Eddy Current Testing Probe Composed of Double Uneven Step Distributing Coils for Crack Detection

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Abstract

Eddy current testing is one of several non-destructive testing methods. It uses the principle of electromagnetism as the basis for conducting examinations. The eddy current testing can perform in a variety of inspections, and the crack detection of metallic structural frames is an important application.

In this thesis, the author proposes a new planar coil with the uneven step distributing structure. Because of the novel structure, the coil can defect position in non-scan mode. Then the new eddy current testing probe composed of double uneven step distributing coils is proposed for crack detection. It can detect crack position in the measurable range beneath it in test surface. Based on its operation mode the new eddy current testing probe is a difference probe for detecting crack in metallic surface. The eddy current testing probe contains three layers including the magnetic layer, the coil layer and the bottom protection layer. By further study based on the multifunctional sensing technology, the new eddy current testing probe is research to detect crack position and width simultaneously. For the multifunctional sensing system of crack detection, the two inputs are crack position and width, and the two outputs are the two equivalent inductances of two coils.

The measurement system of crack detection is represented. In test the LCR meter alternately measures the equivalent inductance of coil controlled by a switch. According to the experiment results, the two functions expressing the relations between the two inputs and the two outputs are obtained by curve fitting method based on the least square principle. So in detection according to the two equivalent inductances, the crack position and width can both be evaluated by solving systems of two equations with two variables crack position and width. Furthermore the estimating errors of crack position and width are both studied.

The traditional crack detection is dynamic in point by point detection mode, so the test work is great and test efficiency is low. The new ECT probe can detect crack in the measurable range in static detection mode, which can reduce
measurement work and advance test efficiency compared with the dynamic point by point detection mode. Also this ECT probe itself has a high resolution for crack position. The new eddy current testing probe can be used to detect the long defect as crack in wide aircraft fuselages, long railway, and long tubes. Also it can be used to inspect a batch of metallic workpieces. Furthermore the probe can still detect crack in some instances when the probe is fixed or can’t be moved in high resolution.
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1 Introduction

1.1 Background

Nondestructive testing has been practiced for many decades. One of the earliest applications is the detection of surface cracks in railcar wheels and axles. The parts are dipped in oil, then cleaned and dusted with powder. When a crack is present, the oil will seep from the defect and wet the powder providing visual indicating that the component is flawed. This eventually leads to oils that are specifically formulated for performing these and other inspections, and this inspection technique is now called penetrant testing.

X-rays were discovered in 1895 by Wilhelm Conrad Roentgen (1845-1923) who was a professor at Wuerzburg University in Germany. Soon after his discovery, Roentgen produced the first industrial radiograph when he imaged a set of weights in a box to show his colleagues. Other electronic inspection techniques such as ultrasonic and eddy current testing started with the initial rapid developments in instrumentation spurred by technological advances, and subsequent defense and space efforts.

In the early days, the primary purpose was the detection of defects. Critical parts were produced with a safe-life design, and were intended to be flawed free during their useful life. The detection of a defect became a cause for removal of the component from service.

In the early 1970's, two events occurred which caused a major change in the way that inspections were viewed. The continued improvement of inspection technology, in particular the ability to detect smaller and smaller flaws, led to more and more parts being rejected, even though the probability of part failure had not changed. At this time the discipline of fracture mechanics emerged, which enabled one to predict whether a crack of a given size would fail under a particular load if a particular material property or fracture toughness were known. Other laws were developed to predict the rate of growth of cracks under cyclic
loading fatigue. With the advent of these tools, it became possible to accept structures containing defects if the sizes of those defects were known. This formed the basis for a new design philosophy called damage tolerant designs. Components having known defects could continue to be used as long as it could be established that those defects would not grow to a critical size that would result in catastrophic failure.

A new challenge was thus presented to the nondestructive testing community. Mere detection of flaws was not enough. One needed to also obtain quantitative information about flaw size to serve as an input to fracture mechanics calculations to predict the remaining life of a component. These needs, which were particularly strong in the defense and nuclear power industries, led to the creation of a number of research programs around the world and the emergence of nondestructive evaluation as a new discipline [1-15].

1.2 Nondestructive Testing and Evaluation

Nondestructive testing (NDT) has been defined as comprising those test methods used to examine an object, material or system without impairing its future usefulness. The term is generally applied to nonmedical investigations of material integrity.

