Chirp-pulsed eddy current testing for crack detection in low-carbon steel

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ABSTRACT

This paper introduces a signal processing feature for chirp-pulsed eddy current testing (C-PECT) to improve crack detection in low-carbon steel, a common material in maritime structures. While C-PECT is an established technique, inspecting ferromagnetic materials is challenging due to significant background noise from lift-off variations and material permeability. The novelty of this work lies in the proposal of a frequency-domain integration feature designed to suppress this noise. The method utilizes a chirp-pulse-excited probe with a Hall sensor to measure the magnetic field response. By integrating the signal's magnitude spectrum, the frequency feature effectively flattens the background and enhances the signal-to-noise ratio. Experimental validation on a low-carbon steel specimen with artificial cracks demonstrates the feature's superior performance in providing clear, high-contrast crack indications compared to a conventional time-domain analysis. The results indicate that this approach offers a simple, computationally efficient, and robust solution for the qualitative detection and localization of cracks, enhancing structural integrity assessments in noisy industrial environments.

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1. INTRODUCTION

Eddy current testing (ECT) has long been a key technique of non-destructive testing (NDT), offering valuable insights into material properties and the presence of cracks. Pulsed eddy current testing (PECT), a modern variant of traditional eddy current methods, is rapidly gaining attention due to its effectiveness in detecting surface cracks, corrosion, and other structural anomalies [1]-[3]. PECT offers significant advantages over conventional methods, particularly in applications requiring high precision and the ability to detect cracks that may not be visible through traditional inspection techniques [4]-[7]. Compared to conventional ECT, PECT utilizes short-duration, wideband pulses that cover a broad frequency range. This allows for deeper penetration into materials and detection of both surface and subsurface cracks, overcoming the limitations posed by the skin effect in traditional ECT methods [7]-[13]. In addition to improving detection depth, PECT signals are easier to interpret, reducing the reliance on highly specialized training for operators. Furthermore, PECT systems tend to have lower power consumption and shorter measurement times, resulting in improved cost-efficiency and faster inspections [14].

Recent advancements in PECT systems have facilitated their adoption across various industries, such as petrochemical, energy, and maritime sectors. These systems excel in operating under challenging conditions, including unclean surfaces, high-temperature environments, and in-service inspections, without the need for equipment shutdowns or extensive pre-inspection setup [13]-[15]. PECT has proven particularly effective for detecting surface cracks in low-carbon steel, a material commonly used in maritime structures like ships and offshore platforms. However, there are several limitations to the widespread use of PECT. Its sensitivity can be influenced by factors such as the edge effect from specimen, surface roughness, the presence of coatings, and the lift-off distance between the sensor and the surface being tested. Additionally, the conventional PECT has a wide bandwidth, which is not selectable, and presents a challenge. This broad frequency range may not always be ideal for detecting certain types of cracks or materials, as the lack of frequency selectivity can decrease the system's sensitivity and reduce its ability to differentiate between various defect types. These limitations highlight the necessity for continued innovation in PECT technology to enhance its versatility and performance, ensuring its broader applicability across different industries. In addition, the inspection of ferromagnetic materials like low-carbon steel presents unique challenges. The high and variable magnetic permeability of these materials, coupled with unavoidable variations in the lift-off distance between the sensor and the surface, can generate significant background noise. This noise often has a magnitude comparable to or greater than the signal from a small defect, making reliable detection difficult and leading to a low signal-to-noise ratio [5], [6].

To address these challenges, advanced excitation strategies such as chirp-pulsed eddy current testing (C-PECT) have been developed. C-PECT, which utilizes a frequency-swept chirp waveform, is an established technique known for its ability to concentrate energy within a specific frequency band, offering enhanced control over the inspection depth and sensitivity [16], [17]. While the use of chirp excitation is not new, a critical challenge remains in developing signal processing methods that can effectively leverage the rich information in the C-PECT response to robustly reject the background noise inherent in ferromagnetic inspections.

