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NON-CONTACT ELECTROMAGNETIC RESONANCE QUALITY CONTROL OF LIQUIDS. (Non-Contact Electromagnetic Resonance Quality Control of Liquids, Including Water and Liquid Food Products within Smart Home Infrastructure Systems)

Vladislav Meleshko [1]

[1] Engineering and development of intelligent water treatment systems Vlamel LLC, Miami, USA

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Abstract

This paper presents a non-contact electromagnetic resonance system for quality control of liquid products, including liquid food products. The increasing importance of liquid quality monitoring is driven by global environmental changes, the widespread use of genetically modified products, and the growing application of chemical fertilizers, all of which introduce new risk factors affecting product safety and composition. Traditional quality control methods are often insufficient for modern multicomponent and composite liquid products. To address these challenges, a sensor system based on magnetic resonance principles has been developed, enabling advanced, reliable, and technologically relevant liquid quality assessment.

Keywords: *Water and liquid product quality control; Electromagnetic resonance quality monitoring; Magnetic resonance-based sensors; Technical requirements for the technological measurement principle; Electromagnetic resonance spectroscopy; Genetically modified liquid products; Composite liquid products; Deep global processes; Liquid food products; Increase in the use of chemical fertilizers; Alternating electromagnetic field; Vortex electromagnetic field; Generation of an alternating electromagnetic field in the spatial domain containing the test sample; Product refinement to the stage of mass production*

Technical Requirements for the Measurement Principle

- The implementation of the technological measurement principle shall ensure:
- Low specific cost per measurement;
- High measurement reliability;
- Simplicity of operation, enabling use by minimally trained personnel or for domestic drinking water quality assessment;
- Compact equipment dimensions;
- Integration capability into existing technological schemes and equipment complexes;

- High throughput performance;
- Continuous 24-hour operation capability;
- High efficiency and high repeatability of results;
- Capability for simple and reliable automation;
- Compatibility with disposable technologies and materials;
- Remote monitoring and remote access to monitoring results;
- Comparative assessment of process and water quality based on a limited number of technological indicators.

Product Description

The product based on the application is:

Water Quality RST-SENSOR

The product consists of a pipeline section with a resonance sensor mounted on its external surface and threaded fittings at both ends for connection to existing pipelines.

A sensor cable is designed for connection to a control and analytical unit or to an integrated pipeline management and control system.

Size Range

- Pipeline diameters from **1/8 inch to 4 inches** – equipped with annular sensors;
- Diameters above **4 inches** – equipped with sector-type sensors;
- Manufactured from various structural materials.

Key Technical Requirements

Measurement Accuracy

The device shall detect variations in chemical composition equivalent to concentrations of **0.000001 mg/L**.

4.2 Simplicity of Design

Only standard or mass-produced components and materials shall be used.

The product shall consist entirely of standard pipeline fittings, ensuring:

- High reliability;
- Maintainability;
- Low manufacturing cost;
- Production without specialized technological equipment.

Reliability and Durability

- Mean time to first failure ≥ 10,000 hours;
- Operational lifetime ≥ 10 years.

Complete Non-Contact Measurement

No direct contact with the measured liquid.

Sensitivity shall not decrease with a dielectric barrier up to 2.5 mm between the sensing element and the liquid.

Integration Capability

Compatible with:

- Industrial process lines,
- Boilers and steam systems,
- Municipal water networks,
- Agricultural irrigation systems,
- Industrial water supply systems.

Low Energy Consumption

Total power consumption shall not exceed **50 W**.

Aggressive and Toxic Liquids

Materials shall permit monitoring of aggressive and toxic liquids.

Ultra-Pure Liquids

Materials shall not contaminate or degrade when exposed to ultra-pure liquids.

Automation Compatibility

Sensor signals shall be compatible with commercially available industrial and agricultural control processors.

Autonomous Operation

The device shall operate independently without integration into centralized control systems.

The device may also function as a **level sensor**, without structural modification from the water quality control configuration.

The fundamental structural and technological principles of the product architecture have been developed.

A baseline universal prototype has been manufactured.

A cycle of preliminary testing has been conducted.

