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INFLUENCE OF THE VARIETY OF STEEL TUBE MATERIALS ON THE IMPEDANCE BEHAVIOR OF NON-DESTRUCTIVE EDDY CURRENT TESTING

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Abstract

This article describes the effects of non-destructive eddy current testing (ECT) on steel pipes. To improve the accuracy of ECT, it is considered important to use numerical analysis. However, we propose finite element modeling for eddy current testing of cracked pipes. The end of this paper describes the results of finite element modeling and numerical analysis for eddy current testing of cracked steel pipes. The results obtained from this method are very similar and consistent with the experimental data. It is proved that the simulation method is also valid for other work.

Keywords: Eddy current testing, finite element method, steel tube, TEAM workshop.

1. INTRODUCTION

Steel materials have been used in industrial structures, pipes, etc. One of the most important problems in pipeline inspection is the detection of embedded defects in fixed structures [1]. It is important to identify these cracks in the early stages of development. Therefore, these cracks lead to repairs including maintenance costs.

To improve the accuracy of eddy current testing (ECT), it is considered important to use numerical analysis and optimize the detection method and the shape of the probe coil [2]. Numerical analysis is required to understand the eddy current distribution in conductors and improve the ECT technique [3].

The eddy-current inspection of cracks is a very important issue for many industrial applications. Thus, the sensor is placed next to the measurement target so that the currents induced in the material have an impact on the change in impedance of the sensor coil [4].

In this paper, we present finite element modeling (FEM) for eddy current testing of cracked pipes. The forward eddy current problem is studied to detect defects by scanning structures. The change in pickup coil impedance is modeled with FEM. Based on the Matlab software with Comsol, a fast simulation program was developed, then the coil impedance changes due to the presence of defects [5].

The reconstruction of defects is a prominent problem of this method. In this way, the TEAM (Testing Electromagnetic Analysis Methods) workshop [7] presented two benchmarking questions for ECT calculations. They are TEAM 15-1 and TEAM 15-2 considered to verify our source code [8-9].

A good comparison is obtained between the experimental and numerical results. Using this source code, the goal of simulating a pipe with cracks is investigated. This problem is similar to general shape, but different in geometry.

2. DESCRIPTION OF THE PROBLEM

The geometry of the considered problem is shown in figure 1. A circular air coil is scanned parallel to the x-axis along the length of a rectangular defect in the steel tube [10-11].

In this work we were chose the frequency above 100 kHz, because the defect is external, not internal. So, if the defect is external, we use a higher frequency (150 kHz – 300 kHz) but where the defect is internal we use a lower frequency (<<100 kHz). This variation in the utilisation of frequency is a function of the skin depth.

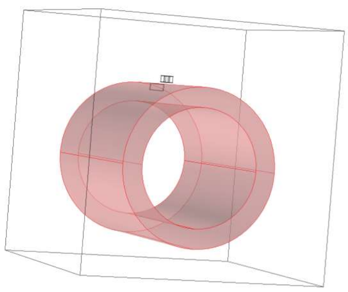


Fig. 1. Schematic diagram of the steel tube with the defect

The dimension of the coil, the crack and the tube are indicated in the figure 2. The geometric parameters are listed in the Table 1.

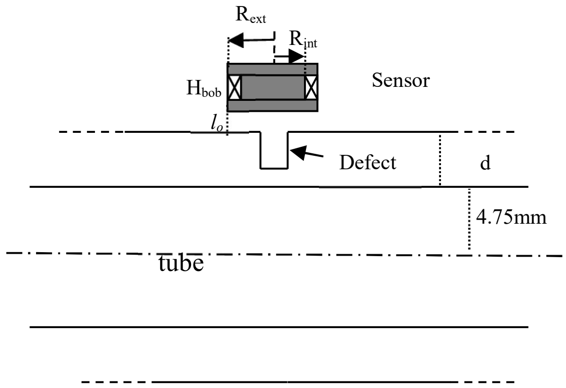


Fig. 2. Coil above a tube with a crack representation

Both frequency and the lift-off are fixed, and the impedance of the probe is calculated based on the center position of the coil. The parameters of this problem are also shown in Table 1.