This paper proposes and evaluates an efficient signal processing feature based on frequency-domain derived from the C-PECT signal, designed specifically to address this gap. Our hypothesis is that by integrating the magnitude of the signal's frequency spectrum, the random, localized influence of background noise and edge effects can be suppressed, thereby enhancing the clarity and reliability of crack detection. This technique enhances sensitivity to surface cracks and offers a more comprehensive inspection compared to traditional methods. The sensor probe, which generates the eddy currents, is driven by the chirp pulse, while a Hall sensor positioned at the center of the coil measures the vertical magnetic field, providing a detailed representation of material cracks. Additionally, the PECT signal is analyzed in the frequency domain provides an effective way to mitigate edge effects—distortions caused by material boundaries or geometric irregularities than conventional analysis in the time domain. This enables more accurate crack detection and reduces the likelihood of false positives in the final results, which is critical for ensuring structural integrity. In the context of maritime applications, C-PECT presents a promising tool for routine inspections of critical components, helping to identify surface cracks in many structures such as offshore platforms, ballast tanks, ship hulls, and pipelines before they lead to catastrophic failures.

2. MATERIALS AND METHODS

2.1. Chirp-pulsed eddy current testing system

Prior to experimental validation, a 3D finite element (FE) model was developed using COMSOL multiphysics V5.6 to achieve two primary objectives in line with established simulation practices. First, to visualize the underlying electromagnetic field interactions and confirm the basic response of the proposed sensor to a surface-breaking crack. Second, and more importantly, to perform a sensitivity analysis on the effect of lift-off variation, a critical source of background noise in practical ECT inspections. The findings from this analysis were instrumental in guiding the development of the signal processing strategy that forms the core of this study's experimental work. The simulation setup, illustrated in Figure 1, models the C-PECT probe, which consists of a cylindrical exciting coil and a central Hall sensor, positioned above a low-carbon steel specimen containing a surface crack. The key parameters used in this model are detailed in Table 1. The simulation visualizes the concentration of the magnetic field and induced eddy currents at the crack tips, confirming the probe's fundamental sensitivity to such defects. The coil is energized with a chirp-pulse waveform, generating an electromagnetic field within the specimen. Variations in the electromagnetic field, caused by the presence of a crack, are detected by the Hall sensor. The Hall sensor measures the vertical magnetic field (B_z) and converts it into a voltage (V_H) through a linear response, as described by (1), where I is the current and k is the Hall sensor's sensitivity constant. The Hall sensors were housed in protective plastic enclosures, and the coil and sensors were numerically coupled to the substrate using a homogenized multiturn model.

