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Evaluation of Pulse Eddy Current for Autonomous Airborne Inspections

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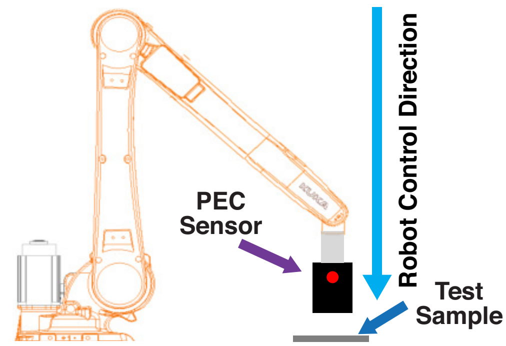

Abstract—Unmanned Aerial Vehicles (UAVs) integrated with Pulsed Eddy Current (PEC) technologies present a potential solution for Non-Destructive Testing (NDT) in environments where manual inspection is impractical or hazardous. PEC inspections conducted via UAVs facilitate remote structural health monitoring and offer invaluable thickness measurements for integrity assessment. Unlike traditional contact ultrasound inspections, PEC provides thickness measurements without necessitating surface contact. However, challenges such as aerodynamic influences, probe angular sensitivity, and alignment errors during autonomous inspections can introduce inaccuracies in thickness measurements. Despite its promising applications, the impact of these challenges on the accuracy and reliability of PEC measurements, particularly in autonomous UAV operations, remains underexplored. Consequently, understanding the influence of PEC sensor alignment on UAV inspections becomes vital for ensuring precise NDT outcomes. This paper evaluates the performance of a conventional commercial PEC sensor for its suitability in autonomous airborne inspections. The PEC sensor is affixed to a robot manipulator and precisely controlled to simulate airborne inspections across various alignment angles. Through systematic analysis, the impact of sensor alignment on inspection accuracy is comprehensively assessed, demonstrating critical factors influencing the reliability of UAV-based PEC NDT. The experimental results indicate that the measurement error in PEC can increase to 0.408 mm when the probe was measuring the thickness of a 20 mm sample and experienced misalignment of 4° along both the x-axis and y-axis. The results enhance knowledge of PEC impacts within UAV setups, improving inspection efficiency, and aiding in UAV design to address these issues—advancements critical for the UAV-based PEC NDT.

Index Terms—Pulse Eddy Current, Accuracy Evaluation, UAV-based Inspections.

I. INTRODUCTION

As the focus on human safety and environmental preservation intensifies [1], there's an escalating demand for comprehensive insights into the state and health of global infrastructure. Increased operational demands, like higher workloads and longer service durations, coupled with decreased investments in new infrastructure, have strained numerous components [2], significantly affecting their condition and operational longevity [3]. To provide infrastructure owners, operators, and planners with vital data about asset status and condition, substantial advancements have been achieved in Non-Destructive Testing (NDT) [3].

One of the Non-Destructive Testing (NDT) methods, the Pulsed Eddy Current (PEC) technique, represents a non-intrusive, non-contact approach that is emerging within the realm of eddy current testing. This method is hailed as both emerging and promising within the field of eddy current NDT, capable of identifying corrosion and flaws within materials typically concealed beneath layers of coating, fireproofing, or insulation. The method's rich spectral components provide extensive information about the component under test, including defect location in multi-layered components and increased stand-off distance for detecting corrosion under insulation. Consequently, it finds widespread application across various engineering domains, such as aircraft [4], and pipes [5], [6].

