

# Design and Research of Differential Probe for Oil Casing

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## Abstract

**Pulsed Eddy Current (PEC) testing is a vital non-destructive technique for assessing corrosion in oil casings, yet its practical application is often hindered by severe interference from lift-off variations and limited detection sensitivity in complex downhole environments. To address these challenges, this study proposes an optimized differential PEC probe system integrated with high-permeability Ni-Zn ferrite cores. A three-dimensional transient magnetic field model was established to investigate the detection mechanism and optimize key structural parameters. Simulation results demonstrate that the proposed differential structure effectively suppresses common-mode noise induced by dynamic lift-off fluctuations, achieving a signal-to-noise ratio improvement of over 22 dB compared to traditional absolute probes. Furthermore, through collaborative optimization of the magnetic core dimensions and coil geometry, the probe's sensitivity to defect signals was enhanced by approximately 2.2 times. The study also reveals a robust monotonic non-linear relationship between the differential signal peak and defect depth, with a fitting accuracy exceeding 0.98, confirming the system's potential for precise quantitative evaluation of corrosion severity. These findings provide a solid theoretical foundation and design framework for developing high-performance downhole inspection tools, significantly advancing the reliability and accuracy of oil casing integrity assessment.**

## Keywords

**Pulsed Eddy Current; Finite Element Analysis; Differential Probe; Casing Detection.**

## 1. Introduction

Oil casings in harsh downhole environments—marked by high temperature, pressure, and corrosion—are prone to thinning, cracking, and perforation, risking well integrity. Precise non-destructive testing (NDT) is thus vital. However, mainstream methods like magnetic flux leakage and ultrasonic testing are limited by strict coupling requirements, inability to penetrate thick scales, and susceptibility to ferromagnetic interference, making them inadequate for complex conditions.

In contrast, Pulsed Eddy Current (PEC) testing, with its broadband excitation characteristics, offers significant advantages: it requires no couplant, can penetrate non-conductive coatings to detect the underlying metal directly, and is capable of full-thickness evaluation. This makes it an ideal solution for overcoming the aforementioned challenges. However, conventional absolute-type PEC probes are extremely sensitive to the dynamically changing "lift-off distance" between the probe and the pipe wall. The strong background noise resulting from this effect often masks weak defect signals, leading to low signal-to-noise ratios (SNR) and poor quantitative accuracy.

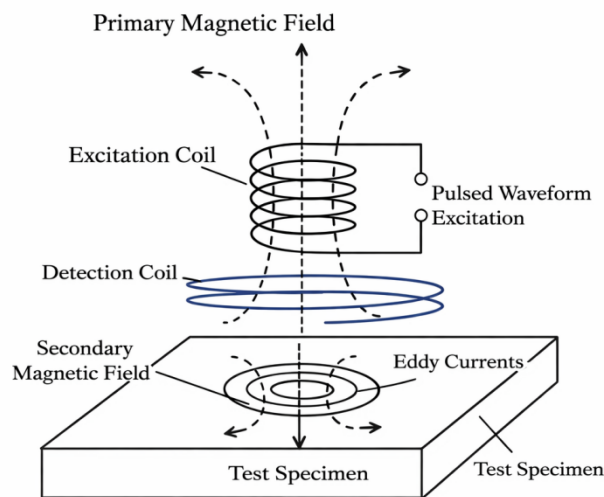
To overcome the lift-off sensitivity of absolute probes, differential designs based on symmetric layouts and common-mode rejection have been developed to suppress noise and enhance sensitivity. Li et al. found that differential, three-core, and U-shaped probes effectively mitigate lift-off and tilt effects while improving the SNR.[1] C. S. Angani et al. successfully detected

defects in insulated stainless steel pipes using dual Hall sensors and time-domain features. [2]Yang et al. identified horizontal detection coils with magnetic shielding as optimal for crack detection. [3]Furthermore, Fan et al. showed that semi-circular focusing probes outperform U-shaped and rectangular versions in energy efficiency[4], and Ona et al. highlighted that optimizing coil spacing can significantly improve sensitivity under high lift-off. [5]

Despite these advancements, existing research on the collaborative optimization of structural parameters for PEC differential probes and the response mechanism of deep-seated defects remains insufficient, lacking systematic design guidance. In view of this, this paper aims to deeply investigate the detection mechanism of differential probes and optimize their key parameters through theoretical analysis and finite element simulation, with the goal of providing reliable theoretical and technical support for high-precision casing defect detection..

