

Review of Pulsed Eddy Current Testing Technology

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Abstract

Pulsed eddy current testing (PECT) is a branch of eddy current testing. It uses square wave or step excitation to obtain component information by measuring the change of magnetic field. Square wave excitation contains a variety of frequency components, and the low-frequency electromagnetic wave has a deeper penetration depth, so it has a better detection effect for deeper defects. PECT technology is widely used in rivet connection of aircraft and internal inspection of pipeline. However, the traditional eddy current impedance analysis method is not suitable for PEC signal analysis. Further exploration is needed in the aspects of testing theoretical model, improved design of sensor and signal processing. In the above aspects, this paper discusses the pulsed eddy current testing technology, summarizes the current research progress, and points out the problems and directions in the development process of the technology.

Keywords

PECT; Theoretical Model; Coil; Signal Processing.

1. Introduction

As a non-destructive testing method, eddy current testing technology adopts non-contact testing, which can penetrate the non-conductive layer without damaging the integrity of the tested component, and is not affected by the oil pollution on the surface of the component. Due to the high integration, convenient use, no radioactive effect, high sensitivity of eddy current testing equipment, it is easy to realize high-speed automatic on-line detection, which attracts a large number of scholars to study deeply and is widely used in industrial production [1].

Pulsed eddy current testing (PECT) technology is a branch of eddy current testing technology. It mainly uses square wave excitation, has higher transient power, contains rich frequency components, and can obtain a variety of different depth information. Compared with traditional eddy current testing, it improves the detection depth and intensity, It avoids the limitation that the traditional eddy current can only detect the defects on the surface of the equipment. The ultra-low frequency eddy current signal can pass through the metal protective layer and the thick non-metal layer to realize the deep defect detection of the tested component and extract the deep layer information of the component. The PEC sensor has a large coverage area and fast detection speed. A large amount of information can be obtained in a few seconds, It can detect large area of metal corrosion, and has more characteristic parameters to characterize defects and thickness [2,3].

Pulsed eddy current testing technology is based on Maxwell's electromagnetic field theory. Its basic principle is to apply pulsed square wave excitation signal at both ends of the excitation coil to produce a changed excitation magnetic field, namely primary field. The component under test senses the changed eddy current to produce a eddy current magnetic field, namely secondary field. The electromagnetic field around the coil is composed of the superposition of the two magnetic fields, And it contains the information of the thickness or defects of the component itself. By taking appropriate methods and detection elements to measure the

secondary field and analyzing the measurement signal, the information of the component can be obtained [4,5].

2. Research Background

In the aviation field, most aircraft airframes are multi-layer metal structures, which are usually connected by bolts and rivets. During the service period of aircraft, especially in the eastern coastal and inland humid areas, due to the external environment corrosion and load effect, the aluminum alloy surface protective coating of aircraft structure is aging, peeling off, and the matrix material is seriously corroded, which is easy to produce interlayer cracks. Therefore, it is of great significance for flight safety to detect the defects in time. The surface defects of fuselage skin and wing panel can be detected by conventional detection methods, but it is not easy to detect the near surface and deep corrosion or cracks [6~8].

Pipes with cladding and metal pipes are widely used in petrochemical, electric power and other industries, in which the inner wall defects, such as pores, delamination, shrinkage, folding and so on, the magnetic sensors of pipeline magnetic flux leakage internal detector have great differences in the amplitude of the detection signal, which makes the detection sensitivity have great uncertainty, and it is easy to cause the misjudgment of the inner and outer wall defects of the pipeline. At present, the conventional nondestructive testing is mainly used for the detection of cladding pipeline, especially for the low-temperature or high-temperature pipeline, which needs to remove the cladding under the shutdown state. The construction period is long, and the economic cost is increased. Therefore, it is of great significance to carry out the non-stop detection without removing the cladding [9].

3. Theoretical model

The research of eddy current testing technology is essentially a study of electromagnetic field problems, so in the process of research, the problems encountered in testing are usually simplified modeling, and the electromagnetic field theory is used for analysis and calculation. Maxwell equations are the theoretical basis of eddy current testing.

3.1. Equivalent circuit model

Some researchers use the transformer coupled mutual inductance circuit model to explain the relationship between the pulsed eddy current sensor and the tested component. The primary circuit is equivalent to the pulsed eddy current sensor, and the measured component is represented by the secondary circuit. The actual resistance r_e represents the resistance of the eddy current circuit of the component under test, which is proportional to the resistivity of the component under test, and the imaginary part $j\omega L_m$ represents the leakage inductance in the circuit. The coupling coefficient K is related to the distance between the sensor and the tested component, and increases with the decrease of the distance.