The universal prototype has been refined based on the results of preliminary testing.

Materials for a patent application have been prepared.

A patent and licensing protection strategy for the technology has been developed.

Activities Required for Transition to Mass Production and Market Deployment

To advance the product to mass production and the active marketing phase, the following activities shall be completed:

- Development of initial product technical requirements incorporating feedback from potential customers;
- Preparation of a formal project technical specification;
- Development of a technical proposal, including design, fabrication, and testing of product models;
- Development of the technical design phase, including engineering, prototype manufacturing, and testing;
- Preparation of detailed working design documentation, including fabrication and testing of pilot units;
- Conformity assessment and certification of products in accordance with applicable standards;
- Certification at an accredited standards institute;
- Production of an initial pilot batch;
- Pilot industrial operation of the initial production batch;
- Development of a comprehensive marketing strategy;
- Preparation of a production and commercialization program for market adaptation;
- Development of a warranty and service support system;
- Identification of a strategic partner;
- Launch of the first phase of active marketing.

Target Industries

Resonance-based devices for non-contact quality monitoring of water and other liquids shall be fully suitable for effective operation in the following industries:

- Pharmaceutical industry;
- Microbiological industry;
- Semiconductor manufacturing;
- Microelectronics;
- Power generation, including nuclear power plants;
- Industrial HVAC systems;
- Water treatment and purification across industrial, residential, and public infrastructure;
- Fine chemical production;
- Cosmetic manufacturing;
- Production of alcoholic and non-alcoholic beverages;
- Food processing industry;
- Greenhouse agriculture;
- Agricultural irrigation systems;
- Electroplating and electrochemical production;
- Oil extraction and production.

Mass-Market Products Resulting from Project Completion

The project is expected to result in the following commercially scalable products:

- Household drinking water purity indicator;
- Industrial water purity indicator;
- Pipeline-sensor for non-contact conductivity monitoring of liquids, based on industrial PVC pipeline components;
- Operating diameters: 1/16; 1/8; 1/4; 3/8; 1/2; 3/4; 1; 1–1/4 inches and increasing in 1/4-inch increments up to 4 inches;
- Designed for integration into automated industrial control systems;
- Pipeline-sensor for non-contact liquid conductivity monitoring, based on polypropylene industrial pipeline components;
- Operating diameters as specified above;
- Designed for integration into automated control systems;
- Autonomous pipeline-sensor for liquid conductivity monitoring, based on PVC industrial components;
- Operating diameters as specified above;
- Autonomous pipeline-sensor for liquid conductivity monitoring, based on polypropylene industrial components;
- Operating diameters as specified above;
- Pipeline-sensor systems as described above, manufactured using polycarbonate industrial pipeline components;
- Pipeline-sensor systems manufactured using Teflon, composite polymer materials, thermosetting plastics, polymer composites with fillers, and high-temperature-resistant materials;

- Sensor systems integrated into automated control complexes for non-contact liquid quality monitoring in pipelines exceeding 4 inches in diameter, manufactured from PVC, polypropylene, thermally resistant polymers, or thermosetting plastics;
- Sensor systems for monitoring liquids supplied to agricultural irrigation systems;
- Sensor systems for monitoring liquids in irrigated agriculture complexes;
- Sensor systems for monitoring liquids in greenhouse agricultural complexes;
- Non-contact level sensor systems with horizontal installation configuration;

1. Non-contact level sensor systems with vertical installation configuration;

- Integrated systems combining level sensing and liquid quality monitoring functions.

Non-Contact Electromagnetic Resonance Quality Control of Liquid Products

Non-contact electromagnetic resonance quality control of liquid products, including liquid food products, represents one of the advanced smart technologies attracting significant interest from entrepreneurs and technical specialists.

The quality of liquid products – particularly liquid food products – has become critically important due to ongoing global processes, including climate change, the widespread use of genetically modified products, and additional risk factors such as the continuous increase in the application of chemical fertilizers.

As technologists emphasize, traditional quality control methods are no longer sufficient for monitoring modern composite and multicomponent food products.

To enable liquid quality control at a level consistent with contemporary technological requirements, a sensor system operating on magnetic resonance principles has been developed.