Table 1. Parameters of the problem

Symbol	Name	Values
R_{int}	Inner radius (mm)	0.6
R_{ext}	External radius (mm)	1.6
H_{bob}	Height of the coil (mm)	0.8
N	Number of turns	140
d	Thickness of the plate (mm)	1.25
l_o	Lift-off (mm)	0.25
	Crack length (mm)	10
	Crack width (mm)	0.28
	Crack depth (mm)	5
μ	Permeability	1
f	Frequency (kHz)	150-300

The electrical conductivity of various ferrous metal materials is shown in Table 3.

3. EDDY CURRENT MODELING USING COMSOL MULTIPHYSICS

The eddy current inspection phenomenon can be represented by the control field equations solved by the three-dimensional finite element method.

In Comsol software, the eddy current system model is used for non-destructive testing [5]. The Magnetic Fields interface of the AC/DC Module is used. The equations defining eddy currents are derived from Maxwell's equations and are written in terms of the magnetic vector potential (A) [12]. Since the field coil is fed by a sinusoidal current, the time-harmonic method is used. The governing equations can be written as follows:

$$\nabla \times \left(\upsilon \cdot \nabla \times \vec{A}\right) + (j\omega\sigma - \omega^2\varepsilon)\vec{A} = \vec{J}_0 \tag{1}$$

With $\vec{J}_0$ the current density source and υ the reluctivity term equal to $(1/\mu)$. σ, μ, and ε denote electrical conductivity, magnetic permeability, and permittivity, respectively.

Boundary conditions for physical boundaries must be specified on all boundaries of the survey area. This condition is imposed by default in Comsol Multiphysics since the magnetic potential is set to $(nA = 0)$.

The mesh is generated as tetrahedral elements. Areas where field variations are important require a finer mesh. We need to refine the mesh around the coils and the cracks in the plate. Because it allows us to obtain accurate solutions with a reduced number of elements and reasonable computation time [5, 15].

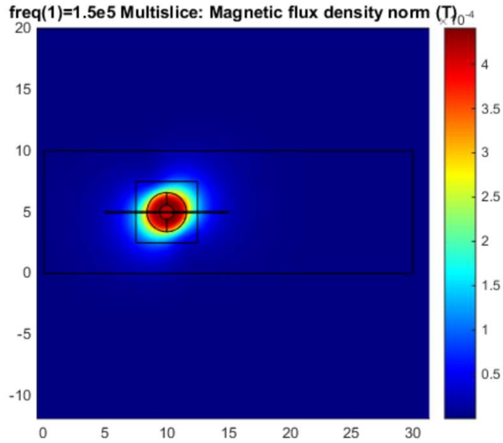


Fig. 3. Magnetic flux density representation

4. IMPEDANCE SENSOR CALCULATION

The change in coil resistance ***R*** and reactance ***X*** of an impedance probe can be determined by energy and power calculations [4, 18]:

$$P = \int_{\Omega} \frac{J_{eddy}^2}{\sigma}\, d\Omega \tag{2}$$

$$W = \frac{1}{2} \cdot \int_{\Omega} B\ H\ d\Omega = \frac{1}{2} \cdot \int_{\Omega} \frac{B^2}{\mu}\, d\Omega \tag{3}$$

$$(R + jX) \cdot I^2 = P + j(2\pi f)\, W \tag{4}$$

I is the intensity of current source at frequency f. $\vec{B}$ and $\vec{H}$ are magnetic induction and magnetic field respectively, and J_{eddy} is the induced current density. Magnetic energy W in the whole domain is used to compute the imaginary part and using the Joule losses P in the conductive media, the real part is calculated.

5. SIMULATION WORK

The eddy current problem is a low frequency electromagnetic field problem. In this paper, the choice fell on the Comsol Multiphysics AC/DC module, which validates its usefulness as a very reliable tool for performing practical eddy current testing studies [13].

The main objective of utilizing eddy current in modeling Non-Destructive Testing (NDT) is to determine the probe's response. In order to achieve this, a scan was carried out along the defect, with the initial position of the probe at $x = 0$. The scanning process involved the use of a displacement step of 1 mm, with the length dimension referring to the distance scanned by the sensor as the probe was moved along the crack length.