$$V_H = k \cdot I \cdot B_Z \quad (1)$$

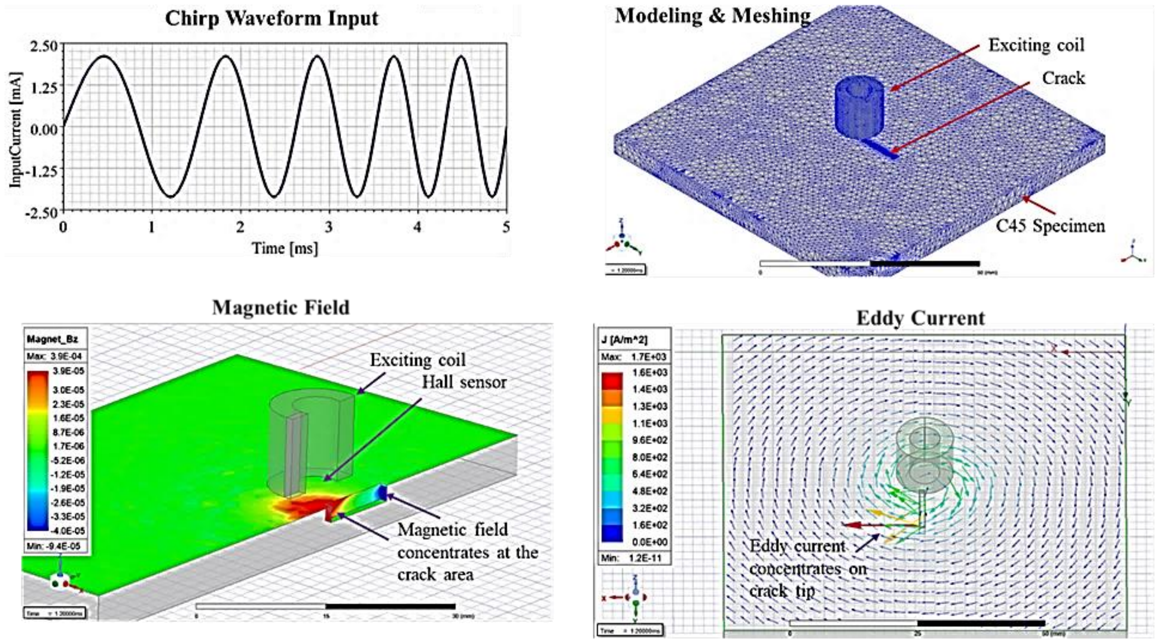


Figure 1. Simulation of magnetic field and eddy currents with a C-PECT sensor

Table 1. Modelling parameters in the FEM simulation

Parameters	Values
Copper wire diameter	0.2 mm
Number of turns of wire	600 turns
Crack	$1{\times}10{\times}2\ mm^3$
Specimen	$80{\times}80{\times}5\ mm^3$
Coil outer diameter	11.3 mm
Coil inner diameter	6.0 mm
Solution type	Transient
Bulk conductivity of specimen	$4.16{\times}10^6$ S/m
Relative permeability	100
Meshing maximum element length	0.02 mm
Time set up	0.005 (s)
Time step	20 [us]

To analyze lift-off sensitivity, the model was used to simulate the sensor's response to both a conventional rectangular pulse and a chirp pulse at various lift-off distances (0.5 mm to 4.0 mm). Figure 2 presents the results in both the time domain (Figures 2(a) and (b)) and the frequency domain (Figures 2(c) and (d)). While both rectangular and chirp pulse waveforms show a clear dependence on lift-off, the frequency spectrum of the chirp pulse (Figure 2(d)) provides a more distinct separation between the signals at different lift-off heights. This pronounced sensitivity to lift-off, clearly visible in the spectral domain, highlights a significant challenge for practical inspections where maintaining a constant probe-to-surface distance is difficult. This finding underscores the necessity for a signal processing feature that can mitigate such noise and directly motivated the central thesis of our experimental work: to develop and evaluate the feature for its ability to suppress these variations and improve crack detectability.

2.2. Experimental setup

The PECT probe is designed to ensure optimal performance in capturing the pulsed magnetic field from the specimen. The probe consists of a cylindrical coil with a height of 10 mm, an outer diameter of 11.3 mm, and an inner diameter of 6.0 mm. An InSb Hall sensor is positioned at the center of the coil to measure the vertical pulsed magnetic field generated by the test specimen. The Hall sensor signal is processed in two stages: first, it is filtered through a 10 kHz low-pass filter implemented using a passive resistor-capacitor circuit; then, it is amplified by 48 dB using an AD620 operational amplifier. The PECT probe and its signal processing unit (SPU) are illustrated in Figure 3.

