Optimal design and error analysis based on pulsed eddy current sensor

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Abstract

Application and analysis method of pulsed eddy current is introduced. The parameters of sensors are optimized according to the detection requirement and suitable results and conclusions are obtained. The feature named attenuation rate is proposed to measure and calculate the thickness of steel plate. Error caused by lift-off effect and other factors is also analyzed.
Key words: **Pulsed eddy current; NDT; Finite element; Thickness measurement**

Introduction

With the rapid development of oil and gas transportation pipeline industry, the damage prevention and safety maintenance work of pipeline is of great significance. On the one hand, the HTHP fluid flowing through the pipe will cause corrosion on the inner wall. On the other hand, the protective coating with the function of thermal insulation will cause chemical corrosion to the external pipe wall [1] -[3] . Therefore, although the safest and most convenient way of offshore oil and gas transportation the submarine pipelines are, they are always taking the risk of thinning and damaging [4] -[9] .

The long service time and backward detection technology make the existing submarine pipelines leakage accidents easy to occur. In order to ensure the safety in operation, pulsed eddy current (PEC) testing technology is used to detect the pipeline. As a kind of new nondestructive testing technique, pulsed eddy current testing can be used to measure the corrosion status of pipelines without affecting the normal operation and destroying the protective layers of submarine pipelines [10] -[16] . And the research of PEC testing technology is of great value to ensure the safe and stable operation of submarine pipelines.

The sensor for PEC testing is composed of two parts: the driver coil and the magnetic field detector (pickup coil, Hall sensor, GMR, etc.) [17] -[21] . In inspection process, rectangular wave current is transmitted to the exciting coil by the drive circuit. The square wave field generated by the excitation signal in driver coil is the source magnetic field. The change of magnetic field intensity will excite the induced electric field in specimen and the eddy current is generated. Magnet field produced by eddy current and the source magnet field together breed the induced electromotive force. By analyzing the detection signal and extracting feature information, detection of thickness or defect is realized.

Theory

The analysis of the PEC theory requires understanding of the electromagnetic field and the analysis of the Maxwell equations. The wave equation which can be derived from the Maxwell equation is written as

$$\nabla^2 \dot{H} = j\omega\mu(\sigma + j\omega\varepsilon)\dot{H} \tag{1}$$

For general metallic material, $\varepsilon_0 = 8.85\times10^{-12}\, F/m$, so $\omega\varepsilon$ is negligible compared with σ. Eq. (1) can be reduced to

$$\nabla^2 \dot{H} = j\omega\mu\sigma\dot{H} \tag{2}$$

Similarly, the following equation is derived as

$$\nabla^2 \dot{E} = j\omega\mu\sigma\dot{E} \tag{3}$$

$$\nabla^2 \dot{J} = j\omega\mu\sigma\dot{J} \tag{4}$$

where $\dot{H}$, $\dot{E}$ and $\dot{J}$ are the complex vector of magnetic field intensity, electric field intensity and current density respectively. These are the basic equations for the analysis of PEC phenomenon.

However, analytical solution is hardly obtained except for a few simple problems by solving the above equations. In order to research the electromagnetic phenomenon of PEC testing, the eddy current loop model is used to study the equivalent circuit. The specimen is modeled as series connections of inductors and resistors. The driver coil, pickup coil and specimen together are simplified as a multi-coil coupling system. Finally, the complex physical field problem is converted into the circuit theory calculation.

The circuit model is shown in Fig. 1. The driver coil in the PEC sensor can be equivalent to the primary coil of the multi-coil coupling system. And the pickup coil and eddy current ring can be equivalent to the secondary coil. The coils are coupled together by magnetic field, and the magnetic properties of the coils are described by self-inductance and mutual inductance.