## 2. Principle of Pulse Eddy Current Testing

Figure 1 illustrates the operational principle of pulsed eddy current (PEC) testing. The technology employs a pulse square wave signal with a fixed duty cycle as the excitation source. Applying this signal across the excitation coil generates a primary magnetic field each time the pulse rises or falls. This primary field induces eddy currents within the test piece. As these eddy currents decay, they generate a secondary magnetic field, which in turn induces a transient voltage within the detection coil, capturing the material's response. Any defect or variation in the test piece's properties, such as permeability or conductivity, will disturb the eddy current flow. This disturbance alters the secondary magnetic field, leading to a corresponding change in the induced voltage within the detection coil. Consequently, analyzing the characteristics of this induced voltage signal provides a means for evaluating the nature of the defect.:

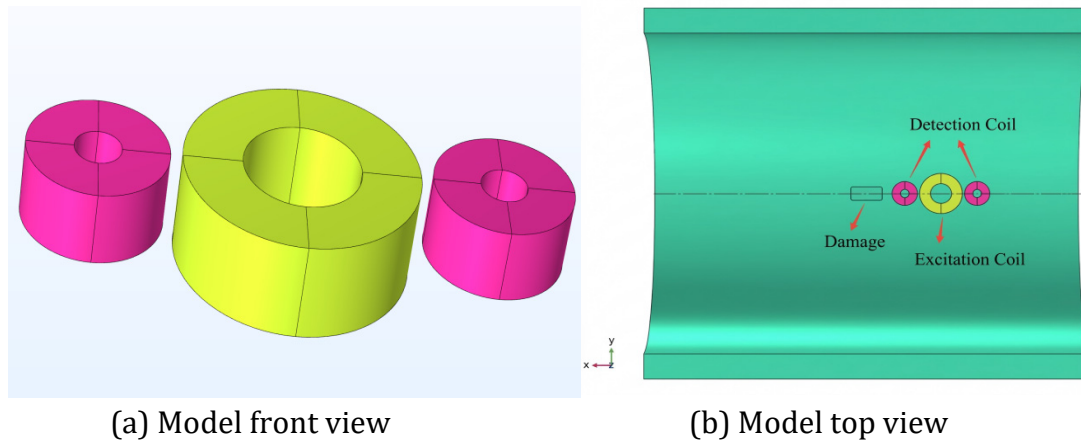


**Fig 1.** Working principle diagram of PEC

## 3. Literature References

In order to further explore the detection mechanism of pulse eddy current differential probes and obtain optimal structural parameters, this chapter establishes a three-dimensional transient magnetic field model for oil casing detection based on electromagnetic field theory using COMSOL Multiphysics multi physics simulation software. This model aims to simulate real underground working conditions, with a focus on analyzing the influence of probe structural parameters on defect response signals. The simulation model mainly consists of an excitation coil, dual receiving coils, magnetic core, tested sleeve, and air domain. Adopting a symmetrical layout of "receiving coil A - excitation coil - receiving coil B. To enhance the

magnetic field aggregation ability and improve the signal-to-noise ratio, a cylindrical magnetic core is embedded inside the coil. The simulation model of differential probe is shown in Figure 2.