The benchmark problem involves moving a multi-turn coil over a conductive test piece in an object to detect faults. The defect detection is done by taking into account the change in coil impedance. The coil moves along the x-axis. The change in impedance was calculated as a function of the coil center position [14].

The developed models are created in 3D so that different configurations can be simulated. In the first part, we should present the results obtained using the software Comsol and Matlab [9] for two problems of TEAM 15.

These experiments have been mentioned in many references, such as [9], where an aircored circular coil was used. Table 2 shows the parameters of this coil.

5.1. TEAM 15-1

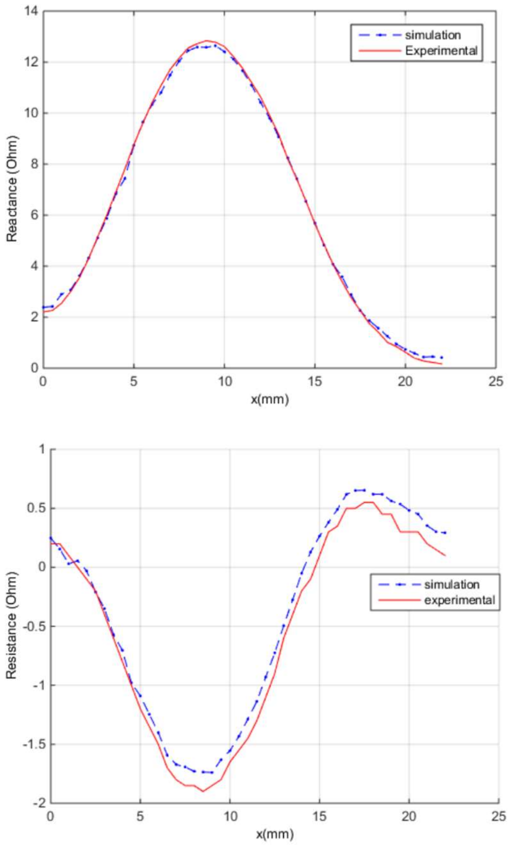


Fig. 4. Real and imaginary components of coil impedance versus the probe position along the crack length (TEAM 15-1)

Script programs are used for calculations. Use a loop to call a function to calculate the impedance for each displacement step [8]. The circular coil translates along the x-axis (figure 1).

The change in impedance was calculated as a function of the coil center position. Compared with the experimental results in references [8] and [9], figure 4 and figure 5 show that the impedance variation results are in good agreement.

In figure 4, the simulation results agree with the experimental results. The frequency used in this problem is 900 Hz.

5.2. TEAM 15-2

The frequency used in this problem is 7 kHz [8-9]. Similarly to the first problem, simulation results match experimental results.

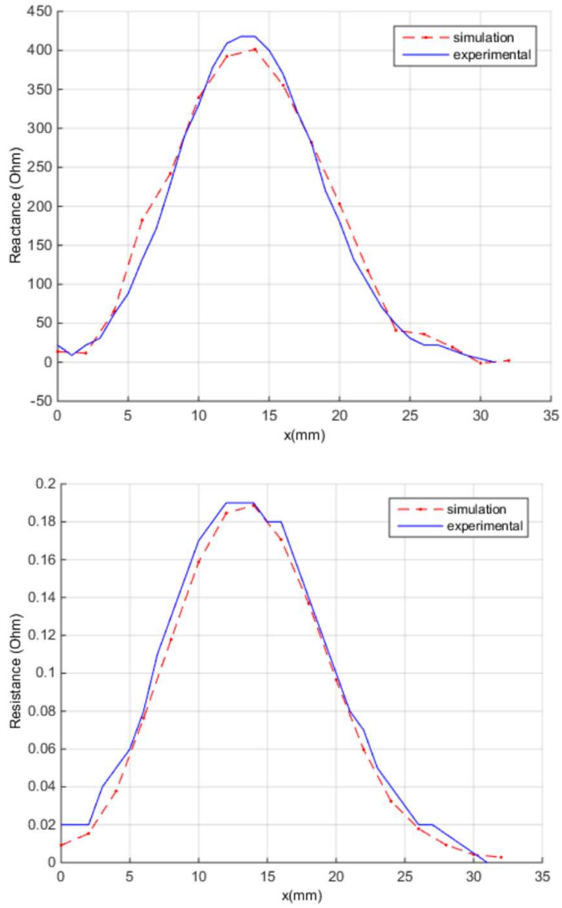


Fig. 5. Real and imaginary components of coil impedance versus the probe position along the crack length (TEAM 15-2)

In order to verify the correct application of a modelling method, numerical calculations must agree with experimental measurements. We simulate the most popular non-destructive testing benchmark problems using eddy currents.