PEC sensing plays a pivotal role in the non-invasive identification and measurement of the physical and geometric attributes of metal specimens. This technique involves measuring the magnetic field resulting from a specimen positioned next to a PEC sensor emitting a pulsed magnetic wave. Among the various geometric attributes measured, the thickness of wall-like specimens is crucial for monitoring the integrity of metal structures [7], [8]. Given that some of these wall-like formations are ferromagnetic, eddy current sensing emerges as a preferred choice among a spectrum of other sensors for determining the thickness of such substances [9], [10]. Compared to other NDT techniques, PEC does not require direct contact with the material, making it advantageous for rough or inaccessible surfaces[4]. Additionally, it is beneficial for autonomous inspections where ensuring good contact is challenging during robot manipulations. Despite its promising applications, the impact of these challenges on the accuracy and reliability of PEC measurements, particularly in autonomous UAV operations, remains underexplored.

A UAV (Unmanned Aerial Vehicle) is an autonomous aerial robot system, typically comprising a flight controller, navigation and communication system, and a functional payload. Their maneuverability and compact design enable UAVs to efficiently carry out various hazardous tasks, such as NDT inspections. Cutting-edge advancements in UAV-based NDT primarily concentrate on

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photogrammetric [11], thermographic[12], and ultrasonic inspections [13]. Prior studies have shown an independent, multi-rotor UAV equipped with a contact-based ultrasonic measurement system for inspecting non-magnetic structures [14]. The UAV successfully conducted inspections on an unpainted, vertically mounted aluminum sample within an indoor laboratory setting [15].

The PEC sensor utilized for autonomous airborne PEC inspections is manufactured by MAXWELL NDT Ltd [16], chosen for its accessibility to the research team. The system consists of a data acquisition unit for data collection and analysis. The system includes 4 probes, each designed for a specific lift-off range to maximize detection capabilities. The smallest probe is ideal for applications requiring less weight without sacrificing inspection quality. While originally designed for manual inspections, these sensors are equipped with specifications enabling accuracy assessments across diverse conditions. However, integrating the sensor into an aerial inspection platform could potentially surpass its designated capabilities. Hence, it is essential to comprehend the sensor's specifications in the context of airborne inspections.

The paper focuses on evaluating the sensor performance which influencing measurement accuracy in autonomous airborne PEC inspections. It investigates sensor tilt angles to understand how deviations affect measurement accuracy, crucial for reliable readings in real-world scenarios with uneven surfaces. This paper contributions are:

1) Evaluation of PEC sensor capabilities for scanning carbon steels of various thicknesses.
2) Investigation of orientation angle effects, particularly relevant for potential deployment on unmanned aerial vehicles.
3) Quantification of thickness errors while the sensor was not perfectly aligned.
4) Defined the UAV stability requirements for meaningful PEC inspections.

II. EXPERIMENTAL SETUP

It's understood that misalignment of the probe can significantly impact the signal, especially if the probe's front face is not aligned parallel to the target surface. To explore this in the context of UAV manipulations, an experiment was set up using a PEC probe mounted on a KUKA KR6 R900 sixx, an industrial robotic manipulator arm [17]. This setup, as shown in Fig. 1, allows for precise positioning of the sensor, offering repeatability and accurate measurement essential for assessing alignment constraints. The PEC operates based on electromagnetic fields, allowing it to function effectively without physical contact. It was positioned at a consistent, small lift-off distance from the sample surface to minimize lift-off effects and avoid collisions when the probe was tilted by the robot.

In contrast to the probe vibrations experienced when mounted on a UAV, the KUKA robot can position the sensor with higher precision at an impressive resolution of 0.01° for angular adjustments and 0.01 mm for translational movements. These adjustments are manually made to navigate the PEC probe without interference from UAV motors.

The probe's body reference frame as shown in Fig. 2, The alignment of the probe was controlled to be normal to the Y-axis of the positioner across all tested ranges. Similarly, the lift-off distance was precisely maintained at 5 mm as measured by the robot's z-axis feedback. The

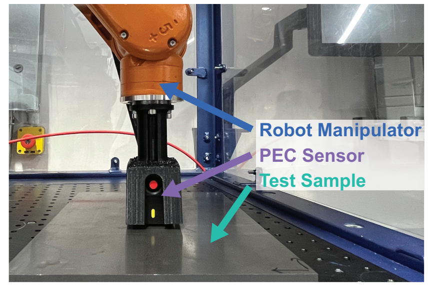

Fig. 1. Robotic manipulator experiment setup.

