

Analysis of the Charge Distribution of a Capacitive Sensor for Inspecting Pipeline Defects

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This paper proposes a capacitive non-destructive testing (NDT) technique for detecting surface defects in pipeline inspection. Finite Element Analysis (FEA) simulations were conducted to analyze changes in surface charge density, electric field and capacitance caused by defects. Experimental data for various defect sizes were obtained using the developed capacitive sensor, and the results were compared with the simulations. Consequently, this confirms that the principle of capacitive sensors is suitable for defect measurement. This research is expected to provide a reference for research in NDT and capacitive sensor applications.

Index Terms— Capacitive sensor, In-Line Inspection (ILI), Non-Destructive Test (NDT), Finite Element Analysis (FEA).

I. INTRODUCTION

Currently, in the field of In-Line Inspection (ILI), systems that combine Magnetic Flux Leakage (MFL) with other detection methods, such as Eddy Current Testing (ECT) and Weak Magnetic Flux Leakage (WMFL), are being developed to distinguish between internal and external defects [1-2]. However, systems relying on the permeability of pipelines face challenges due to signals originating from unintended locations caused by leakage magnetic fields. Addressing this issue requires algorithms to accurately identify defect locations, leading to increased power consumption, system weight, and complexity in both hardware and software.

This paper proposes a capacitive inspection method that is compatible with MFL. This method operates independently of the permeability of the pipeline, relying solely on the electric field generated between the sensor electrode and the target surface [3-4]. This enables the detection of surface defects exclusively. Finite Element Analysis (FEA) is conducted to model the pipeline environment and analyze the electrical properties of the sensor. For validation, a capacitive sensor module is developed, and its performance is compared and analyzed with simulation results across various defect sizes.

II. PRINCIPLE OF MEASUREMENTS

Capacitance ($C = \epsilon S/d$) depends on geometric parameters, such as the electrode area S and the distance between electrodes d , and material parameters, such as the permittivity ϵ of the dielectric material as shown in fig. 1-(a).

However, this explanation only accounts for the capacitance of an ideal infinite parallel plate and is insufficient to describe the complex and finite geometries of actual inspection system shown in Fig. 1-(b). Therefore, the capacitance is more appropriately defined by total charge Q , which reflects the non-

uniform charge density, and the potential V between the driving electrode and the target, expressed as $C = Q/V$.

The total charge is calculated by integrating the surface charge density, $Q = \int_S \rho_s dS$. Here, surface charge density ρ_s depends on the radius of curvature, which exhibits a non-uniform distribution due to the geometry of the electrode. According to Gauss's law, In the case of conductor, the surface charge density per unit area can be expressed as by $\rho_s = \hat{n} \cdot \vec{D}$, with the normal component $\hat{n}$ of the flux density.

In an electrode driven by constant voltage, changes in the distance between the target and the electrode result in changes in the electric field strength while maintaining the potential, which is defined as $V = - \int_l \vec{E} dl$.

The electric flux density is defined as $\vec{D} = \epsilon \vec{E}$, representing the electric field strength in a medium with permittivity. In the sensor, this is related to the substrate material on which the electrode is printed. By this definition, the total charge can be expressed as $Q = \int_S \hat{n} \cdot (\epsilon \vec{E}) dS$.

If the electric field strength changes in a specific region due to the target position, it indicates that the surface charge density of electrode, which is the source of the electric field, has also changed. This subsequently leads to a change in the total charge, which is ultimately reflected in the capacitance. Accordingly, Capacitance is expressed as,

$$C = \frac{\epsilon \int_S \hat{n} \cdot \vec{E} dS}{- \int_l \vec{E} dl} \quad (1)$$

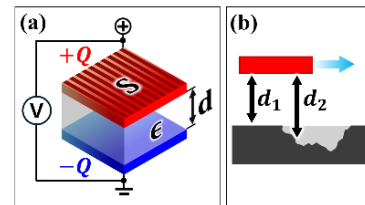


Fig. 1. (a) Principle of capacitance, (b) Working principle of a capacitive sensor.

III. RESULTS AND ANALYSIS

A. Simulation results

The electrode design and simulation are conducted using the Finite Element Analysis (FEA) software COMSOL Multiphysics. The electrode is designed as 10 mm × 24 mm with a thickness of 0.035 mm, is positioned at the distance of 2 mm from the pipeline. This electrode passes over a defect, designed with a diameter of 24 mm and a depth of 3 mm. Electrical states are set using the AC/DC module; the electrode is supplied with 2.5 V, and the pipeline is grounded.

The surface charge density and the normal component of the electric field at positions P₁, P₂, and P₃ are shown in Fig. 2-(b) and (c). At P₁, where the electrode is positioned away from the defect edge, the surface charge density and the electric field are relatively uniform and strong. As the electrode overlaps with the defect at P₂, the surface charge density decreases due to the defect, weakening the electric field in the overlapped area. Upon reaching the center of the defect at P₃, the surface charge density and the electric field are reduced across the entire electrode area. From P₄ to P₅, these changes reverse, with the surface charge density and the electric field gradually recovering as the electrode moves away from the defect.