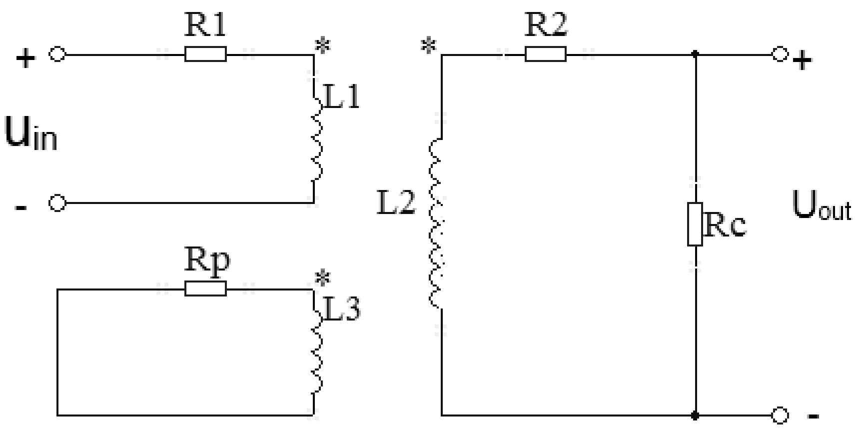

Fig. 1 Circuit model of PEC testing

The following equation is given according to the circuit theory

$$\begin{cases} u_1(t) = R_1 i_1(t) + L_1 \frac{\mathrm{d}i_1(t)}{\mathrm{d}t} + M_{12}\frac{\mathrm{d}i_2(t)}{\mathrm{d}t} + M_{13}\frac{\mathrm{d}i_3(t)}{\mathrm{d}t} \\ u_{out}(t) = -R_c i_2(t) = R_2 i_2(t) + L_2\frac{\mathrm{d}i_2(t)}{\mathrm{d}t} + M_{12}\frac{\mathrm{d}i_1(t)}{\mathrm{d}t} + M_{23}\frac{\mathrm{d}i_3(t)}{\mathrm{d}t} \\ 0 = R_p i_3(t) + L_3\frac{\mathrm{d}i_3(t)}{\mathrm{d}t} + M_{13}\frac{\mathrm{d}i_1(t)}{\mathrm{d}t} + M_{23}\frac{\mathrm{d}i_2(t)}{\mathrm{d}t} \end{cases} \tag{5}$$

Where R_1, R_2 and R_p represent resistance value of driver coil, pickup coil and eddy current loop, L_1, L_2 and L_3 represent self-inductance respectively. M is the mutual inductance among the coils.

Although the circuit model is intuitive and convenient, too much approximation reduces the scope of application in the process of design and analysis.

Simulation optimization

In the process of analysis and calculation in PEC testing, a plenty of approximations are needed in modeling. The difficulties of obtaining analytical solution are great and the inaccuracy can't be neglected. Hence the numerical simulation model by finite element method is established in the time domain. It can simplify the calculation process and calculate the detection signal quantitatively. COMSOL is used as simulation software, which is practical with abundant CAD modeling tools, powerful meshing ability, a large number of physical modules and extended functions.

During pulsed eddy current testing, most of the time the diameter of the pipeline is obviously larger than that of the excitation coil. Therefore, the pipeline can be equivalent to a flat plate structure and the wall thickness of the pipeline is assumed as the thickness of a plate approximately.

The two-dimensional axisymmetric model is used to calculate the solution, which reduces the calculation time and lower the difficulty of analysis. Simulation has showed that the three-dimensional model has no obvious advantages compared with the two-dimensional axisymmetric model under the circumstance of a cylindrical coil.

The Maxwell equations and the following equations are applied in the calculation of simulation model.

$$(\mathrm{j}\omega\sigma - \omega^2\varepsilon)A_\phi + \nabla\times\left(\mu^{-1}\nabla\times A_\phi\right) = J_\phi^e \tag{6}$$

$$J_\phi^e = \sigma\varepsilon = -(\nabla \mathrm{JV} + \frac{\partial A_\phi}{\partial t}) \tag{7}$$

$$\mathrm{H} = \frac{B}{\mu} = \frac{\nabla\times A_\phi}{\mu_0\mu_r} \tag{8}$$

Where ω is angular frequency, σ is dielectric constant, μ is permeability, J_ϕ^e is current density.

In order to analyze the relationship among the structural parameters of the coil, the magnetic field around the coil and the eddy current in the test piece, the most important parameters of the coil are simulated and analyzed to obtain more accurate detection results. The height, inner diameter and outer diameter are considered as the main structural parameters of the coil. Only one parameter is changed at a time when variation of eddy current distribution.is researched.

Fig. 2 shows the simulation results of the eddy current distribution in the test parts when inner and outer diameter of the coil are the same and the height of coil is 30mm, 20mm and 10mm respectively. It can be seen from the graph that the magnetic induction line will come close to the coil with the decrease of coil height when the inner and outer diameter stay the same, which is conducive to the improvement of the resolution of the detection system.

