Feasibility Study of Mutual Inductance-Based Non-Destructive Testing Method Under Varied Dimensions of Hidden Crack

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Abstract
This study delves into the results and discussion of a study employing a 2D-axisymmetric finite element model to investigate the interaction between coils and an interposed plate sample, with a primary focus on detecting potential defects such as cracks, and assessing parameters including crack dimensions, depth, specimen thickness, and coil specifications. Mesh independency, a crucial aspect of numerical simulations, is explored, emphasizing its significance in achieving accurate and reliable results in various scientific and engineering fields. The research further investigates mutual inductance in a system designed to detect cracks of varying dimensions. It analyzes the impact of parameters, including sheet thickness, crack depth, crack radius, wire radius, air gap, and inner coil radius, on mutual inductance. The results suggest that thicker sheets and smaller cracks make crack detection more challenging, whereas a thinner wire radius enhances system performance. The air gap has minor effects. The study also introduces an improved system design that significantly enhances mutual inductance values, making it a promising method for non-destructive (NDT) testing when design parameters are appropriately considered. These findings contribute to the development of NDT methodologies for various engineering applications.

Keywords: Non-destructive testing (NDT), Mutual inductance, Magnetic field, Crack, Sensors

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Introduction

In today's fast-paced and technologically advanced world, the demand for reliable and efficient materials and structures is paramount. Industries ranging from aerospace and manufacturing to oil and gas heavily rely on the structural integrity of components for safe and smooth operations. However, flaws and defects can often develop within materials during manufacturing or due to environmental factors, potentially leading to catastrophic consequences if left undetected [1]. Non-Destructive Testing (NDT) has emerged as a vital discipline that addresses this challenge by providing a comprehensive and non-invasive means of inspecting materials and structures [2].

The significance of NDT cannot be overstated in ensuring safety, quality, and reliability in engineering and industrial applications [3]. By employing NDT techniques, engineers can assess the internal and external integrity of components without causing any damage, thereby preserving the functionality of the inspected materials [4]. Regular NDT inspections aid in identifying defects, cracks, corrosion, and other flaws that might compromise the structural strength, leading to potential failures and accidents [5].

Beyond the immediate safety benefits, NDT also contributes to cost-effectiveness and sustainability. By detecting flaws early in the lifecycle of materials, maintenance and repair efforts can be targeted more precisely, reducing downtime and avoiding costly unscheduled shutdowns. The ability to extend the lifespan of components through proper monitoring and assessment enhances the overall operational efficiency and maximizes the return on investment for assets [6].

NDT finds applications in diverse industries, encompassing various materials and structures. Some key applications include:

- Aerospace and Aviation: In the aerospace industry, NDT is fundamental for inspecting critical components of aircraft, such as wings, landing gear, and engine components. Ultrasonic testing, magnetic particle inspection, and radiographic testing are commonly used techniques to assess the integrity of these high-value assets [7–9].
- Oil and Gas: The oil and gas sector heavily relies on NDT to inspect pipelines, pressure vessels, storage tanks, and drilling equipment. Eddy current testing, guided wave testing, and acoustic emission testing are essential tools for identifying flaws and ensuring the structural integrity of these facilities [10].
- Manufacturing and Welding: NDT is integral to quality assurance in manufacturing processes, especially in welding applications. Techniques such as radiographic testing, ultrasonic testing, and penetrant testing are widely used to assess weld quality and detect potential defects [11].
- Infrastructure Inspection: Civil engineering projects, including bridges, dams, and buildings, require regular NDT inspections to monitor structural health. Ultrasonic testing, ground-penetrating radar, and visual inspection aid in identifying defects, corrosion, and degradation in these critical structures [2,12].

NDT techniques operate based on different physical principles, each catering to specific inspection needs. Some common mechanisms include:

- Ultrasonic Testing (UT): UT utilizes high-frequency sound waves that propagate through materials. Changes in the sound wave behavior, such as reflection or refraction, provide valuable information about material thickness, internal flaws, and structural characteristics [13–15].
- Eddy Current Testing (ECT): ECT relies on electromagnetic induction to generate eddy currents in conductive materials. Variations in the eddy current flow caused by defects or changes in material properties are detected and analyzed [16,17].
- Radiographic Testing (RT): RT employs X-rays or gamma rays to penetrate materials, creating shadow images that reveal internal defects and structures [18,19].
- Magnetic Particle Inspection (MPI): MPI uses magnetic particles applied to magnetized components. These particles accumulate at areas of magnetic flux leakage, indicating the presence of surface-breaking defects [20].
- Liquid Penetrant Testing (LPT): LPT involves applying a liquid dye to a surface and allowing it to seep into surface-breaking defects. Excess dye is then removed, and a developer is applied to reveal the defects [21].
- Acoustic Emission Testing (AET): AET monitors stress-induced acoustic emissions in materials. Active defects generate acoustic waves that are detected and analyzed to assess the structural health of the material [22].

