

## APPLICATION OF ELECTROMAGNETIC SENSORS IN REAL-TIME WATER QUALITY MONITORING

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### Abstract

Water quality monitoring is essential for identifying contamination and protecting public health. Electromagnetic sensors provide a useful method for detecting changes in the physical and chemical properties of water without destroying the sample. These sensors work by measuring the interaction between electromagnetic signals and the material under test. In real-time water monitoring, microwave nondestructive sensing can identify changes in parameters such as conductivity and permittivity. The sensor response is then analyzed through signal processing and modeling techniques. This approach is useful because it is fast, low-cost, simple to operate, and suitable for continuous monitoring. Therefore, electromagnetic sensors can play an important role in improving modern water quality assessment systems.

### Keywords

Electromagnetic Sensors, Water Quality Monitoring, Microwave Sensing, Nondestructive Testing, Real-Time Detection, Material Characterization.

### Introduction

Water contamination has become a serious environmental and health-related issue. Contaminants present in water can affect drinking water safety, agriculture, industries, and living organisms. Traditional laboratory-based testing methods are useful, but they often require sample collection, chemical processing, trained staff, and more time. Due to these limitations, there is a need for fast, accurate, and nondestructive techniques for monitoring water quality in real time.

Electromagnetic sensors offer a practical solution for this purpose. These sensors use the principles of applied electromagnetism to detect changes in electrical properties of materials. In water quality monitoring, the sensor interacts with the water sample and produces a response based on its conductivity, permittivity, and other physical or chemical characteristics. Microwave nondestructive sensing is especially useful because it offers good penetration in nonmetallic materials, low cost, high resolution, simple operation, and real-time monitoring capacity. A sensing system generally includes a sensor, a transceiver, and a platform for signal generation, collection, and analysis. The application of electromagnetic sensors in water quality monitoring can support rapid detection of contaminants and reduce dependence on slow laboratory testing. With the help of signal processing, forward modeling, and inverse modeling, the response of the sensor can be connected with the actual condition of the water sample. This makes electromagnetic sensing a promising technique for real-time environmental monitoring.

### THE ELECTROMAGNETIC FIELD INTENSITY SENSORS

Researchers and scientists have been successful in inventing a wide variety of devices that are able to detect the intensity of magnetic fields throughout the course of the past forty to fifty years because of their efforts. There is the potential for the measurement of a wide range of potential parameters. Every single strategy has its own set of distinctive qualities that set it apart from the others. The fact that it is suitable for specific applications and systems is improved as a consequence of this. In order to carry out their functions, these sensors make substantial and frequent use of the fundamentals of applied electromagnetism. In addition to this, it investigates a wide range of product categories and types, in addition to associated evaluations and collections of examples of remarkable design ideas. There are essentially three primary types that can be found within the arena of magnetic field sensors that are applied in the real world:

- 1) Resistive Electromagnetic Characteristic Sensors
- 2) Capacitive Electromagnetic Characteristic Sensors

### 3) Inductive Electromagnetic Characteristic Sensors

#### **The Resistive Characteristic Sensors**

This rule is adhered to by resistive electromagnetic sensors and devices because it specifies that the electrical resistance that is created in a material, which is referred to as a resistor, is equal to the ratio of its voltage value to its current value. Ohm's rule states that this ratio is equal to the electrical resistance that is formed in the material. Because of the influence that the electromagnetic field has on the magnetic circuit, electric current is able to flow into a node. This is because the electromagnetic field has an impact on the magnetic circuit. The examination of these electric circuits was carried out in line with the notion, with Kirchhoff's laws serving as the basis for the study. These sensor circuits are responsible for the production of both voltage and current generated by the sensors themselves.

#### **The Capacitive Characteristic Sensors**

When it comes to capacitive electromagnetic sensors and devices, the Coulomb electric charge law is relevant to the electromagnetic field, which is known to contain particular traits and characteristics. This legal principle is applicable to electromagnetic fields. Capacitive sensors rely on the same concept as noncontact nonelectrolyte sensors or contact electrolyte sensors in order to collect and quantify data with a high degree of accuracy and precision. This is one of the reasons why capacitive sensors are so widely used. It is possible to estimate the electrical conductivity of a material by measuring its thickness or density in relation to its position in a magnetic or electromagnetic field. Additionally, you may calculate the thickness or density of the material. Due to the fact that these materials were produced expressly for the purpose of carrying out operations related to material target sensing, the potential charges of the materials themselves are not significantly altered by their use. Because of their broad application, research articles commonly discuss the universal application of both types of capacitive sensors in electromagnetic and magnetic environments. This is due to the fact that these sensors are both widely used.

