Chapter 2
The Pulsed Eddy Current Testing

As one kind of eddy current testing technology, the pulsed eddy current testing technology is based on the principle of electromagnetic induction and is used to detect the defects in conductive materials. The principle of pulsed eddy current testing is basically the same as that of traditional eddy current testing, and differences are the means of excitation and the signal analysis method.

In the early 1970s of the twentieth century, Witting et al. proposed the pulsed eddy current method. With this method, the rectangle pulse is applied to the exciting coil, and time-domain analysis is conducted to the voltage pulse received by the testing coil [1]. In recent years, in order to overcome the shortcomings of the conventional eddy current testing method, the Iowa State University and the US Federal Aviation Administration have jointly commissioned a study of the pulsed eddy current method and developed a corresponding testing device. At the 2002 ATA NDT Forum held in Houston, the pulsed eddy current method was universally recognized by the aviation industry.

Due to the jumps of the excitation pulse at the rising and falling edges, eddy currents will be induced in the specimen. Compared to the conventional eddy current testing using single frequency sinusoidal excitation, frequency spectrum of the excitation signal of the pulsed eddy current testing has richer contents, and with it, the response will contain multiple frequency components. In view of the relationship between the eddy current penetration depth and the frequency of excitation source, from one single pulse excitation, all the defect information within a certain depth is obtained.

Basic principle of the pulsed eddy current testing is conducting transient analysis for the magnetic field generated by the eddy current signal sensed by the testing coil and studying the defects through detecting the peak value of the voltage induced by the magnetic field and its corresponding time instant. The smaller is the depth of the defect, the stronger is the magnetic field generated by the eddy current, and the

© Tsinghua University Press and Springer Science+Business Media Singapore 2016

S. Huang and S. Wang, *New Technologies in Electromagnetic Non-destructive Testing*,
Springer Series in Measurement Science and Technology,
DOI 10.1007/978-981-10-0578-7_2

higher is the peak value of the induced voltage, the sooner is the time instant that this peak value appears. On the other hand, with the same depth, the bigger is the defect, the higher is the peak value of the induced voltage.

In conventional eddy current testing device, different sensors and signals of different frequencies must be configured to detect defects at different depths of the tested object. While with the pulsed eddy current testing, it is not necessary to replace the sensor and change the frequency of the excitation signal according to the testing depth, because with one test, defects of different depths in the sample can be detected [2].

In the pulsed eddy current testing, another advantage of the wideband signal is better noise suppression. Based on the principle of the multifrequency eddy current, response of each frequency can cancel out an interferencing factor. In the response of the pulsed eddy current testing, more frequency components are included, so noises from different sources can be suppressed. The pulsed eddy current testing also has other advantages. The operation is simple, the testing speed is high, the structure is simple [3], and the excitation signal is stable and so on.

The analysis of the data of the pulsed eddy current testing is mainly conducted in the time domain, for example, at the Iowa State University, and the defects in the aircraft structure were evaluated using the peak value and the corresponding time instant [4]. With only the time-domain analysis, the rich information about the defects contained within the wideband pulse excitation is not fully exploited. At Newcastle University, a principal component analysis (PCA) method was used to extract the “time rising point,” the extracted features were used to classify the surface, subsurface, and corrosion cracks, and the performance was better than that with the classification according to the time-domain features [5, 6].

In recent years, the pulsed eddy current testing method is applied in stress evaluation [7]. It is also used to heat the tested object to conduct a fast and large area thermography testing [8].

2.1 Basic Principle of Electromagnetism

When the detection coil loaded with alternating current is placed near the object to be tested, because of the effect of the exciting magnetic field, eddy currents will be induced in the tested object. The amplitude, phase, and path of the eddy current are under the influence of the properties of the object to be tested, and the magnetic field generated by the eddy current in the tested object will induce a voltage in the coil. Thus, by observing the changes of induced voltage on the coil, we can determine whether the tested object is flawed.

Because the magnetic field generated by the alternating excitation current is also alternating, the eddy current in the tested object is alternating. Then, the magnetic field in the testing coil is a combination of the excitation magnetic field and the magnetic field of the eddy current.

Assuming that the excitation signal does not change, and the distance between the coil and the tested object remains unchanged, then the intensity and distribution of the eddy current and the generated magnetic field are determined by the nature of the metal being tested. Therefore, from the synthetic magnetic field, whether the properties of the tested object change could be told, the change could be transformed by the magnetic sensor into electrical signal outputs. The pulsed eddy current testing is based on the theory of electromagnetic induction, so Maxwell's equations become the necessary analysis tools.

2.1.1 The Penetration Depth and the Skin Effect

As a theoretical basis for analysis of eddy current testing, Maxwell's equations are as follows:

$$\begin{cases} \nabla \times H = J + \frac{\partial D}{\partial t} \\ \nabla \times E = -\frac{\partial H}{\partial t} \\ \nabla \cdot D = \rho \\ \nabla \cdot B = 0 \end{cases} \tag{2.1}$$

in which $B = \mu H, D = \varepsilon E, J = \sigma E$, σ is the electric conductivity, μ is the magnetic permeability, ε is the electric permittivity, J is the electric current density, E is the electric field strength, H is the magnetic field strength, B is the magnetic induction strength, D is the electric flux density, and ρ is the free charge density.

For the traditional sinusoidal excitation, $H = H_{\mathrm{m}}e^{j\omega t}$, and H_{m} is the peak value of the sinusoidal magnetic field, and then, from Eq. (2.1), $\nabla^2 H = j\omega\sigma\mu H - \omega^2\mu\varepsilon H$. Let $k^2 = j\omega\sigma\mu - \omega^2\mu\varepsilon$, then,

$$\nabla^2 H - k^2 H = 0 \tag{2.2}$$

When testing, the coil is placed at the surface of the object being tested. The axial direction of the coil is selected as the z-axis, and one tangent of the coil is the y-axis. Another tangent of the coil that is perpendicular to the z-axis and the y-axis simultaneously is the x-axis. Because the magnetic field strength along the y-axis and z-axis is not decaying, we have $\nabla = \mathrm{d}/\mathrm{d}x$, and Eq. (2.2) could be expressed as follows:

$$\mathrm{d}^2 H_z/\mathrm{d}x^2 - k^2 H_z = 0 \tag{2.3}$$

Solving the PDE (2.3),

$$H_z = c_1 e^{-kx} + c_2 e^{kx} \tag{2.4}$$

in which the boundary restriction coefficients c_1, c_2 are constant.

During inspection, if the area of the tested object under the coil is assumed to be infinite, then H_z is not restricted in the x direction, so $c_2 = 0$, $H_z = c_1 \mathrm{e}^{-k_1 x}$, in which $k_1 = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$. Since $\omega\varepsilon \ll \sigma$, we have

$$H_z = c_1 \mathrm{e}^{-x(1+j)\sqrt{\omega\mu\sigma/2}} \tag{2.5}$$

When $x = 0$, $H_z = H_{z0}$, so $c_1 = H_{z0}$, i.e.

$$H_z = H_{z0} \mathrm{e}^{-x(1+j)\sqrt{\omega\mu\sigma/2}} \tag{2.6}$$

and because $\mathrm{d}H_z/\mathrm{d}x = -J_x$, the eddy current density in the tested object is as follows:

$$J_x = (1+j)\sqrt{\omega\mu\sigma/2} H_{z0} \mathrm{e}^{-x(1+j)\sqrt{\omega\mu\sigma/2}} \tag{2.7}$$

Equation (2.7) indicates that the eddy current density in the tested object decreases exponentially with the increasing distance from the coil, while the phase difference of the eddy current increases proportionally with the increasing depth. Equation (2.7) is rewritten as follows:

$$J_y = J_0 \mathrm{e}^{-x\sqrt{\pi f \sigma\mu}} \tag{2.8}$$

where J_0 is the eddy current at the surface of the object, x is the distance to the defect surface, J_x is the eddy current density at the depth of x in the tested object, and f is the frequency of the excitation signal. This phenomenon is the skin depth effect.

Generally, the depth where the eddy current is $1/e$ of that of the surface is called the standard penetration depth, expressed with δ. Because the phase difference increases proportionally with the increasing depth, when the depth is the standard penetration depth, the phase of the eddy current lags 1 rad.

$$J_y / J_0 = \mathrm{e}^{-x\sqrt{\pi f \sigma\mu}} = 1/e \tag{2.9}$$

So $\delta = 1/\sqrt{\pi\sigma\mu f}$. It shows the range of depth for the eddy current testing, and the maximum depth of the eddy current testing is around 3 times of δ, but the eddy current density at this position is only 5 % of that at the surface, so the testing sensitivity is relatively low. Normally, the excitation frequency, electric conductivity, and magnetic permeability parameters should be selected such that the calculated standard penetration depth δ is bigger than 1/3 of the testing depth to realize effective inspection. If it is required to detect defects deep under the surface of the tested object, the excitation frequency must be reduced. The testing depth of the eddy current not only depends on the frequency, but also is associated with the diameter of the probe. When the probe is at the surface of the tested object, the penetration depth, into the tested object, of the excitation magnetic field produced by the probe is about 1/4 of the probe diameter. However, although with large-diameter probes, deeper testing depth can be obtained, and the range of distribution of the eddy current in the tested object also increases with the probe diameter, making the defects relatively smaller compared with the cross section of the eddy current flow, resulting in decreased sensitivity of the probe, so we should design the probe properly, according to the actual situation, and considering the experimental results.

2.1.2 Principle of Probe Design

In eddy current testing, coils are often used as the probes, and their shapes and sizes are related to the sensitivity of the probes and testing range. In order to improve the performance of pulsed eddy current testing probes, we always hope for a larger testing range and higher sensitivity. To obtain a larger range, axial distribution of the excitation magnetic field must be increased, and to gain a high sensitivity, the amount of change of the eddy current loss power when moving the probe should be relatively large. According to Biot–Savart law, with the same excitation current, current-loading coil with a smaller radius will generate a larger magnetic induction strength near the coil, but the magnetic field attenuates more fast along the axial direction; for the current-loading coil with a bigger radius, although the magnetic induction strength near the coil is smaller than that of the coil with a smaller radius, the magnetic induction strength at a farther position is bigger than that of the coil with a smaller radius, i.e., the testing range of a coil with a bigger radius is larger. However, because the axial magnetic field of the small radius coil changes faster, the testing sensitivity of a small diameter coil is higher. A coil could be seen as being composed of several single-turn coils, so its magnetic field can be considered as a superposition of the magnetic fields of the corresponding single-turn coils.

Theoretical calculation and experimental validation show that the bigger is the outer diameter of the coil, the deeper is the testing depth, but the sensitivity decreases; for the small outer diameter, the linear range will be smaller, but the sensitivity is increased. The smaller is the difference between the inner and outer diameters of the coil, i.e., the thinner is the coil, the higher is the sensitivity of the probe. Therefore, when designing a probe, to ensure that a probe with a fixed outer diameter has a large testing range and sensitivity as high as possible, it is required that the coil thickness is as thin as possible. For probes requiring large testing range, the outer diameter should be big; if the testing range is small and the sensitivity is required to be high, the outer diameter of the probe should be small.

Designs of the probes are based on the above conclusions and implemented by a model test method. As for the mathematical models of conventional eddy current probes, the target function of optimized design is generally related to the inner and outer diameters of the exciting coil, the length of the axis, inductance, resistance, number of turns, wire diameter, wire strands, fill factor, excitation frequency, the geometry of the object to be tested, electric conductivity, and magnetic permeability. For the pulsed eddy current testing, because the excitation signal contains multiple frequencies, it is difficult to obtain a clearly expressed objective function, especially the optimization design between multiple frequencies is difficult to achieve. However, design methods applied in traditional single frequency eddy current probe design are still applicable for the pulsed eddy current probe design, except for the influence of the frequency.