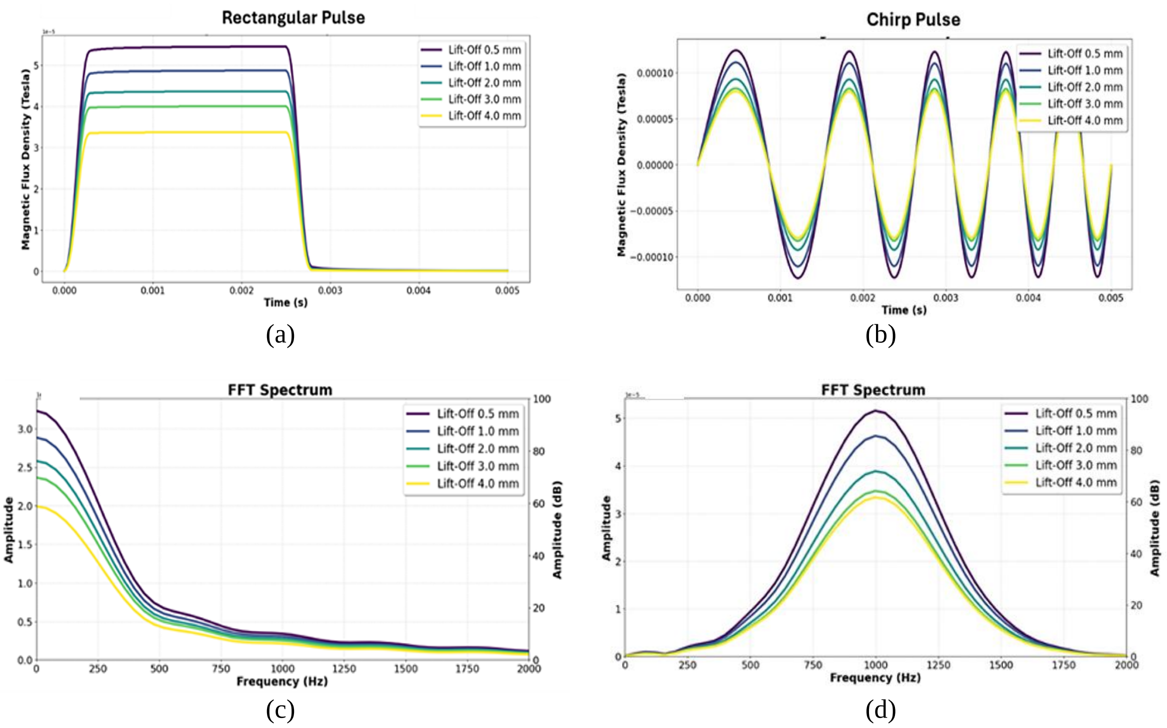


Figure 2. Vertical magnetic field measured at the Hall sensor's position for (a) a rectangular pulse; (b) a chirp pulse, along with their corresponding magnetic flux density spectra; (c) rectangular pulse; and (d) chirp pulse

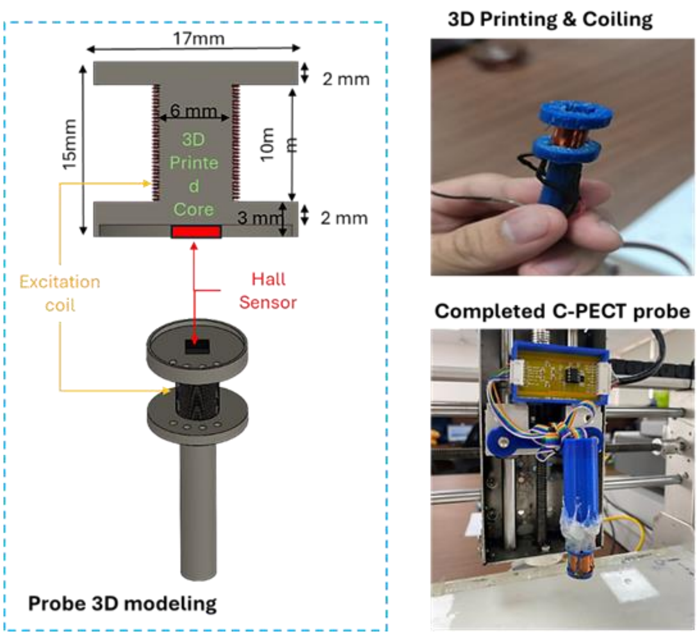


Figure 3. C-PECT probe and SPU

Figure 4 depicts the experimental setup of the C-PECT system. The C-PECT probe, specifically designed by the authors. The system comprises several components: the PECT probe, SPU, XY scanner, power supply for the SPU and Hall sensor, power amplifier for the coil, multifunction device (NI-6531

USB), and a PC running LabVIEW software. The LabVIEW software facilitates data acquisition, pulse generation, and XY scanner control. Rectangular pulses with a frequency of 200 Hz are generated via the digital-to-analog converter (DAC) channel of the NI-6531 and amplified by the power amplifier (BA4825) to deliver an RMS current of approximately 200 mA to the PECT coil. Simultaneously, the NI-6531 triggers the signal reception channel to convert the Hall sensor signals from analog to digital using an analog-to-digital converter (ADC) after passing through the SPU. The SPU processes the Hall sensor's output voltage using a 10 kHz low-pass filter and a 48 dB gain amplifier. Additionally, the LabVIEW software controls the XY scanner, setting a scanning speed of 6 mm/s and a step size of 1.0 mm. The experimental validation was conducted on a low-carbon steel (C45) specimen measuring 150 mm × 100 mm × 5 mm. A set of 15 artificial surface-breaking cracks was fabricated using electrical discharge machining (EDM) to ensure precise and repeatable dimensions. The cracks all had a uniform width of 1.0 mm, with varying lengths (4.0, 9.0, and 14.0 mm) and depths (0.5 mm to 4.0 mm), as detailed in Table 2 and illustrated in Figure 5. These well-defined defects were chosen for this proof-of-concept study. The goal was not to test the limits of detection, but to provide a clear and strong defect signal. This allowed us to reliably evaluate our signal processing feature's ability to suppress background noise, which is the primary focus of this work. Validating the method under these controlled conditions is a critical first step before applying it to smaller, more challenging defects in future research.