Fresh research has consistently introduced novel NDT techniques. On occasion, these techniques constituted a combination of earlier approaches, while in other instances, they originated from inventive mechanisms. Therefore, studying mutual inductance-based NDT techniques is important because it provides a valuable and efficient method for evaluating the integrity of the plates without causing any damage. Plates are widely used in various industries, including construction, aerospace, automotive, and manufacturing. Ensuring the quality and reliability of these plates is crucial to prevent structural failures, optimize performance, and maintain safety standards. Mutual inductance-based NDT techniques utilize the principle of magnetic interaction between two coils where the test plate is positioned between them. By generating a magnetic field and measuring the resulting mutual inductance, these techniques can detect and characterize defects in the plate's material. Cracks, delaminations, and voids within the plate can be detected, providing insights into potential structural weaknesses or areas of concern. By studying and refining mutual inductance-based NDT techniques, researchers and practitioners can improve defect detection capabilities, enhance the accuracy of evaluations, and optimize inspection procedures for plates. This, in turn, leads to increased confidence in the structural integrity of plates, reduces the risk of failures, and ultimately improves the overall quality and reliability of the products or structures in which these plates are employed.

Methodology

Mutual inductance-based NDT harnesses the principles of electromagnetic induction to evaluate the condition of materials and components. Unlike conventional testing methods that may involve physical contact or invasive procedures, mutual inductance NDT relies on the interaction between coils and the material under inspection. By analyzing the electromagnetic response of the sample to alternating magnetic fields generated by these coils, this technique provides valuable insights into the material's structural integrity, defects, and other critical attributes.

This innovative NDT method holds great promise for a wide range of applications, from detecting hidden flaws in welds and assessing the thickness of pipelines to verifying the quality of composite materials used in advanced manufacturing. As industries continue to push the boundaries of performance and reliability, mutual inductance-based NDT emerges as a valuable tool in the arsenal of NDT methodologies. In this exploration, we delve into the feasibility and effectiveness of mutual inductance-based NDT, shedding light on its capabilities and potential benefits in enhancing industrial inspection and evaluation processes. Through systematic research and experimentation, we aim to contribute to the development and advancement of NDT techniques, paving the way for safer, more efficient, and higher-quality materials and products in various sectors.

Maxwell's equations provide a set of fundamental equations that describe the behavior of electric and magnetic fields in the presence of electric charges and currents. Mutual inductance can be calculated indirectly using Maxwell's equations, specifically Faraday's law of electromagnetic induction.

Faraday's law states that the electromotive force (EMF) induced in a closed loop is equal to the negative rate of change of magnetic flux through the loop. For two coils nearby, Faraday's law can be used to calculate the mutual inductance (M) as follows [23]:

$$M = \frac{N_2 \Phi_{B1}}{I_1} \tag{1}$$

Where M is the mutual inductance between the coils, N_2 is the number of turns in the second coil, and Φ_{B1} is the magnetic flux through the first coil produced by the current I_1 in the first coil. However, magnetic flux in space do not have simple calculations. Finite Element Method (FEM) is a numerical method used for solving engineering and scientific problems by dividing complex structures or systems into smaller, more manageable subdomains called finite elements.

In current research, we utilized the FEM to explore the potential of NDT for sheets using the mutual induction technique. To illustrate this study, we designed a rectangular section of a sheet with a specific thickness. By varying the thickness of the sheet, we evaluated the method's effectiveness across different thicknesses. To create a test scenario, we initially designed a sheet and then removed a cylinder with specified depth and diameter from its volume. Subsequently, we designed another defect-free sheet layer identical to the previous one. By unifying these two layers, we constructed a sheet containing a hidden crack. This design allowed us to detect failures on the sheet at the crack location using two coils with particular specifications. We compared the mutual inductance measurements when a crack was present with those when there was no crack. This comparison enabled us to assess the extent of changes in mutual inductance and determine its suitability for crack detection. Furthermore, by varying the cylinder's diameter and height, we investigated the method's capability to detect cracks at different depths and sizes.