In the practical design of pulsed eddy current testing probe, according to the needs, typically, there is a scale range for the diameter of the coil. In a given range, one should try to reduce the outer diameter of the coil to increase the sensitivity of testing; meanwhile, a probe with small outer diameter is easy to use, i.e., inclination of the probe causes less impact. When the geometrical dimensions of the coil are fixed, for a certain amount of inductance, the number of turns of the coil can be determined. However, note that corresponding to different frequencies, the inductance of the coil will vary; therefore, corresponding to the different frequency components in the signal, the equivalent inductance of the coil is also different. In the actual design, it is only required to be in a range. Based on the magnitude of the excitation current and the maximum allowable current density in the wire, the diameter of wire could be calculated. Sometimes, when the current is large while the wire is fine, multiple strands of wire could be used, and according to given wire parameters and the geometry of the coil, the resistance of the coil could be obtained.

2.1.3 Principle of the Pulsed Eddy Current Testing

Using the pulse signal as the excitation, according to the Fourier transform, solving the Fourier transform of a time-domain function is just to compute the spectrum of this time function; that is, a pulse can be expressed as the sum of an infinite number of harmonic components.

If $\Phi_n(x)$ is the family of standard orthogonal functions, then

$$C_n = \int_a^b f(x)\Phi_n(x)\mathrm{d}x \quad (n = 1, 2, 3, \ldots) \tag{2.10}$$

A pulse signal $f(t)$ could be expanded as the generalized Fourier series of the family of standard orthogonal functions $\Phi_k(t)$,

$$f(t) = \sum_{n=1}^{\infty} C_k\Phi_k(t) \tag{2.11}$$

In the above equation, the Fourier coefficients C_k could be calculated with (2.12),

$$C_k = \int_0^{\infty} f(t)\Phi_k(t)\mathrm{d}t \tag{2.12}$$

Thus, in theory, a pulse can be expanded into an infinite number of harmonic components. The pulsed eddy current testing is different from the conventional eddy current testing, in that in the traditional eddy current testing, the coil impedance is investigated to determine whether a defect exists, while in the pulsed eddy current testing, the transient variation of the induced voltage is tested. For the pulsed eddy current testing, when the probe is moved past a defect, the probe output waveform is as shown in Fig. 2.1.

Therefore, the surface and subsurface defects have more influence on the first half section of the transient signal, while less influence on the latter half section of the signal. By contrast, the situation is just the reverse for the deep defects. Often in the pulsed eddy current, the two features of the peak value of the signal and the corresponding time are used to quantify the defects. Among them, the signal peak value is related to the size of the defect. The bigger is the defect, the higher is the signal peak value. Meanwhile, the peak value also depends on the depth where the defect resides. The time corresponding field, that is, the defect location. While the penetration path of the magnetic field is not linear with the time corresponding to the peak value. However, the deeper is the defect location, the later is the time corresponding to the peak value of the transient signal, and from this, the depth of the defect location could be analyzed qualitatively.

Figure 2.2 shows the transient signal waveforms corresponding to the same flaw at different depths. In the experiments, defects are manufactured on the surface of a metal sample, and metal plates of the same material and different thicknesses are placed above it, and the two are pressed together, to simulate the internal defects at different depths in the testing. Figure 2.2 shows that the deeper is the defect, the

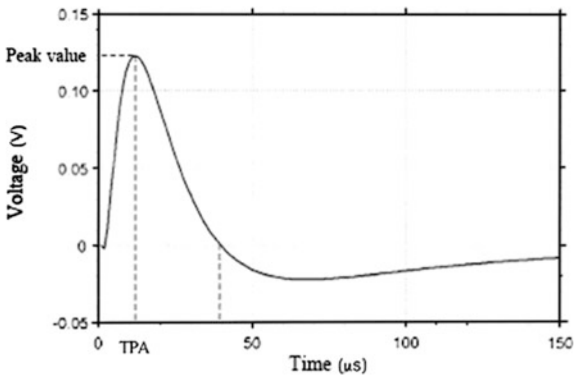


Fig. 2.1 The transient waveform of the pulsed eddy current testing

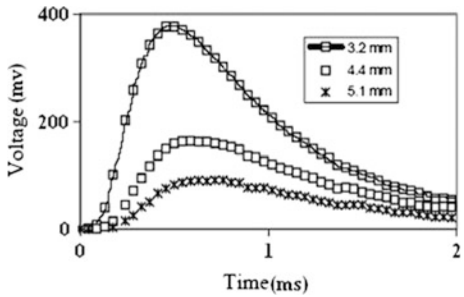


Fig. 2.2 The probe output waveforms corresponding to defects with different depths

lower is the peak value of the sensor output signal, and the longer is the time required for the signal to rise to the peak value.

Influenced by the skin effect, the conventional eddy current testing is mainly used to detect surface defects. Because pulsed eddy current contains low-frequency components, it can also detect deeper defects. The structure of the pulsed eddy current testing device is simple, and the cost is low. The device also has strong anti-interference ability. At present, air core and ferrite core coil probes are applied to the pulsed eddy current testing. With ferrite cores, the magnetic field is better gathered, thus improving the signal-to-noise ratio of the sensor, but introduction of ferrite makes the analysis more complex. Some researchers have conducted experimental analysis and theoretical study of the air core and ferrite core coil probes, comparing air core coil and ferrite core coil with the same geometrical shape, and assuming there are no other differences for the two coils except for the ferrite core. Experiments showed that the signal waveforms of the two probes are similar proportionally with a scaling factor as the difference.

In practice, pulsed eddy current has been used to detect the defects in the conductive multilayer connection parts and decide their locations, especially in the testing of the aircraft components. Pulsed eddy current testing device used for this purpose can differentiate effectively the internal defects of the connection parts, surface warping, dents, change of surface protection layer thickness of the tested object, bolts, and other geometrical deformations.

2.2 The Coil Sensors in the Pulsed Eddy Current Testing

In the pulsed eddy current testing, to meet the testing requirements of the work-pieces with different shapes and sizes, it is necessary to design different testing probes or coils.

2.2.1 Classifications of the Testing Coils

According to the mutual positional relationship between the coil and the tested object, the testing coils could be classified into three categories,

(a) Through coil
For the through coil, the tested object is put inside the coil and moved through the coil. It can be used to test tubes, rods, and wires that can pass through the inside of the coil. With the through coil, it is easy to implement in eddy current testing high speed and automatic mass production. Therefore, it is widely used in quality inspection of tubes, rods, and wires and in addition also can be used to detect skew and eccentric rods.

(b) Inner passing coil
When testing the inner wall of the pipe, the coil must be placed in the inside of the pipe; this type of coil inserted inside the tested object is known as inner passing coil, also known as the internal coil; it is currently mainly used for the in-line inspection of the condenser.

(c) Placed coil
It is also known as the probe coil. During testing, the coil is placed at the surface of the tested object. The coil is usually small, with an internal magnetic core, which could gather the magnetic field, so its sensitivity is high. The placed coil is suitable for surface inspection of all kinds of sheet, strip, and large-diameter pipes and rods and also suitable for local testing of parts with complex shapes.

2.2.2 Working Modes of the Testing Coils

In the testing, a coil or multiple separate coils can be used, but according to testing purpose, the coils must be connected into a certain form, called working modes of the coils in this chapter. The working mode where only one coil is used is called the absolute mode, while the mode that two coils are connected reversely is called a differential mode. According to the position with relevance to the tested object, the differential probes could be further classified into the standard and the self-comparison modes.

With the absolute coil, the output voltage of the coil is directly measured and the magnitude and phase of this voltage are used to determine whether defects exist in the object to be tested. The general testing process includes first testing the standard specimen with the coil, the corresponding output voltage is used as a reference, and then, the tested object is put into the coil. If the output voltage exceeds the previously established reference, then it is regarded that there exist flaws. The absolute working mode can also be used for the sorting and the thickness measurement of the material, and the output voltage when testing a standard specimen is generally adjusted to 0; then, if there is no output, it is indicated that the tested object has the same parameters as the standard part.

The working mode of standard comparison is the typical differential testing, and specifically, the two coils are reversely connected to obtain a differential form. A standard workpiece is placed in a coil, and the other coil is used to check the tested object. Because the two coils are connected as a differential form, when the object to be tested is different from the standard workpiece, there is signal output in the coil, so the testing is achieved.

The self-comparison mode is one special case of the standard comparison mode, and its name is derived from that the different parts of the same tested object are used as the references of comparison. When two adjacent coils are used to check the adjacent parts of the tested object, the differences of the physical and geometrical parameters of the two tested locations are generally small, and the influence on the coil output voltage is relatively weak. When the defect exists, output voltage signal with an abrupt change is generated in the coil close to the defect, and output of the other coil is still essentially the same without any defect. Therefore, there will be an abrupt change in the differential output, and from this signal, the existence of the defect could be judged.

In addition, the coils can be connected into various forms of bridge circuits. In the bridge mode of connection, a probe composed of two coils is commonly used to detect small impedance variations caused by the defects. Two coils are set at the adjacent bridge arms; if one coil serves as a testing coil, and another is used as a reference coil, then the probe is known as an absolute probe; if both coils are used to test the object simultaneously, then it is a differential probe.

In the pulsed eddy current testing, the absolute probe could reflect the material properties including the electric conductivity, magnetic permeability, the geometry of the object being tested, and the various changes of the defects, while the comparison signal of the adjacent parts of the tested object is the output of the differential probe. In this chapter, mainly the placed probe is used to test the surface and subsurface defects of the object under investigation. The absolute coil is prone to drift when the temperature is instable and its anti-interference ability is inferior to that of the differential probe.

2.2.3 Probes of the Pulsed Eddy Current Testing

Probe, also known as sensor, is an important part of the pulsed eddy current testing device. In the pulsed eddy current testing, the defect in the tested object could be reflected by the change of the output voltage of the pulsed eddy current testing probe. Magnetic sensing devices such as coil, Hall sensor, magnetic sensing diode, and the magnetoresistance can all be used to develop pulsed eddy current probe. In the conventional eddy current testing, a testing coil is generally applied, but in the pulsed eddy current testing, sometimes in order to detect the low-frequency signal, Hall element is often accepted. Experiments show that magnetic field of about 10^{-8} T could be detected in the testing coil, while with a Hall sensor, only 10^{-6} T magnetic field could be measured, so the testing coil has higher resolution. Secondly, the Hall element detects the magnetic field strength, while a coil could detect changes in the magnetic field. During steady-state operation, the Hall element outputs a voltage and the voltage is much larger than the voltage generated by the defect. If the voltage is seen as the background noise, then the probe's signal-to-noise ratio is relatively low.

According to the principle of pulsed eddy current testing, first in the probe there must be the exciting coil fed with repeated pulse sequence to generate the exciting magnetic field in its surrounding and within the tested object, while in order to detect defects in the object to be tested, a testing coil is needed. The probe should have three functions: first, generating eddy current in the tested object and second, testing and obtaining signal reflecting the situation of the tested object and doing the analysis and evaluation. Then, the pulsed eddy current probe is required to have the ability to suppress noises; for example, in defect detection, interferences from the probe tilt, liftoff, temperature, humidity, and the electromagnetic interference from the outside world should be suppressed.

2.2.3.1 Requirements of the Working Conditions of the Pulsed Eddy Current Testing

In the pulsed eddy current testing, the surface of the tested object is often covered with non-conductive protective materials, or dirt, grease, and so on. Therefore, in the testing when the sensor is moved at the surface of the tested object, the distance between the probe and the tested object will change inevitably because of jitter or changes in the surface conditions of the tested object. The eddy current in the tested object induced by the probe will also change with this distance. The greater is the distance, the smaller is the magnitude of the eddy current induced in the tested object. Therefore, when the probe departs from the position close to the surface of the tested object, the testing sensitivity will decrease, and this phenomenon is called the liftoff effect.