#### **Inductive Electromagnetic Characteristic Sensors**

The inductive electromagnetic sensor, which applies the eddy current law, comes in at number three on the list of electromagnetic sensors. Inductive electromagnetic characteristic coil sensors are noncontact devices that detect electric currents, voltages, and the real conductivity of the magnetic field and intensity. These sensors do not require contact with the magnetic field. Inductive electromagnetic sensors are another name for these types of semiconductor sensors. Both the sensitivity of the B-H curve and the strength of the electromagnetic field for a number of different signals are taken into consideration in order to provide an illustration of the quality of the sensor. Electromagnetic inductive characteristic sensors are unaffected by the existence of conductive or dielectric materials, regardless of whether the probes or field gaps are constructed from any of these types of materials. Given the nature of the situation, it is imperative that they possess the capacity to endure the difficult circumstances in which they are now functioning. It is possible that this void might be filled by materials such as oil, coolants, liquids, dielectric films, and other things that are comparable, which would be a very practical option. Copper, steel, aluminum, titanium, zinc, and other coil materials have a significant impact on the sensitivity performance of electromagnetic inductive characteristic sensors. This is because coil materials have a significant influence on the performance of the sensors. After then, this performance is altered according to the type of stimulus and the level of accuracy that is being applied.

#### **NONDESTRUCTIVE TESTING**

Recently, the American Society for Nondestructive Testing (ASNT) has recognized and approved microwave nondestructive sensing techniques. These techniques are a unique technology that has the potential to be utilized for imaging applications as well as the characterisation of materials. Over the past few years, this sector has experienced a substantial expansion. The techniques are extremely useful for a wide variety of applications, including but not limited to the following: monitoring water quality, analyzing bone mineral density, evaluating porosity in polymers, measuring moisture, monitoring cure of resin, binders, rubber products, and cement-based materials, detecting and evaluating corrosion under paint and composite laminates, and sizing fatigue cracks in metal surfaces. These are just some of the applications that can benefit from the techniques. There are a number of advantages that microwave nondestructive technologies provide, including the following: high resolution, low cost, good penetration in nonmetallic materials, simple operation, long-lasting construction, the ability to monitor in real time, and the presence of nonionizing radiation. These methodologies compare and contrast with other methods, such as ultrasound, optical spectrometry, X-ray, eddy current, and acoustic emission, amongst others.

Comparisons and contrasts are made between these approaches and other methods. In nondestructive microwave sensing, the primary goal is to offer a description of the distinctive signal spectrum signature that is produced as a consequence of the interaction between the sensor and the material that is of interest for investigation. This occurs as a result of the contact between the sensor and the material. For any nondestructive microwave sensing system to be able to perform broadband analysis of the distinctive signal spectra signatures of the reflected signal, which are determined by parameters such as conductivity and permittivity, amongst others, the system must first have a quantitative numerical model of the sensor communication with the material under test (MUT). This is necessary in order for the system to be able to conduct the analysis. A nondestructive microwave sensing system is comprised of three basic components: the sensor, the transceiver, and the platform that generates, gathers, and analyzes signals that are incorporated in the hardware and software. These three components are necessary for the system to function properly. Signal processing techniques examine the response of the sensor and correlate it with the electrical characteristics of the material at a number of different frequency points. This is done in order to determine the electrical properties of the material. This makes it possible to monitor the material's changes in both its physical and chemical properties. There is also the possibility of including a wireless link, which would make it possible for data to be sent from the sensor to a mobile application. This is an extra potential function. Problems that are relevant from a theoretical, computational, and experimental point of view are brought forth as a result of the considerable effect that electromagnetic forward and inverse modeling has on the design of such systems. It is conceivable for the model to capture the behavior deltas of multilayer materials that are homogenous as well as those that are not homogeneous. In addition to assisting in the design of the most effective sensor for comprehensive material characterization, this also assists in describing the behavior of the materials. On the other hand, the vast majority of the models that have been made available up until this point either need a substantial amount of computer power or are not compatible with a wide range of sensors from different manufacturers. A processing paradigm and solution are required for the collection of crucial data from the reactions of the sensors in order to provide the findings of the investigation to the non-technical workers of these assessment frameworks. This is necessary in order to ensure that important information is delivered.