Results and discussion

We utilized a 2D-axisymmetric model, implemented through the FEM, to examine the interaction between coils and the influence of an interposed plate sample. Our primary objective was the identification of potential defects, with a particular focus on parameters such as crack dimensions, depth, and the thickness of the specimen. The schematic representation of the system under investigation is provided in Figure (1).

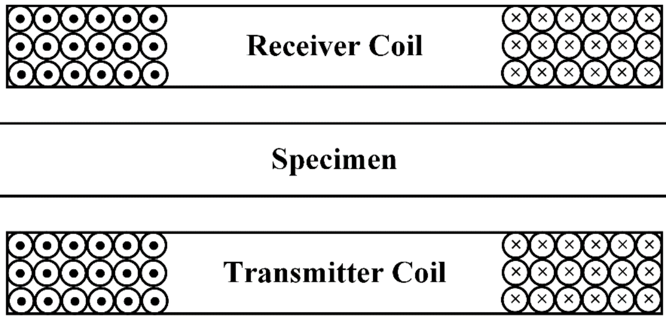

Figure (1) The structure of the utilized system.

An electric current-carrying coil generates a magnetic field, which permeates through a second coil. The sinusoidal nature of the current results in an equivalent sinusoidal magnetic field, inducing the second coil. This process facilitates wireless power transmission. This research endeavors to evaluate the feasibility of employing this methodology to detect cracks of varying dimensions and depths, along with specimen thickness variations. These deliberately designed cracks incorporate voids at the center of the specimen, and the mutual inductance of the coils was assessed across different scenarios. In the realm of numerical simulations, one critical aspect that often plays a pivotal role in ensuring the precision of these simulations is mesh independence. One of the most common approaches is to perform a grid refinement study. In this study, the mesh is successively refined to determine the impact of mesh size on the simulation results. This process entails running the simulation with different mesh resolutions and comparing the results to identify when they start to converge. In this study, 4 stages of mesh refinement have been performed. The results show that in the first case, the error was 0.0092593, which shows that the results are not dependent on the mesh (see Figure (2)).

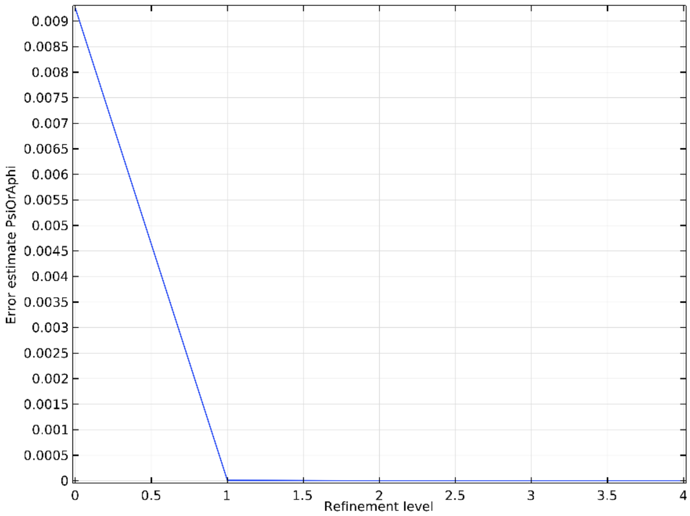

Figure (2) Mesh independency analysis.

In this study, the mutual induction of the presented system is studied in different cases. The impact of each parameter related to the size of the crack including its radius and height and the thickness of the sample has been evaluated. Each of the cases has been compared with the case without cracks to check the feasibility of using this method. The specifications of the windings, which are considered unchanged in all cases, are given in Table (1). First, we calculated the mutual inductance for the sample without cracks. In this case, the crack radius and depth are assumed as 20 mm and 0.8 mm, respectively. Also, the wire cross-sectional radius is 0.5 mm. Furthermore, the thickness of the sample is assumed 2 mm. Under these circumstances, the mutual inductance is calculated at 367.31 μH.

In the following, we analyzed the mutual inductance of the coils in a situation in which the sample with a crack is placed between the coils. Also, the effect of sheet thickness, crack radius, and crack depth on the mutual inductance is investigated.