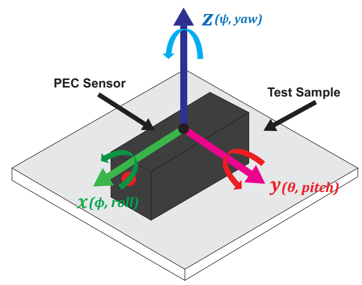

Fig. 2. The PEC probe's body reference frame.

arm of the robot is manually manipulated to adjust the probe within a ±4° range in roll, pitch, and yaw, incrementally changing by 2° steps. ±4° was selected as the upper limit for reasonable and meaningful thickness measurements. For each orientation, five measurements were conducted to reduce uncertainties during the measurements.

The test samples were BRT 080A15 carbon steel plates (300 × 200 mm) in three thicknesses: 6, 10, and 20 mm. These thicknesses were chosen to accurately represent the variety of pipes typically used in industries. The use of uniform and flat plates was adopted to establish a controlled baseline for assessing sensor performance. Uniform structures are essential for performance validation because they offer consistent properties that enable precise evaluations of sensor accuracy and repeatability. This ensures that any deviations observed are due to the sensor itself rather than inconsistencies in the structure. Flat plates were selected to simplify the test environment, minimizing the impact of external factors like curvature, surface roughness, and thus providing a clear benchmark for the sensor's capabilities. Additionally, no coatings or variations in thickness were applied to guarantee that the sensor's measurements were solely influenced by the alignments, avoiding any masking of the sensor's true performance and sensitivity by different material properties or layering effects.

The accuracy of the measurements was determined by calculating the Root Mean Square Error (RMSE), which evaluates the differences between the ground truth measured by a caliper and the measurements obtained from the PEC sensor, as below.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left\| d_i - \widehat{d_i} \right\|^2}{N}} \tag{1}$$

, where d_i is the measured thickness from the PEC transducer, $\widehat{d_i}$ is the ground truth thickness, N represents the number of measured data points and i is the variable.

It is worth noting that systematic errors have been subtracted by using the measurement readings with perfect alignments.