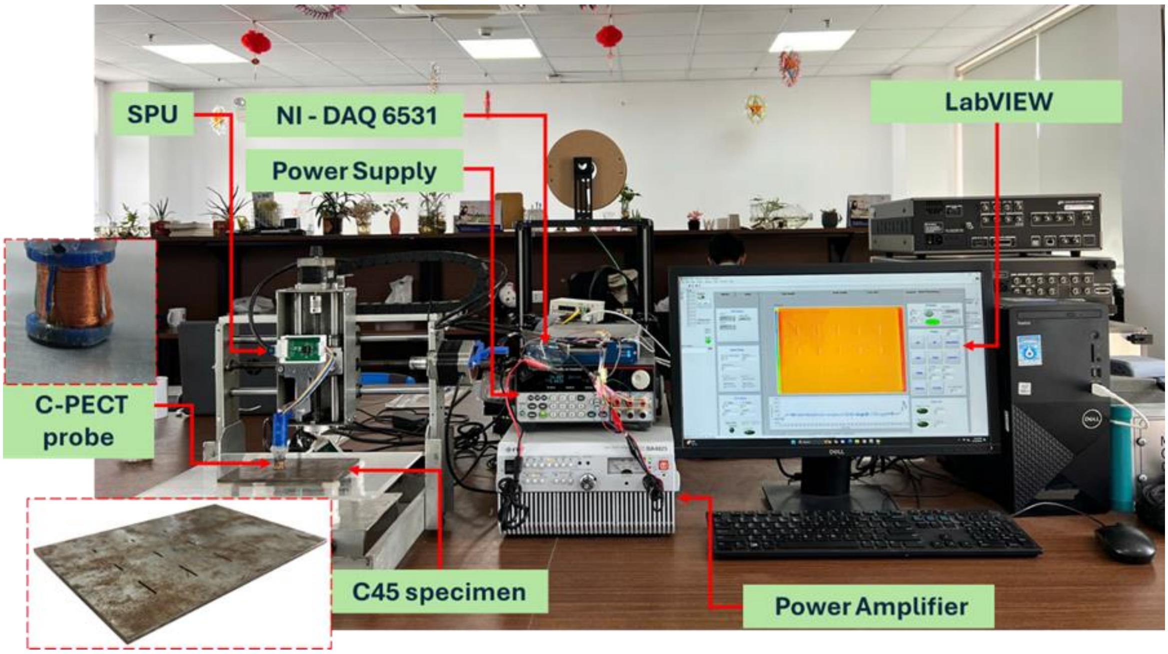


Figure 4. Experimental setup

Table 2. Artificial cracks size on the low-carbon steel specimen

Cracks	Depth (mm)	Length (mm)	Width (mm)
#1	0.5	4.0	1.0
#2	1.0	4.0	1.0
#3	2.0	4.0	1.0
#4	3.0	4.0	1.0
#5	4.0	4.0	1.0
#6	0.5	9.0	1.0
#7	1.0	9.0	1.0
#8	2.0	9.0	1.0
#9	3.0	9.0	1.0
#10	4.0	9.0	1.0
#11	0.5	14.0	1.0
#12	1.0	14.0	1.0
#13	2.0	14.0	1.0
#14	3.0	14.0	1.0
#15	4.0	14.0	1.0

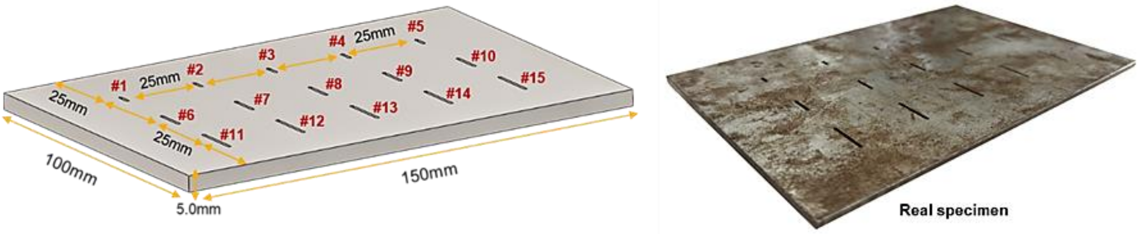


Figure 5. Test C45 low-carbon steel specimen with artificial crack of various diameters (*Φ*) and depths (*d*)