Strictly speaking, this definition of nondestructive testing does include noninvasive medical diagnostics. Ultrasound, X-rays and endoscopes are used for both medical testing and industrial testing. In the 1940s, many members of the American Society for Nondestructive Testing (then the Society for Industrial Radiography) were medical X-ray professionals. Medical nondestructive testing, however, has come to be treated by a body of learning so separate from industrial nondestructive testing that today most physicians never use the word nondestructive.

Nondestructive testing is used to investigate the material integrity of the test object. A number of other technologies, for instance, radio astronomy, voltage and amperage measurement and rheometry (flow measurement), are nondestructive but are not used to evaluate material properties specifically.
Nondestructive testing is concerned in a practical way with the performance of the test piece. How long may the piece be used and when does it need to be checked again? Radar and sonar are classified as nondestructive testing when used to inspect dams, for instance, but not when they are used to chart a river bottom.

The field of nondestructive Testing (NDT) is a very broad, interdisciplinary field that plays a critical role in assuring that structural components and systems perform their function in a reliable and cost effective fashion. NDT technicians and engineers define and implement tests that locate and characterize material conditions and flaws that might otherwise cause planes to crash, reactors to fail, trains to derail, pipelines to burst, and a variety of less visible, but equally troubling events. These tests are performed in a manner that does not affect the future usefulness of the object or material. In other words, NDT allows parts and materials to be inspected and measured without damaging them. Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost effectiveness. Generally speaking, NDT applies to industrial inspections. While technologies are used in NDT that are similar to those used in the medical industry, typically nonliving objects are the subjects of the inspections.

Nondestructive evaluation (NDE) is a term that is often used interchangeably with NDT. However, technically, NDE is used to describe measurements that are more quantitative in nature. For example, a NDE method would not only locate a defect, but it would also be used to measure something about that defect such as its size, shape, and orientation. NDE may be used to determine material properties such as fracture toughness, formability, and other physical characteristics [16-24].

1.3 Purposes of Nondestructive Testing

Since the 1920s, nondestructive testing has developed from a laboratory curiosity to an indispensable tool of production. No longer is visual examination the principal means of determining quality. Nondestructive tests in great variety
are in worldwide use to detect variations in structure, minute changes in surface
finish, the presence of cracks or other physical discontinuities, to measure the
thickness of materials and coatings and to determine other characteristics of
industrial products.

Modern nondestructive tests are used by manufacturers (1) to ensure product
integrity, and in turn, reliability; (2) to avoid failures, prevent accidents and save
human life; (3) to make a profit for the user; (4) to ensure customer satisfaction
and maintain the manufacturer's reputation; (5) to aid in better product design; (6)
to control manufacturing processes; (7) to lower manufacturing costs; (8) to
maintain uniform quality level; and (9) to ensure operational readiness.

(1) Ensuring the integrity and reliability of a product

The user of a fabricated product buys it with every expectation that it will give
trouble-free service for a reasonable period of usefulness. Few of today's
products are expected to deliver decades of service but they are required to give
reasonable unfailing value. Year by year the public has learned to expect better
service and longer life, despite the increasing complexity of our everyday
electrical and mechanical appliances.

Today the railroads, automobiles, buses, aircraft and ships carry people to
more places faster than ever before. And people expect to get there without
delays due to mechanical failure. Meanwhile factories turn out more products,
better, faster and with more automatic machinery. Management expects
machinery to operate continuously because profits depend on such sustained
output. The complexity of present-day products and the machinery which makes
and transports them requires greater reliability from every component.

(2) Preventing accidents and saving lives

Ensuring product reliability is necessary because of the general increase in
performance expectancy of the public. A homeowner expects the refrigerator to
remain in uninterrupted service, indefinitely protecting the food investment, or
the power lawnmower to start with one pull of the rope and to keep cutting grass
for years on end. The manufacturer expects the lathe, punch press or fork lift to
stand up for years of continuous work even under severe loads.

But reliability merely for convenience and profit is not enough. Reliability to
protect human lives is a valuable end in itself. The railroad axle must not fail at high speed. The front spindle of the intercity bus must not break on the curve. The aircraft landing gear must not collapse on touchdown. The mine hoist cable must not snap with people in the cab. Such critical failures are rare indeed. And this is most certainly not the result of mere good luck. In large part it is the direct result of the extensive use of nondestructive testing and of the high order of nondestructive testing ability now available.