The calculated capacitance is shown in Fig. 2-(d). As the electrode moves from P₁ to P₂, the overlapping area with the defect increases, leading to a decrease in the total charge of the electrode and a subsequent reduction in capacitance, reaching a minimum at the defect center, at P₃. Moving from P₄ to P₅, the total charge increases, and the capacitance eventually recovers to its initial value.

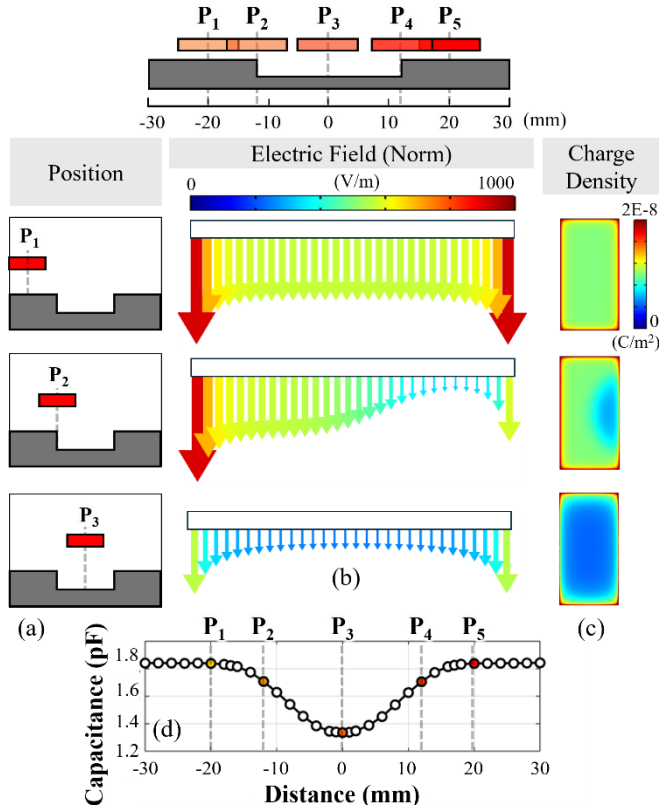


Fig. 2. (a) Position of the electrode at P₁, P₂ and P₃, (b) Normal component of electric field and (c) surface charge density distribution on the electrode surface at P₁, P₂ and P₃, (d) Capacitance at various distances.

B. Experimental results

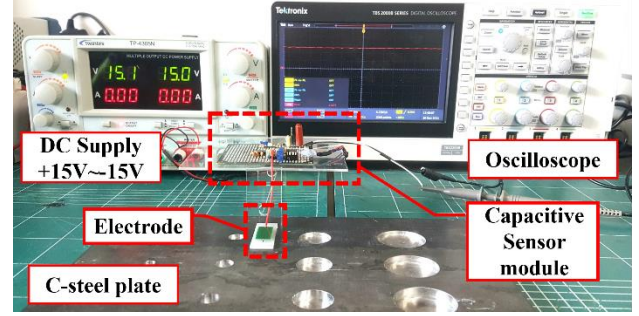


Fig. 3. Experimental setup.

Since it will operate alongside MFL, it is important to design the module so that the circuit topology is not affected by stray magnetic fields. For this reason, the CAV424 from Analog Microelectronics is adopted. The constructed circuit and experimental setup are shown in Fig. 3, and the comparison between the experimental and simulation results is presented in Fig. 4.

The experimental results showed a maximum error of 2.2% compared to the simulation for a defect diameter of 24 mm, whereas the smallest defect size, with a diameter of 8 mm, exhibited a minimum SNR of 13.2 %. Additional detailed data and analysis supporting these findings will be provided in the full paper.

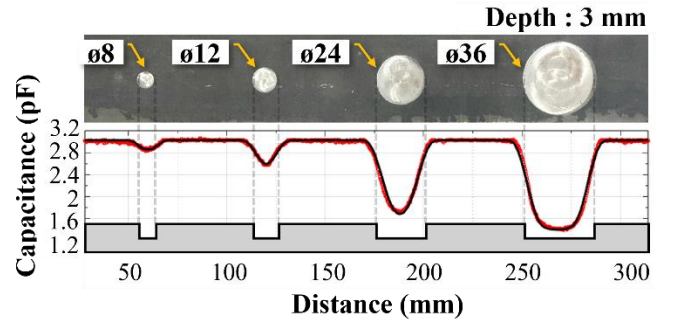


Fig. 4. Capacitance results for various defect sizes: comparison between experimental data (red dot) and simulation data (black line).

IV. CONCLUSION

Analysis of the experimental results revealed a low SNR for defects with a diameter of 8 mm. To improve sensor performance, future studies will consider incorporating shielding to reduce environmental interference and adopting the out-of-phase driving mode to enhance electrical stability.

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