Table (1) Constant parameters and values in the study.

Parameter	Value
Coil material	Copper
Sample material	Iron
Coil current	1 A
Coil inner radius	50 mm
Coil outer radius	100 mm
Coil height	10 mm
Coil filling factor	0.7
Distance between coil and sample	0.5 mm

Sheet Thickness

In this section, the effect of sheet thickness is investigated, and the mutual inductance is determined while a crack is present at the center of the sample. Different sample thicknesses, namely 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, and 12 mm, are considered for all cases, with the crack radius and depth assumed to be 20 mm and 0.8 mm, respectively. The wire's cross-sectional radius is also taken as 0.5 mm. Similar calculations are performed to analyze mutual inductance for samples with varying thicknesses but without a crack. With this, the mutual inductance for samples with and without a crack at different sheet thicknesses can be compared, and the feasibility of the method can be assessed. Table (2) shows the mutual inductance calculations for different sheet thicknesses.

Table (2) Mutual inductance calculations for different sheet thicknesses.

Sheet thickness (mm)	**Mutual inductance without crack (µH)**	**Mutual inductance with crack (µH)**	**Absolute difference ($\|I - II\|$)**	**Relative difference ($\left\|\frac{I-II}{I}\right\|$)**
2	362.16	361.83	0.33	0.0911%
4	243.91	243.72	0.19	0.0779%
6	197.6	197.45	0.15	0.0759%
8	170.13	170.01	0.12	0.0705%
10	150.66	150.56	0.1	0.0664%
12	135.5	135.41	0.09	0.0664%

The results show that as the thickness of the sheet increases, the mutual induction between the windings shows fewer changes than the case without cracks. In all cases, the cracks have the same size while the sheet has a different thickness. In the thicker case, the crack is very thin compared to the entire thickness of the sheet, which leads to less variation in the mutual induction.

Therefore, we performed the previous calculations in another way. In this study, we considered the crack depth to be half of the sheet thickness. This comparison may better show the performance of the system in different thicknesses. Table (3) shows the mutual inductance calculations for different sheet thicknesses and half of the sheet thickness crack depth.

Table (3) Mutual inductance calculations for different sheet thicknesses and half of sheet thickness crack depth.

Sheet thickness (mm)	Mutual inductance without crack (µH)	Mutual inductance with crack (µH)	Absolute difference ($\|I - II\|$)	Relative difference ($\left\|\frac{I-II}{I}\right\|$)
2	362.16	361.83	0.33	0.0911%
4	243.91	243.7	0.21	0.0861%
6	197.6	197.43	0.17	0.0860%
8	170.13	169.99	0.14	0.0823%
10	150.66	150.54	0.12	0.0796%
12	135.5	135.38	0.12	0.0886%

The results show that with the increase in thickness, the mutual inductance between coils decreases. Also, based on the absolute difference decrease, it could be claimed that the crack detection by this system becomes more difficult when the thickness of the plate grows.

Crack Depth

The crack depth analysis could give insights to understand how practical is this system to test the specimens. For this purpose, the effect of crack depth on the mutual inductance is investigated. The mutual inductance of coils is calculated with crack depths of 0.1 mm, 0.3 mm, 0.5 mm, and 0.7 mm. Table (4) shows the mutual inductance calculations for different crack depths. The mutual inductance of coils when a sample without crack is placed is calculated at 362.16 µH

Table (4) Mutual inductance calculations for different crack depths.

Crack depth (mm)	Mutual inductance with crack (µH)	Absolute difference ($\lvert I - II \rvert$)	Relative difference ($\lvert\frac{I-II}{I}\rvert$)
0.1	361.91	0.25	0.0691%
0.3	361.85	0.31	0.0857%
0.5	361.83	0.33	0.0912%
0.7	361.83	0.33	0.0912%

The results indicate that the higher crack depth leads to higher absolute and relative differences. Thus, when the crack depth is high, the crack detection would be easy.

Crack Radius

The crack radius is also investigated in the present study. The mutual inductance is calculated while the crack radii are assumed to be 10 mm, 20 mm, 30 mm, and 40 mm. Table (5) illustrates the mutual inductance calculations for different crack radii. The mutual inductance of coils when a sample without crack is placed is as same as the previous case study, equaling 362.16 µH

Table (5) Mutual inductance calculations for different crack radii.