(3) Ensuring customer satisfaction

While it is true that the most laudable reason for the use of nondestructive tests is that of safety, it is probably also true that the most common reason is that of making a profit for the user. The sources of this profit are both tangible and intangible.

The intangible source of profit is ensured customer satisfaction. Its corollary is the preservation and improvement of the manufacturer's reputation. To this obvious advantage may be added that of maintaining the manufacturer's competitive position. It is generally true that the user sets the quality level. It is set in the market place when choosing among the products of several competing manufacturers. Certainly the manufacturer's reputation for high quality is only one factor. Others may be function, appearance, packaging, service and price. But in today's highly competitive markets, actual quality and reputation for quality stand high in the consumer's mind.

(4) Aiding in product design

Nondestructive testing aids significantly in better product design. For example, the state of physical soundness as revealed by such nondestructive tests as radiography, magnetic particle or penetrant testing of a pilot run of castings often shows the designer that design changes are needed to produce a sounder casting in an important section. The design may then be improved and the pattern modified to increase the quality of the product. This example is not academic; it occurs almost daily in manufacturing plants the world over.

Somewhat outside the scope of discontinuity detection are nondestructive tests to determine the direction, amount and gradient of stresses in mechanical parts, as applied in the field of experimental stress analysis. These play a very
important part in the design of lighter, stronger, less costly and more reliable parts.

(5) Controlling manufacturing processes

Control is a basic concept in industry. Engineers, inspectors, operators and production personnel know the problems of keeping any manufacturing process under control. The process must be controlled, and the operator must be trained and supervised. When any element of a manufacturing operation gets out of control, quality of the affected product is compromised and waste may be produced.

Almost every nondestructive testing method is applied in one way or another to assist in process control and so ensure a direct profit for the manufacturer. As one example of thousands which could be cited, consider a heat treating operation. The metallurgist sets up a procedure based on sound material of a given analysis. One nondestructive test, applied to all parts or to a few from each batch of parts, tells whether the chemical analysis of the material is so erratic that the procedure will fail to produce the desired hardness or induce cracking. A second test may show when and where cracking has occurred. Another test may show that the desired hardness has not been developed. If so, process variables may be corrected immediately. In these ways, cost and processing time are saved for the manufacturer.

(6) Lowering manufacturing costs

There are many other examples of both actual and potential cost savings possible through the use of nondestructive tests. Most manufacturers could cut manufacturing costs by deciding where to apply the following cost reduction principle: a nondestructive test can reduce manufacturing cost when it locates undesirable characteristics of a material or component at an early stage, thus eliminating costs of further processing or assembly. An example of this principle is the testing of forging blanks before the forging operation. The presence of seams, large inclusions or cracks in the blanks may result in a woefully defective product. Using such a blank would waste all the labor and forge hammer time involved in forming the material into the product.

Another profit making principle is that a nondestructive test may save
manufacturing cost when it produces desirable information at lower cost than some other destructive or nondestructive tests. An example of this principle is the substitution of a magnetic particle test for acid pickling to detect seams or cracks. As it has in many plants, a straightforward economic study of comparative costs of the two methods may show the cost saving advantage of the nondestructive test over the pickling examination.

(7) Maintaining uniform quality level

Improved product quality should be an aim of and a result of nondestructive testing. Yet this is not always the case, for there is such a thing as too high a quality level. The true function of testing is to control and maintain the quality level that engineers or design engineers establish for the particular product and circumstances.

Quality conscious engineers and manufacturers have long recognized that perfection is unattainable and that even the attempt to achieve perfection in production is unrealistic and costly. Sound management seeks not perfection but pursues excellence in management of workmanship from order entry to product delivery. The desired quality level is the one which is most worthwhile, all things considered. Quality below the specified requirement can ruin sales and reputation. Quality above the specified requirement can swallow up profits through excessive production and scrap losses. Management must decide what quality level it wants to produce and support. Once the quality level has been established, production and testing personnel should aim to maintain this level and not to depart from it excessively either toward lower or higher quality.

In blunt language, a nondestructive test does not improve quality. It can help to establish the quality level but only management sets the quality standard. If management wants to make a nearly perfect product or wants at the other extreme to make junk, then nondestructive tests will help make what is wanted, no more and no less. In preparing a drawing for a part, the designer sets tolerances on dimension and finish. If a drawing specifies a certain dimension as 32 mm (1.25 in.) but fails to specify the tolerance, the machine shop supervisor rejects the drawing as incomplete or assumes the standard tolerance. In nondestructive testing, a quality tolerance (the tolerance on the characteristic
being tested) or criteria for acceptance or rejection must also be specified.

