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CAPACITIVE NDT OF IMPACT/PRESS INDUCED STRUCTURAL DEGRADATION IN AGRICULTURAL MACHINERY

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Abstract: *In capacitive measurements using fixed-width, spaced coplanar plates, the study aimed to determine the dielectric constant of the medium between these plates, which includes both air and the material (iron plate). Measurements were taken from three regions: the damaged area under external pressure, the undamaged region, and the transitional boundary zone. At least five measurements were collected from each region, potentially more for a comprehensive analysis. In the case of the 7mm-thick plate, the average capacitance values within the undamaged, transition, and damaged zones are measured at 1.127298 pF, 1.070874 pF, and 1.035826 pF, respectively. Similarly, for the 10mm-thick plate, the average capacitance values in the undamaged, transition, and damaged zones are determined to be 1.129858 pF, 1.087194 pF, and 1.075432 pF, respectively. These results reveal variations in capacitance across different thicknesses and regions within the tested plates. Significantly, these findings underscore the discernible decrease in dielectric constants in regions characterized by higher material conductivity, a phenomenon particularly prominent in compressed metals. This has significant implications for capacitive measurement systems, as it suggests they can effectively detect and visualize damaged areas, making them valuable for applications involving material alterations or deformations.*

Key words: *Capacitive NDT, Press-induced damage, Structural degradation, Material inspection*

1. INTRODUCTION

The design and production of agricultural machinery prioritize safety, efficiency, and durability, making Non-Destructive Testing (NDT) highly relevant in this context [1]. NDT is instrumental in ensuring the safety, longevity, and efficiency of these machines. It detects potential defects and cracks, thus enhancing worker safety and durability in challenging operational conditions. Efficient agricultural machinery operation is essential for business owners, and NDT helps maintain continuous performance and prevent unexpected malfunctions. NDT methods encompass various techniques that assess an object's physical condition without causing damage, providing qualitative or quantitative information about defects like density, size, location, and morphology [2]. Available techniques include Visual Inspection Testing (VT), Dye Penetrant Testing (PT), Magnetic Particle Testing (MT), Electromagnetic Testing (ET), Thermal/Infrared Testing (IR), Radiographic Testing (RT), Acoustic Emission Testing (AE), Ultrasonic Testing (UT), and Electrical Capacitive NDT [3]. NDT plays a crucial role in ensuring the reliability, safety, and quality of products across industries. Electrical Capacitive NDT, employed in this study, detects structural defects in metal samples by measuring changes in electrical charge storage capacities [4]. Its advantages include cost-effectiveness, speed, precision, and non-destructiveness. However, it requires good conductivity and operator sensitivity. The study investigates the application of Capacitive NDT to detect structural damage in iron samples used in agricultural machinery, induced by press/impact, offering a cost-effective alternative for structural integrity monitoring.

2. LITERATURE REVIEW

Impact damage, resulting from various mechanical forces, can significantly compromise the performance and reliability of

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structural components. Detecting and characterizing impact damage is essential to ensure the continued safe operation of critical systems. Capacitive imaging, based on the measurement of capacitance changes, is a non-invasive and non-contact technique that holds promise for assessing impact damage in a wide range of materials and structures.

When studies in the literature on capacitive imaging are examined, it is observed that the technique has been employed in various applications. In the literature, the planar array capacitance detection technique is considered a novel approach rooted in the principles of electrical capacitance tomography (ECT), offering distinct advantages such as non-invasiveness, rapid response, and cost-effectiveness [5-9]. When compared to conventional methodologies like ultrasound [10,11], X-ray [12], and infrared thermography [13,14], this technique is noted for its significant benefits in the identification of internal defects within composite components. It effectively penetrates surface materials to access the inner adhesive layer without requiring the removal of the test sample from its substrate, while also demonstrating reduced susceptibility to the influence of material properties [15].