**Fig 2.** 3D simulation model of differential probe

Using a unipolar square wave voltage as the excitation source, with an amplitude of 10V, a fundamental frequency of 100Hz, and a duty cycle of 0.4. This excitation waveform can generate a transient magnetic field containing rich low-frequency harmonics, ensuring effective penetration of thick walled casing. Considering the eddy current loss caused by high-frequency harmonic components of pulsed eddy currents, Ni Zn ferrite with high resistivity and permeability is selected as the magnetic core material. The specific parameters are shown in Table 1.

**Table 1.** Key parameters of differential probe model

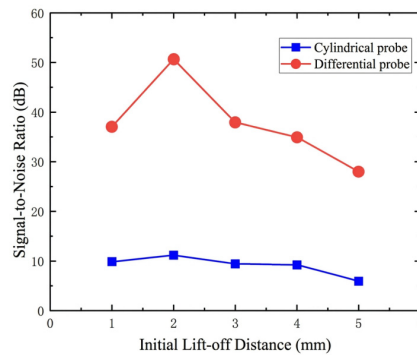
Model Parameters	Parameter Description	Model Parameters	Parameter Description
Excitation coil outer diameter	20 mm	Outer diameter of induction coil	10 mm
Excitation coil inner diameter	10 mm	Inner diameter of induction coil	6 mm
Excitation coil height	8 mm	Induction coil height	6 mm
Excitation coil turns	250 turns	Number of turns of induction coil	500 turns
Excitation coil wire diameter	0.2 mm	Check the diameter of the coil wire	0.1mm
Coil permeability	1	Probe lifting distance	1mm
Coil conductivity	$5.998 \times 10^7$ S/m	Coil spacing	1 mm
Magnetic permeability of iron core	2000	Iron core conductivity	$2e-6$ S/m

To verify the effectiveness of the differential structure in suppressing lift off noise, this section conducted comparative simulations between the traditional absolute probe (single receiving coil) and the differential probe proposed in this paper under identical geometric dimensions and excitation conditions. The simulation scenario is set to scan the non-destructive casing surface with a probe, while introducing dynamic lifting distance fluctuations of 1mm to 5mm to simulate the actual working conditions of unstable centering of downhole instruments.

Table 2 shows the specific signal-to-noise ratios of cylindrical probes and differential probes at different initial lift offs, while Figure 3 shows the signal-to-noise ratio comparison curve between differential probes and traditional absolute cylindrical probes.

**Table 2.** Signal to noise ratio value

Initial lifting distance(mm)	Cylindrical probe SNR (dB)	Differential probe SNR (dB)	Signal to noise ratio improvement amplitude (dB)
1	9.87	37.09	27.22
2	11.16	50.67	39.51
3	9.42	37.95	28.53
4	9.23	34.93	25.70
5	5.98	27.99	22.01

