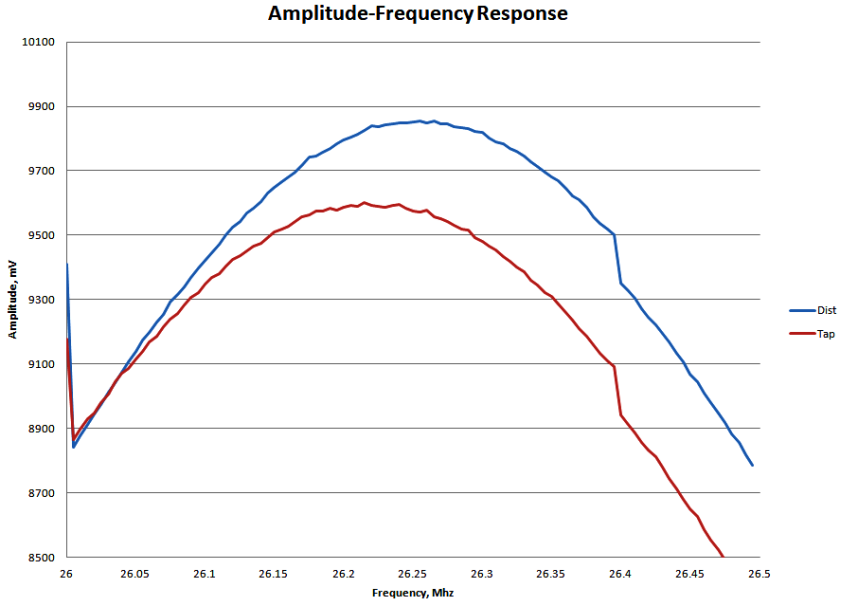
Preliminary results indicate that the wall thickness of the cylindrical housing inserted into the sample container does not have a significant influence on measurement performance.

Comparison of Sensor Response in Distilled and Drinking Water

A comparative evaluation should be performed to determine differences in the sensor response when operating in distilled water and drinking (tap) water.

The objective of this assessment is to quantify the influence of dissolved ions and the resulting electrical conductivi-

ty of the medium on the electromagnetic resonance response and overall measurement characteristics of the sensor system.



Results of Deep Sensor Immersion in the Test Liquid

The diagram illustrates the measurement results obtained with the sensor immersed deeply into the monitored liquid.

As shown in the graph, a pronounced contrast of approximately **400 mV** is observed between measurements performed in **distilled water** and **drinking (tap) water**.

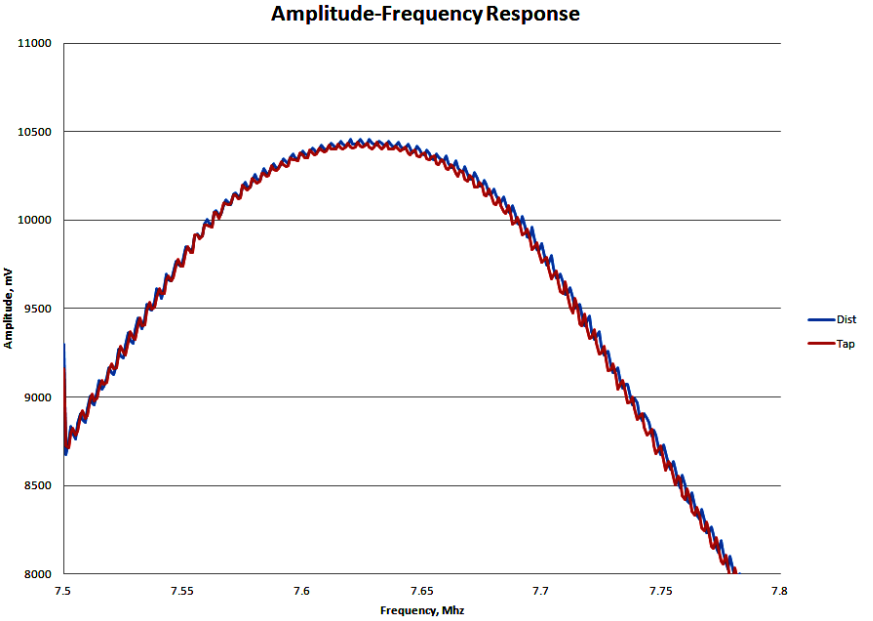
The next stage of the study will involve testing the same sensor configuration while varying the acidity of the samples from **neutral (pH 7)** to **moderately acidic (pH 4)**.

Evaluation of System Performance at Low Operating Frequencies

For the selected device dimensions and measurement configuration, experiments performed at reduced excitation

frequencies demonstrated that such frequencies do not provide sufficient measurement contrast in media containing low concentrations of active ions, including distilled water and low-conductivity drinking water.

A similar series of experiments is planned using drinking-water samples containing controlled additions of concentrated hydrochloric acid, producing acidity levels below pH 7, in order to evaluate the effectiveness of the system under low-frequency operating conditions across a wider range of acidity levels.



Analysis of the Influence of Cable Length on System Sensitivity

Following the identification of this issue, a series of dedicated measurements and experimental studies was conducted. The results demonstrated a partial dependence of signal quality on the length of the cables (conductors) connecting the

sensor solenoids to the signal acquisition and analytical processing unit.

Additional investigations will be performed using samples with higher electrical conductivity and stronger signal amplitudes in order to evaluate the influence of cable length under operating conditions representative of practical applications.

Methodology and Materials for Adjusting the Acidity of Liquid Samples

Following the recommendations of a leading Silicon Valley laboratory, concentrated hydrochloric acid was selected as the reference reagent for adjusting the acidity of the test samples. The reagent used in the calibration experiments is shown in the subsequent photographs.