The planar array capacitance detection technique's distinctive feature is its arrangement of electrodes on a common horizontal plane, enabling a unidirectional approach to the object under examination. Consequently, it facilitates single-sided detection when geometric constraints limit access to the test object [16,17]. However, the sensitivity distribution of this method is influenced by the soft field effect induced by polarization phenomena, resulting in a non-linear relationship that is influenced by the distribution of the surrounding medium [18]. This characteristic introduces disparities in sensitivity distribution, often characterized by regions of high sensitivity and others displaying lower sensitivity due to the presence of guard electrodes [19,20]. These disparities have a significant impact on the quality of image reconstruction [21,22].

Damage to composite materials can also have significant consequences, including a substantial reduction in both buckling load capacity and stiffness. These effects, in turn, can compromise the overall structural performance [23,24]. What makes the situation particularly challenging is that damage resulting from impacts is often not readily visible or is barely discernible to the naked eye, concealing significant sub-surface damage. As a result, the use of non-destructive evaluation (NDE) techniques becomes crucial for inspecting these composite materials. NDE methods offer the advantage of detecting hidden damage, ensuring the structural integrity of composite components, and preventing potentially catastrophic failures in applications ranging from aerospace to automotive and beyond. By employing NDE techniques, engineers and inspectors can proactively assess and address damage, enhancing the safety and reliability of composite structures.

Capacitive sensing is a non-destructive testing (NDT) technique that relies on the utilization of electric fields to discern variations in the dielectric properties of materials. This method proves invaluable for imaging the internal structure of non-conductive materials such as plastics, ceramics, composites, metals, and biological tissues by quantifying the capacitance between electrodes positioned on or in proximity to the sample's surface. Capacitive NDT systems are typically designed in a coplanar or parallel plate configuration, with the former being particularly advantageous for detecting surface-level alterations, as the electric field's impact diminishes as one moves deeper into the specimen, thereby reducing its detection capabilities. In order to surmount this limitation, parallel plate configurations are often preferred, although they necessitate the mechanical synchronization of the two plates.

In capacitive sensing, one or more electrodes are subjected to an alternating current (AC) voltage, which serves as an excitation signal. Following the generation of scattered electric fields in the inter-electrode region, the signal reaching the other plate is captured and the capacitance value is computed. The magnitude of capacitance between the electrodes is contingent upon several factors, including the permittivity and geometry of the material under examination, as well as the frequency and amplitude of the AC voltage.

By scanning the sensor across the specimen's surface, a two-dimensional (2D) image of subsurface characteristics can be acquired. Capacitive sensing offers numerous advantages over alternative NDT techniques, notably its non-contact nature, cost-effectiveness, expeditiousness, and ease of implementation [25,26]. Nevertheless, it is not without its challenges, including susceptibility to environmental noise, the requisite calibration for diverse materials, and constraints related to penetration depth and resolution [27,28].

3. MATERIAL AND METHOD

3.1 Design of Capacitive Non-Destructive Testing

The microscopic camera-based capacitive measurement system designed within the scope of this study is presented in Figures 1 and 2. The capacitive sensor is of coplanar structure, with a 15mm distance between two plates. The plates have a width of 5mm and a length of 10mm.

Within this compact and precise system, both the capacitor and the camera are accurately enclosed within a 3D-printed case, ensuring their stability and protection. Despite the microscopic nature of the area under observation through the microscope, measuring just 10mm x 10mm, the camera operates with impressive precision, capturing high-resolution images at 640x480 pixels, in a compact frame of 5mm x 4mm.

To provide a visual representation of the region where capacitive measurements are taken, the system relies on a microscope camera, offering a comprehensive and real-time view of the examination area. In the process of quantifying capacitance values, a specialized 24-bit capacitive-to-digital converter (C2D) integrated circuit plays a pivotal role. This integrated circuit allows for precise and accurate measurements.

Measurements are conducted continuously in single-ended mode with excitation enabled, ensuring that the system operates efficiently and without interruption. In the proposed setup, one of the capacitive sensor's plates is connected to the excitation terminal, while the other is linked to the capacitive measurement terminal (Cin). The C2D is intricately connected to the microcontroller through the Inter-Integrated Circuit method.