According to Lenz's law, the magnetic field of the eddy current in the tested object is in the opposite direction of the exciting magnetic field. In the testing, when the probe approaches to the tested object, due to the magnetic field generated by the eddy current, a part of the induced voltage in the coil from the exciting magnetic field will be canceled out. When the probe is lifted from the tested object, i.e., the distance between the tested object and the probe increases, the voltage in the coil induced by the exciting magnetic field is essentially the same. While because the distance increases, in the tested object, the strength of the exciting magnetic field of the probe decreases, so the eddy current produced in the tested object gets smaller. Similarly, because the distance between the probe and the tested object gets larger, the voltage in the testing coil of the probe induced by the magnetic field of the eddy current will be smaller. Therefore, when liftoff exists, in the testing coil, the counter-reaction of the magnetic field generated by the eddy current to the excitation magnetic field gets weaker, so the resulting amplitude of the induced voltage of the probe gets larger. This phenomenon can also be seen as that a noise is superimposed on the induced voltage signal, thus making the induced voltage larger, so this superposition is also called the liftoff noise. The liftoff noise can sometimes cover up the voltage changes of the minor defects. If the alarm threshold of the testing device is unreasonable or the liftoff noise is excessive, the testing device may generate false alarms, which will affect the inspection.

Another issue of the pulsed eddy current inspection is how to effectively detect cracks in all directions in the tested object. Taking the example of the surface fatigue crack, its extension may be in any direction on the 2D plane. According to the testing principle, when the flowing direction of the eddy current in the tested object is perpendicular to the defect direction, the alteration of the magnetic field of the eddy current exerted by the defect is maximized; when the two are parallel, the influence of the defect on the eddy current distribution is minimized. Therefore, how to design the probe, so that it can effectively detect the flaws in all directions, is also one of the main problems of the pulsed eddy current testing to be solved.

2.2.3.2 Selection of the Material of the Probe Magnetic Core

The properties of the magnetic core material directly determine the value of the coil inductance and will affect the testing performance of the probe. Commonly used core materials are the pure iron, ferrite, and amorphous alloy.

Even though the pure iron has high magnetic permeability, its high-frequency response characteristic is poor. When using the pure iron as the core, there will be large amount of eddy current in the iron, which consumes the energy of the excitation source, also makes the temperature of the probe increase, and causes a temperature drift. In addition, compared with materials such as ferrite and amorphous alloys, the magnetic permeability of the pure iron is relatively low.

Amorphous alloy is a new kind of high magnetic permeability material developed after the 1970s of the twentieth century; it has the advantage of high efficiency, low loss, and high magnetic permeability. Compared with traditional metal magnetic materials, atoms of the amorphous alloy are not in order, and crystal anisotropy does not exist, so in applications, this alloy has high permeability and low loss and can be used in place of silicon steel, permalloy, ferrite, and other traditional materials. Using amorphous alloy as the probe core, the sensitivity of the probe could be improved effectively, and the volume of the probe is reduced, the weight is decreased, and the energy loss is lowered. However, amorphous alloy cores are usually thin, and this kind of material is brittle and easily broken. When hand winding the coil, it is necessary to stack several pieces of amorphous alloy together as the magnetic core, which makes winding more difficult to operate. So when hand winding the coil, amorphous alloy core is not recommended.

Ferrite is often used as the magnetic core material in actual testing; it can increase the inductance of the coil, improve the quality factor of the coil, and enhance the testing sensitivity of the probe.

For the ferrite strips in Fig. 2.3, the parameters are as follows:

Initial magnetic permeability	$\mu 0 = 2500 \pm 25$ %
Amplitude permeability	3200
Saturation magnetic flux density (25 °C)	510 mT
Magnetic remanence (25 °C)	110 mT
Magnetic coercive force (25 °C)	Hc = 12 A/m
Curie temperature	220 °C
Density	4800 kg/m^3
Dimensions	12.5 mm × 5 mm × 1.2 mm

This model of ferrite has high initial permeability and Curie temperature, and when used as cores for pulsed eddy current probes, they can meet the testing needs well. Tests show that in the above three materials, the ferrite is the most appropriate. The magnetic permeability of the pure iron is relatively low, and large amount of excitation energy will be consumed because of the iron loss when used as the core material. In addition, the density of the pure iron is big, and this increases the weight of the probe, so it is not appropriate as probe core material; If the amorphous alloy is used as the magnetic core material, the difficulty in building a probe is increased; meanwhile, the sensitivity of the probe is too high, and the probe is prone to the interferences, so the useful signal might be buried in the noises, which

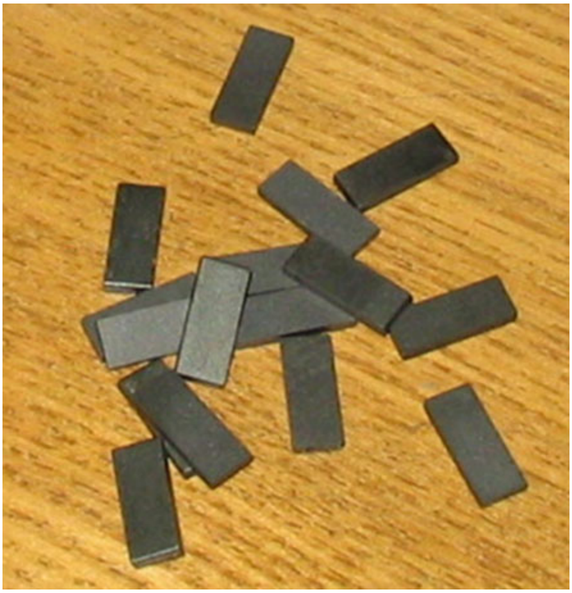


Fig. 2.3 Ferrite magnetic cores

apparently is not helpful to detect the defects; the ferrite cores are easy to make, and the density is moderate. During the development of the probes, u-shaped and cup-shaped ferrite magnetic cores are used to gather the magnetic field and improve the sensitivity of the probe.

2.2.3.3 Winding of the Probe Coil

When the temperature changes, the probe will have performance shift. In order to reduce the effect of the change of temperature on the sensor performance, in addition to the previously mentioned differential connection method, the relationship between the probe wire and the temperature drift should be considered. When high-frequency large current excitation is used, the probe temperature will rise greatly and even gets hot; therefore, for the wire of the probe, material with low resistance coefficient and low temperature coefficient should be selected. Made of metal and insulating varnish, the wires should have good quality, and when the probe temperature rises, the internal metal and external insulating varnish of the wire will expand when heated. When the temperature is high, the large expansion may cause the shedding of insulating varnish, and the exposure of the wire will result in a short circuit inside the coil, reducing the inductance of the coil. When temperature rises, the wire resistance will also increase, and the impedance characteristics of the probe will be changed.

The thermal expansion coefficient and resistivity of copper wires are both low, and they are suitable as coil wires. In order to reduce the resistance of the coil, the number of turns of the wounded coils in this work is between 100 and 150, and the diameter of the wire is 0.1 mm. If the wires are too thin, on the one hand, the coil resistance is large, and on the other hand, in the process of probe making, the wire is easy to break. If the wires are too thick, the thickness of the coil will be affected. For the multilayer winding, this also causes uneven distribution of the coil. Meanwhile, the skin effect of current distribution in the coil will be more obvious; i.e., when the frequency of the excitation signal is high, the current density at the surface of the wire is far greater than that at the center of the wire. Because the effective current-loading area becomes smaller, the equivalent resistance of the probe becomes bigger, and the skin effect of the current also changes the equivalent inductance. The increase of the wire diameter also increases the instability of the inductance; so in the design, all the factors should be considered integrally, and diameter of core wire should be selected reasonably.

In order to reduce the interference to the signal transmitted from the probe to the testing device, shielded signal cable can be used as the signal transmission line. The signal cable has shielding net woven with fine copper wires and can effectively reduce the interference of electromagnetic environment on the transmission line. The shielding layer of the signal cable is connected to the ground at the ground point of the circuit board of the testing device.

2.2.3.4 Supression of the Liftoff Effect of the Probe

In the pulsed eddy current testing, the liftoff effect can be seen as the consequence of the change of the interaction of the magnetic fields caused by the change of the distance of the probe and tested object. If not controlled, the liftoff noise can cover up the testing signal. In particular, for the absolute probe, the liftoff effect is a major problem influencing its normal operation. The liftoff effect is not linear with the lift distance. The closer is the probe to the tested object, the greater the liftoff will influence the probe output voltage. In order to improve the sensitivity of the probe, the probe should be placed as close as possible to the tested object, which requires that when testing the object closely, the liftoff effect of probe caused by jitter should be suppressed.

When using the probe that the exciting coil and the testing coil are separated, at the same time that the excitation magnetic field induces eddy current in the tested object, voltage u_1 is induced in the testing coil, and the induced voltage u_e in the testing coil by the eddy current is in the opposite direction of u_1, and the closer is the probe to the tested object, i.e., the closer to the eddy current, the stronger is the magnetic field generated by the eddy current and sensed by the testing coil. Therefore, the larger is u_e, the smaller is the output voltage $u = u_1 - u_e$. With liftoff of the probe, u_e gets smaller, and because the relative position of the exciting coil with respect to the testing coil makes no change, u_1 can be considered approximately constant, so the probe output u increases. When choosing the peak value of the probe output voltage as the basis of judging whether a defect exists, the increase of the output signal resulted from the liftoff sometimes will surpass the change of voltage caused by the tiny defects in the tested object, which will lead to that the defects could not be detected effectively by the device.

In view of the above problem, the solution is to remove the voltage induced by the original exciting magnetic field in the testing coil and only measuring the change of voltage Δu caused by the defect. When there is no defect, the probe output is 0. When there is a defect, as the liftoff distance increases, the output signal of the probe decreases. Then, when voltage is used as the basis of judging, there will be no false alarms due to the change of the liftoff distance.

The liftoff effect originates from the change of the eddy current in the tested object caused by the change of distance between the exciting coil and the tested object, and the change of the strength of the magnetic field in the testing coil generated by the eddy current. For the probe design, the liftoff noise should be reduced as much as possible or even removed. An implementation is using the self-comparison probe. The two coils of the differential probe are placed closely side-by-side; when the probe is at a certain liftoff height, the distances of the two coils from the surface of the tested object are kept the same, so the liftoff noises of the two coils are the same. With the differential connection, the liftoff noises in the two coils are canceled out, and the background noises, temperature drift, and interference of the earth magnetic field are also removed. Of the differential probes, the electric differential probe is the most typical.

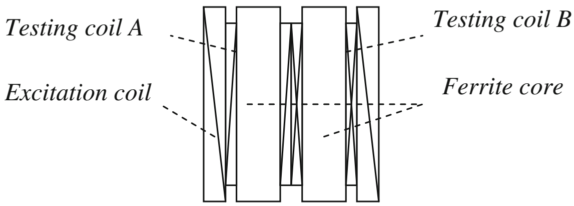


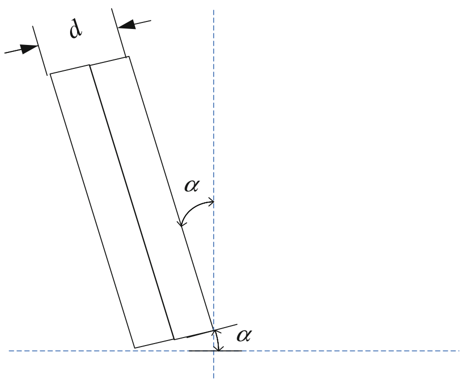
Fig. 2.4 The electric differential probe

The structure of the electric differential probe is as shown in Fig. 2.4. This probe is composed of two testing coils and an exciting coil. The two testing coils are connected in a differential form. During operation, the induced voltages of the two testing coils are subtracted, so the probe is called an electronic differential probe.

The testing coils A and B have the same structure and are made of the same material with the same manufacture process. In theory, the two coils have the same parameters, such as induction and resistance. When they are located in the same exciting magnetic field, the same voltages will be induced in the coils A and B. Connecting the two coils at the dotted terminals and measuring the voltages at the other two ends, then the net output voltage after subtraction will be 0. For the electric differential probe, the same interferences confronted by the two coils, such as temperature, humidity, external electromagnetic interference and earth magnetic field, can be effectively suppressed through a differential design. When the two testing coils are placed closely and perpendicular to the surface of the tested object, the two testing coils have the same liftoff height. Using the differential design, theoretically the liftoff effect can be canceled out. But in the actual testing, the probe moves at the surface of the tested object, and it is difficult to ensure that the probe movement is always perpendicular to the surface of the tested object; i.e., the probe may deviate from the vertical direction at an angle of α, as shown in Fig. 2.5.