1.4 Nondestructive Testing Methods

The number of NDT methods that can be used to inspect components and make measurements is large and continues to grow. Researchers continue to find new ways of applying physics and other scientific disciplines to develop better NDT methods. However, there are six NDT methods that are used most often. These methods are visual inspection, penetrant testing, magnetic particle testing, electromagnetic or eddy current testing, radiography, and ultrasonic testing. These methods and a few others are briefly described below.

(1) Visual and optical testing (VT)

Visual inspection involves using an inspector eye to look for defects. The inspector may also use special tools such as magnifying glasses, mirrors, or borescopes to gain access and more closely inspect the subject area. Visual examiners follow procedures that range from simple to very complex. [25-27]

(2) Penetrant testing (PT)

Test objects are coated with visible or fluorescent dye solution. Excess dye is then removed from the surface, and a developer is applied. The developer acts as blotter, drawing trapped penetrant out of imperfections open to the surface. With visible dyes, vivid color contrasts between the penetrant and developer make bleedout easy to see. With fluorescent dyes, ultraviolet light is used to make the bleedout fluoresce brightly, thus allowing imperfections to be readily seen. [28]

(3) Magnetic particle testing (MT)

This NDE method is accomplished by inducing a magnetic field in a ferromagnetic material and then dusting the surface with iron particles (either dry or suspended in liquid). Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections, previewing a visual indication of the flaw. [29]

(4) Electromagnetic testing (ET) or eddy current testing (ECT)

Electrical currents are generated in a conductive material by an induced alternating magnetic field. The electrical currents are called eddy currents
because they flow in circles at and just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the conductive and permeability properties of material, can be detected with the proper equipment. [5, 14, 30]

(5) Radiography (RT)

Radiography involves the use of penetrating gamma or X-radiation to examine parts and products for imperfections. An X-ray generator or radioactive isotope is used as a source of radiation. Radiation is directed through a part and onto film or other imaging media. The resulting shadowgraph shows the dimensional features of the part. Possible imperfections are indicated as density changes on the film in the same manner as a medical X-ray to show broken bones. [31-36]

(6) Ultrasonic testing (UT)

Ultrasonics use transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces. [37-47]

(7) Acoustic emission testing (AE)

When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." As in ultrasonic testing, acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity, rate, and location. [48-52]

(8) Leak testing (LT)

Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas penetrant techniques, and a simple soap-bubble test. [53-55]
1.5 Eddy Current Testing

1.5.1 Introduction of Eddy Current Testing

Eddy current inspection is one of several NDT methods that use the principal of electromagnetism as the basis for conducting examinations. Several other methods such as remote field testing, flux leakage and Barkhausen noise also use this principle.

Eddy currents are created through a process called electromagnetic induction. When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor. This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in a circular path. They get their name from eddies that are formed when a liquid or gas flows in a circular path around obstacles when conditions are right.

The variety of inspections and measurements can be performed by eddy current testing as an NDT tool. In the proper circumstances, eddy currents can be used for: crack detection, material thickness measurements, coating thickness measurements, conductivity measurements.

Some of the advantages of eddy current inspection include:

1. Sensitive to small cracks and other defects.
2. Detects surface and near surface defects.
3. Inspection gives immediate results.
4. Equipment is very portable
5. Method can be used for much more than flaw detection
6. Minimum part preparation is required
7. Test probe does not need to contact the part
8. Inspects complex shapes and sizes of conductive materials.

There are still some of the limitations of eddy current inspection including:

1. Only conductive materials can be inspected.
(2) Surface must be accessible to the probe.
(3) Skill and training required is more extensive than other techniques.
(4) Surface finish and roughness may interfere.
(5) Reference standards needed for setup.
(6) Depth of penetration is limited.
(7) Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable.

1.5.2 Present State of Eddy Current Testing

Eddy current testing is used in a variety of industries to find defects and make measurements. One of the primary uses of eddy current testing is for defect detection when the nature of the defect is well understood. In general, the technique is used to inspect a relatively small area and the probe design and test parameters must be established with a good understanding of the flaw that is to be detected. Since eddy currents tend to concentrate at the surface of a material, they can only be used to detect surface and near surface defects.