Within the microcontroller, a meticulously prepared code facilitates initialization and configuration of the C2D register settings. This configuration is essential for precise data acquisition. The data, represented in Farads, is then efficiently transmitted to the computer through the serial port (UART). This well-engineered system brings together technology, precision, and functionality to provide a robust platform for microscopic capacitive measurements.

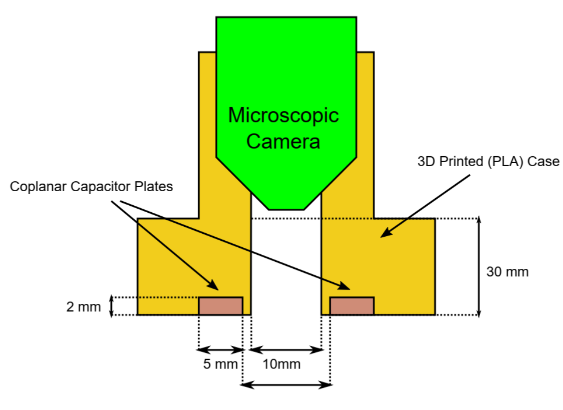

Fig. 1. Capacitive Probe with Microscopic Camera

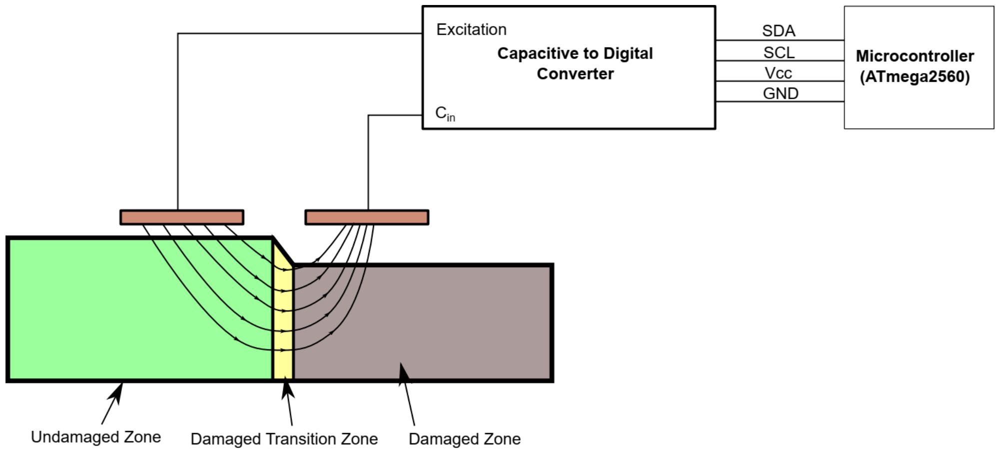

Fig. 2. The Schematic Diagram Depicting Capacitive Imaging Approach

3.2 Sample Preparation and Data Collection

The samples intended for the study are depicted in Figures 3 and 4. These specimens, fabricated from S235 material and having thicknesses of 7mm and 10mm, are visually presented in Figures 3 and 4. A pressure of 150 bar was applied.

Fig. 3. Sample with 7mm thickness

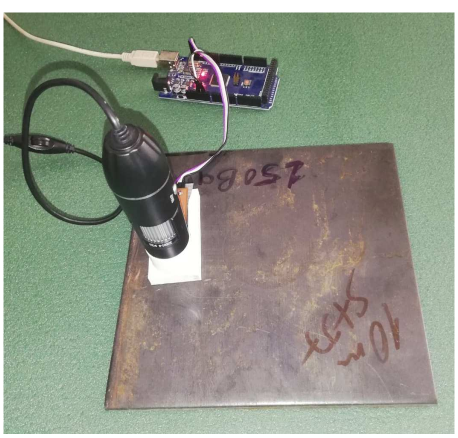

Fig. 4. Sample with 10mm thickness

4. RESULTS AND DISCUSSION

The measurement process pertains to five measurements each taken from the undamaged, transition, and damaged regions. For the 7mm-thick plate presented in Figure 5, the average capacitance values for the undamaged, transition, and damaged zones are 1.127298 pF, 1.070874 pF, and 1.035826 pF, respectively. The standard deviation values for measurements in these zones are 0.001285, 0.001692, and 0.000428, respectively.