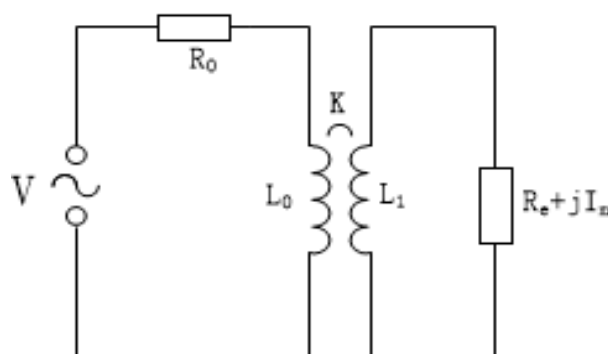


Figure 1. Equivalent model diagram

Kirchhoff voltage theorem is used to describe the equivalent circuit model, as shown in formula (1) and formula (2):

$$R_0 I + j\omega L_0 I - j\omega M_2 I_e = V \quad (1)$$

$$R_e I_e + jI_m I_e + j\omega L_1 I_e - j\omega M_1 I = 0 \quad (2)$$

Where, angular frequency ω is related to the excitation frequency f , i.e. $\omega = 2\pi f$. R_0 and L_0 represent the resistance and inductance of the primary coil of the pulsed eddy current sensor under no-load condition, respectively Ω , H; R_e and L_1 represent the resistance and inductance of the inductive eddy current circuit respectively. M_1 and M_2 refer to the mutual inductance of the two coils, namely $M_1 = KL_0$ and $M_2 = KL_0$.

When the pulsed eddy current sensor is close to the component under test, the influence of induced eddy current is equivalent to the equivalent impedance Z_e of the primary circuit, and the expression is shown in equation (3), where the real part and imaginary part of the impedance are shown in (4) and (5) respectively:

$$Z_c = R_c + j\omega L_c = R_0 + jL_0\omega + \frac{K^2 L_0 L_1 \omega^2}{R_e + jL_1\omega + jI_m} \quad (3)$$

$$R_c = R_0 + \frac{(\omega K)^2 L_0 L_1 R_e}{R_e^2 + (\omega L_1 + I_m)^2} \quad (4)$$

$$L_c = L_0 - \frac{(\omega K)^2 L_0 L_1 (L_1 + I_m/\omega)}{R_e^2 + (\omega L_1 + I_m)^2} \quad (5)$$

The equivalent resistance of the coil increases and the equivalent inductance decreases due to the existence of the eddy current in the tested component. Equation (3) indicates that the induced eddy current inside the tested component regulates the impedance of the coil of the pulse eddy current sensor, so as to change the total magnetic field.

3.2. Analytical calculation model

The analytical calculation model can get a clear expression by formula derivation, which has the advantages of clear physical significance, high efficiency and high precision. Forster is one of the first scholars to carry out analytical modeling of eddy current theory. He solved Maxwell's equations under specific boundary conditions, and used two-dimensional planar impedance method to analyze and verify them. In the 1960s, Dodd and Deeds used the axial symmetry of eddy current field to solve the governing equation of magnetic vector potential by using the method of separating variables. They creatively derived the analytical expressions of coil impedance in the form of Bessel integral of magnetic vector potential for two classical model structures: the coil above two infinite conductors and the coil outside two cylindrical conductors. It lays the theoretical foundation of electromagnetic eddy current nondestructive testing[10].

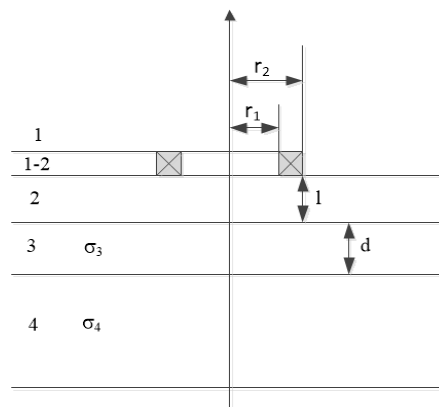


Figure 2. The placement coil is located above the two-layer conductor plate

Dodd et al. derived the expression of the model magnetic vector a shown in Fig. 2 as follows:

$$\frac{\partial^2 A}{\partial r^2} + \frac{1}{r} \frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r^2} - j\omega\mu_i\sigma_i A = 0 \quad (6)$$

Using separating variable method, the magnetic vector position can be described as:

$$A(r, z) = [A_i e^{\beta_i z} + B_i e^{-\beta_i z}] \times [C_i J_1(\alpha r) + D_i Y_1(\alpha r)] \quad (7)$$