In the differential probe design, the thickness of the probe d should be minimized, so that the difference between the liftoff distances of the two coils (difference

Fig. 2.5 The diagram of tilting of the differential probe



of heights from the centers of the two coils), $\Delta h = 0.5d \cdot \sin\alpha$, is small. When winding the probe, coils are wounded on the two cores, respectively, and then, the two coils are fixed closely side-by-side. If the coil is thin, it will be helpful to ensure uniform geometry of the coil, to avoid concentrating the coil in a region. If the geometry of the coil is not uniform, for example, there is a hump, then the two coils cannot be placed closely side-by-side; on the one hand, increasing the thickness of the probe and, on the other hand, making it difficult to guarantee the two coils are on the same horizontal position. If the two coils cannot be placed side-by-side on the same level, even if the probe is perpendicular to the surface of the tested object, the liftoff heights of the two coils are not the same; that is, in this case, it would be difficult to effectively suppress the liftoff noises.

The structure of the magnetic differential probe is as shown in Fig. 2.6. In testing, the two exciting coils with the same number of turns and the same structure are connected reversely and fed with the same excitation current, so the excitation magnetic fields of the same magnitude and opposite directions are generated by the two exciting coils.

As shown in Fig. 2.6, two exciting coils are wounded on the ferrite cores, respectively, and then connected in the differential mode. Winding testing coil at the outside of the two exciting coils, when the magnetic differential probe is placed at a point without any defect at the tested object, the magnetic fields generated by the two exciting coils in the testing coil are canceled out, and then, the coil output is 0, indicating there is no defect in the tested object. When one of the two exciting coils is close to a defect, the magnetic field generated by the exciting coil will change due to interference of the defect, resulting in that the magnetic fields generated by the two exciting coils cannot cancel each other out, and the testing coil will output a voltage value reflecting the defect. In the course of the probe passing by the defect, according to the differential subtraction relation, when the two exciting coils pass by the defect, respectively, the magnetic fields in the testing coils are in the opposite direction. While when the defect is between the two coils, the instant synthetical magnetic field is 0; therefore, induction voltages of the testing coils are alternating. If judging the existence of the defect from the signal amplitude, there will be two abrupt voltage changes when the magnetic differential probe passes by the same defect. Compared with the absolute probe, the number of missed defects can be effectively reduced.

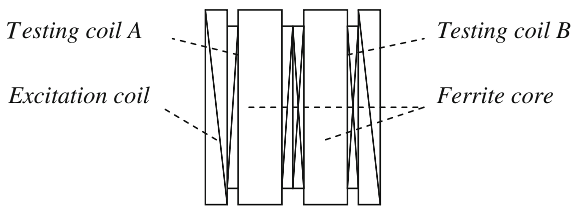


Fig. 2.6 The magnetic differential probe

In the absence of defects, the output of the magnetic differential probe is 0. When there is a defect, the output is the voltage change caused by the defect. When the magnetic differential probe is lifted to a certain height, as what is detected by the testing coil is only the voltage induced by the change of the magnetic field of the eddy current caused by the defect, with the magnetic differential probe, the liftoff noises can be effectively suppressed.

Observing the structures of the magnetic differential probe and electronic differential probe, it is not difficult to see, both structures are exactly the same, only the functions of the exciting coil and the testing coil are interchanged, and thus, testing probes with similar functions can be constructed. This idea will be described in detail later. In this book, it is called the reciprocity rule of probe design.

2.2.3.5 Sensors with Closed Magnetic Circuits

Learned from the preceding analysis, the liftoff noise is in fact not from a separate source and superimposed on the signal, but due to the decrease of the signal caused by that a testing coil is moved away from the magnetic field. With probes that can suppress the liftoff effect, the increase of the output voltage of the probe with the increasing liftoff height has been suppressed, and the expected results are achieved; that is, the probe output gets smaller when the liftoff is increased. In actual testing, under the most circumstances, it is required to implement a non-contact testing; that is, there should be a distance between the probe and the tested object. Meanwhile, in actual testing, the probe will inevitably be affected by the interference of the noise; if the signal is too weak, it is difficult to extract it from the noise and analyze it. Therefore, a certain degree of sensitivity should be maintained when the probe is at some liftoff height.

Therefore, for the probe design, it is necessary to slow down the trend that the output voltage decreases with the increasing liftoff height, and make sure a high signal-to-noise ratio is achieved. This on the one hand means increasing the amplitude of the signal, ensuring that when the probe is at a certain liftoff height, it still maintains a high output; on the other hand, it is required to reduce the noise and suppress the interference.

To suppress the phenomenon of the decrease of the probe output signal caused by the liftoff, it is necessary to reduce the trend that the magnetic field generated by the eddy current decreases with the increasing distance, so as to make the magnetic field generated by the eddy current in a certain liftoff range maintain a certain intensity in the testing coil. On the one hand, this requires that the strength of the excitation magnetic field in the tested object be enhanced, making the magnetic field strength changes gradually in a certain liftoff range; on the other hand, this means reducing the change of the magnetic field generated by the eddy current in the coil when the liftoff changes.

According to the concept of effective magnetic permeability of the magnetic circuit, when there is an air gap in the magnetic circuit, the magnetic permeability of the whole magnetic circuit is as follows

$$\mu_e = \frac{\mu_i}{1 + g\mu_i / l_e} \tag{2.13}$$

in which μ_i is the initial magnetic permeability, g is the length of the air gap, and l_e is the length of the effective magnetic circuit. Equation (2.13) is an approximate calculation of the effective magnetic permeability of the magnetic circuit in case of a small air gap. When the air gap is large, part of the magnetic flux will pass through the outer part of the gap, and its effective magnetic permeability is slightly larger than the result of calculation in accordance with Eq. (2.13).

Viewing the liftoff distance as the air gap of the magnetic circuit, the effective magnetic permeability could be used to analyze the magnetic field when the probe is lifted. The higher is the effective permeability of the whole magnetic circuit, the more will the magnetic force lines concentrate, and the larger is the strength of the magnetic field in the magnetic circuit. In order to ensure enough magnetic field strength, it is required to design a probe making the effective magnetic permeability of the magnetic circuit high. The idea of design is to try to make the probe core and the tested object form a closed magnetic circuit, so that it has a high effective magnetic permeability.

In order to enhance the excitation magnetic field based on the differential design and closed loop, a U-shaped magnetic core probe could be used, and its structure is shown in Fig. 2.7.

The two testing coils of A and B of the u-shaped magnetic core probe are wounded respectively around the two yokes of the u-shaped ferrite core, and the exciting coil position is as in Fig. 2.7; i.e., the two testing coils share a common magnetic circuit, in the same exciting magnetic field.

Because the magnetic flux of the u-shaped magnetic core probe is not leaking, so under the same excitation intensity, the excitation magnetic field strength of the u-shaped core probe is about twice of that of the three-core probe.

2.2.3.6 The Two-Level Differential Probe

The purpose of using the two-level differential probe is to better suppress the noise and keep the consistency of the coils on the two cores. The structure of the designed two-level differential probe is as shown in Fig. 2.8.

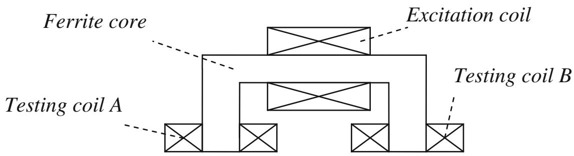


Fig. 2.7 The U-shaped magnetic core probe

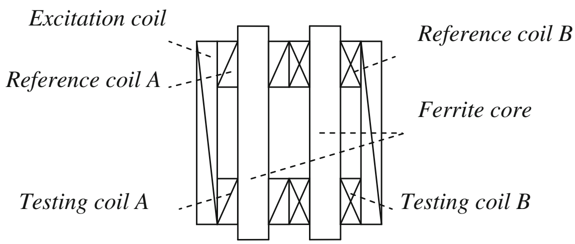


Fig. 2.8 The structure of the two-level differential probe

In Fig. 2.8, the structures of the reference coil A and B and the testing coil A and B are the same. The so-called two-level differential probe is connecting first the two coils on the same core differentially; that is, the dotted terminal of reference coil A is connected to the dotted terminal of the testing coil A; the reference coil B and the testing coil B are also connected into the differential form. At this point, the reference coil of the first-level differential is equivalent to a testing coil placed on top of a non-conductive material under the same excitation magnetic field. In the design of a differential probe, the coil used as the reference could be the coil placed at a point of the tested object without any defect, or the coil placed on top of the non-conductive material.

The purpose of adopting the design in Fig. 2.8 is to better ensure the consistency of the two coils with magnetic cores. When winding the electrical differential probe, often the output voltage is not 0 because inductances of the two testing coils are different. When winding the coil, first the upper part of the core is wounded *N* turns in one direction, and then, the bottom half of the core is wounded *N* turns in the reverse direction. The reference coil should be as close as possible to the top of the core, while the testing coil should be as close as possible to the bottom of the coil. When not testing, the overall inductance of the coils on each core is 0, but when the probe is placed on the surface of the conductor to be tested, the testing coil is closer to the eddy current than the reference coil, and the magnetic field strength is larger, so the differential output of the coils on one single core is not 0. Then, the coils on the two cores are connected into the differential form, so after subtracting the induced voltages of the two coils on the same core, subtraction is then conducted for voltages of different cores, in order to better suppress the liftoff noise.

When designing two-level differential probes, the design idea of the aforementioned closed magnetic circuit could be introduced, increasing the magnetic field strength by increasing the effective permeability of the magnetic circuit, particularly making the magnetic field strength generated by the defects small, and improving the phenomenon that the magnetic field decreases rapidly with the increase of the liftoff distance. Based on the three-core probe structure, the two-level differential probe structure is shown in Fig. 2.9.

In the winding of the coils shown in Fig. 2.9, we should ensure that the four coils, i.e., the testing coils A and B, and the reference coils A and B, have the same structure. However, when using the three-core two-level differential probe, there is the problem that the excitation magnetic fields of the two magnetic circuits may

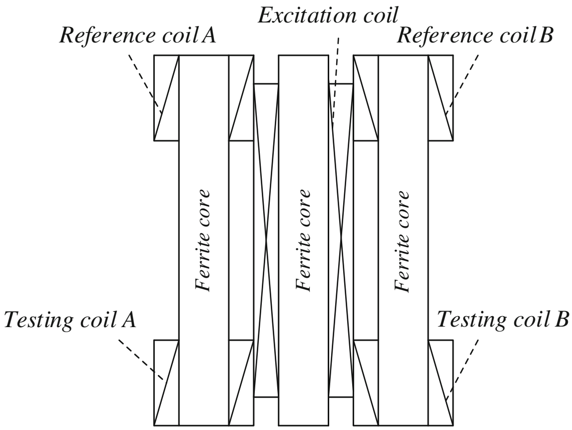


Fig. 2.9 Three-core two-level differential probe

have difference; meanwhile, its exciting magnetic field strength is only half of that of the U-core probe. Therefore, in this book, a two-level differential probe with u core is also given, as shown in Fig. 2.10.

In Fig. 2.10, in the magnetic circuit composed of ferrite cores, the tested object, and the liftoff air gap, the reference coil A and the testing coil A are connected differentially into a new coil. The reference coil B and the testing coil B are also connected differentially. Then, in the second level of differential, outputs of the coils on the two yokes of the U-shaped probe are subtracted.