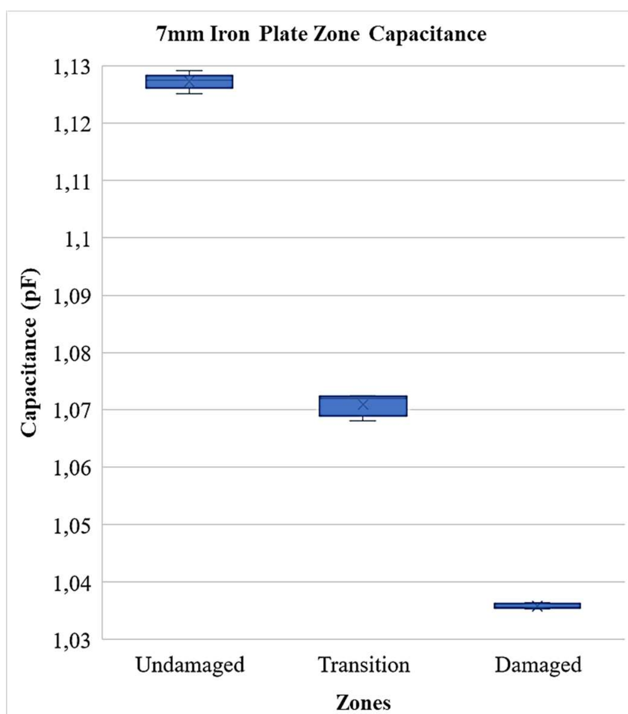

Fig. 5. 7mm Iron Plate Zone Capacitance (undamaged, transition and damaged zones)

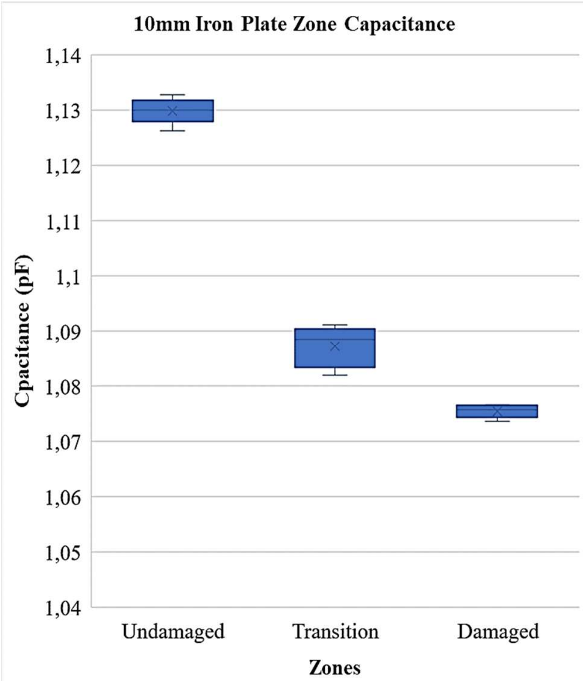

Fig. 6. 10mm Iron Plate Zone Capacitance (undamaged, transition and damaged zones)

In Figure 6, the 10mm-thick plate is presented, and the respective average capacitance values for the undamaged, transition, and damaged zones are 1.129858 pF, 1.087194 pF, and 1.075432 pF. The standard deviation values in these zones are 0.002142, 0.003349, and 0.001109, respectively.