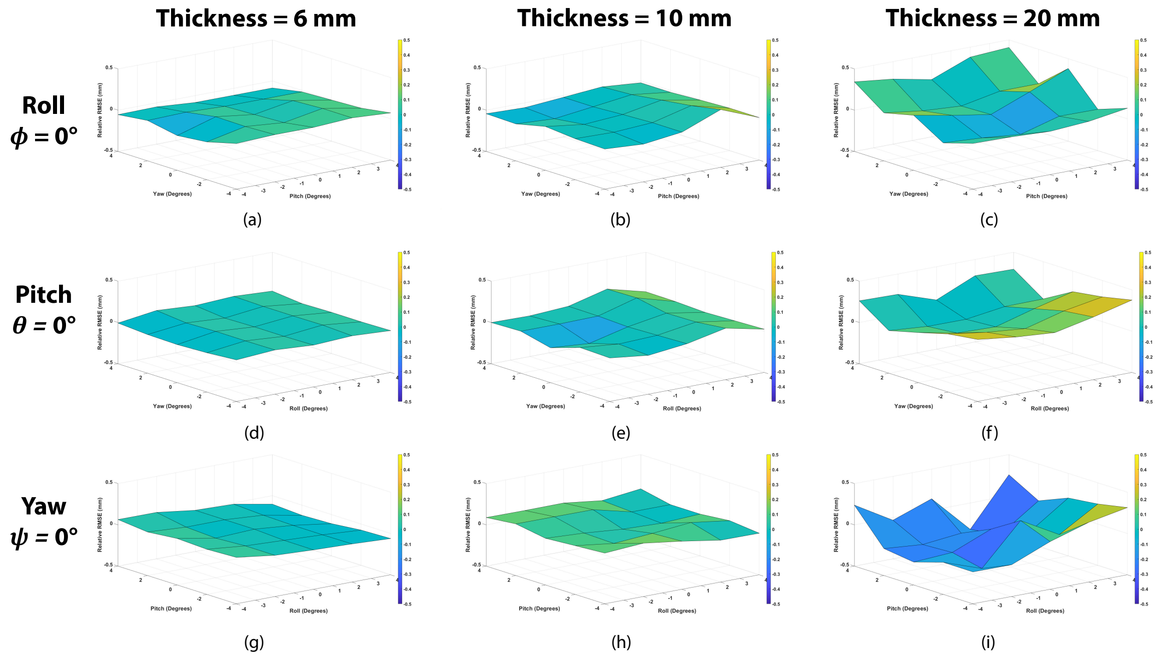

Fig. 3. The RMSE error when the probe was measuring steel samples of different thicknesses. (a), (d), and (g) show results for the 6 mm thickness, (b), (e), and (h) for the 10 mm thickness, and (c), (f), and (i) for the 20 mm thickness. The orientation of the probe was varied, with the roll angle fixed in (a), (b), and (c), the pitch angle fixed in (d), (e), and (f), and the yaw angle fixed in (g), (h), and (i).

Due to the asymmetrical physical structure of the PEC probe, variations in misalignments can lead to different impacts on measurement accuracy. To comprehensively assess these impacts, experiments were designed around three different orientations. In each setup, while one angle remains constant, the other two are manipulated by the arm to explore a range of configurations. This approach allows for a detailed examination of how orientation affects the accuracy of measurements under varied conditions.

III. RESULTS AND DISCUSSIONS

The experimental results displayed in Fig. 3 demonstrate that the performance of the PEC probe on steel samples varies with sample thickness and orientation. Fig. 4 are the representative raw signals, captured with different thickness and orientation. The PEC transducer was able to measure thickness even when the probe was not perfectly aligned, and it provided reasonably accurate output.

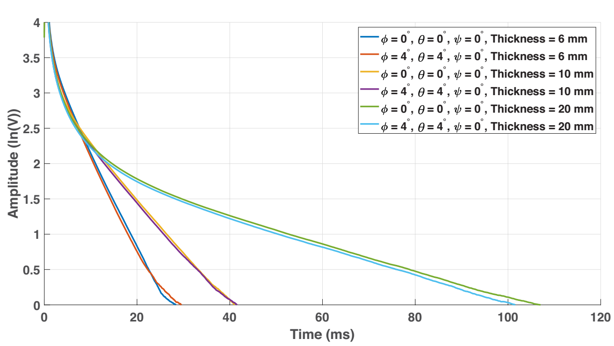

Fig. 4. Representative raw signals, captured with different setups, were exported from the MAXWELL software.

For the 6 mm thickness samples, the probe demonstrates high accuracy and stability across all fixed orientations. The highest recorded error stood at 0.122 mm. The RMSE remains low and consistent whether the roll, yaw, or pitch angle is fixed. This consistency suggests that the probe's measurements are reliable and less sensitive to changes in orientation for thinner samples. The minimal error variation across different angles indicates that the probe's design and calibration are well-suited for thinner steel samples, ensuring precise measurements.

When the sample thickness increases to 10 mm, there is a noticeable, albeit slight, increase in RMSE values and variability. With the roll angle fixed, the probe still maintains relatively low errors, although there is a slight increase compared to the 6 mm samples. This trend continues with fixed yaw and pitch orientations, where the RMSE remains generally low but exhibits more variability. The increased thickness introduces more complexity in the measurement process, yet the probe's performance remains within an acceptable range. This suggests that the probe is capable of handling medium-thickness samples effectively, but users should be aware of the slight increase in measurement error.