Physical Principle of the Method

The method is based on the generation of an alternating electromagnetic field in the spatial domain where the test sample is located. This field serves as an intermediary coupling medium between the resonance circuit and the sample under examination.

The resonance circuit simultaneously acts:

- as an emitter of the electromagnetic field, and
- as a receiver (sensitive element) detecting distortions introduced into the field by the test sample.

Even in the absence of a sample, the alternating electromagnetic field generated by the solenoid represents the superposition of two electromagnetic fields varying in opposite phase:

1. A field generated by the variation of magnetic induction in the solenoid of the sensing element, resulting in a vortex electric field (Maxwell–Faraday equation).
2. A field generated by variation of the electric field caused by the potential difference between:
   - the most distant turns of the solenoid (if the sample is placed inside the solenoid), or
   - the turn closest to the measured element and the element itself (if positioned opposite the end of the solenoid),
3. resulting in a vortex magnetic field (Ampère's circuital law with Maxwell's correction).

Interaction with the Test Sample

Under the influence of the external alternating electromagnetic field, the following phenomena may be simultaneously induced in the test sample, depending on its physical nature:

- Linear conduction currents;
- Eddy conduction currents;
- Linear displacement currents (caused by dielectric polarization);
- Eddy displacement currents;
- Linear ionic currents;
- Eddy ionic currents (ordered ion motion).

According to the principle of field superposition, these induced electrical phenomena distort the external alternating electromagnetic field.

These distortions are detected by the solenoid of the resonance sensor.

Equivalent Electrical Model

The resonance circuit of the sensing element responds to these distortions as if additional electrical components were introduced into the circuit:

- Additional capacitance,
- Additional inductance,
- Additional resistance.

The combination of these additional capacitive, inductive, and resistive components forms an additional impedance introduced into the system by the test sample.

This additional impedance is the parameter measured by the resonance sensor.

Changes in the resonance circuit parameters result in modifications of its amplitude–frequency characteristics, specifically:

- Shift in resonance frequency,
- Change in resonance amplitude.

By analyzing the magnitude and nature of these changes, the impedance characteristics of the sample can be determined.

Device Design

The magnetic resonance device for water and aqueous solution quality control consists of:

- A pipeline section;
- A ring-shaped sensor mounted externally on the pipe surface;
- A power supply unit;
- A control, amplification, and signal identification system.

The system may optionally include a wireless transmission module for sending the processed signal to:

- An operator console,
- A computer display,
- A mobile device.

Calibration and Operation

The system is calibrated using a reference sample of water or another liquid, taking into account local operating conditions.

The sensor detects any deviation in the state of the monitored liquid.

The signal is identified and transmitted to the operator console, computer monitor, or mobile device.

The measurement frequency can be configured within the range:

- From one test every 0.1 seconds;
- To one test per minute.

Key Sensor Parameters

The primary performance parameters of the resonance sensor for water quality control include **accuracy and sensitivity**.

The principal parameter is **sensitivity**, defined as the ability to detect, distinguish, and identify variations equivalent to **0.000001 grams per liter (1 µg/L)**.

Limitations of Conventional Technologies

In conventional liquid quality control systems:

- Highly qualified personnel are required, with labor costs exceeding USD35 per hour;
- Typically, no more than one test per day can be performed;
- Between tests, the condition of the liquid remains unmonitored;
- This gap may result in delayed detection of contamination or system failure;
- The time between fault detection and corrective action is prolonged due to lack of continuous monitoring;
- Information transmission is not real-time, thereby increasing the risk of emergency situations.

Proposed Remote Monitoring Method

The proposed method for remote monitoring of material object parameters includes:

- Formation of a three-dimensional spatial system in which the sensing element surrounds the monitored element;
- Alignment of symmetry centers of the cross-sections of both sensing and monitored elements;
- Stabilization of a uniform gap between the external surface of the monitored element and the sensing element;
- Generation of an energy-saturated spatial region in the form of an alternating electromagnetic field with controlled and adjustable intensity;
- Exposure of the monitored element to the alternating electromagnetic field and induction of:

– Linear and eddy conduction currents;

– Linear and eddy displacement currents,

– Linear and eddy ionic currents;
- Identification and comparative analysis of distortions introduced into the electromagnetic field;
- Perception of these distortions by the resonance circuit as equivalent additional electrical components (capacitance, inductance, resistance);
- Measurement of resonance circuit parameter changes (frequency shift and amplitude variation);
- Evaluation of the resulting impedance of the monitored object, reflecting its state parameters.