In thin materials such as tubing and sheet stock, eddy currents can be used to measure the thickness of the material. This makes eddy current a useful tool for detecting corrosion damage and other damage that causes a thinning of the material. The technique is used to make corrosion thinning measurements on aircraft skins and in the walls of tubing used in assemblies such as heat exchangers. Eddy current testing is also used to measure the thickness of paints and other coatings.

Eddy currents are also affected by the electrical conductivity and magnetic permeability of materials. Therefore, eddy current measurements can be used to sort materials and to tell if a material has seen high temperatures or been heat treated, which changes the conductivity of some materials.

Eddy current equipment and probes can be purchased in a wide variety of configurations. Eddy scopes and a conductivity tester come packaged in very small and battery operated units for easy portability. Computer based systems are also available that provide easy data manipulation features for the laboratory.
Signal processing software has also been developed for trend removal, background subtraction, and noise reduction. Impedance analyzers are also sometimes used to allow improved quantitative eddy-current measurements. Some laboratories have multidimensional scanning capabilities that are used to produce images of the scan regions. A few portable scanning systems also exist for special applications, such as scanning regions of aircraft fuselages.

A great deal of research continues to be done to improve eddy current measurement techniques. A few of these activities, which are being conducted at Iowa State University are described below.

(1) Photoinductive imaging (PI)

A technique known as photoinductive imaging was pioneered at CNDE and provides a powerful, high-resolution scanning and imaging tool [56]. Microscopic resolution is available using standard-sized eddy-current sensors. Development of probes and instrumentation for photoinductive imaging is based on the use of a medium-power argon ion laser. This probe provides high resolution images and has been used to study cracks, welds, and diffusion bonds in metallic specimens. The photoinductive imaging technique is being studied as a way to image local stress variations in steel.

(2) Pulsed eddy current (PEC)

Research is currently being conducted on the use of a technique called pulsed eddy current testing. This technique can be used for the detection and quantification of corrosion and cracking in multi-layer aluminium aircraft structures. Pulsed eddy-current signals consist of a spectrum of frequencies meaning that, because of the skin effect, each pulse signal contains information from a range of depths within a given test specimen. In addition, the pulse signals are very low-frequency rich which provides excellent depth penetration. Unlike multi-frequency approaches, the pulse-signals lend themselves to convenient analysis. [57-67]

Measurements have been carried out both in the laboratory and in the field. Corrosion trials have demonstrated how material loss can be detected and quantified in multi-layer aluminium structures. More recently, studies carried out on three and four layer structures show the ability to locate cracks emerging from
fasteners. Pulsed eddy-current measurements have also been applied to ferromagnetic materials. Recent work has been involved with measuring the case depth in hardened steel samples.

1.6 Organization of the Thesis

In chapter 1, the author briefly introduces the background of non-destructive testing and evaluation. Nondestructive testing is employed to examine an object, material or system without impairing its future usefulness. Then the author briefly presents the purposes of nondestructive testing and the six non-destructive testing methods that are used most often. Particularly the eddy current testing as an important non-destructive testing method is introduced. The advantages and limitations of eddy current testing are discussed. Finally the author presents the present state of eddy current testing.

In chapter 2, firstly the author presents several basic laws of electromagnetic. Then the phenomenon of induction, inductance and principle of eddy current testing are discussed. The author analyses the equivalent circuit of eddy current testing, and discusses the equivalent impedance and the fact quality. The author also presents the lift-off and standard depth of penetration of eddy current testing. The eddy current testing probe is introduced, and the operation modes and configurations of probe are presented. Finally the author introduces the scanning system of eddy current testing.

In chapter 3, firstly the author proposes a new planar coil called uneven step distributing coil. The basic principle of crack position detection by using the uneven step distributing coil is discussed. Then a new ECT probe composed of double uneven step distributing coils is proposed and the probe terminal and the multi-layer configuration are presented. The author introduces the measuring system of experiment for crack detection by using the new probe. The evaluation of crack position is established and the error estimation of crack position detection is studied. The content in chapter 3 has been published in IEEJ Transactions on Sensors and Micromachines ([1] in journal papers) and IEEE International Conference on Industrial Technology 2008 ([1] in international
In chapter 4, the author does further research on the new ECT probe composed of double uneven distributing coils. Based on the multifunctional sensing technology, the ECT probe can be employed to detect crack position and width simultaneously. Then the non-destructive evaluation of the multifunctional ECT probe is studied. Also the error estimation of crack position and width is studied. The content in chapter 4 has been submitted to SICE Journal of Control, Measurement, and System Integration ([2] in journal papers).