Crack radius (mm)	Mutual inductance with crack (µH)	Absolute difference ($\lvert I - II \rvert$)	Relative difference ($\lvert\frac{I-II}{I}\rvert$)
10	362.13	0.03	0.0083%
20	361.83	0.33	0.0912%
30	360.69	1.47	0.4076%
40	358.07	4.09	1.1422%

The results indicate that the higher crack radii result in higher absolute and relative differences. Thus, when the crack radius is high, the crack detection would be easy. The crack radius is more effective than the crack depth.

Wire Radius

The effect of coil wire radius on mutual inductance is also investigated. In this study, the inner and outer radii of the coil are kept constant. This means that by using thin wire we have higher turns in the coil. This results in higher mutual inductance. However, the differences between the mutual inductance of the sample with and without crack are significant. Here, we analyzed the mutual inductance in the case the wire radius is changed to 0.05 mm, 0.15 mm, 0.25 mm, and 0.35 mm for both samples (with and without cracks) and compared the results in Table (6).

Table (6) Mutual inductance calculations for different wire radii.

Wire radius (mm)	Mutual inductance without crack (mH)	Mutual inductance with crack (mH)	Absolute difference ($\lvert I - II \rvert$)	Relative difference ($\lvert\frac{I-II}{I}\rvert$)
0.05	3631.8	3628.5	3.3	0.0909%
0.15	44.829	44.789	0.04	0.0892%
0.25	5.8075	5.8023	0.0052	0.0895%
0.35	1.5111	1.5098	0.0013	0.0860%

The results show that the thinner wire improves the performance of the system to detect hidden cracks.

Air Gap

Regarding the position of the coils, the air gap between the coils and the sample is investigated. The air gap of 1 mm, 2 mm, 3 mm, and 4 mm is used to calculate the mutual inductance. The crack-less analysis is also conducted to compare the results with each other. Table (7) shows the mutual inductance calculations for different air gaps

Table (7) Mutual inductance calculations for different air gaps.

Air gap (mm)	Mutual inductance without crack (μH)	Mutual inductance with crack (μH)	Absolute difference ($\lvert I - II \rvert$)	Relative difference ($\lvert \frac{I-II}{I} \rvert$)
1	409.57	409.22	0.35	0.0855%
2	396.92	396.58	0.34	0.0857%
3	384.83	384.5	0.33	0.0858%
4	373.25	372.92	0.33	0.0884%

The results indicate that the air gap does not have a significant impact on the mutual inductance differences, although minor changes indicate the superiority of the larger distance.

Inner radius

We also analyzed the impact of the inner radius of the coil on the mutual inductance difference. The outer radius is kept constant. Thus, lowering the inner radius results in a higher number of turns for the coil. the mutual inductance calculations are done for 10 mm, 30 mm, 50 mm, and 70 mm of inner radii. The results are shown in Table (8).

Table (8) Mutual inductance calculations for different inner radii.

Inner radius (mm)	Mutual inductance without crack (μH)	Mutual inductance with crack (μH)	Absolute difference ($\lvert I - II \rvert$)	Relative difference ($\lvert \frac{I-II}{I} \rvert$)
10	503.58	501.28	2.3	0.4567%
30	468.11	467.1	1.01	0.2158%
50	362.16	361.83	0.33	0.0911%
70	192.73	192.65	0.08	0.0415%

Decreasing the coil's inner radius makes the differences higher. Therefore, the lower inner radius helps to detect the crack.

Improved System

The obtained results are taken into account and in this part, the mutual inductance analysis is conducted under the circumstances in which they help to detect the crack easier. The values of Table (9) are used to perform this analysis.

Table (9) Specifications of the analyzed improved system.

Parameter	Value
Coil inner radius	10 mm
Sheet thickness	1 mm
Crack depth	0.5 mm
Air gap	20 mm

We conduct this analysis for the cracks with radii of 120 mm, 160 mm, and 180 mm. The results are gathered in Table (10).

Table (10) Mutual inductance calculations for the improved system in different crack radii.

Crack radius (mm)	Mutual inductance with crack (μH)	Absolute difference ($\lvert I - II \rvert$)	Relative difference ($\lvert \frac{I-II}{I} \rvert$)
120	962.01	225.18	23.4072%
160	1000.4	263.57	26.3465%
180	1005.3	268.47	26.7055%

Although the results in the previous studies were frustrating, the results in this study show promising values (see Figure (3) and Figure (4)). The mutual inductance of coils when a sample without crack is placed is calculated at 736.83 μH. However, when a sample with a crack is placed, the mutual inductance becomes higher even more than 1000 μH. Therefore, the results indicate that this method is a promising method for NDT if the design parameters are assumed, properly.