Adjustment of the sample acidity will be performed by the controlled dropwise addition of hydrochloric acid into the liquid sample using a precision dispensing device.

In addition, to simulate the presence of nutrient components within the test samples during this stage of the calibration program, food-grade vinegar will also be introduced dropwise, in parallel with the hydrochloric acid additions, thereby enabling assessment of the influence of additional organic constituents on the sensor response.

Comments on the Calibration Tests

The calibration experiments confirmed the fundamental feasibility of the proposed measurement methodology and provided valuable information for optimizing both the sensor configuration and the experimental procedures.

The obtained results indicate that the measurement system exhibits sufficient sensitivity and stability for distinguishing liquid samples with different acidity levels under controlled laboratory conditions. At the same time, the experiments identified several parameters requiring further optimization, including excitation frequency, cable length, sample temperature, and the electrical conductivity of the measured medium.

The calibration program also demonstrated the importance of maintaining standardized sample preparation procedures and strict control of environmental conditions in order to achieve maximum measurement repeatability and accuracy.

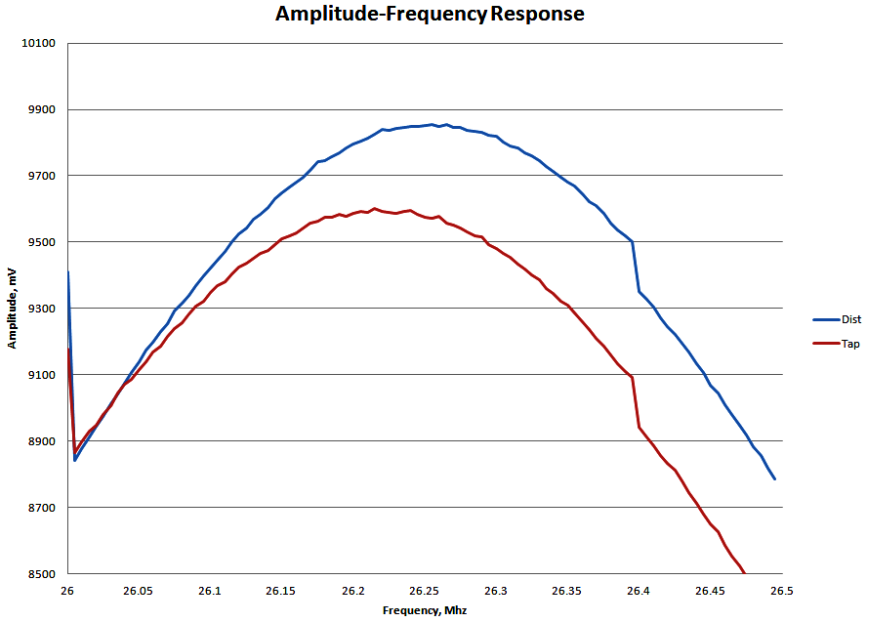


Diagram 1. Frequency and Amplitude Measurements of Distilled and Tap Water Samples

The findings obtained during this stage will serve as the basis for subsequent experimental investigations aimed at improving the autonomous sensor capsule and validating its performance under conditions representative of biomedical, industrial, and research applications.

The diagram presents the measured frequency and amplitude responses obtained from **distilled water** and **tap water** samples under identical room-temperature conditions and equivalent excitation signal (pulse) parameters.

The objective of this experiment was to verify whether the measurement system possesses sufficient sensitivity to reliably distinguish between distilled water and tap water.

The evaluation was performed using the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

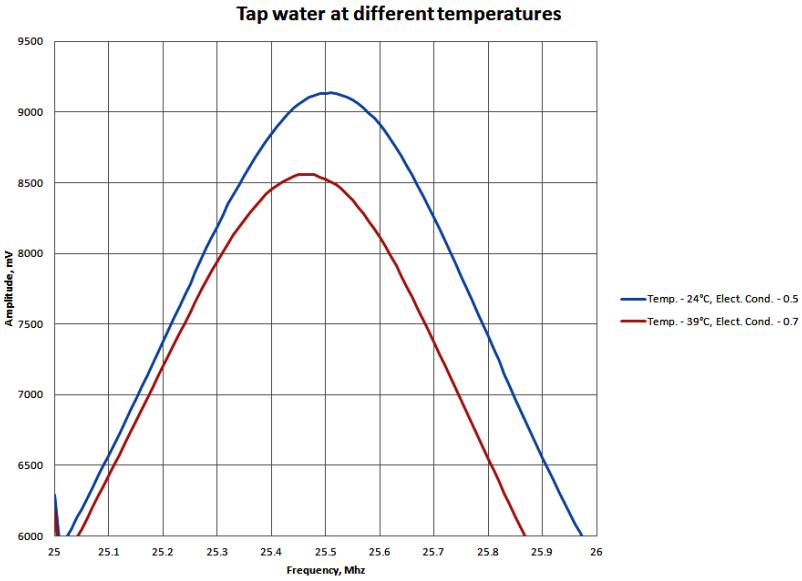


Diagram 2. Frequency and Amplitude Measurements of Tap Water Samples at Different Temperatures

The experimental results demonstrated a high sensitivity potential of the proposed technology. Despite the relatively small physicochemical differences between distilled and tap water, the system produced clearly distinguishable measurement responses, confirming its capability to detect subtle variations in the electrical properties of the monitored media.

The diagram presents the measured frequency and amplitude responses obtained from tap water samples at room temperature (24 °C) and 39 °C, using identical excitation signal (pulse) parameters. The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between water samples differing only in temperature by 15 °C.

The evaluation was performed on the experimental test bench by varying the frequency and amplitude of the directed excitation signal (pulse).