If Y_1 is divergent at the origin, then in all regions $D(\alpha)$ Equation (7) can be simplified as:

$$A(r, z) = [C_i e^{\beta_i z} + B_i e^{-\beta_i z}] J_1(\alpha r) \quad (8)$$

$$\beta_i = \sqrt{\alpha^2 + j\omega\mu_i\sigma_i} \quad (9)$$

Where i is the number of layers of the model, B_i and C_i are the coefficients, which can be solved by the boundary conditions between the regions shown in equations (10) to (13).

$$A^{(l)}(r, l_0) = A^{(2)}(r, l_0) \quad (10)$$

$$\left. \frac{\partial A^{(l)}(r, z)}{\partial z} \right|_{z=l_0} = \left. \frac{\partial A^{(2)}(r, z)}{\partial z} \right|_{z=l_0} - \mu_0 I \delta(r - r_0) \quad (11)$$

$$A^{(i)}(r, z) \Big|_{z=-d} = A^{(i+1)}(r, z) \Big|_{z=-d}, i = 2, 3 \quad (12)$$

$$\left[\frac{1}{\mu_i} \frac{\partial A^{(i)}(r, z)}{\partial z} \right] \Big|_{z=-d} = \left[\frac{1}{\mu_{i+1}} \frac{\partial A^{(i+1)}(r, z)}{\partial z} \right] \Big|_{z=-d}, i = 2, 3 \quad (13)$$

Then the induced voltage obtained by the final solution is:

$$\Delta U = \frac{j\pi\omega\mu_0 n^2 I}{(r_2 - r_1)^2 (l_2 - l_1)^2} \times \int_0^\infty \frac{1}{\alpha^6} I^2(r_2, r_1) \times (e^{-2\alpha l_2} + e^{-2\alpha l_1} - 2e^{-2\alpha(l_1+l_2)}) \times \frac{(\alpha + \beta_3)(\beta_3 - \beta_4) + (\alpha - \beta_3)(\beta_3 + \beta_4)e^{2\beta_3 d}}{(\alpha - \beta_3)(\beta_3 - \beta_4) + (\alpha + \beta_3)(\beta_3 + \beta_4)e^{2\beta_3 d}} d\alpha \quad (14)$$

The disadvantages of this model are also obvious. When the number of conductor layers is n , $2(n-1)$ equations need to be established. The number of equations is huge and the solution is cumbersome. The calculation results include the double integral of Bessel function, which is not suitable for calculation and the adjustment of calculation accuracy is not convenient.

On this basis, Theodoulidis of Greece proposed the truncated region characteristic function expansion method (TREE), which limits the radial infinite solution region of Dodd deeds model to the cylinder space region with finite radius, so as to transform the integral expression of electromagnetic field signal into the expression of series[11]. As shown in equation (15), the numerical

$$\Delta U = \frac{j2\pi\omega\mu_0 n^2 I}{(r_2 - r_1)^2 (l_2 - l_1)^2} \times \sum \frac{1}{[(\alpha h)J_0(\alpha h)]^2 \alpha^5} I^2(r_2, r_1) \times (e^{-2\alpha l_2} + e^{-2\alpha l_1} - 2e^{-2\alpha(l_1+l_2)}) \times \frac{(\alpha + \beta_3)(\beta_3 - \beta_4) + (\alpha - \beta_3)(\beta_3 + \beta_4)e^{2\beta_3 d}}{(\alpha - \beta_3)(\beta_3 - \beta_4) + (\alpha + \beta_3)(\beta_3 + \beta_4)e^{2\beta_3 d}} \quad (15)$$

calculation process is simplified and the calculation efficiency is improved.

In addition, Theodoulidis has made a lot of achievements in the analytical calculation of electromagnetic nondestructive testing, introducing the second-order vector magnetic potential method (SOVP) and using Fourier transform to solve the analytical expressions of coil impedance of flat semiconductor, tubular conductor, conductor with cylindrical through hole, long coil and conductive plate with long slot. The analytical calculation method of the model of the coil facing the edge of the right angle conductor is studied. Cheng extended Dodd deeds model to any multilayer structure by using transfer matrix method[12].

For casing inspection, Sun Hu [13] et al used pulse excitation function to carry out analytical calculation, gave a voltage type pulse excitation eddy current inspection method for casing, and derived its analytical solution in time domain.