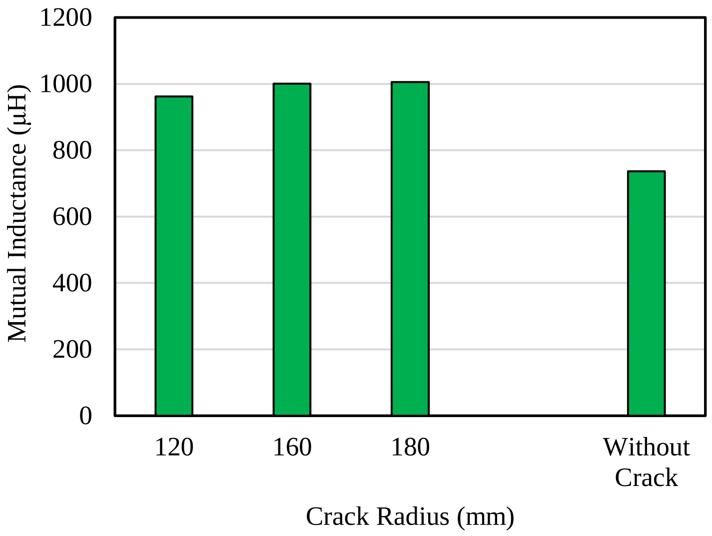

Figure (3) Mutual inductance calculations for different crack radii using the improved system.

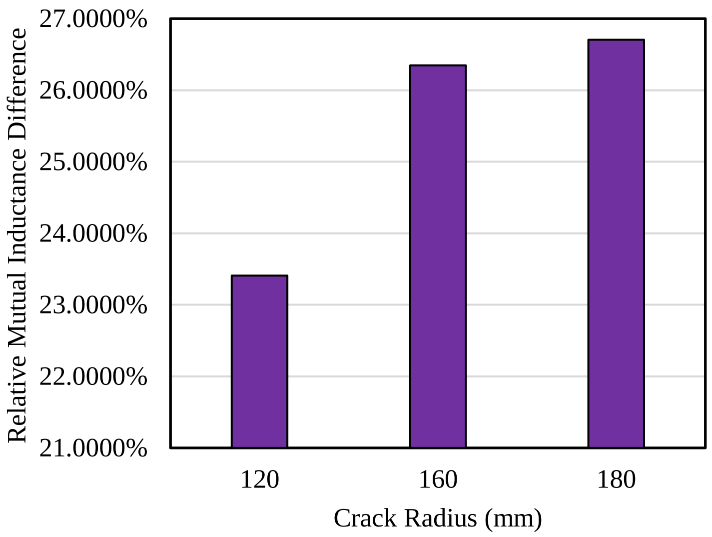

Figure (4) Relative mutual inductance difference for different crack radii using the improved system.

Conclusion

This study has delved into the realm of non-destructive testing (NDT) with a focus on the interaction between coils and an interposed plate sample, particularly in the context of detecting cracks and assessing various parameters affecting mutual inductance. The findings provide valuable insights into the practicality and limitations of this NDT methodology.

The analysis of mutual inductance under varying conditions, including sheet thickness, crack depth, crack radius, wire radius, air gap, and inner coil radius, has revealed important insights into the system's performance. It has been observed that thicker sheets and smaller cracks pose challenges to crack detection, while a thinner wire radius

improves the system's ability to detect cracks. The impact of the air gap and inner coil radius was found to be relatively minor.
Moreover, the study introduced an improved system design, which significantly enhanced mutual inductance values. This promising development suggests that, when design parameters are properly considered, the method can be highly effective for NDT applications. These findings have the potential to revolutionize NDT practices in engineering, allowing for more accurate and efficient detection of defects in materials and structures.
In conclusion, the research presented in this article contributes to the advancement of NDT methodologies by providing a comprehensive understanding of the factors that influence the performance of the mutual inductance-based system. This knowledge can inform the design of more effective NDT systems, ultimately enhancing the quality and reliability of inspections across a wide range of engineering applications. As technology continues to evolve, the insights gained from this study will play a critical role in ensuring the safety and integrity of various structures and materials.

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