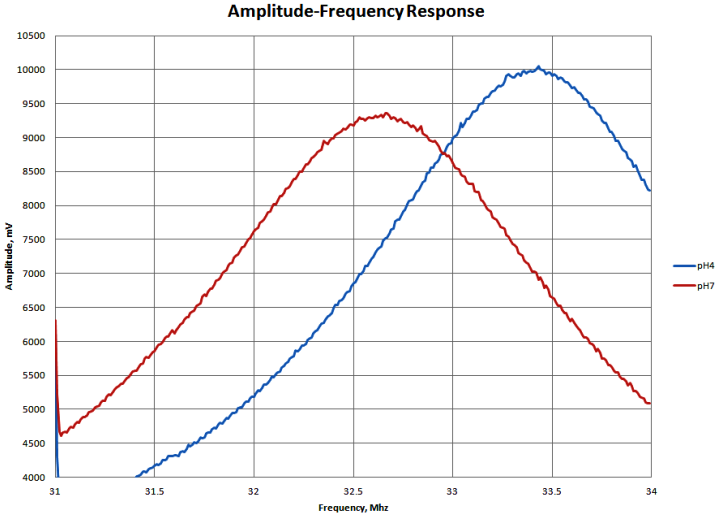


Diagram 3. Frequency and Amplitude Measurements of Distilled and Tap Water Samples with pH Values of 4 and 7

The experimental results demonstrated a high sensitivity potential of the proposed technology. Despite the relatively small difference in the physical properties of the water caused solely by the 15 °C temperature variation, the system produced clearly distinguishable frequency and amplitude responses, confirming its capability to detect subtle temperature-induced changes in the electrical characteristics of the measured medium.

The diagram presents the measured frequency and amplitude responses obtained from **distilled water** and **tap water** samples with acidity levels of **pH 4** and **pH 7**, measured at room temperature under identical excitation signal (pulse) conditions.

The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between **pH 4** and **pH 7** in samples prepared using distilled water and tap water. The required acidity levels were obtained by adjusting the samples with controlled additions of hydrochloric acid.

The evaluation was performed on the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

The experimental results demonstrated a high sensitivity potential of the proposed technology. Although the physicochemical differences between distilled water and tap water are relatively small, and the detection of the difference between **pH 4** and **pH 7** becomes particularly challenging in media with low ionic strength and low dissolved salt concentrations, the measurement system successfully produced distinguishable frequency and amplitude responses. These results confirm the capability of the proposed technology to detect subtle variations in acidity even under low-conductivity conditions.

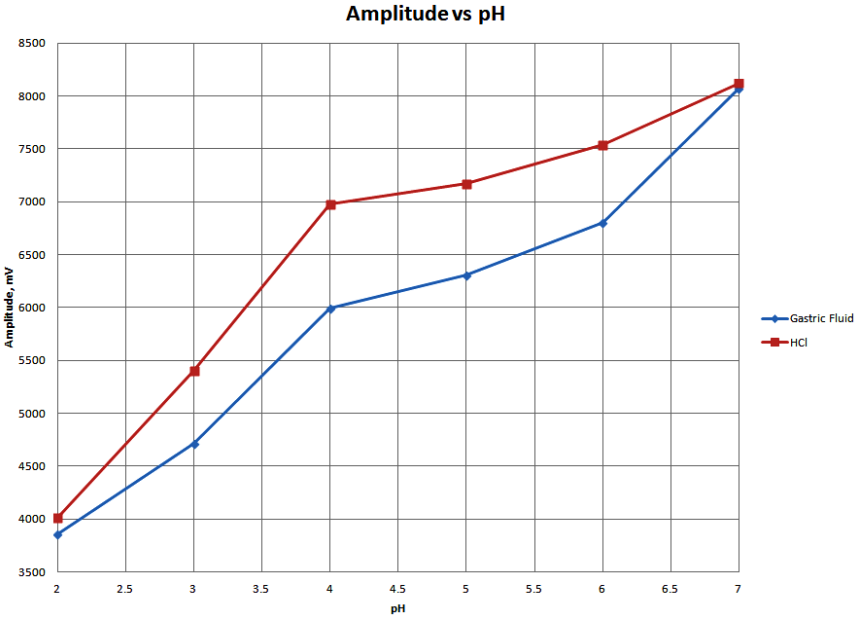


Diagram 4. Frequency and Amplitude Measurements of Simulated Gastric Fluid and Hydrochloric Acid Samples with pH Values from 2 to 7

The diagram presents the measured frequency and amplitude responses obtained from samples prepared using **simulated gastric fluid** and **hydrochloric acid**, with acidity levels of **pH 2, 3, 4, 5, 6, and 7**, measured at room temperature under identical excitation signal (pulse) conditions.

The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between **pH values of 2, 3, 4, 5, 6, and 7** in samples prepared using simulated gastric fluid and hydrochloric acid. The desired acidity levels were obtained by adjusting the samples through the controlled addition of tap water.

The evaluation was performed on the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

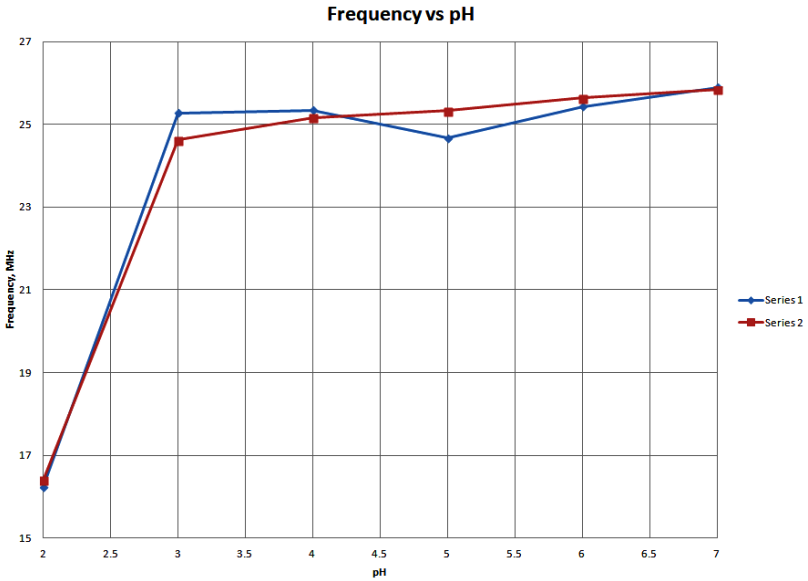


Diagram 5. Frequency Measurements of Simulated Gastric Fluid and Hydrochloric Acid Samples with pH Values from 2 to 7 Following a One-Hour Measurement Interval