Another probe with a closed magnetic circuit is the double U-type two-level differential probe, as shown in Fig. 2.11. Experimental results showed that, although sharing the same exciting coil, because the reluctance of the lower part of the magnetic circuit is small, most of the flux distribution is in the U-shaped magnetic circuit of the lower part of the probe. Because the excitation magnetic field sensed by the reference coil is different from that of the testing coil, the noise reduction, especially the liftoff noise suppression, is no better than the two-level differential probe shown in Fig. 2.10, but better than the probe without a two-level differential design.

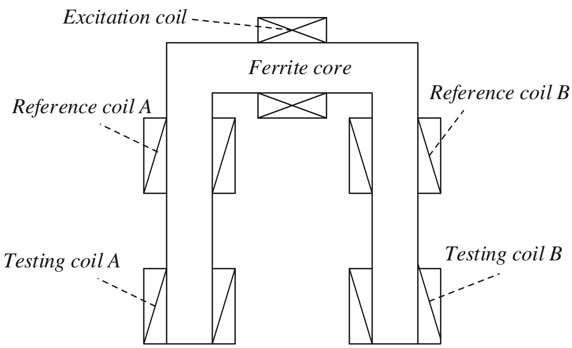


Fig. 2.10 Two-level differential probe with U core

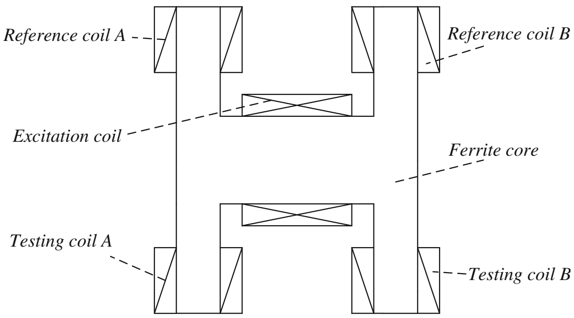


Fig. 2.11 The two-level differential probe with different excitation magnetic field

In the two-level differential, the first-level difference is used to eliminate the voltage in the coil induced by the exciting magnetic field, and the second-level differential is used to remove the eddy current at the position without any defect, or induced voltage of the eddy current without amplitude and phase changes caused by the defects. After the two-level differential, the output of the probe is the voltage induced by the magnetic field generated by the eddy current changed by the defect.

The thing to note is, for the electrical differential probes and the three-core probes, in coil winding, two identical coils with magnetic cores could be wounded with the same winding direction and then connecting the lower terminals. However, magnetic fluxes on both yokes of the probe with the U-shaped magnetic cores are in the opposite direction, so attention should be paid to the coil winding, avoiding sequential connection.

2.2.3.7 Rotating Magnetic Field Probe

The pulsed eddy current is mainly used for detection of defects on the surface of the tested object, especially the fatigue cracks, so the extensions of the defects may be in any direction on the 2D plane; i.e., the directions of the defects are in different angles with the scan direction of the probe; therefore, it is needed to ensure the probe can produce an appropriate response signal to the defects in any direction.

With the differential probes, for long cracks, when the extension of the crack and the probe movement are in the same direction, there are only alarm outputs at the beginning and end of the crack. When the two coils are located on the same long crack, the probe's output will be 0, so the long crack will be mistaken recognized as two separate small cracks.

According to the principle of the eddy current testing, it is desired to detect the change of the magnetic field resulting from the changes of the magnitude and phase of the eddy current caused by defects. When the defect is perpendicular to the flow of the eddy current in the tested object, the defect can change the eddy current distribution on the maximum; therefore, the signal detected by the probe reaches the maximum and vice versa when the defect is parallel to the eddy current flow; because the change of the eddy current is very small, the slight change of the signal caused by the defect is difficult to detect. When designing the probes, we should take into account the relationship between the extension direction of the defect and the probe output signal. By designing the cooperation between the excitation and testing subsystems properly, defects along different directions can be detected.

In the absolute coil often used in the conventional eddy current testing, the eddy currents produced in the tested object are several eddy current rings below the coil, while the coil itself is a symmetrical cylinder, so the probe has no directional differences. Where there are no defects, the generated eddy currents are concentric rings. The absolute coil has poor anti-interference performance and especially is sensitive to liftoff. In testing, when there is liftoff between the probe and the tested object, the reverse voltage caused by the defect becomes small rapidly, introducing the liftoff noise while at the same time also reducing the sensitivity of the probe itself. Absolute coil has no directional differences, but is limited by its poor anti-interference ability and lack of testing sensitivity and is rarely used in actual testing.

With the rotating magnetic field eddy current testing probe, cracks in all directions can be detected. The probe produces a periodically rotating exciting magnetic field, so the eddy current on the tested object is also periodically rotating. Fig. 2.12 shows the structure diagram of the composite coil used to generate the rotating exciting magnetic field.

The excitation coil in Fig. 2.12 is composed of two orthogonal excitation coils wounded on a cubic magnetic core. Sinusoidal signals with a phase difference of 90° are loaded, respectively, into the two coils. According to the principle of electromagnetic induction, the eddy current induced by the coil in the tested object is parallel to the direction of the excitation current.

Because the two excitation signals are sinusoidal signals with a phase difference of 90°, the generated eddy currents also have approximately sinusoidal waveforms. If the eddy current induced by the excitation coil in the tested object is represented as follows:

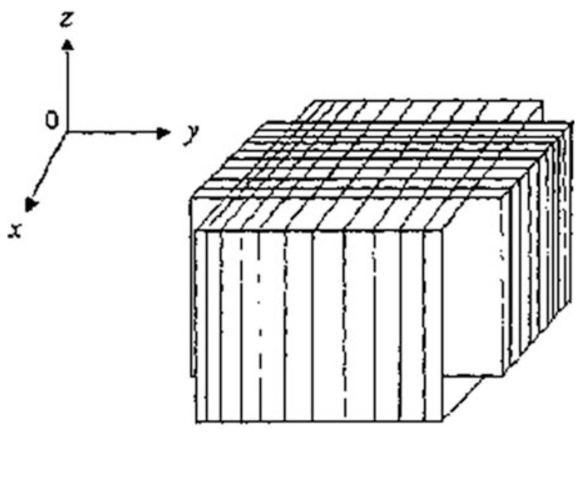


Fig. 2.12 Structure diagram of the composite exciting coil used to generate the rotating exciting magnetic field

$$I_x = I_0 \sin(\omega t + \varphi) \quad (2.14)$$

then the eddy current induced by the other excitation coil in the tested object is as follows:

$$I_y = I_0 \sin(\omega t + \varphi + \pi/2) = I_0 \cos(\omega t + \varphi) \quad (2.15)$$

in which $\omega = 2\pi f$, with f as the frequency of the excitation signal and φ as the initial phase of the eddy current.

When the excitation coil is wounded upright, each exciting coil only generates magnetic field along the axis; accordingly, only eddy currents parallel to the excitation currents are produced in the tested object. The two eddy currents are perpendicular to each other, so below the probe in the tested object, the amplitude of the combined eddy currents is as follows:

$$I = \sqrt{I_x^2 + I_y^2} = I_0\sqrt{\sin^2(\omega t + \varphi) + \cos^2(\omega t + \varphi)} = I_0 \quad (2.16)$$

The phase angle of the combined eddy current is as follows:

$$\theta = \arctan\left(\frac{I_y}{I_x}\right) = \arctan\left(\frac{\cos(\omega t + \varphi)}{\sin(\omega t + \varphi)}\right) = -(\omega t + \varphi) \quad (2.17)$$

Therefore, for the exciting coil as shown in Fig. 2.12, when using two sinusoidal signals with a phase difference of 90° as the excitation signals of the two orthogonal coils, in the tested object, eddy current with a constant amplitude and a rotating frequency the same as the excitation signal frequency will be generated. The direction of the eddy current vector rotates one full revolution clockwise in one rotating cycle.

2.2.3.8 Probe with a Cup-Shaped Magnetic Core

The purpose to use a cup-shaped core is to make up for the limitation of the absolute coil. Structures of the cup-shaped core probe are as shown in Figs. 2.13 and 2.14. Figure 2.13 shows the vertical cross section of the probe, and Fig. 2.14 shows the horizontal cross section of the probe.

As shown in Figs. 2.13 and 2.14, the testing coil and the excitation coil of the cup-shaped core probe are both wounded on the cylinder in the middle of the magnetic core. The radius of the exciting coil could be enlarged to increase the linear range of the probe. When designing the probe, because the testing coil with a small radius has a higher sensitivity, the testing coil is wounded at the inside, and the exciting coil is wounded at the outside. Throughout the outside of the cup-shaped core, there is a shielding shell, and its function, on the one hand, is to reduce the magnetic leakage and, on the other hand, is shielding electromagnetic interference from outside, in order to improve the signal-to-noise ratio.

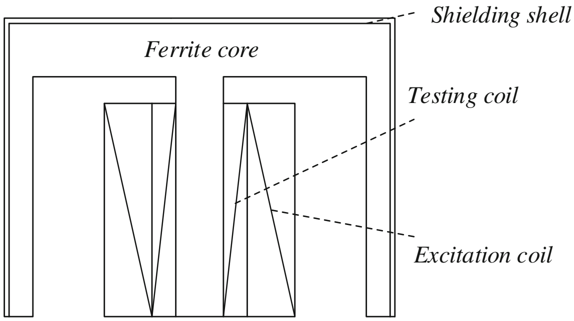


Fig. 2.13 Vertical cross section of the probe with a cup-shaped magnetic core

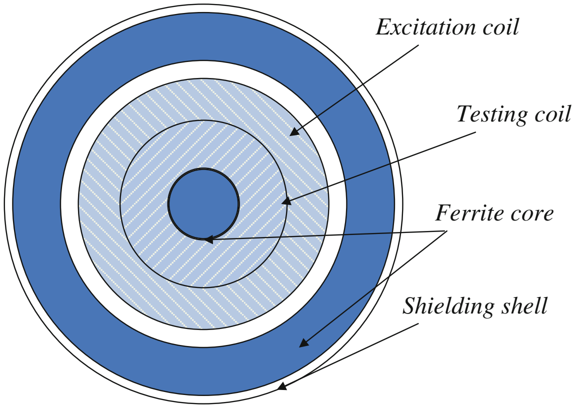


Fig. 2.14 Horizontal cross section of the probe with a cup-shaped magnetic core

With the cup-shaped core, the ability of the absolute coil to suppress the liftoff effect has been greatly improved, and meanwhile, it has a good shielding to other noise, especially the electromagnetic noise. The geometry of a cup-shaped core effectively concentrates the exciting magnetic field distribution and makes the tested object and the magnetic core together form a closed magnetic circuit.

The eddy currents induced by the cup-shaped core probe in the tested object have distributions of concentric rings. According to geometric principles, an arbitrary straight line through the center of a circle is perpendicular to the arc intersecting the line. Therefore, when using the cup-shaped core probe to detect cracks with arbitrary directions, if a crack defect is located directly below the probe, the crack is perpendicular to the eddy current rings in the tested object, so with the probe, the defect will be more effectively detected. If the excitation coil and the testing coil are wounded evenly around the cylinder at the middle of the magnetic core, because of the central symmetric characteristic of the entire probe, no matter at what angle will the probe rotate, the performance of the probe will not be affected by the directivity. Using the cup-shaped core also helps to avoid errors due to deviation from the axis of the coil.

When the cup-shaped core probe is placed at the surface of the tested object without any defect, its output is a constant voltage, called the inherent voltage. With the cup-shaped core probe, when a defect is detected, the output voltage becomes larger, but the voltage increment is small compared to the inherent voltage. If we take the inherent voltage as the background noise, then the signal-to-noise ratio of the system is low. In order to eliminate the background noise and other interferences, another cup-shaped core probe with the same structure is placed in defect-free region of the tested object as a reference, and the output signals of the two probes are subtracted. In testing, the reference probe is fixed, and the testing probe is moved at the surface of the tested object.

With the cup-shaped core probe, cracks in different directions could be detected. At the same time, the liftoff noise suppression is also taken into account.