In the next part of the analysis, we will look at a more complex problem where the defect is in the steel tube [14] and [15].

Table 2. Parameters of the TEAM problem

Symbol	Name	Values
R_{int}	Inner radius (mm)	6.15
R_{ext}	External radius (mm)	12.4
H_{bob}	Height of the coil (mm)	6.15
N	Number of turns	3790
	Thickness of the plate (mm)	12.22
	Lift off (mm)	0.88
	Crack length (mm)	12.6
	Crack width (mm)	0.28
	Crack depth (mm)	5
μ	Permeability	1
σ	Conductivity (MS/m)	30.6
f	Frequency (kHz)	0.9-7

6. SIMULATION OF STEEL TUBES

This case study describes the modelling of industrial inspection of steel pipes using the eddy current method. In this section, we should introduce the simulation work for pipe cracks [13]. Three materials were used: carbon steel, stainless steel and Inconel. Table 3 gives the conductivity of each material. If the tube radius is much larger than the coil size, the tube wall can be regarded as a plate and the problem is simplified [16-17].

The simulation work provided the results shown in figures 6, 7 and 8. Figure 6 show the distribution of the current density in a plane of section perpendicular to the crack for a position of the center of the coil. The figure 6 verifies that the crack acts as an impermeable barrier to the induced current.

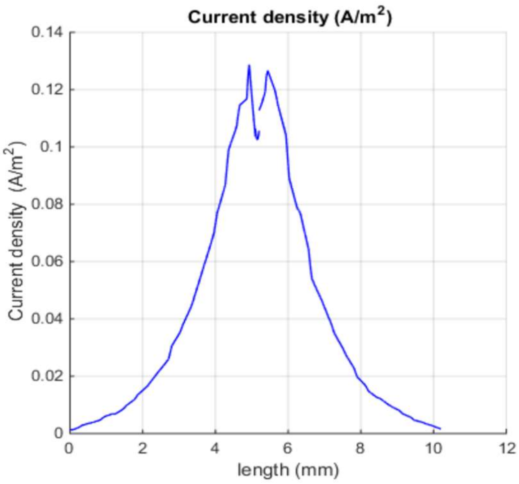


Fig. 6. Distribution of the current density in a plane

Figures 7 and 8 shows that we have good agreement in terms of the real and imaginary parts of the impedance variation results compared to the results obtained in references [16] and [17]. We can see the effect of the conductivity of different materials on the resistance of the probe and the change in resistance near the plates. The change in resistance is large because it is inversely proportional to conductivity.