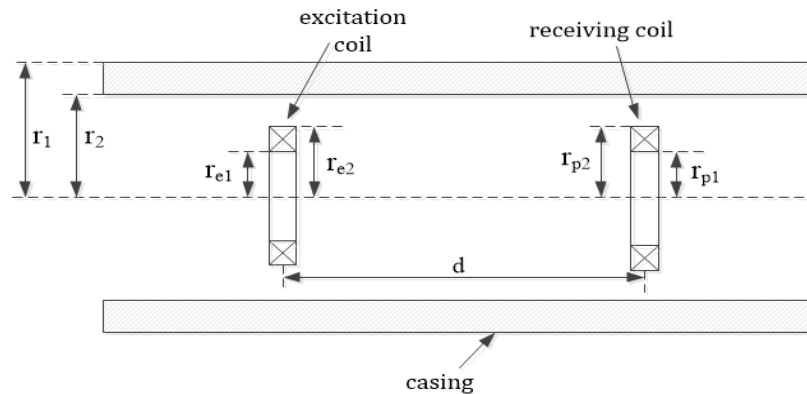


Figure 2. The model of ferromagnetic pipeline inspection

The model is shown in the figure, where R_1 and R_2 are the inner radius and outer radius of ferromagnetic bushing respectively, r_{e1} , r_{e2} and r_{p1} , r_{p2} represent the inner and outer radius of excitation coil and receiving coil respectively, the center distance between two coils is expressed by d , and the coil and bushing are coaxial. L and L_2 are the length of the coil respectively. There are four regions, 1: $0 < \rho \leq r_{e1}$, region 2: $r_{e2} < \rho \leq r_1$, region 3: $r_1 < \rho \leq r_2$, region 4: $r_2 < \rho$. Analytical solution of excitation current in time domain:

$$I(t) = \frac{u_0}{TR} (2\tau - \gamma) - \frac{4u_0}{T\gamma} \sum_{n=1}^{\infty} H \times \frac{\cos(\omega_n t)(R - \omega_n v) + \sin(\omega_n t)\omega_n(L+u)}{(R - \omega_n v)^2 + \omega_n^2(L+u)^2} \quad (16)$$

Here u and v are eddy current coefficients respectively $\xi(\omega_n)$. The real part and the imaginary part of the harmonic due to the different ω_n is different, so u and v must be recalculated in each harmonic component calculation [14].

3.3. Numerical simulation model

There are inherent limitations in analytical calculation. It is difficult to derive the corresponding analytical solution through mathematical derivation for the electromagnetic field problems with complex shape and fuzzy boundary. The numerical calculation transforms the field equation which requires solution into algebraic equation in each region by discretization, which reduces the complexity of the solution. The common numerical calculation methods in eddy current nondestructive testing are finite difference method, finite element method, boundary element method and volume integral equation method.

Finite difference method (FDM) is the most mature numerical method developed so far, which has intuitive mathematical concept and is suitable for the finite element model with simple boundary conditions and physical fields, but the calculation speed is slow. The finite element method can be applied to the finite element model with complex shape and field. It can be used to solve nonlinear problems and has good convergence. It is the most commonly used numerical calculation method at present, but it has the problem that the solution matrix is too large and takes up computer memory. Both boundary element method and volume equation method are numerical calculation methods based on integral Maxwell equations. The volume element method can be used to solve the defects with complex shape, but the boundary element method can not deal with the nonlinear problems, especially the complex boundary problems.

4. Detection Probe

4.1. Excitation Coil

When the outer diameter of the coil is big, the deeper the probe is, the lower the sensitivity is; When the outer diameter of the coil is small, the linear range becomes smaller, but the sensitivity increases; At the same time, the smaller the difference between the inner diameter and the outer diameter of the coil, that is, the thinner the coil, the higher the sensitivity of the

probe. Therefore, in the design of the probe, in order to make the probe with fixed outer diameter have a larger detection range and as high sensitivity as possible, the thinner the coil, the better [15~17].

Directional PEC detector probe has become a hot research topic at home and abroad. Compared with the traditional cylindrical probe, the rectangular probe has the advantages of no cancellation-self effect, slow attenuation speed and large detection depth. [18] He Yunze [19] of the University of national defense science and technology has pointed out that the rectangular probe is wound around the detection coil in three different directions to pick up the magnetic field components in B_x , B_y and B_z directions, and proposed the methods of "two-dimensional butterfly diagram" and "three-dimensional butterfly diagram" to quantitatively analyze the length and depth of defects. Okam et al. proposed a rotatable eddy current testing probe, which is composed of two excitation coils and five detection coils. The research shows that the rotating induced magnetic field can detect the micro cracks outside the pipeline, and is not disturbed by the external support components [20]. Zhu Yunhong [21] of Ordnance Engineering College designed a cone-shaped PEC differential probe. Firstly, the analytical model of the magnetic field of the sensor was established, and the tilt angle was determined as the main factor affecting the signal. Through experiments, it was verified that compared with the traditional differential sensor, the cone-shaped differential sensor can reduce the interference of the test signal and is not easy to be affected by the lift off. The ability to detect defects is superior.