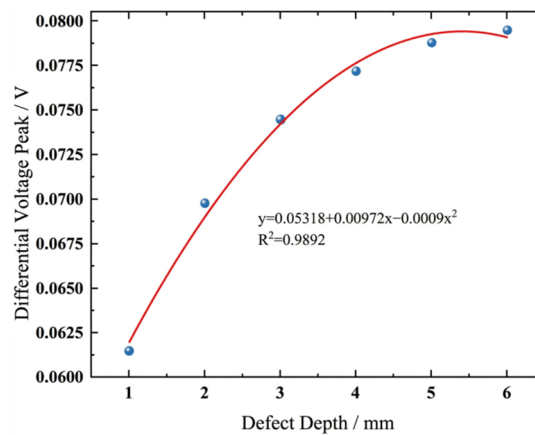


**Fig 3.** Noise ratio comparison chart

From the experimental data and variation curves, it can be observed that firstly, the signal-to-noise ratio of the differential probe and the cylindrical probe has a strong consistency with the variation of the lift off distance. The signal-to-noise ratio curve of the differential probe also shows a trend of "first increasing and then decreasing". The signal-to-noise ratio reaches its peak at a lifting distance of 2mm, which proves that the 2mm lifting height is the optimal lifting working point under this design parameter. Even in the case of a large lift off (5mm), the signal-to-noise ratio of the cylindrical probe has dropped to the failure edge of 5.98dB, while the differential probe remains at a high level of 27.99dB, with an improvement of 22.01dB. Secondly, although the change pattern is similar, the signal-to-noise ratio of the differential probe is much higher than that of the cylindrical probe throughout the entire range. From the table data, it can be seen that the SNR of differential probes is generally distributed between 27dB and 50dB, and the performance improvement is particularly significant compared to the 6dB to 11dB level of cylindrical probes. This fully demonstrates that the differential structure has successfully achieved "common mode suppression" of lift off interference signals through the physically symmetrical design of two pickup coils.

**Table 3.** Differential voltage peak values at different defect depths

Defect depth(mm)	Differential voltage peak value(V)	Defect depth(mm)	Differential voltage peak value(V)
1	0.0615	4	0.0772
2	0.0698	5	0.0788
3	0.0745	6	0.0795



**Fig 4.** Trend chart of peak variation of differential voltage

In order to explore the recognition law of defects with different degrees of defects, the axial width of the defect is first fixed at 15mm, and the response law of differential induced voltage is obtained by changing the defect depth (ranging from 1mm to 6mm). During the simulation process, the center of one of the detection coils was kept aligned with the axis of the defect center, and the simulation results are shown in Table 3.

Fit the data in Table 3, and the fitting results are shown in Figure 4. According to Figure 4, it can be observed that the fitted curves of different depths of defects and peak differential voltage are as follows:  $y = 0.05318 + 0.00972x - 0.0009x^2$ , The correlation coefficient is 0.9892, showing a quadratic function relationship, and the fitting effect is good. It can also be observed that as the depth of the defect increases, the peak value of the differential induced voltage shows a monotonically increasing trend, and the magnitude of the increase gradually decreases.

#### 4. Summary

This study addresses the critical challenges of non-destructive testing for oil casings operating in harsh downhole environments characterized by high temperature, pressure, and corrosion. While Pulsed Eddy Current (PEC) testing offers distinct advantages over traditional methods, such as the ability to penetrate non-conductive coatings without couplants, conventional absolute-type probes suffer from severe sensitivity to lift-off variations, resulting in low signal-to-noise ratios and poor quantitative accuracy. To overcome these limitations, this paper proposed an optimized differential PEC probe system and systematically investigated its detection mechanism and performance through theoretical analysis and finite element simulation. Comparative simulations demonstrated that the proposed differential probe, based on symmetric layout and common-mode rejection principles, effectively eliminates background noise caused by dynamic lift-off fluctuations. Unlike absolute probes whose signals decay exponentially with lift-off changes, the differential structure maintains a stable zero-baseline in defect-free regions, improving the signal-to-noise ratio by over 22 dB under identical dynamic lift-off conditions. Building on this robust noise suppression capability, a collaborative optimization of key structural parameters was conducted, focusing on the synergy between Ni-Zn ferrite cores and coil geometry. By optimizing the core dimensions and matching the excitation and receiving coil spacing, the magnetic flux focusing effect was maximized, increasing the peak differential voltage response to typical defects by approximately 2.2 times compared to the initial design. Furthermore, the study established a clear mapping relationship between defect depth and differential signal amplitude, revealing a monotonic, non-linear correlation with a fitting accuracy exceeding 0.98. This stable response characteristic validates the feasibility of using the optimized differential probe for precise quantitative assessment of

casing corrosion depths. In summary, this work provides a solid theoretical foundation and a validated design framework for high-precision PEC inspection of oil casings. The proposed optimized differential probe not only resolves the persistent lift-off interference issue but also significantly enhances detection sensitivity and quantitative reliability, offering valuable technical support for the development of next-generation downhole inspection tools and contributing to improved safety and integrity management of oil and gas wells.

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