The experimental results demonstrated a high sensitivity potential of the proposed technology. Despite the relatively small physicochemical differences between the two sample media, the measurement system successfully differentiated samples across the entire investigated **pH range from 2 to 7**. Detecting these acidity levels is particularly challenging because of the relatively low concentration of dissolved salts and the similarity of the electrical properties of the test media. Nevertheless, the system produced distinct frequency and amplitude responses corresponding to each pH level, confirming the capability of

the proposed technology to perform accurate and reliable differentiation of acidity over the investigated range.

The diagram presents the measured frequency responses obtained from samples prepared using simulated gastric fluid and hydrochloric acid, with acidity levels of pH 2, 3, 4, 5, 6, and 7, measured at room temperature under identical excitation signal (pulse) conditions. The measurements were repeated after a one-hour interval.

The objective of this experiment was to evaluate the capability of the measurement system to reliably distinguish between pH values of 2, 3, 4, 5, 6, and 7 in samples prepared from simulated gastric fluid and hydrochloric acid following a defined period of sample stabilization. The required acidity levels were obtained by controlled adjustment of the samples through the addition of tap water.

The evaluation was carried out using the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

The experimental results demonstrated a high sensitivity and excellent short-term stability of the proposed technology. Despite the minimal physicochemical differences between the two sample media and the relatively low concentration of dissolved salts, which makes discrimination between pH values of 2 to 7 particularly challenging, the system consistently generated distinguishable frequency responses after the one-hour interval. These findings confirm that the proposed measurement technology maintains reliable performance and measurement repeatability over time while preserving its ability to differentiate subtle variations in acidity under controlled laboratory conditions.

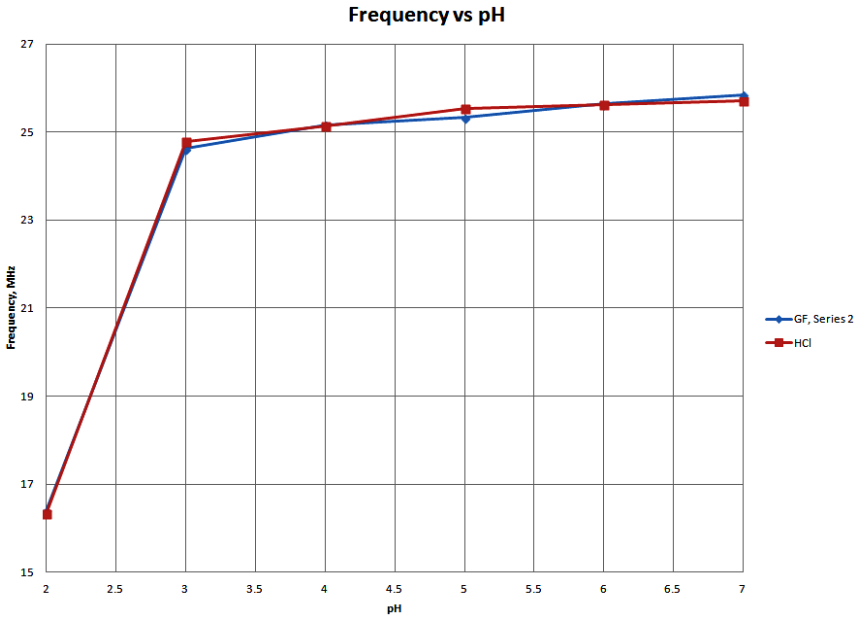


Diagram 6. Frequency Measurements of Simulated Gastric Fluid and Hydrochloric Acid Samples with pH Values from 2 to 7

The diagram presents the measured frequency responses obtained from samples prepared using simulated gastric fluid and hydrochloric acid, with acidity levels of pH 2, 3, 4, 5, 6, and 7, measured at room temperature under identical excitation signal (pulse) conditions.

The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between pH values of 2, 3, 4, 5, 6, and 7 in samples prepared using simulated gastric fluid and hydrochloric acid. The required acidity levels were achieved by adjusting the samples through the controlled addition of tap water.

The evaluation was carried out on the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