Method for Liquids, Mixtures, and Aerosols

For liquids, liquid mixtures, liquid-gas mixtures, or aerosols, the method further includes:

- Enclosing the monitored element within a geometrically stabilizing shell;
- Ensuring concentric alignment between sensing and monitored elements;
- Maintaining a stable uniform dielectric gap;
- Generating a controlled alternating electromagnetic field characterized by frequency and field intensity;
- Sequential variation of field parameters proportional to the number of components in the material object;
- Sequential measurement of impedance variations corresponding to individual components.

The "energy-saturated space" in this context refers to an alternating electromagnetic field defined by frequency and field strength.

Controlled modulation of this field ensures measurement flexibility and high precision across various material types.

Importantly, the method does not differentiate between:

- Solid or liquid materials,
- Liquid or solid mixtures,
- Liquid-gas systems.

Calibration is therefore limited to a minimal number of technological parameters.

Application to Liquid Food Products

From a practical standpoint, non-contact monitoring of liquid food products suggests that sensor sensitivity and measurement accuracy are strongly influenced by the number of components within the liquid mixture.

Transitioning, even partially, to **multicomponent packaging** would significantly reduce the number of components monitored simultaneously, thereby:

- Increasing measurement accuracy;
- Improving reliability;
- Enabling practical implementation of non-contact measurement technology.

Multicomponent Packaging Concept

Advanced designs of dual-component plastic packaging have been developed, along with non-contact measurement methodology compatible with smart home infrastructure modules.

The bottle design consists of two coaxial cylindrical chambers of identical outer diameter.

When placed inside a vertical or horizontal solenoid sensor:

- Independent integral amplitude values can be measured for each chamber;
- Laboratory reference amplitude values are determined for each liquid;
- At points of sale or storage, measured amplitude values are compared with reference values.

Deviation indicates:

- Contamination,
- Structural degradation,
- Fermentation processes,
- Biological decomposition.

Operational Advantages

Because the monitoring process does not require specialized training:

- Any operator can perform quality checks;
- Continuous monitoring becomes feasible;
- Product safety increases;
- Consumer quality of life improves without substantial capital investment.
- **Experimental Validation**

To demonstrate feasibility, experimental laboratory equipment was developed.

Ionized water was used as the monitored medium.

To ensure samples differed only in pH level:

- Preparation was performed in a flow-through electrochemical reactor;

- Municipal water (mineralization approximately 40 mg/L, San Francisco) was ionized;
- The flow was divided into two parallel streams:
  - One acidic,
  - One alkaline.

This configuration allowed controlled testing of sensor sensitivity to compositional changes.

In order to additionally track the influence of water layer thickness on the result, the sensor was immersed in communicating cylindrical vessels whose diameters differed by a factor of two.

As demonstrated by the tests and measurements, the amplitude in the measured samples of the same water, with a pH level of 3 units and an alkalinity level of 11 units (with equal initial mineralization of 40 milligrams), differed by 1000 millivolts.

This simple experiment proves the possibility of monitoring even the smallest changes in the condition of liquids in each of the chambers of a two-component package.

The obtained sensor sensitivity makes it possible to detect, during monitoring, changes not only in each component separately, but also to track the slightest variations in the components through their sequential comparison with each other.

Such a comparison method makes it possible to predict potential variations in the qualitative composition of the mixture obtained after mixing both components.

Thus, it becomes entirely realistic to conclude that, in order to increase the level and accuracy of detection and identification of even the smallest changes in the quality of water and liquid food products, it is advisable to use multicomponent packaging for storage, transportation, and effective mixing prior to consumption.

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Contact: vladyslav.meleshko@gmail.com