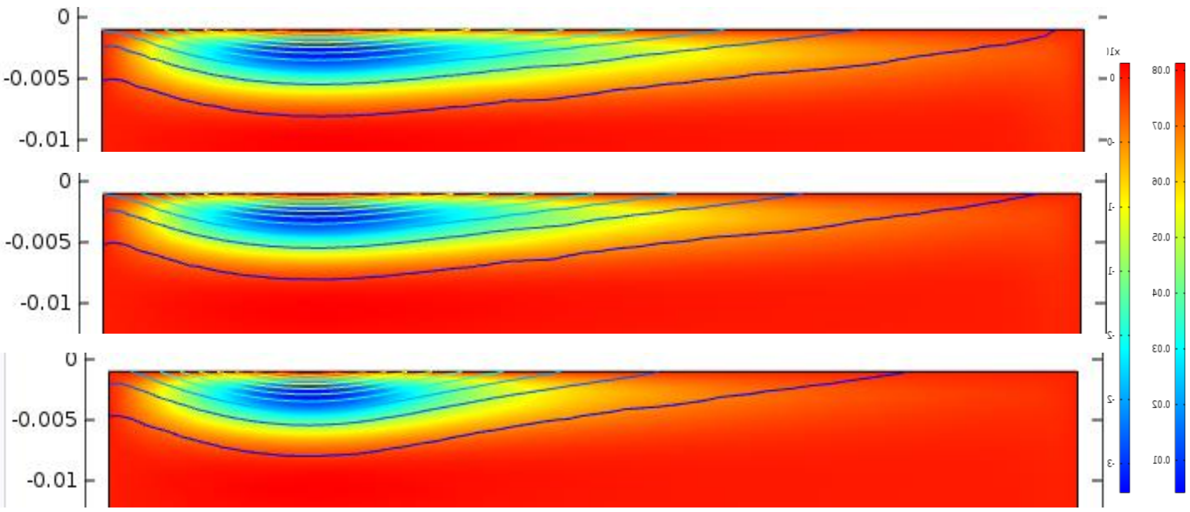

Fig. 2 Current distribution with different height of coil

Fig. 3 shows the simulation results of the eddy current distribution in the test parts when inner diameter and height of the coil are the same, outer diameter is 5mm, 15mm and 25mm respectively. It can be seen from the graph that the eddy current intensity will increase with the increase of outer diameter when the inner diameter and height of the coil stay the same, which is conducive to the improvement of the sensitivity of the detection system.