In chapter 5, the author presents the conclusions and discussions of the research on the new ECT probe for crack detection. Finally represents the recommendation for further work.
2 Eddy Current Testing

2.1 The Physics of Eddy Current

2.1.1 Basic Laws of Electromagnetics

Ohm's law is the most important, basic law of electricity. It defines the relationship between the three fundamental electrical quantities: current, voltage, and resistance. When a voltage $U$ is applied to a circuit containing only resistive elements, the current $I$ flows according to Ohm's Law as shown in Fig. 2.1.

\[ I = \frac{U}{R} \]  

Fig. 2.1 Circuit containing only resistive elements

Where:
- $I$: electrical current (A)
- $U$: voltage (V)
- $R$: resistance ($\Omega$)

Ohm's law states that the electrical current $I$ flowing in a circuit is proportional to the voltage $U$ and inversely proportional to the resistance $R$. Therefore, if the voltage is increased, the current will increase provided the resistance of the circuit does not change. Similarly, increasing the resistance of the circuit will
lower the current flow if the voltage is not changed. The formula can be reorganized so that the relationship can easily be seen for all of the three variables.

Magnetic flux is a measure of quantity of magnetism, taking into account the strength and the extent of a magnetic field. The magnetic flux $\Phi$ through a surface is proportional to the number of magnetic field lines that pass through the surface.

$$d\Phi = B \cdot dS$$ \hspace{1cm} (2.2)

where:
$\Phi$: magnetic flux
$B$: magnetic field
$S$: surface

The Biot-Savart Law that is an equation in electromagnetism that describes the magnetic field $B$ generated by an electric current. The vector field $B$ depends on the magnitude, direction, length, and proximity of the electric current, and also on a fundamental constant called the magnetic constant. Here the symbols in boldface denote vector quantities.

$$dB = \frac{\mu_0}{4\pi} \frac{Idl \times \hat{r}}{r^2}$$ \hspace{1cm} (2.3)

Where:
$\mu_0$: the magnetic permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$ N·A$^{-2}$;
$I$: current;
$dB$: the differential contribution to the magnetic field resulting from this differential element of wire;
$dl$: a vector whose magnitude is the length of the differential element of the wire and whose direction is the direction of conventional current;
\( \hat{r} \): the displacement unit vector in the direction pointing from the wire element towards the point at which the field is being computed;
\( r \): the distance from the wire element to the point at which the field is being computed.

### 2.1.2 Induction and Inductance

In 1824, Oersted discovered that current passing through a coil created a magnetic field capable of shifting a compass needle. Seven years later, Faraday and Henry discovered just the opposite. They noticed that a moving magnetic field would induce current in an electrical conductor. This process of generating electrical current in a conductor by placing the conductor in a changing magnetic field is called electromagnetic induction or just induction. It is called induction because the current is said to be induced in the conductor by the magnetic field.

Faraday also noticed that the rate at which the magnetic field changed also had an effect on the amount of current or voltage that was induced. Faraday's Law for an uncoiled conductor states that the amount of induced voltage is proportional to the rate of change of flux lines cutting the conductor. Faraday's Law for a straight wire is shown below.

\[
\varepsilon = \frac{d\Phi}{dt}
\]

(2.4)

Where:
\( \varepsilon \): induced voltage in volts (V)
\( \frac{d\Phi}{dt} \): rate of change of magnetic flux (W/s)

Soon after Faraday proposed his law of induction, Heinrich Lenz developed a rule for determining the direction of the induced current in a loop. Basically, Lenz's law states that an induced current has a direction such that its magnetic field opposes the change in magnetic field that induced the current. This means that the current induced in a conductor will oppose the change in current that is
causing the flux to change. Lenz's law is important in understanding the property of inductive reactance, which is one of the properties measured in eddy current testing.

\[ \varepsilon = -\frac{d\Phi}{dt} \quad (2.5) \]

Induction is measured in unit of Henry (H) which reflects this dependence on the rate of change of the magnetic field. One Henry is the amount of inductance that is required to generate one volt of induced voltage when the current is changing at the rate of one ampere per second. Note that current is used in the definition rather than magnetic field. This is because current can be used to generate the magnetic field and is easier to measure and control than magnetic flux.