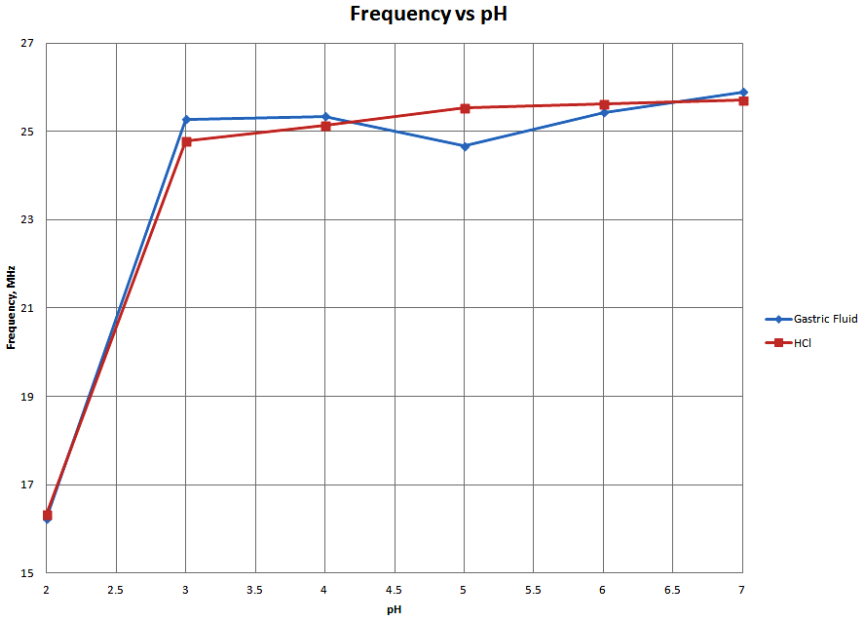


Diagram 7.

The experimental results demonstrated the high sensitivity of the proposed technology. Although the physicochemical differences between the two types of test media are relatively small, and discrimination between pH values of 2 to 7 is particularly challenging because of the low concentration of dissolved salts, the measurement system generated clearly distinguishable frequency responses across the entire investigated pH range. These findings confirm the capability of the proposed technology to accurately differentiate subtle variations in acidity under controlled laboratory conditions, supporting its suitability for non-contact analytical monitoring applications.

The diagram 7 shows the results of frequency measurements for samples based on simulated gastric juice and hydrochloric acid, with acidity levels of 2, 3, 4, 5, 6, and 7 units, at room temperature and with similar and equivalent signal (pulse) parameters.

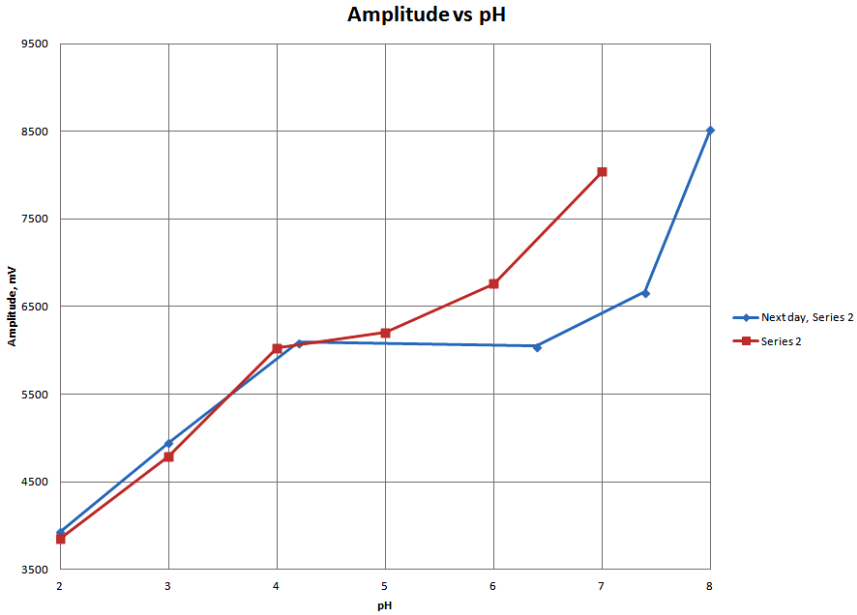


Diagram 8. Amplitude Measurements of Simulated Gastric Fluid and Hydrochloric Acid Samples with pH Values from 2 to 8 Following a 24-Hour Measurement Interval

The purpose of this experiment is to verify that the sensitivity of the device is sufficient to distinguish between acid levels of 2, 3, 4, 5, 6, and 7 units in samples based on simulated gastric juice and hydrochloric acid, while adjusting the acid level by introducing tap water into the sample The test was carried out on a test bench when changing the frequency and amplitude of the directional signal (pulse)

The test showed a high potential for the sensitivity of the technology, due to the fact that the difference in the characteristics of the two types of samples is minimal, and the acid level of 2, 3, 4, 5, 6, and 7 units in combination with a low level of salt concentration in the samples is quite difficult to catch.

The diagram presents the measured amplitude responses obtained from samples prepared using simulated gastric fluid and hydrochloric acid, with acidity levels of pH 2, 3, 4, 5, 6, 7, and 8, measured at room temperature under identical excitation signal (pulse) conditions.

The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between pH values of 2, 3, 4, 5, 6, 7, and 8 in samples prepared from simulated gastric fluid and hydrochloric acid. The desired acidity levels were achieved by adjusting the samples through the controlled addition of tap water. The measurements were repeated after a 24-hour interval to assess the stability and repeatability of the system over time.

The evaluation was performed on the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

The experimental results demonstrated a high sensitivity and excellent long-term stability of the proposed technology. Despite the minimal physicochemical differences between the two types of test media and the low concentration of dissolved salts – which makes discrimination between pH values from 2 to 8 particularly challenging – the system generated clearly distinguishable amplitude responses throughout the investigated pH range. The consistency of the results obtained after

the 24-hour interval confirms the repeatability, stability, and analytical capability of the proposed measurement technology for long-term non-contact monitoring applications.