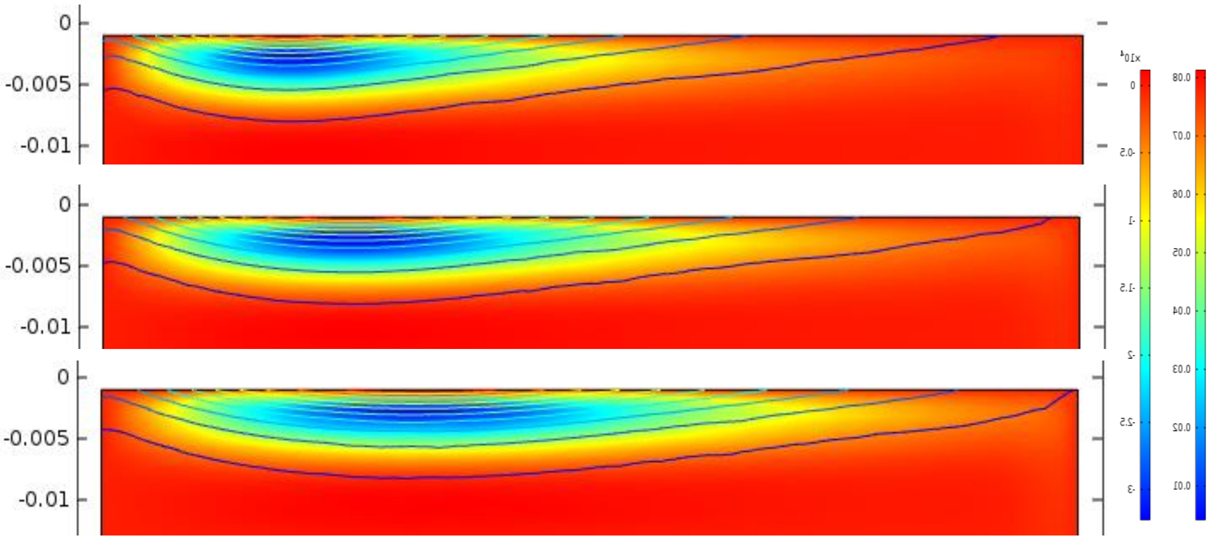

Fig. 3 Current distribution with different outer diameter of coil

Fig. 4 shows the simulation results of the eddy current distribution in the test parts when outer diameter and height of the coil are the same, inner diameter is 25mm, 15mm and 5mm respectively. It can be seen from the graph that the magnetic field distribution concentrate with the decrease of outer diameter but there is no obvious change in eddy current intensity. It indicates that the decrease of inner diameter is conducive to the improvement of the resolution of the detection system.

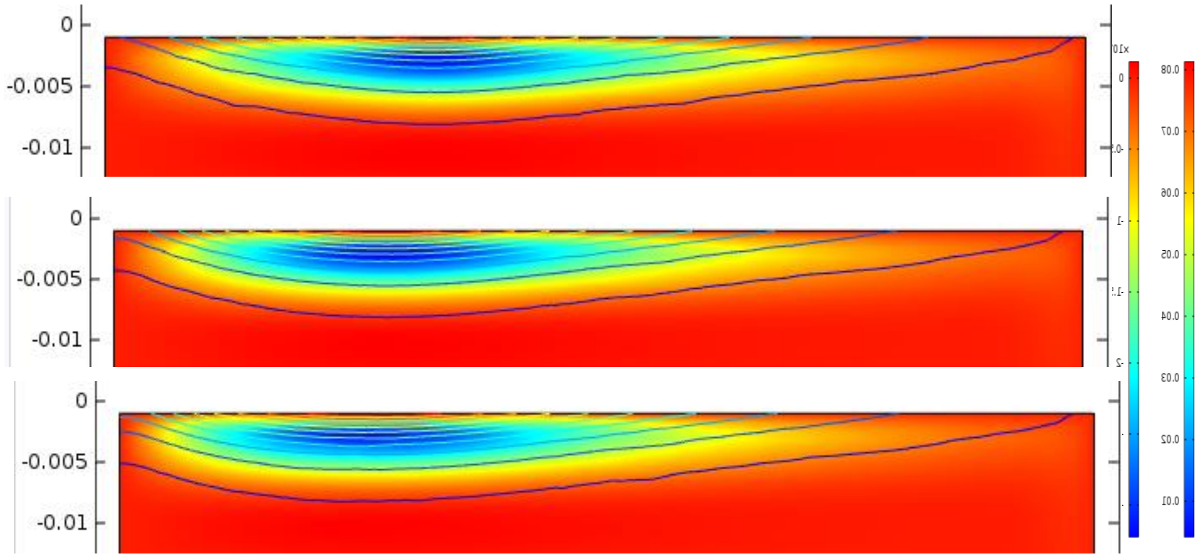

Fig. 4 Current distribution with different inner diameter of coil

It can be seen from the simulations that a relatively smaller inner diameter, larger outer diameter and lower height for the coil are beneficial to the improvement of the resolution and sensitivity of a PEC testing system. If necessary, an iron core can be added to reinforced the effect.

Error analysis

After optimizing the structure of the PEC sensor, steel plate with different thickness is simulated to find proper features from the detection signal. The thickness of the steel plate is in the range from 10mm to 25mm. Due to the large range of voltage variation in detection coil, the logarithm of voltage is taken. As shown in Fig. 5 plotted by time(s) on the horizontal axis and logarithm of voltage(V) on the vertical, the rear part of the induction voltage curve on semi log coordinate is approximate to right line. And the attenuation rate of the signal increase as the thickness of the steel plate decreases. Therefore, the thickness can be calculated by taking the attenuation rate of detection signal in the rear part as the feature.