3. RESULTS AND DISCUSSION

Figure 6 illustrates the magnetic scan images obtained using the rectangular pulse and chirp pulse excitation methods, referred to as scan-rect and scan-chirp, respectively. These images provide a visual representation of the measured magnetic field variations across the inspected surface, enabling defect characterization and analysis. Figure 6(a) shows rectangular pulse in the time domain, Figure 6(b) shows chirp pulse in the frequency domain, Figure 6(c) shows scan images with rectangular pulse, and Figure 6(d) shows scan images with the chirp pulse. For the scan-rect approach, each data point in the image is extracted by applying a slice window to the transient time-domain signal. This conventional method, as described in [18], [19], involves isolating specific time intervals in the signal where the transient response is most sensitive to defects. The data extraction process is mathematically expressed in (2), which highlights the relationship between the time slice and the corresponding magnetic field response. While this method aims to capture the overall energy of the received pulse, it is highly vulnerable to noise sources that are prevalent when inspecting ferromagnetic materials. The resulting image is heavily corrupted by strong, low-frequency background variations. These artifacts originate from two primary sources: i) minor, unavoidable changes in the lift-off distance between the probe and the specimen during the automated scan, and ii) local inhomogeneities in the magnetic permeability of the C45 steel. These noise sources produce signal variations that are of a similar or greater magnitude than the defect signals themselves. Furthermore, the strong electromagnetic field interaction at the specimen's boundaries creates a pronounced edge effect. The combination of these factors makes it exceedingly difficult to distinguish the true crack indications from the noisy background, rendering this conventional feature ineffective for reliable qualitative analysis in this context.

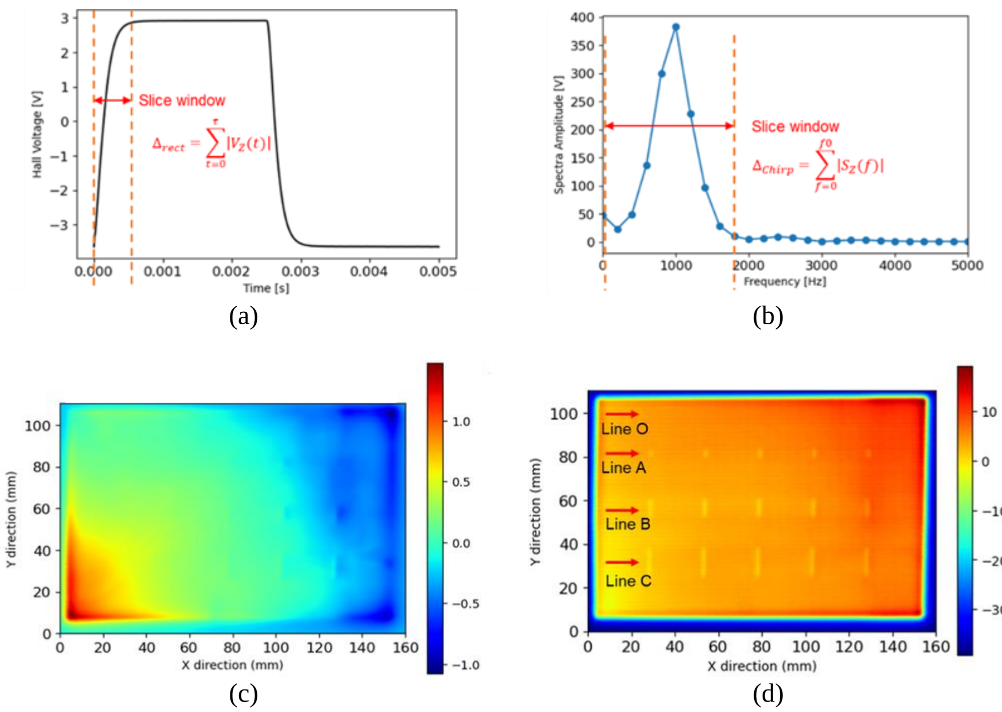


Figure 6. Experimental results of (a) rectangular pulse in the time domain, (b) chirp pulse in the frequency domain, (c) scan images with rectangular pulse, and (d) scan images with the chirp pulse