2.2.3.9 Cross-Winding Probe

In order to improve the signal-to-noise ratio, the inherent voltage should be removed, so it is desired to design probes with zero adjustment function; i.e., at defect-free parts of the tested object, the probe output is zero. In design, we can make the direction of the combined magnetic field at the point without any defect parallel to the testing coil, and then, the probe output is zero. When there is a defect in the tested object, the direction of the combined magnetic field will change, and then, there is flux interacting with the testing coil, so the probe will output a voltage reflecting the defect.

The purpose of the cross-winding probe is to design a probe with auto zero adjustment function and able to detect cracks along various directions. The structure of the cross-winding probe is as shown in Fig. 2.15.

With the cross-winding coil, two coils are wounded on the cylindrical ferrite core, both perpendicular to each other, one as the excitation coil and the other as the testing coil. Both coils have the same numbers of turns and are both perpendicular to the surface of the tested object. The magnetic field of the excitation coil is parallel to the testing coil, and the eddy current magnetic field is opposite to the exciting magnetic field, but also parallel to the testing coil, and therefore, when

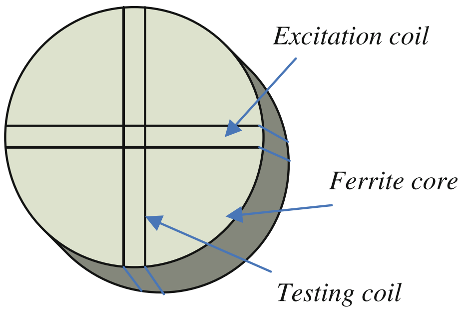


Fig. 2.15 The structure of the cross-winding probe

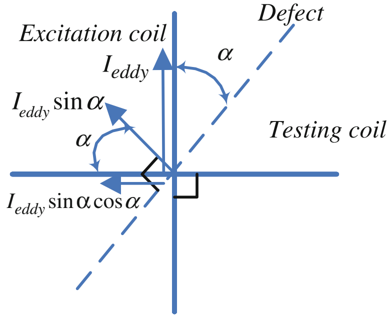


Fig. 2.16 Analysis of the cross-winding probe

there is no defect, the output of the cross-winding probe is 0. When the eddy current distribution is altered by the defects in the tested object, the magnitude and direction of the magnetic field generated by the eddy current will change so that defects are reflected in the probe output voltage. Diagram of the testing process of the cross-winding probe is as shown in Fig. 2.16.

Assuming the angle between the extension direction of the crack and the excitation coil is α, the eddy current of the excitation magnetic field is parallel to the excitation coil plane, as shown in Fig. 2.16. If the eddy current is decomposed into one component parallel to the crack and another component perpendicular to the crack, the eddy current component parallel to the crack is affected very little by the crack, basically causing no voltage change in the testing coil, so only the eddy current component $I_{\text{eddy}}\sin\alpha$ perpendicular to the crack is effective. In addition, the eddy current causing the change of the induced voltage in the testing coil is the component parallel to the testing coil. Therefore, if once again decomposing the part of the eddy current affected by the defects (eddy current component perpendicular to the crack), the probe output will depend on the component parallel to the testing coil after decomposition.

$$I_{\text{eff}} = I_{\text{eddy}}\sin\alpha\cos\alpha = 0.5I_{\text{eddy}}\sin 2\alpha \tag{2.18}$$

The above equation shows that the situation when the angle between the extension direction of the crack and the direction of the current in the excitation coil is $0-\pi$, it is the same as that when the angle is $\pi-2\pi$.

When $\alpha = 0$ or 0.5π, the extension direction of the crack is parallel to the excitation coil or the testing coil, and the probe output voltage is 0. With this configuration, the cross-winding coil probe cannot detect the cracks.

2.2.3.10 Star-Shaped Coil Probe

The star-shaped coil probe is an improvement based on the cross-winding coil probe. The purpose is to make up for the testing blind region of the cross-winding probe. The star-shaped coil is composed of two testing coils and an exciting coil,

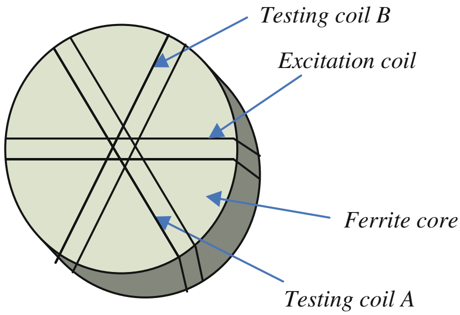


Fig. 2.17 The structure of the star-shaped coil probe

and the three coils are all perpendicular to the surface of the tested object. The structure of the star-shaped coil probe is as shown in Fig. 2.17.

The three coils on the star-shaped coil probe split the circle equally; that is, the angle between any two coils is $\pi/3$. Similarly, let the angle between the crack and the excitation coil be α, because the eddy current direction is parallel to the current in the excitation coil; after decomposition of the eddy current, the eddy current component vertical to the crack $I_{\text{eddy}} \sin\alpha$ will generate voltage in the testing coil. Then, we decompose the eddy current component vector further into two components parallel to the two testing coils, respectively. Assuming I_1 is the component parallel to the excitation coil A, and I_2 is the component parallel to the excitation coil B, the process of decomposition is as in Fig. 2.18.

Then, it could be known that $\beta = \pi/2 - \pi/3 - \alpha = \pi/6 - \alpha$.

According to the law of sines,

$$I_1 = 2I_{\text{eddy}} \sin\alpha \sin\left(\frac{\pi}{6} + \alpha\right) \tag{2.19}$$

$$I_2 = 2I_{\text{eddy}} \sin\alpha \sin\left(\frac{\pi}{6} - \alpha\right) \tag{2.20}$$

When connecting two testing coils into one testing coil, they can be in series or differential. When the two testing coils are connected into the differential form,

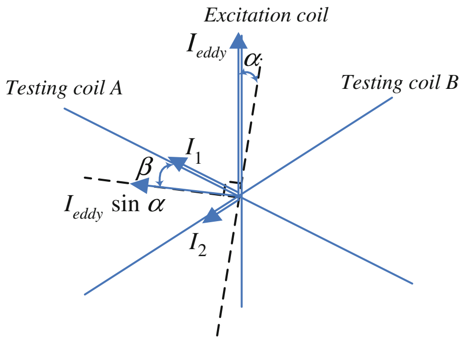


Fig. 2.18 Analysis of the testing process of the star-shaped coil probe

because the two testing coils have the same numbers of turns and characteristics, therefore, it can be approximated that the output of the differential star-shaped coil probe $u = u_1 - u_2$ depends on the eddy current $I_1 - I_2 \propto I_{\text{eddy}} \sin^2 \alpha$. Therefore, when the extension of the crack is parallel to the excitation coil, output voltage of the differential star-shaped coil probe is zero; i.e., crack along this direction cannot be detected. In terms of the structure, the differential star-shaped coil probe is symmetric about the exciting coil. When there are no defects, the eddy current components along the directions parallel with the two testing coils are equal; therefore, differential output voltage is 0 when there are no defects; i.e., the differential star-shaped coil probe has the function of auto-zero adjustment. The differential design also cancels out the common interference factors to the two testing coils and improves the signal-to-noise ratio of the probe. Compared to the cross-winding probe, the differential star-shaped coil probe has increased performance.

When the two testing coils are connected in series, the output voltage of the probe is the sum of the induced voltages of the two testing coils. Similarly, the output of the star-shaped coil probes in series is $u' = u_1 + u_2$, which can be thought of as depending on $I_1 + I_2 \propto I_{\text{eddy}} \sin 2\alpha$. When detecting the defects in the tested object, the star-shaped coil probes in series have similar characteristics with the cross-winding probe, but the scale factor is different. Also, it is worth noting that when the probe is placed at a region free from defects, the probe output voltage is not 0, and the output signal is the sum of the induced voltages of the two coils, so the star-shaped coil probes in series do not have auto-zero adjustment. When testing cracks parallel or perpendicular to the excitation coil with the in series star-shaped coil probes, there is no signal output, so we cannot distinguish these two defects.

With the star-shaped coil probe, some improvements are made based on the cross-coil probe, and some of the shortcomings are made up for, but there are still testing blind spots.

2.2.3.11 The Horizontal–Vertical Coil Probe

The excitation coil placed horizontally on the surface of the tested object will generate in the tested object eddy current opposite to the excitation current in the coil. When the testing coil is perpendicular to the surface of the tested object, the excitation magnetic field and the magnetic field of the eddy current are both parallel to the testing coil. Therefore, when the probe is placed at the tested object where there is no defect, the horizontal–vertical coil probe output signal is 0, so it has the auto-zero adjustment function. The structure of the horizontal–vertical coil probe is as shown in Fig. 2.19.

During testing, if the probe is moved in the defect-free region, the eddy currents in the tested object have ring distributions, as shown in Fig. 2.20a. When the horizontal–vertical coil probe is above the crack, the crack will intersect with the

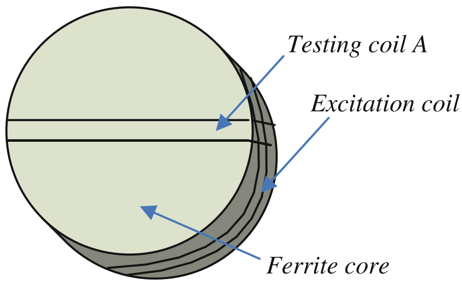


Fig. 2.19 The structure of the horizontal–vertical coil probe

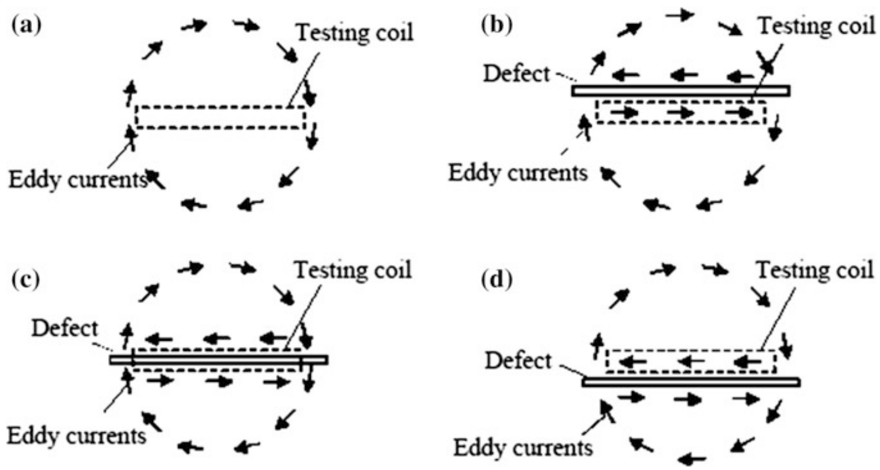


Fig. 2.20 The mechanism of the horizontal–vertical coil probe. **a** With no defect. **b** Testing coil on one side of the defect (positive output). **c** Testing coil on the central of the defect (0 output). **d** Testing coil on the other side of the defect (negative output)

eddy current ring. At the place of intersection with the defect, the conducting material can be seen as an open circuit, and along both sides of the crack, there will be eddy currents with opposite directions and equal magnitudes. These eddy currents, together with the original eddy current loops, will form two new loops. The mechanism of the horizontal–vertical coil probe is as shown in Fig. 2.20.

As in Fig. 2.20b, the eddy currents on both sides of the defect are in the opposite direction, but the magnetic field of eddy current on the circumference is parallel to the testing plane, so no voltage is induced in the testing coil. Moving the probe makes the testing coil approach the eddy current on one edge of the crack, although eddy currents on both edges have equal magnitudes; because the distances from the testing coils are different, voltage will be induced in the testing coil, and this voltage can be assumed positive. When the probe is moved such that the testing coil is just above the defect, as shown in Fig. 2.20c, the opposite eddy currents on the two edges have equal distances from the testing coil, so the magnetic fields of the two eddy currents cancel each other out, and the probe output is 0. With the probe continuing to move, the situation as shown in Fig. 2.20d will emerge. As the distance to the eddy current of the lower part in Fig. 2.20d is smaller, the probe output voltage is negative. In the whole process of moving the probe to detect a crack, the probe output voltage will go from zero to a positive value and then from a peak positive voltage drop pass zero, until reaching the negative voltage peak. When the probe leaves the crack, its output voltage changes to 0 again.