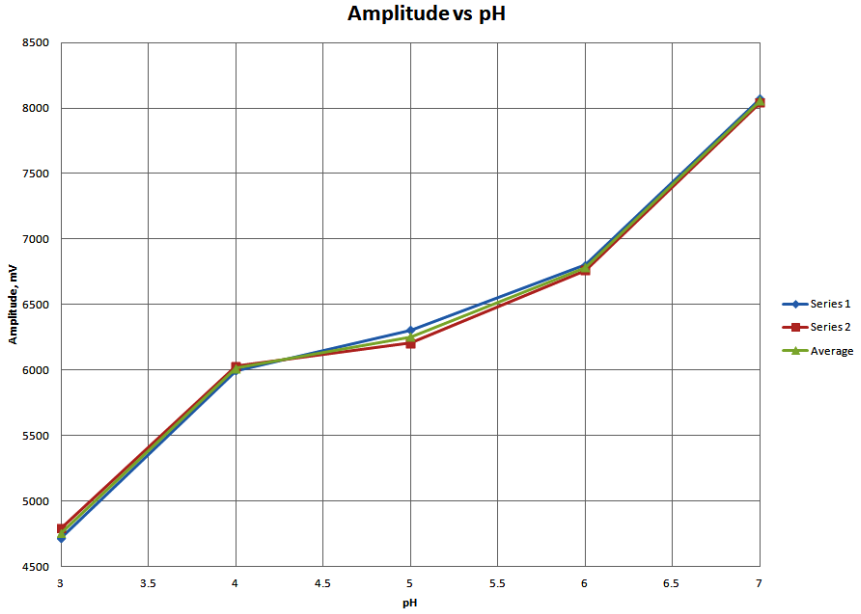


Diagram 9. Amplitude Measurements of Simulated Gastric Fluid and Hydrochloric Acid Samples with pH Values from 2 to 8

Diagram 9 presents the measured **amplitude responses** obtained from samples prepared using **simulated gastric fluid** and **hydrochloric acid**, with acidity levels of **pH 2, 3, 4, 5, 6, 7, and 8**, measured at room temperature under identical excitation signal (pulse) conditions.

The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between pH values of 2, 3, 4, 5, 6, 7, and 8 in samples prepared using simulated gastric fluid and hydrochloric acid. The required acidity levels were achieved by adjusting the sam-

ples through the controlled addition of tap water. Two series of measurements were performed with a one-hour interval, and the mean amplitude value was calculated for each sample.

The evaluation was carried out on the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

The experimental results demonstrated a high sensitivity potential of the proposed technology. Although the physico-chemical differences between the two types of test media are relatively small, and discrimination between pH values from 2 to 8 is particularly challenging because of the low concentration of dissolved salts, the system generated clearly distinguishable amplitude responses throughout the investigated pH range.

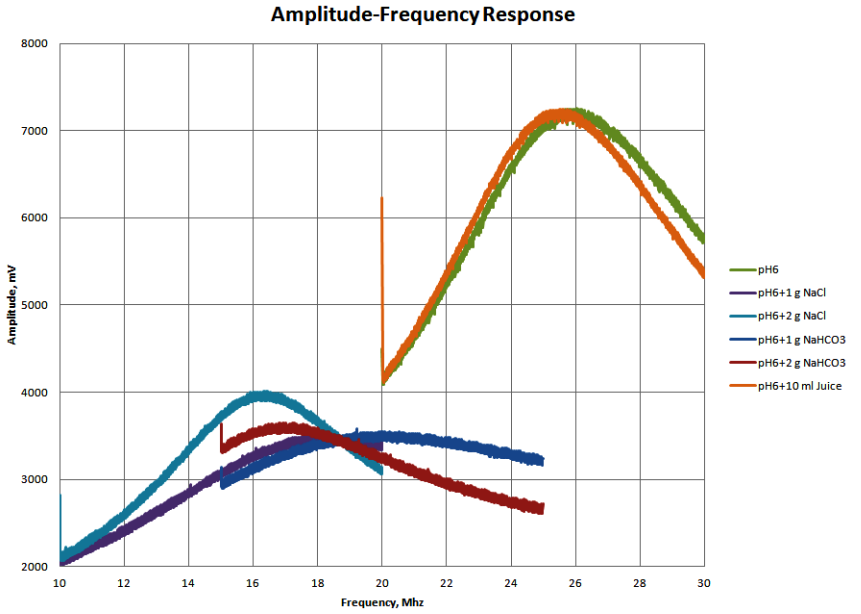


Diagram 10. Influence of Additional Components on the Measurement Response of Samples with pH 6

Furthermore, comparison of the two measurement series performed with a one-hour interval showed only minimal deviations in both amplitude and frequency, demonstrating excellent short-term repeatability, measurement stability, and reliability of the proposed non-contact sensing technology.

Diagram 10 presents the measurement results obtained from various samples with an acidity level of pH 6, prepared in accordance with the technical specification (Table of 22 test samples). The samples were based on simulated gastric fluid diluted with distilled water and included the following additives:

- 10% fruit juice;
- sodium chloride (table salt) at concentrations of 1 g/100 mL and 2 g/100 mL;
- sodium bicarbonate (baking soda) at concentrations of 1 g/100 mL and 2 g/100 mL.

The objective of this experiment was to evaluate the influence of representative food-related additives on the electromagnetic response of the sensor while maintaining a constant acidity level.

The experimental results demonstrated that the addition of 10% fruit juice produced virtually no change in the measured signal amplitude at an excitation frequency of 25.5 MHz, yielding results comparable to those obtained from the reference sample with pH 6 and no additives.

Similarly, the addition of sodium bicarbonate and sodium chloride, tested at an excitation frequency of 16 MHz, produced measurement responses closely matching those of the reference pH 6 sample measured under the same operating conditions.