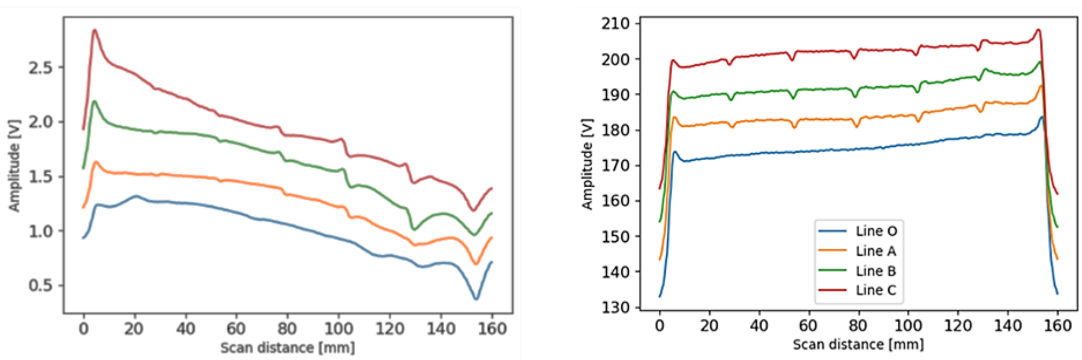
In contrast, the scan-chirp approach leverages the broadband frequency content of the chirp pulse excitation. Here, each data point is computed by applying a slice window to the excited bandwidth of the signal's spectral representation. This method, expressed in (3), enables a more comprehensive analysis by focusing on frequency-specific information. By moving the analysis from the time domain to the frequency domain, the feature is fundamentally less sensitive to the low-frequency noise that dominates the scan-rect image. The integration across the spectrum effectively averages out the random fluctuations from lift-off and material properties while preserving the distinct spectral signature introduced by a crack. The resulting c-scan image demonstrates the profound effectiveness of this strategy. The background is remarkably flat and uniform, indicating a successful suppression of the lift-off and permeability-induced noise. The disruptive edge effect is also substantially minimized. As a result, all 15 artificial cracks are clearly and unambiguously resolved with high contrast and excellent signal-to-noise ratio. This dramatic improvement in image quality directly validates the central scientific contribution of this paper: the frequency feature provides a simple, robust, and computationally efficient method for enhancing crack detection by effectively rejecting noise in challenging ferromagnetic inspection environments.

$$\Delta_{rect} = \sum_{t=0}^{\tau} |V_Z(t)| \quad (2)$$

$$\Delta_{Chirp} = \sum_{f=0}^{f0} |S_Z(f)| \quad (3)$$

Where, $S_Z(f)$ is spectra of the chirp pulse.

Figure 7 presents four scan lines taken from the center of cracks that all have identical lengths, providing a direct comparison between the scan results obtained using the rectangular pulse (Figure 7(a)) and the chirp pulse (Figure 7(b)). The scan data acquired with the Rectangular pulse shows significant fluctuations and high gradients in the background signal. These steep variations in the signal intensity introduce noise and make it challenging to clearly identify the presence of the crack. The high gradients often mask the subtle changes caused by the crack, resulting in a more difficult task for interpretation, as the crack signal may become buried within the complex background signal. This issue is especially problematic in practical applications where detecting fine surface features like cracks is essential for structural integrity assessments. In contrast, the scan lines generated using the Chirp pulse exhibit a much smoother, more consistent background. The signal profile is relatively flat, which greatly enhances the ability to distinguish the crack signal from the surrounding noise. This flattening effect reduces the interference caused by factors such as material properties, surface roughness, and lift-off variations, allowing the crack signal to stand out more clearly. The reduced background noise and smoother signal make it easier to observe and analyze the crack, leading to more accurate detection and characterization of the crack's location and features. Overall, the use of the chirp pulse demonstrates a clear advantage in terms of signal clarity and interpretability, facilitating a more reliable and efficient detection process.