### **Nondestructive Sensing Technique**

In the field of nondestructive microwave sensing, there are two basic schools of thought that may be distinguished from one another by the specific sensing technologies that are applied to characterize various kinds of materials. These technologies are used to determine the characteristics of the materials. Probe reflection is the foundation of the first method, whereas free space transmission and reflection are the two methods that are utilized in the second method. Both of these approaches are open to consideration. Because it does not require substantial sample preparation, the free space transmission/reflection technique, which is a broadband approach, is suitable for the characterisation of materials. This is because the method does not require considerable sample preparation. There are a number of drawbacks associated with this method, including the fact that it requires two separate sensors, the fact that it is most effective when applied to extremely large flat sheets, the fact that it incurs diffraction effects at the sample borders, and the presence of multiple reflections and mutual coupling between the sensors. These are just some of the drawbacks. On the other hand, the approach that is based on reflection is more user-friendly, comes with fewer components, and may be used to liquid, semisolid, and solid materials without the need for considerable sample preparation. Throughout the entirety of the sending and receiving operations, it is dependent on a single sensor. The design of the sensor, which may be either narrow band or broadband depending on the circumstances, is a determining factor in whether or not the technique can be applied. To this point, researchers have determined that a method that is based on microwave reflectivity is the most promising choice for a wide variety of nondestructive sensing activities. This is the conclusion that they have reached. Furthermore, there are a number of sensors that are utilized for the goal of characterizing materials based on the reflectance of microwaves. These sensors offer a wide range of capabilities. The overall classification system will determine whether these sensors are classed as planar sensors or open ended waveguide based sensors. Both of these classifications are possible. Planar sensors have a wide range of applications, including those in the agricultural and biological sciences. Split ring resonator sensors, vivaldi antennas, resistively loaded dipole antennas, flexible wideband antenna arrays based on polymer technology, and flexible interdigitated electrodes (IDE) are some examples of the applications that fall under this category. In order to explore the electromagnetic interaction that took place between the sensor and the material that was being assessed, the great

majority of these planar sensors made use of commercial simulators that were freely accessible. These simulators were used to carry out experiments.

It is difficult to provide an accurate description of the substance that is being evaluated because of the mistakes that occur during measurement. This method is not only computationally demanding, but it also requires the testing of a large range of different materials that are already known. Due to the fact that the majority of these sensors have narrow band characteristics, it is not possible for them to offer a broadband characterisation of the chemical that is being examined. Open-ended waveguide-based sensors are widely used by researchers for the goal of full broadband characterization and microwave imaging of homogeneous or non-homogeneous materials. There are a number of reasons for this widespread utilization. The reason for this is often due to the fact that these sensors have more closely tailored interactions with the substance. Open-ended waveguide-based sensors are utilized in a variety of applications for the purpose of conducting nondestructive evaluations of materials. Open-ended coaxial probe (OECW) sensors, open-ended rectangular waveguide (OERW) sensors, and open-ended circular waveguide (OECW) sensors are all examples of these types of sensors. Despite the fact that open ended coaxial probe (OECW) sensors are the most fundamental, inexpensive, and widely used, open ended radio frequency (OERW) sensors offer greater coupling and structural endurance due to their larger aperture diameters. This is despite the fact that they have a narrower band. This occurs as a result of the smaller band that OERW sensors possess. In contrast to open ended circular waveguide (OECW) sensors, open ended circular waveguide (OECW) sensors provide an additional orthogonal field component. This is in contrast to the OECW sensors. This makes it possible to have a stronger field interaction on inhomogeneous materials without sacrificing the structural resilience of the material. In situations when the substance being measured is homogeneous, semi-liquid, or liquid, the open ended coaxial probe (OECW) sensor is the one that should be employed. When used to non-homogeneous solids and layered dielectric materials, on the other hand, OERW and OECW are very effective compared to other methods. Although the OECW sensor provides higher sensitivity to the OERW sensor without losing structural robustness, the analysis is more challenging for the OECW sensor than it is for the OECW or OERW sensors. This is despite the fact that the OECW sensor gives superior sensitivity to the OERW sensor. A further orthogonal field component is present in the OECW sensor, which is the reason for this result. Researchers ought to devote a greater amount of their attention to OECW sensors in order to facilitate the development of applications for material characterization tools.