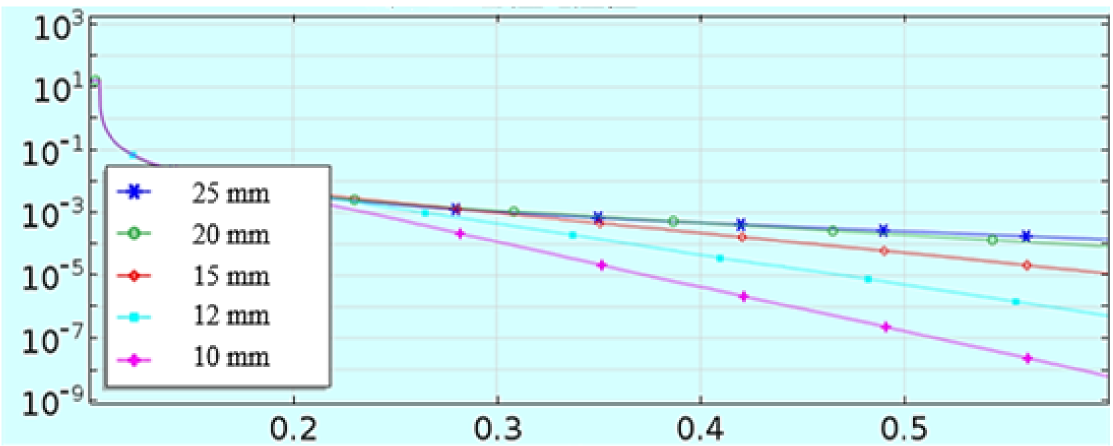

Fig. 5 Voltage curves in pickup coil for steel plates

According to the simulation results, a set of PEC testing system is designed and optimized to finish the thickness measurement. Thickness of each segment is executed for four times.Signal segments from 0.15V to 0.05V are captured to do linear fitting and the feature related to thickness, attenuation rate of the signal is calculated and averaged. Measurement results are as shown in Table 1, in which M1 to M4 represents the first to fourth measurement.

Table 1 Decay rate for measurement of steel plates with different thickness

Thickness (mm)	**M1 (dB/s)**	**M2 (dB/s)**	**M3 (dB/s)**	**M4 (dB/s)**	**Average (dB/s)**
9.5	-385.159	-384.046	-385.061	-390.297	-386.141
12.3	-257.593	-258.678	-258.521	-262.188	-259.245
14.9	-194.135	-191.178	-191.188	-194.907	-192.852
17.5	-151.232	-151.171	-152.706	-149.093	-151.0505
20.1	-109.259	-110.543	-111.276	-110.614	-110.423
22.5	-92.5183	-92.4155	-91.494	-92.4588	-92.22165
25.0	-84.9723	-84.057	-84.800	-84.551	-84.59507
27.6	-85.1229	-84.4194	-84.108	-82.743	-84.09833

Fitting with exponential function, the following equation can be obtained

$$y = -64.363 - 1670.85 \times e^{-0.17352x} \tag{9}$$

Where x is the thickness of steel plate, y is the attenuation rate.

According to the equation above, the thickness of measurement can be calculated. Compared with the actual thickness, relative error is computed as shown in Table 2

Table 2 Thickness measurements and relative errors

measurement	Actual thickness (mm)	decay rate (dB/s)	Thickness for measurement (mm)	relative error
1st	10.9	-306.004	11.14	2.19%
2nd	12.2	-267.289	12.15	0.41%
3rd	14.9	-198.577	14.53	2.53%
4th	16.2	-174.51	15.67	3.37%
5th	13.55	-227.587	13.4	1.08%
6th	21.3	-102.445	21.79	2.26%
7th	22.55	-96.44	22.78	1.01%
8th	25.05	-87.035	24.78	1.09%
9th	23.8	-89.4	24.2	1.69%
10th	26.3	-87.756	25.7	6.91%

It can be seen from the table that when the measured value is less than 25mm, relative error is less than 5%, The relatibe error increases when the thickness of the steel plate is a little bit larger.

Simulation proves that lift-off effect has little effect on measurement when attenuation rate is taken as a feature.However, actual measurement results shows that the influence of lift-off effect cannot be ignored. All the amplifying and filtering or noise in hardware circuit may make the lift-off effect more influential. Exponential fitting is not always the best method. Polynomial fit in different order or neural network algorithm may bring distinct precision results. Magnetic shielding acting on coils can make sensitivity improve.

Conclusion

In PEC testing system, a relatively smaller inner diameter, larger outer diameter and lower height for the coil bring about better resolution and sensitivity. Attenuation rate from rear part of the induction voltage curve can be used as a feature to measure thickness of steel plate. Thicker steel plate will lead to lower measurement accuracy. the influence of lift-off effect needs to be take into consideration to reduce errors.

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