When the crack is perpendicular to the testing coil, the magnetic field of the eddy current is parallel to the testing coil plane. Now, the horizontal–vertical coil probe output is zero, so we are unable to detect a crack perpendicular to the testing coil.

2.2.3.12 The Improved Horizontal–Vertical Coil Probe

Because the horizontal–vertical probe has testing blind region, i.e., with it we cannot detect cracks perpendicular to the testing coil. Another testing coil is needed to make up for this shortcoming. When the two testing coils are not parallel, the second testing coil can detect cracks perpendicular to the first testing coil, which makes up the testing blind region of the probe. In order to obtain a higher degree of sensitivity, for the improved probe, the two testing coils should be mutually perpendicular, so that for the cracks perpendicular to the first testing coil, the eddy current in the tested object will be parallel to the second testing coil, and thus, the crack is detected with a higher sensitivity. The structure of the improved horizontal–vertical coil probe is as shown in Fig. 2.21.

Figure 2.21 shows that the three coils are all wounded on the ferrite magnetic core, and the testing coil A is perpendicular to the testing coil B, and both are perpendicular to the excitation coil. The exciting coil is placed horizontally. Similarly, we can know that, when there are no defects, the output of the improved horizontal–vertical coil probe is 0, so it has zero adjustment characteristic.

Given that when the defect is on both sides of the testing coil, the direction of the induced voltage will change, and the two testing coils are not connected as a whole. Instead, two channels are used to analyze the induced voltages in the two testing coils. In this way, in the testing device, two signal processing and A/D conversion channels are required to work simultaneously. The analysis of the two signals takes

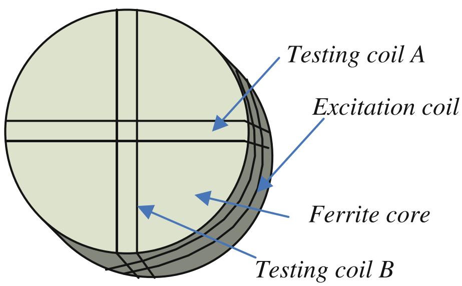


Fig. 2.21 The structure of the improved horizontal–vertical coil probe

the logical OR; that is, when the recorded voltage on any of the channel exceeds a threshold, the testing device will output an alarm signal, so that cracks along each direction can be detected effectively.

2.2.4 The Reciprocity Rule in Probe Design

Applying the reciprocity rule in probe design reasonably is helpful to extend the ideas in probe development and design.

For the probe with isolated excitation coil and testing coil, if the functions of the excitation coil and the testing coil are swapped, i.e., inputting a pulse excitation in the original testing coil, and at the same time measuring the change of induction voltage in the original excitation coil, then making adjustments according to the specific situation of testing, functions similar with the original probe can be implemented. This law is called the reciprocity rule in probe design. Previously mentioned electrical differential probe and magnetic differential probe reflect this idea.

In order to detect cracks along each direction, several probes developed by the authors have been introduced earlier. For the cup-shaped magnetic core probe and the cross-winding coil probe, if the functions of excitation and testing are swapped, it is still the original probe. In particular, for the cross-winding probe, there will be no change in performance after the swap. For the cup-shaped magnetic core probe, considering the actual requirements on the testing coil, setting the exciting coil outside and the small radius testing coil inside is more helpful for improving linearity range and the testing sensitivity, although after the swap the new cup-shaped core probe can still achieve similar capabilities to the original probe, the testing sensitivity is reduced.

2.3 Circuits of the Pulsed Eddy Current Testing

Circuits of the pulsed eddy current testing are mainly composed of the excitation source, the probe, the analog signal processing unit, the microcontroller subsystem, and other components. There is also a power supply module for the entire device. Among them, the analog signal processing unit contains the amplifier, the envelope detector, the front-end and back-end filtering, and other function circuits; the microcontroller subsystem consists of the microcontroller (including the A/D converter), manual reset, sound and light alarm, quantification display, expanded memory, and serial communication circuits. The structure of the testing circuit is shown in Fig. 2.22.

Periodic pulse signal with adjustable frequency and duty cycle is generated by the excitation source and input into the exciting coil of the probe. On the rising and falling edges of the excitation signal, eddy currents are induced in the tested object, and the change of the magnetic field generated by the eddy current in the tested

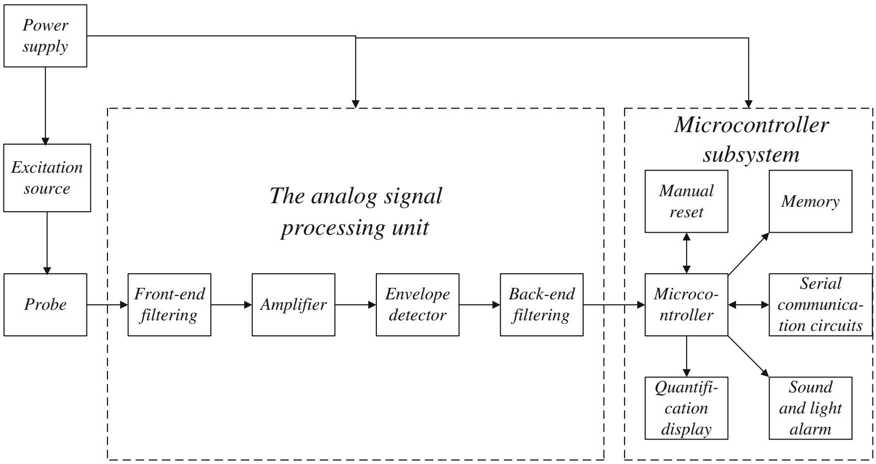


Fig. 2.22 Diagram of the structure of the pulsed eddy current testing circuit

object is detected by the testing coil of the probe. The defect signal detected by the probe is transmitted to the analog signal processing unit, through the processing including the amplification, waveform detection, and filtering and then obtaining signal suitable for analysis and processing on the microcontroller. Via the built-in A/D converter (ADC), the digitization of the measured analog signal is completed in the microcontroller. Then, appropriate judgment, analysis, calculation, and processing are done according to user requirements, and after the testing, the data stored in memory are transmitted to the PC via a serial port using asynchronous communication.

2.3.1 The Power Supply Module

There are three voltage levels for the portable pulsed eddy current testing device, namely +5, +3, and −5 V. The +5 V power supply provides power for microcontroller, signal source, and other digital IC, the −5 V power supply works as the reverse voltage of the operational amplifier, and the +3 V power supply is for the external flash memory. Among them, the −5 and +3 V power supplies can be built on top of the +5 V power supply. Therefore, we should first design a stable +5 V power supply.

The instrument is powered with four normal dry batteries, but during working, the battery voltage will decrease gradually, and therefore, the battery cannot be used directly as a stable DC power supply. Meanwhile, the power supply module should also have a large output current to provide enough power, particularly instantaneous pulse output power. The TPS60110 power chip from Texas Instruments is adopted, in accord with the characteristic of the battery that the voltage gradually decreases.

The input voltage range required for the chip to work normally is 2.7–5.4 V, and in this range, the chip can output stable +5 V DC voltage, and the maximum output current is up to 300 mA. The power source circuit of the pulsed eddy current testing instrument is shown in Fig. 2.23.

In Fig. 2.23, in circuit design, attention should be paid that pin 3 is the enable terminal, and it must be connected to the power supply to make it a high voltage level, and then, the circuit will work properly; that is, the pin must not be suspended. The output of the power source is type Π filtering circuit, to restrain the superposed high-frequency ripple in the DC voltage output of the power supply. The entire circuit only uses a few external capacitors, so the structure of the circuit is simple.

The −5 V power supply is converted by the +5 V DC voltage using the converter chip MAX764. The conversion circuit is shown in Fig. 2.24.

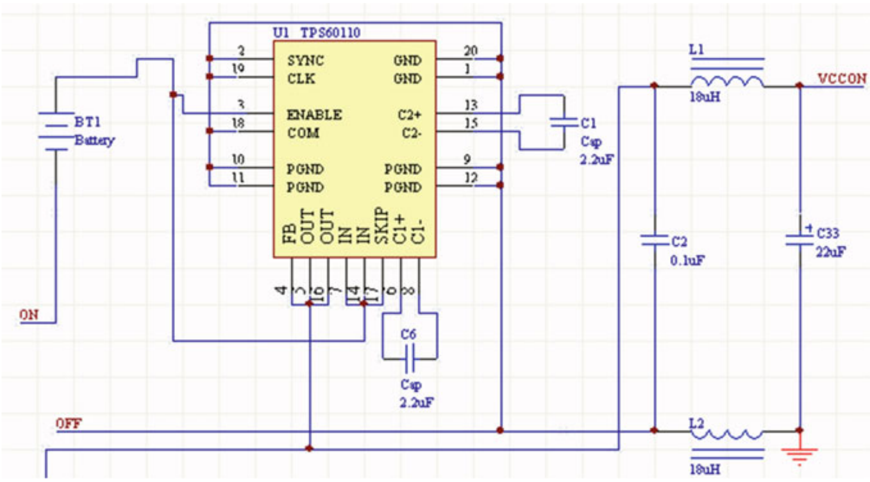


Fig. 2.23 The +5 V power source circuit with TPS60110

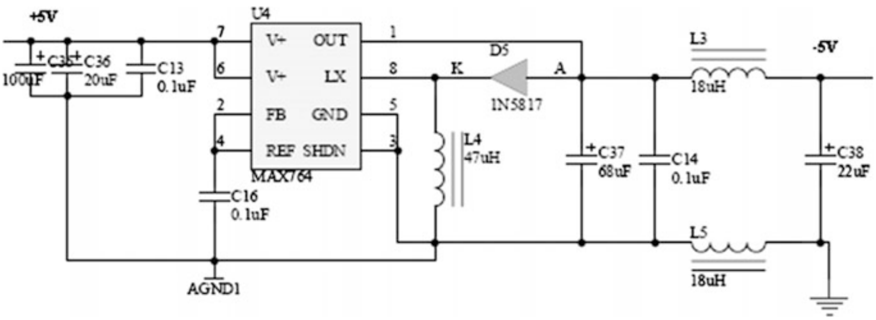


Fig. 2.24 The −5 V power source module

The +3 V power supply also uses the +5 V DC voltage as input, with three terminal regulator chip AS117-3.0. In layout, the power sources for the respective purposes are placed close to corresponding chips and separated from the other levels, in order to reduce interference between them.

2.3.2 The Excitation Source

A periodic repetitive pulse is used as the excitation signal for the pulsed eddy current testing instrument. In experiments, in order to test the effects of pulse parameters on the testing performance, a pulse generating circuit with adjustable repetition frequency and duty cycle is designed. A 555 timer is used to generate the pulse with continuously adjustable duty cycle. The design of the excitation signal generating circuit is shown in Fig. 2.25.