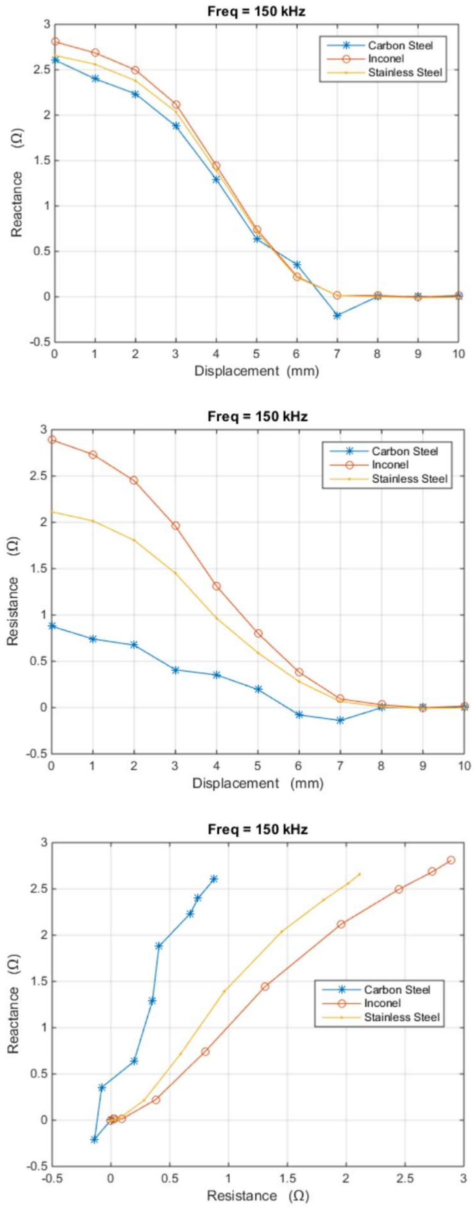
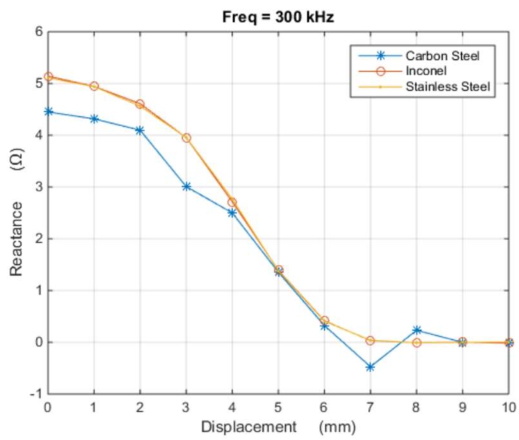
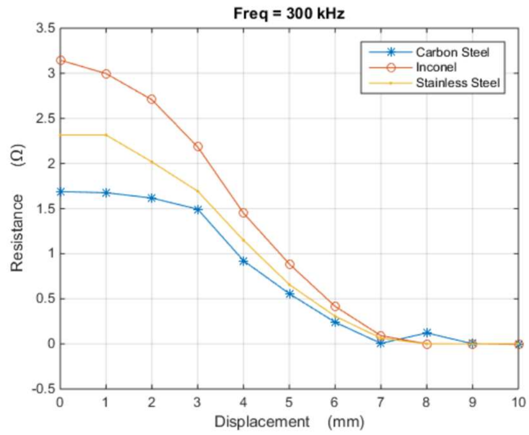


Fig. 7. Real and imaginary components of coil impedance versus the probe position along the crack at 150 kHz





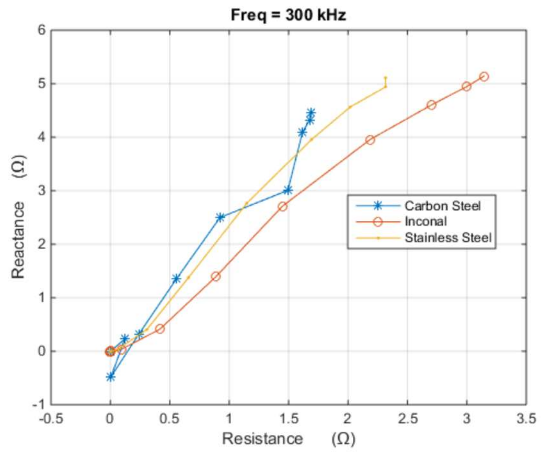


Fig. 8. Real and imaginary components of coil impedance versus the probe position along the crack at 300 kHz

Table 3. The conductivity of some ferrous materials

Materials	σ (MS/m)
Carbon Steel	6.99
Stainless Steel	1.43
Inconel	1

7. CONCLUSION

This study aimed to detect defects in steel pipes by leveraging finite element software that incorporates a detection coil. By utilizing this approach, we were able to accurately identify faults and assess their severity.

In summary, we have implemented computer codes for each proposed model and conducted numerical experiments to validate their accuracy. To calculate impedance, a computer with Intel i7 processor and with 8 Gb RAM memory was utilized, and the results showed that the required CPU time is almost independent of the crack mesh size, with a runtime of under three minutes. Additionally, the successful simulation of the coiled tube problem using the coiled plate model was achieved in cases where the tube radius was considerably greater than the coil size. These findings have significant implications for the development of more efficient and accurate techniques for detecting defects in steel pipes.

The results obtained from this investigation have important implications for the maintenance and safety of steel pipes, which are commonly used in various industrial applications.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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