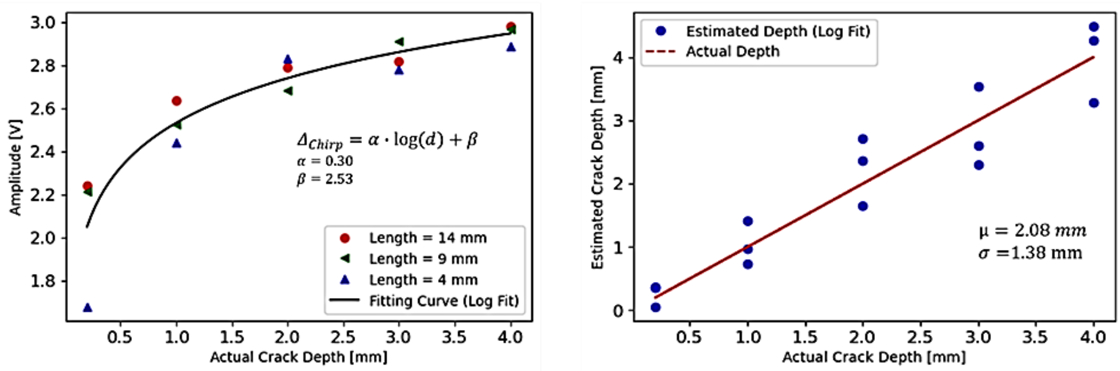


(a) (b)

Figure 7. Scan lines with (a) rectangular pulse and (b) chirp pulse

To further characterize the cracks, the depth of each crack was estimated by analyzing the peak-to-peak value of the crack signal. This method is based on the established logarithmic relationship between the peak-to-peak value of the signal and the actual crack depth, which is governed by a mathematical model, as shown in (4). In this equation, a scale factor of α=0.30 and a shift factor of β=2.53 are used to account for the influence of various factors on the signal's amplitude and the corresponding crack depth. These factors include material properties, lift-off variations, and the measurement conditions, which all play a role in determining the magnitude of the signal variation observed during testing. By applying this logarithmic relationship, it is possible to convert the peak-to-peak values measured during the scan into an estimate of the crack depth. The inverse of the logarithmic (4) is employed to obtain the estimated crack depth from the measured peak-to-peak signal value. The results of this estimation process, including the fitting curve and the calculated crack depths, are presented in Figure 8. Figure 8(a) shows the logarithmic fitting curve that approximates the relationship between the measured signal amplitude and the actual crack depth for different crack lengths. Figure 8(b) presents the comparison between the actual and estimated crack depths obtained from the model. The estimated crack depths demonstrate a reasonable level of accuracy, with the calculated values yielding a mean depth of 2.08 mm and a standard deviation of 1.38 mm. These results highlight the robustness of the proposed method for estimating crack depth, offering a reliable means of assessing crack severity in practical applications. The low standard deviation suggests that the method is consistent and can provide accurate depth estimations even in the presence of noise and other measurement uncertainties.

$$\Delta_{Chirp} = \alpha \cdot log(d) + \beta, \text{with } \alpha = 0.30, \beta = 2.53 \quad (4)$$



(a) (b)

Figure 8. Crack depth estimation of (a) logarithm fitting curve and (b) estimated depth

4. CONCLUSION

This study successfully demonstrated the effectiveness of a novel frequency-domain integration feature for C-PECT to improve the detection of surface cracks in low-carbon steel. The primary contribution of this work is the validation of the frequency feature for the C-PECT sensor as a simple and computationally efficient method for suppressing the significant background noise inherent in testing ferromagnetic materials. By analyzing the C-PECT signal in the frequency domain, our proposed feature was shown to produce c-scan images with a dramatically improved signal-to-noise ratio compared to a conventional time-domain analysis. This method effectively mitigated noise from lift-off variations and material permeability, enabling the clear and reliable detection and localization of all artificial cracks.

Compared to conventional rectangular PECT, C-PECT provides clearer crack signals by producing a flatter background, making crack detection more reliable even in complex conditions. The analysis of the Chirp pulse signal in the frequency domain revealed that its focused-wideband excitation improves sensitivity to the crack, offering better penetration and crack detection. Spectral changes in the signal, particularly in magnitude correlate with crack size and depth, enhancing defect identification. Crack depth estimation was achieved using a logarithmic relationship between the peak-to-peak value of the signal and crack depth. The method yielded a mean crack depth estimate of 2.08 mm, with a standard deviation of 1.38 mm, validating the approach's accuracy.

Future work will focus on two key areas: i) extending the validation to smaller, sub-millimeter defects and natural cracks to assess the method's practical sensitivity and ii) developing more sophisticated signal processing or machine learning models that build upon the frequency feature to achieve accurate quantitative characterization. Nevertheless, the proposed feature shows strong potential as a practical tool for enhancing the reliability of NDT in industries like maritime, petrochemical, and energy.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Minhhuy Le	✓				✓		✓			✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

There is no ethical need to be approved in this research.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, ML, upon reasonable request.

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