The duty cycle of the output pulse of the excitation source can be adjusted over a wide range; the diodes D_1 and D_2 provide charging and discharging channels for the capacitor C_1, respectively. Potentiometers P_1 and P_2 control the charging and discharging cycles of the output pulse, respectively. The charging circuit is composed of R_1, D_2, input resistance R_{P2} of the potentiometer P_2, and capacitance C_1 and the discharging circuit is composed of R_2, D_1, input resistance R_{P1} of the potentiometer P_1, and capacitance C_1. The charging cycle determines the time duration $T_{\rm H}$ of the high-level voltage of the output pulse, while the discharging cycle is the time duration $T_{\rm L}$ of the low-level voltage of the pulse, and the sum of them $T = T_{\rm H} + T_{\rm L}$ is just the pulse cycle. When $R_1 = R_2 = 1\,\mathrm{k\Omega}$, and the total resistance of the potentiometer P_1 and P_2 is $1\,\mathrm{M\Omega}$, by adjusting the potentiometer, the ratio of the charging cycle and the discharging cycle of the timer, i.e., the ratio of the high-level voltage duration and the low-level voltage duration, changes between 10,000:1 and 1:10,000. In addition, the duty cycle of the output excitation signal is as follows:

$$\text{Duty} = \frac{T_{\rm H}}{T_{\rm H} + T_{\rm L}} \times 100\,\% \tag{2.21}$$

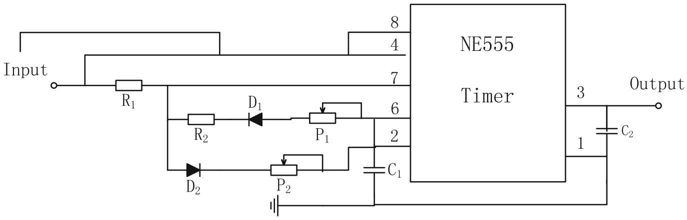


Fig. 2.25 Excitation source circuit

In the excitation source circuit, duty cycle of the pulse can be adjusted continuously between 0.01 and 99.99 %. Pin 7 of the NE555 is discharging pin, and pin 2 is trigger pin. When the voltage on pin 2 is lower than 1/3 of the input voltage, it is seen as that the trigger signal emerges, and the timer output voltage is high level. Pin 6 is the threshold pin. When voltage of pin 6 is higher than 2/3 of the input voltage, it is seen as that the signal exceeds the threshold, and then, it is needed that voltage of pin 2 is no lower than 1/3 of the input voltage, and the timer output voltage is low level.

Therefore, the time duration of high-level output of the timer is as follows:

$$T_{\mathrm{H}} = RC_1 \ln \frac{u_{cc} - 0.6 - u_1}{u_{cc} - 0.6 - u_2} \tag{2.22}$$

in which 0.6 V is voltage drop of the diode, u_{cc} is the input voltage, $u_1 = u_{cc}/3$ is the low triggering threshold, $u_2 = 2u_{cc}/3$ is the high triggering threshold, R is the equivalent resistance in the charging circuit, and $R = R_1 + R_{P2}$. Similarly, the time duration of the low level is as follows:

$$T_{\mathrm{L}} = (R_2 + R_{p2})C_1 \ln \frac{u_{cc} - 0.6 - u_1}{u_{cc} - 0.6 - u_2} \tag{2.23}$$

and then the repetition period of the pulse is

$$T = T_{\mathrm{L}} + T_{\mathrm{H}} = (R_1 + R_2 + R_{P1} + R_{P2})C_1 \ln \frac{u_{cc} - 0.6 - u_1}{u_{cc} - 0.6 - u_2} \tag{2.24}$$

and the duty cycle is as follows:

$$\mathrm{Duty} = \frac{R_1 + R_{P2}}{R_1 + R_2 + R_{P1} + R_{P2}} \tag{2.25}$$

2.3.3 The Analog Signal Processing Module

The probe output signal is generated by the change of the electromagnetic field caused by a defect. This signal is often weak, has poor anti-interference ability, and includes noises. So before entering the probe signal into the A/D converter and the microcontroller, the analog signal should be processed accordingly. The noise should be removed, and the signal must be amplified to improve the anti-interference ability and the signal-to-noise ratio. Then, the probe output signal passes through the A/D convertor and changes into the kind of signal suitable for processing in the microcontroller. The analog signal processing module includes several sections such as the front-end filtering, isolation–amplification, envelope detection, and the back-end filtering.

When analyzing and processing the probe output signal, although in the probe design noise suppression measures have been taken, signal processing circuit is still needed for further processing. The probe output signal contains high-frequency noise, influencing measurement of the waveform. Therefore, it is required to filter the signal first. Some noises are generated with the signal at the same time, and others are superimposed in the transferring process. The process of eliminating or reducing the noise and extracting the useful signal, depending on the different characteristics of the signal and the noise, is just filtering.

The response of the pulsed eddy current testing has a very wide spectrum, but mainly the middle frequency and low frequency parts of the spectrum are analyzed. The front-end filter is designed as a low-pass filter. For implementation, a circuit composed of the RC circuit and the operational amplifier is used as the active RC low-pass filter.

Because the active filter circuit is applied, the probe output signal will also be enhanced while removing the high-frequency noise. However, the probe output signal is often weak and needs further amplification to enhance the useful signal and improve the resistance of the signal to noises introduced in the later stages of the circuit. The so-called isolation primarily refers to making the working status of the current circuit not affected by change of load in the subsequent circuit. Because a voltage follower is used in the filter circuit, the main function of the amplification circuit is to amplify the signal, but it also plays the role of isolating the previous and later circuits. The optical isolation is often used as the circuit isolation, but the magnitude of the eddy current transducer signal is normally from dozens of millivolts to hundreds of millivolts; that is, the signal is small and not suitable for optical isolation.

The portable pulsed eddy current testing instrument determines whether there is any defect in the tested object based on the peak value of the probe output signal, so it is necessary to extract the peak value of the probe output signal. An envelope detector module is added to the testing device. The principle of envelope detection is to obtain the envelope of the signal waveform through the RC charging–discharging.

2.3.4 The Microcontroller Subsystem

The microcontroller subsystem mainly accomplishes functions such as A/D conversion, threshold setting, alarming, data storage, serial port communication, and quantified display of the inspection data.

For the microcontroller chip, a high-performance microcontroller ADuC812 from ADI (Analog Device Inc) company is selected. It is a fully integrated 12-bit data acquisition system, and the chip contains a high-performance 8-channel ADC with self-calibration, 2-channel 12-bit DAC, and a programmable 8-bit MCU.

The serial port circuit of the pulsed eddy current testing instrument has two functions: the first is downloading and online debugging the microcontroller program, and the second is transferring the data in the memory of the testing device to the PC. The selected chip ADuC812 has online programming function, provided by the Development Kit of QuickStart development system, which contains the support of ADuC812. Under this system, the microcontroller system can be debugged directly, and after debugging, the program can be downloaded to ADuC812.

At the three cases of power up, power down, and power off, the reset circuit of ADuC812 has the corresponding functions. When the power supply voltage of the microcontroller is less than 2.5 V, it is required to keep the RESET pin high; when the power supply voltage is higher than 2.5 V, the RESET pin should remain low voltage level for at least 10 ms; the power-on reset circuit should be able to work under 1.2 V or even lower voltages. In this book, the active low reset chip max705 capable of manual resetting is used. When the MCU is powered on, the system is reset; the program runs from the starting position. During operation, the reset switch can be pressed manually to implement the system reset.

With the reset circuit, in addition to ensuring normal operation of the microcontroller, the designed manual resetting function can be used to implement alarm threshold setting of the device. If the selected alarm threshold is set in the microcontroller program in advance, the scope of application of the testing device could be limited to only detecting defects of a certain material; that is, when using it to test other materials, phenomena like false alarms or missed defects are possible. Therefore, when using the testing device under different testing conditions on tested objects with different materials, appropriate alarm thresholds should be set depending on the specific tested object.

The steps of operation include first placing the probe at the region of the tested object without any defect and pressing the manual reset button to reset the microcontroller. In the initial phase of the program, the threshold is selected and set by the device first, i.e., starting the ADC continuous sampling and comparing the acquired data in the microcontroller, selecting the maximum value, and setting the sum of the maximum value and an additional margin as the alarm threshold of defect detection. With such a design, on the one hand, the device can be used to test different materials so that the range of application is widened; on the other hand, the respective testing threshold values can also be set according to different testing conditions, such as changes of the liftoff height and changes of the environmental temperature. As described earlier, when there is liftoff at the probe, the amplitude of the output signal will be reduced. If the device maintains the preset threshold value, missed tests will emerge. Therefore, when the probe is used at a liftoff height different from the original one, by pressing the reset switch, the alarm threshold under the new testing conditions is set.

The oscillator circuit and the clock circuit of the microcontroller decide together the timing of the microcontroller. According to the difference of the hardware circuits, ADuC812 can use the on-chip clock oscillator, or the external clock source. To make the circuit as simple as possible, the on-chip clock oscillator is used, so that it is only required that the crystal oscillator be connected in parallel between the XTAL1 and XTAL2 pins, and two capacitors be connected between the two pins and the ground. The capacitor value is generally between 10 and 60 pF.

Whether using the on-chip clock oscillator, or the external clock source, the clock working range of ADuC812 should be selected in the range of 400 kHz–16 MHz. Although the kernel of ADuC812 is static, i.e., its operating frequency can be as low as DC, the maximum sampling rate of the ADC is 200kSps, so when the clock frequency is lower than 400 kHz, the ADC will not work properly. In addition, choice of the crystal oscillator also affects transmitting rate of the serial port communication. In order to guarantee the transmitting rate of the serial port, the crystal oscillator frequency of the microcontroller should not be too low.

Four tricolor LEDs placed side-by-side are used as the defect display of the testing device, and they divide the detected signal amplitude from the 0 to 2.5 V into eight uniform levels. If connecting different pins of the light-emitting diodes, we can choose to make them emit red or green light. In testing, the amplitude of the signal can be judged based on the location and color corresponding to the diode. Arranged from left to right, if the LED on the left is lit, it indicates that the voltage is small; when the same diode emits red light, the indicated voltage level is higher than that when emitting the green light.

After acquiring the data with the ADC of the microcontroller, the MCU program will analyze and judge the samples, divide them into proper ranks according to their values, output the number of this rank through ports P33, P34, and P35, and connect the output high level to the pin of the corresponding diode through a decoder 74LS138. In this way, on the one hand, the circuit is simplified, saving resources of the microcontroller; on the other hand, this also decreases the volume and reduces the power consumption.

The function of the alarm circuit is that when a defect is detected, an alarm signal is raised. A sound and light alarm is used; that is, when a defect is found, the microcontroller will output a high voltage level and light the alarm LED and drive the buzzer to emit the sound at the same time. In order to enhance the load-carrying capacity of the port of the microcontroller, a pull-up resistor is set at the port, and two reversers are used to enhance the signal.

References

1. Auld, B.A., Moulder, J.C.: Review of advances in quantitative eddy current nondestructive evaluation. J. Nondestr. Eval. **18**(1), 3–36 (1999)
2. Fenghe, Y., Jiang, T., Sun, Y.: Analysis of the characteristics of pulsed eddy current fields. Instrum. Tech. Sens. (5), 38–39 (2003) (in Chinese)
3. Binfeng, Y., Feilu, L.: The pulsed eddy current non-destructive testing device based on the integrated Hall sensors. Meas. Tech. (10), 8–9 (2004) (in Chinese)
4. Bieber, J.A., Shaligram, S.K., Rose, J.H., Moulder, J.C.: Time-gating of pulsed eddy current signals for defect characterization and discrimination in aircraft lap-joints. Rev. Prog. QNDE 1915–1921 (1997)
5. Sophian, A., Tian, G.Y., Taylor, D., Rudlin, J.: A feature extraction technique based on principal component analysis for pulsed eddy current NDT. NDT E Int. **36**(1), 37–41 (2003)
6. Tian, G.Y., Sophian, A.: Defect classification using a new feature for pulsed eddy current sensors. NDT E Int. **38**(1), 77–82 (2005)

7. Deqiang, Z., Tian, G., Wang, H., Wang, P.: Evaluation of applied stress using pulsed eddy current technology. Chin. J. Sci. Instrum. **31**(7), 1588–1593 (2010) (in Chinese)
8. Abidin, I.Z., Tian, G.Y., Wilson, J., Yang, S., Almond, D.: Quantitative evaluation of angular defects by pulsed eddy current thermography. NDT E Int. **43**(7), 537–546 (2010)

Springer

http://www.springer.com/978-981-10-0577-0

New Technologies in Electromagnetic Non-destructive Testing
Huang, S.; Wang, S.
2016, X, 222 p. 193 illus., 146 illus. in color., Hardcover
ISBN: 978-981-10-0577-0