Numerous models of electromagnetic scattering have been provided in the literature, each with its own level of computational complexity, with the intention of identifying the near-field electromagnetic interaction that takes place between the sensor and the layered medium. These models have been presented with the objective of detecting electromagnetic scattering. There is a model that is based on the finite element or finite difference time domain method, which is frequently seen in software that is available for commercial usage. This model is one side of the coin. This model offers a realistic description of the electromagnetic interaction that takes place between the sensor and the layered medium; nevertheless, it poses a major strain on the computations that are performed and requires a significant number of resources to be utilized. Nevertheless, these models usually assume that there is an infinite material area and a probe flange. On the other hand, there are a number of quantitative mathematical models that can be found in the published literature. These models can be found in the published literature. This model's principal purpose is to ascertain the aperture admittance of an open-ended transmission line sensor that is terminated into a number of MUTs. This is the fundamental aim of this model. The model then attempts to derive the connection between the reflection coefficient and the electrical properties of MUTs by using this information as its basis.

Several mathematical models, including as the integral Hankel transform model, the technique of moments, and the capacitance model, have been published in the academic literature with the intention of conducting research on the analysis of the interaction between waveguide sensors and materials. This research intends to be conducted in order to achieve the objective of conducting research. The goal of these models was to investigate the interaction, and they were designed for that purpose. Gardiol et al. provide a green function technique in order to depict the electromagnetic forward scattering problem that is experienced when utilizing OERW and OECW sensors for applications that include nondestructive material characterization. This problem is faced when the sensors are used for applications that involve the characterisation of materials. Bakhtiari et al. provided a method that makes use of an integral Hankel transform analysis for the goal of studying the interaction of OECW sensors when they are in contact with stratified materials.

Furthermore, in order to establish a variational expression for the aperture admittance of OERW sensors that were terminated into multi-layered dielectric media, they applied the Fourier transform boundary matching technique. This was done in order to achieve the desired result. In their model of electromagnetic forward scattering, Zoughi et al. incorporate the effect of higher order modes, which is an augmentation of the approach that was previously utilized. Furthermore, iterative approaches for electromagnetic inverse modeling were applied in order to map the response of the sensor with the non-linear physical features of the component material. This allows for a more accurate representation of the sensor's response. There are many other applications that have found use for the model that was given in. Some examples of these applications include monitoring the healing process of autogenous cracks in cementitious materials and analyzing concrete to discover the composition of its constituent parts. Examples of these applications may be found in. Using these results, Naseer and his colleagues were able to locate faults in outdoor non-ceramic insulators. This was accomplished by expanding the theory and building an electromagnetic inverse model with the assistance of an artificial neural network. In order to simulate the aperture admittance of a single-layer dielectric-covered open-ended circular waveguide, the authors Bailey et al. provide an integral transform approach. This technique is used for the aim of modeling the apertures. The use of circular waveguide apertures appears to confer significant computational benefits in compared to the use of rectangular waveguide apertures. This is because, as was said earlier, the solution in cylindrical coordinates may be condensed to a single integral, which significantly reduces the amount of time that is required for numerical integration. This is the reason why this is the case. In order to analyze the reflection characteristics of absorber panels that make use of open-ended circular waveguide sensors, Rudduck and his colleagues created a plane wave spectrum theory. This theory was established in order to evaluate the qualities of the absorber panels. The extension of the theory to include multilayer external dielectric medium was the means by which this was done. However, the complexity of calculating the infinite domain integral that spans several singularities is a barrier that must be solved. The use of plane wave spectrum theory for near field analysis of OECW sensors provides generalizability; however, it is hampered by the complexity of the calculation. As a consequence of this, the techniques have not received a great deal of attention in terms of their application to the characterisation of materials.

A computationally efficient model for forward and inverse electromagnetic scattering of a large number of open-ended transmission line sensors is developed within the scope of this thesis. This model involves the scattering of electromagnetic waves in both directions. We think that by utilizing this model, we will be able to solve the inadequacies of the prior model, which was established on the theory of the near field plane wave spectrum in. Any application that requires the characterisation of homogeneous or non-homogeneous materials can make use of the model that was built in this thesis. It is available for use by any application. The model in question is open source. In addition, the model is utilized in the process of constructing a prototype of a software-defined radio system. This system is designed to establish a correlation between the response of the sensor and the real quantity of the material. The system's prototype has been put to excellent use for applications that include nondestructive microwave sensing, such as monitoring water contaminants in real time. These applications have been achieved with great success.

### Conclusion

Electromagnetic sensors are useful tools for real-time water quality monitoring because they can detect changes in water properties quickly and without damaging the sample. Microwave nondestructive sensing provides advantages such as low cost, high resolution, simple use, and continuous monitoring ability. By analyzing sensor responses through signal processing and modeling techniques, contaminants in water can be identified more effectively. Although further improvement is needed in sensor accuracy, model compatibility, and field-based validation, electromagnetic sensor systems have strong potential for practical water quality assessment and environmental protection.

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