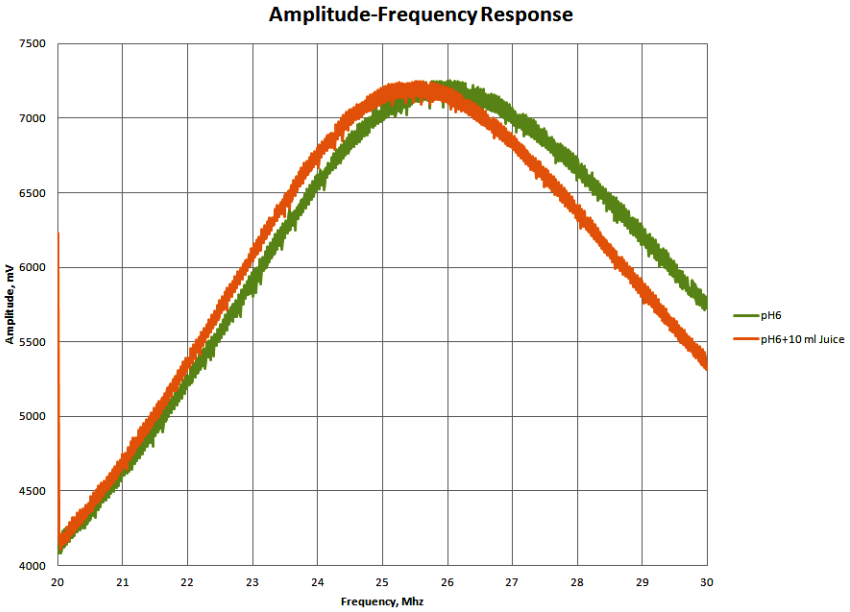


Diagram 11. Comparison of Measurement Results for Simulated Gastric Fluid Before and After the Addition of Fruit Juice with Pulp

These findings indicate that the proposed sensing technology exhibits a high degree of selectivity toward acidity (pH) while demonstrating minimal sensitivity to moderate concentrations of common food constituents, confirming its suitability for reliable measurements in complex biological media.

Figure 11 compares the measurement responses obtained from a simulated gastric fluid sample with an acidity level of pH 6 and the same sample following the addition of 10% fruit juice with pulp (10 mL per 100 mL of sample). Measurements were performed using an excitation signal at 25.5 MHz. As illustrated in the diagram, the measurement responses of the two samples are virtually identical.

The addition of fruit juice with pulp at a concentration of 10% produced no significant change in the measured signal amplitude at 25.5 MHz, with the response remaining essentially the same as that of the reference simulated gastric fluid sample at pH 6.

These results indicate that moderate concentrations of fruit juice containing suspended pulp do not significantly affect the electromagnetic response of the sensor under the selected operating conditions, demonstrating the robustness and selectivity of the proposed measurement technology for pH determination in complex biological media.

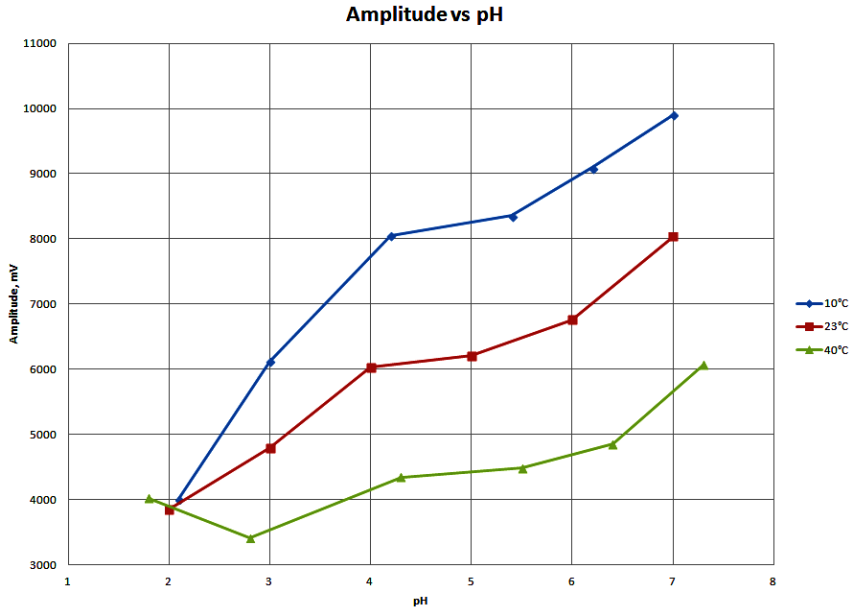


Diagram 12. Amplitude Measurements of Simulated Gastric Fluid Samples Across Different Temperatures and pH Levels

Diagram 12. Figure 12 presents the amplitude measurement results obtained from simulated gastric fluid samples with acid-

ity levels of pH 1, 2, 3, 4, 5, 6, 7, and 8, measured at temperatures of 10 °C, 23 °C, and 40 °C, in accordance with the technical specification (Table of 22 test sample configurations).

During the experiments, changes in the acidity levels of the samples resulting from temperature variation were also monitored.

At 23 °C, the measured pH values of the reference samples were 2, 3, 4, 5, 6, and 7.

When the sample temperature was reduced to 10 °C, the corresponding measured pH values changed to approximately 2.1, 4.2, 5.45, and 6.25.

At 40 °C, the measured pH values shifted to approximately 1.8, 2.8, 4.35, 5.5, 6.47, and 7.3.

The comparative measurement results demonstrate that the proposed sensing technology makes it possible to establish accurate tolerance limits and reference amplitude values for measurements performed over the operating temperature range of 10 °C to 40 °C. These findings confirm the feasibility of implementing temperature-compensated calibration procedures, thereby ensuring reliable and accurate pH determination under varying thermal conditions.