The increase in conductivity of compressed metals often leads to a reduction in the dielectric constant, consequently impacting capacitance. Therefore, as evident in Figures 5 and 6, the capacitance value decreases progressively from the undamaged area towards the damaged region. It is noteworthy that the conductivity exhibits a less significant decrease when the same force is applied to thicker metal, primarily due to reduced compression. This observation stresses the role of material properties and thickness in affecting the electrical characteristics of the tested specimens. The presented findings highlight the relationship between mechanical forces, material properties, and the changes in capacitance. This understanding is crucial for interpreting capacitive NDT data accurately, emphasizing the need to consider the presence of damage and the material composition and thickness.

5. CONCLUSION

This study aims to utilize capacitive NDT techniques to detect and evaluate the structural degradation induced by impact or pressure in agricultural machinery components. The use of capacitive NDT in the context of structural degradation within agricultural machinery represents an advancement in condition monitoring and maintenance. This technique has proven to be valuable in detecting internal damage and defects, thus improving safety and operational efficiency.

Capacitive NDT offers several advantages for agricultural machinery, allowing comprehensive inspections without harm to equipment. Additionally, it provides insights into the extent of damage, facilitating informed maintenance decisions in the agricultural sector.

The experimental results demonstrate variations in capacitance across different thicknesses and regions within the tested plates, notably indicating a decrease in dielectric constants in regions with higher material conductivity, particularly observed in compressed metals.

As technology continues to advance, capacitive NDT is likely to become increasingly valuable in the agricultural machinery sector. Ongoing research and development efforts may refine the technique and expand its applicability. Incorporating capacitive NDT into routine maintenance and inspection practices can contribute to prolonged equipment lifespan and enhanced agricultural productivity.

Future research directions should involve not only establishing correlations between capacitive NDT inspection outcomes and component lifespans but also conducting comprehensive cost-benefit analyses. Understanding the economic implications of adopting capacitive NDT in agricultural machinery maintenance will be crucial for widespread acceptance. Additionally, investigating the environmental sustainability implications of capacitive NDT can contribute to the development of eco-friendly practices within the agricultural sector.

In summary, capacitive non-destructive testing (NDT) in agricultural machinery marks a shift towards intelligent, efficient, and sustainable farming practices. As capacitive NDT matures, it promises to transform agriculture, making equipment maintenance proactive, data-driven, and integral to the objectives of precision agriculture, aligning with the industry's commitment to resource optimization and environmental sustainability.

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NDT capacitiv al degradării structurale indusă de impact/presiune în mașinile agricole

În măsurătorile capacității utilizând plăci coplanare fixe şi separate printr-o lățime dată, studiul își propune să determine constanta dielectrică a mediului dintre aceste plăci, incluzând atât aerul, cât și materialul (placa de fier). Măsurătorile au fost efectuate în trei regiuni distincte: zona afectată sub presiune externă, zona neafectată și zona de tranziție la limita acestora. S-au colectat cel puțin cinci măsurători din fiecare regiune, posibil mai multe pentru o analiză cuprinzătoare. În cazul plăcii cu grosimea de 7 mm, valorile medii ale capacității în zonele neafectată, de tranziție și afectată au fost măsurate la 1,127298 pF, 1,070874 pF și, respectiv, 1,035826 pF. Similar, pentru placa cu grosimea de 10 mm, valorile medii ale capacității în aceleași zone au fost determinate la 1,129858 pF, 1,087194 pF și, respectiv, 1,075432 pF. Aceste rezultate relevă variații ale capacității în funcție de grosimea și regiunile plăcilor testate. În mod semnificativ, aceste constatări subliniază scăderea semnificativă a constantelor dielectrice în regiunile caracterizate prin conductivitate materialului mai mare, fenomen deosebit de evident în metalele comprimate. Acest lucru are implicații semnificative pentru sistemele de măsurare capacitivă, sugerând că acestea pot detecta și vizualiza eficient zonele afectate, făcându-le valoroase pentru aplicații care implică modificări sau deformări ale materialelor.

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