4.2. Detection Element

The detecting element can be the same coil as the exciting coil or different elements. The commonly used detection elements include detection coil, Hall sensor, tunnel electromagnetic group (TMR), giant magneto resistance (GMR) and superconducting quantum interference device (SQUID). The detection coil has the advantages of simple fabrication, low cost and maximum dynamic range of magnetic field, so many PEC detection sensors use cylindrical coil. HALL has a wide measurement range of magnetic field, which is suitable for the detection of deep defects requiring strong primary magnetic field or external magnetization. In addition to the high variation of reluctance and high sensitivity to weak magnetic field, GMR has good directivity [22,23].

5. Signal processing

5.1. Characteristic quantity

The response signals of pulsed eddy current to magnetic and non-magnetic materials are different, so the signal characteristics are also different [24]. In the time domain analysis, the characteristic quantities for magnetic materials mainly include -3dB point, bending point, late signal slope, etc., while those for non-magnetic materials mainly include peak amplitude (PA), time to peak amplitude (TPA), time to zero crossing (TZC), lift off intersection (LOI), etc.

5.2. Signal de-noising

Because of the factors such as the smoothness of the tested parts, the testing environment and the system noise, the detected signal is often accompanied by a lot of noise. Obviously, it is necessary to denoise the original detection signal. From the perspective of position noise prediction, based on Kalman filter theory, using RBF optimized Kalman filter, the position noise eigenvalue of welding tracking center was extracted and the welding tracking center was established. The results show that the signal filtered by this method has good stability.

Now PEC signal processing methods generally include: classical and modern filtering, wavelet denoising, data normalization, polynomial fitting, fast Fourier transform (FFT), principal component analysis (PCA), independent component analysis (ICA), etc.

Zhang Min [25] et al. Used principal component analysis to reduce the dimension of six characteristic parameters of pulsed eddy current signal, such as peak amplitude, peak time, zero crossing time, main peak area, attenuation time and peak frequency, constructed a principal component feature, and input the principal component feature into the logistic classifier to reduce the information redundancy. Based on the principal component, defect recognition was carried out, and the accuracy was 93%, Multiple features are fused into a principal component feature, and the key information of defect identification is retained, which greatly reduces the difficulty of data analysis and information screening in engineering detection.

6. Engineering application

Metal pressure pipeline is used to transport crude oil, water, steam, chemical liquid and vapor products in petrochemical, thermal power and heat supply industries. Its internal transmission is easy to be damaged due to corrosion.

Based on PEC technology, Jiang Lifan and others designed a flat U-shaped structure sensor, which can detect the corrosion of the inner pipe in the double-layer steel pipe gap without being affected by the casing, and the thinning information of the inner and outer walls of the inner pipe can be obtained at the same time by one scan. From the results of the test curve, the attenuation curve of the cylindrical probe has a more sensitive change. The specific performance is the increase of the amplitude of the induced voltage signal and the increase of the attenuation time, which reflects the greater influence of the surrounding metal due to the closer distance. The test results show that for the detection of large area corrosion defects, the detection sensitivity of U-type probe is higher than that of coaxial cylindrical probe, and it has strong interference ability, which is closer to the practical application. [26~29]

BABBAR and UNDERHILL designed an 8-channel symmetrical array probe. The frequency domain analysis of the detection signal was carried out through the combination of experiment and simulation. The PCA analysis method was used to identify the crack signal. The experimental results show that the method can effectively identify the cracks around the rivet. [30~32]

DIB and Yang proposed a rotating current orthogonal plane coil excited EC-GMR array probe to detect cracks in all directions of aircraft multi-layer structure rivets. The simulation model was used to test the cracks in all radial directions of aircraft multi-layer structure rivets by using orthogonal coil probe and GMR sensor. The results show that the detection effect is good [33].

7. Conclusion

Based on the development background of PEC detection, this paper introduces the valuable research achievements in recent years in the aspects of theoretical model, probe design and signal processing of PEC technology. On the engineering application of PEC, the detection technology of defects around metal pipe and rivet hole is briefly described. According to the shortcomings and application requirements of PEC detection, the development trend is mainly focused on the design of sensors, overcoming lift off effect, far-field eddy current detection and imaging technology.

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