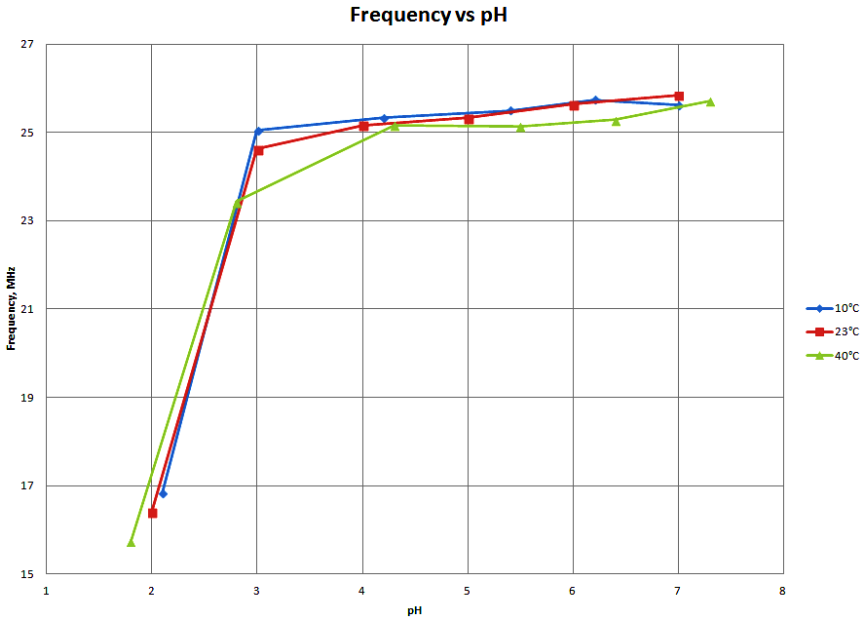


Diagram 13. Frequency Measurements of Simulated Gastric Fluid Samples Across Different Temperatures and pH Levels

Figure 13 presents the frequency measurement results obtained from simulated gastric fluid samples with acidity levels of pH 1, 2, 3, 4, 5, 6, 7, and 8, measured at temperatures of 10 °C, 23 °C, and 40 °C, in accordance with the technical specification (Table of 22 test sample configurations).

During the experiments, changes in the acidity levels of the samples associated with temperature variation were also monitored.

At 23 °C, the reference samples exhibited pH values of 2, 3, 4, 5, 6, and 7. When the sample temperature was reduced to 10 °C, the corresponding measured pH values shifted to approximately 2.1, 4.2, 5.45, and 6.25.

At 40 °C, the measured pH values changed to approximately 1.8, 2.8, 4.35, 5.5, 6.47, and 7.3.

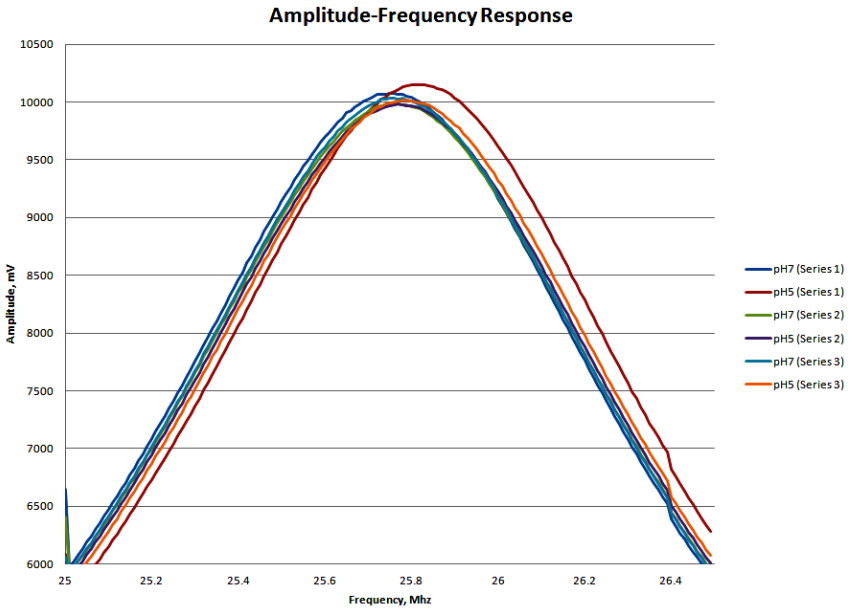


Diagram 14. Frequency and Amplitude Measurements of Simulated Gastric Fluid and Hydrochloric Acid Samples with pH Values of 5 and 7

The comparative frequency measurements demonstrate that the proposed sensing technology enables the establishment of accurate tolerance limits and reference frequency values for measurements performed over the operating temperature range of 10 °C to 40 °C. These findings confirm the feasibility of implementing temperature-compensated frequency calibration, thereby ensuring reliable and reproducible pH measurements under varying thermal conditions while maintaining the required analytical accuracy.

The diagram presents the measured frequency and amplitude responses obtained from samples prepared using simulated gastric fluid and hydrochloric acid, with acidity levels of

pH 5 and pH 7, measured at room temperature under identical excitation signal (pulse) conditions. Each sample was measured three times, with a one-hour interval between successive measurements.

The objective of this experiment was to evaluate whether the measurement system possesses sufficient sensitivity to distinguish between pH 5 and pH 7 in samples prepared using simulated gastric fluid and hydrochloric acid. The required acidity levels were achieved by adjusting the samples through the controlled addition of tap water. To assess short-term measurement stability and repeatability, three consecutive measurements of each sample were performed, with a one-hour interval between corresponding measurements.

The evaluation was carried out using the experimental test bench by systematically varying the frequency and amplitude of the directed excitation signal (pulse).

The experimental results demonstrated the high sensitivity and excellent repeatability of the proposed technology. Despite the minimal physicochemical differences between the two types of test media and the relatively low concentration of dissolved salts – which makes discrimination between pH 5 and pH 7 particularly challenging – the system consistently produced distinct frequency and amplitude responses. Moreover, only minimal deviations were observed between the three measurement series conducted at one-hour intervals, confirming the short-term stability, repeatability, and reliability of the proposed non-contact sensing technology.