For the 20 mm thickness samples, the RMSE values increase significantly, indicating greater measurement challenges. When the roll angle is fixed, the RMSE shows larger variability across different yaw and pitch angles, suggesting that the probe's accuracy is more affected by thicker samples. An error peak of 0.408 mm occurred when the probe was misaligned by 4° along both the x-axis and y-axis. Similar trends are observed for fixed yaw and pitch orientations, where the RMSE values are higher, and the error variability increases. This indicates that the probe's performance is less stable with thicker samples. Misalignments can increase the signal attenuation, leading to more pronounced discrepancies in measurements of thicker materials, as opposed to thinner ones where the signal does not have to travel as deeply, maintaining more of its integrity. Additionally, in thicker materials, minor angular misalignments at the surface can translate into substantial spatial errors at greater depth due to geometric effects, impacting the accuracy of the readings.

Across all thicknesses, the fixed roll and yaw orientations generally result in lower RMSE values compared to the fixed pitch orientation. This trend is particularly evident for the thicker samples, where fixing the pitch angle leads to higher errors and greater variability. This indicates that the probe's design may be more optimized for stability in roll and yaw orientations, whereas pitch changes introduce more complexity into the measurement process. In the terms of autonomous inspections, robots should take this orientation sensitivity into account when planning measurements, especially for thicker samples. Additional calibration or compensation techniques might be necessary to ensure accurate measurements.

Overall, the probe performs best with thinner steel samples, demonstrating high accuracy and stability across different orientations. As the thickness increases, the measurement accuracy decreases, with significant challenges observed for 20 mm samples. However, the errors increased by less than 0.5 mm, and therefore the sensor was still working well even with the imperfect alignments. The orientation of the probe plays a crucial role in the measurement accuracy, with fixed roll and yaw orientations generally providing better stability compared to fixed pitch. These findings highlight the importance of considering both sample thickness and probe orientation to achieve reliable and accurate measurements in practical inspections.

IV. CONCLUSION

An extensive study was conducted on the performance and system characterization of the MAXWELL PEC P1 probe when used to scan various thicknesses of BRT 080A15 carbon steels. The research particularly focused on how small changes in orientation angles affect thickness measurements, simulating conditions like those encountered when the probe is mounted on a hybrid-crawler UAV [18].

Experimental results highlight the PEC probe's varied performance on steel samples, influenced by thickness and alignment. The 20 mm thick samples exhibited slightly greater susceptibility to orientation effects, yet errors remained below 0.5 mm. Conversely, alignment had a limited impact on thinner samples (6 mm), with the maximum error reaching only 0.122 mm. The thicker samples are more sensitive to alignment due to deeper probe penetration, causing signal attenuation and spatial errors. Consistently, the probe overestimates thickness. These insights inform strategies to optimize probe deployment and improve accuracy in non-destructive testing.

Importantly, these findings are critical for addressing challenges associated with sensor sensitivity and measurement accuracy, particularly in the context of UAVs. Ultimately, this research serves as a foundation for future advancements in NDT techniques, offering a roadmap for using PEC probes in UAV deployments. As industries increasingly rely on automation and robotics for inspection and monitoring tasks, the insights gathered from this study pave the way for enhanced efficiency, precision, and reliability in industrial operations.

Despite promising results, several limitations exist. The controlled lab setting with an industrial robotic manipulator does not fully replicate real-world UAV environments. The test samples were uniform, flat carbon steel plates, not reflecting real-world variability in material properties, surface roughness, and geometry. Additionally, environmental factors like temperature fluctuations and humidity were not explored, which could impact sensor performance.

Future research will include field tests with UAVs equipped with PEC sensors in real-world environments. Non-uniform components, such as drawn pipes, can vary in material composition and thickness, affecting probe performance and requiring a broader understanding of probe behaviour. Non-planar structures, common in industrial settings, also pose challenges for accurate thickness measurement. Investigating these factors will help develop more sophisticated and robust NDT methods for modern industrial applications.

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