When induction occurs in an electrical circuit and affects the flow of electricity it is called inductance expressed as \( L \). Self-inductance or simply inductance is the property of a circuit whereby a change in current causes a change in voltage in the same circuit. When one circuit induces current flow in a second nearby circuit, it is known as mutual inductance expressed as \( M \). When an alternating current is flowing through a piece of wire in a circuit, an electromagnetic field is produced that is constantly growing, shrinking and changing direction due to the constantly changing current in the wire. This changing magnetic field will induce electrical current in another wire or circuit that is brought close to the wire in the primary circuit. The current in the second wire will also be alternating current and in fact will be similar to the current flowing in the first wire. An electrical transformer uses inductance to change the voltage of electricity into a more useful level. In nondestructive testing, inductance is used to generate eddy currents in the test piece.

It should be noted that since it is the changing magnetic field that is responsible for inductance, it is only present in alternating current circuits. High frequency alternating current will result in greater inductive reactance since the magnetic field is changing more rapidly.
2.1.3 Self Inductance and Inductive Reactance

The property of self-inductance is a particular form of electromagnetic induction. Self inductance is defined as the induction of a voltage in a current-carrying wire when the current in the wire itself is changing. In the case of self inductance, the magnetic field created by a changing current in the circuit itself induces a voltage in the same circuit. Therefore the voltage is self-induced.

The term inductor is used to describe a circuit element possessing the property of inductance and a coil of wire is a very common inductor. In circuit diagrams, a coil or wire is usually used to indicate an inductive component. Taking a closer look at a coil will help understand the reason that a voltage is induced in a wire carrying a changing current. The alternating current running through the coil creates a magnetic field in and around the coil that is increasing and decreasing as the current changes. The magnetic field forms concentric loops that surround the wire and join to form larger loops that surround the coil as shown in the image below. When the current increases in one loop, the expanding magnetic field will cut across some or all of the neighboring loops of wire, which will induce a voltage in these loops. This causes a voltage to be induced in the coil when the current is changing.

![Magnetic flux generated by coil with turns](image)

Fig. 2.2 Magnetic flux generated by coil with turns
By studying Fig. 2.2 of a coil, it can be seen that the number of turns in the coil will have an effect on the amount of voltage that is induced into the circuit. The increase of the number of turns or the rate of change of magnetic flux will result in increasing the amount of induced voltage. Therefore, Faraday’s Law must be modified for a coil of wire and becomes equation (2.6).

$$\varepsilon = -N \frac{d\Phi}{dt} \quad (2.6)$$

Where:

$\varepsilon$: induced voltage in volts (V)
$N$: number of turns in the coil
$\frac{d\Phi}{dt}$: rate of change of magnetic flux (W/s)

The equation simply states that the amount of induced voltage ($\varepsilon$) is proportional to the number of turns in the coil and the rate of change of the magnetic flux ($d\Phi/dt$). In other words, when the frequency of the flux is increased or the number of turns in the coil is increased, the amount of induced voltage will also increase.

The magnetic flux linkage $\Psi$ is a property of a coil of conducting wire and the magnetic field through which it passes. It is determined by the number of turns of said coil and the flux of the magnetic field defined in equation (2.7).

$$\Psi = N\Phi \quad (2.7)$$

Then equation (2.8) is obtained from equations (2.6) and (2.7).

$$\varepsilon = -\frac{d\Psi}{dt} \quad (2.8)$$

In a circuit, it is much easier to measure current than to measure magnetic flux,
so we need to find the relation between the induced voltage $\varepsilon$ and the exciting current $I$. According to the Biot-Savart Law, the magnetic field $B$ generated by current $I$ is proportion to the current $I$. Also the magnetic flux $\Phi$ is proportion to the magnetic field $B$. So the magnetic flux linkage $\Psi$ is proportion to the current $I$.

$$\Psi = L \cdot I \quad (2.9)$$

From equations (2.8) and (2.9), we obtain equation (2.10) which can be used to determine the induced voltage if the inductance and the current frequency are known. Also it can be reorganized to calculate inductance when the induced voltage and the current frequency are known.

$$\varepsilon = -L \frac{dI}{dt} \quad (2.10)$$

Where:
- $\varepsilon$: induced voltage (V)
- $L$: value of inductance (H)
- $dI/dt$: rate of change of current (A/s)

The reduction of current flow in a circuit due to induction is called inductive reactance. By taking a closer look at a coil of wire and applying Lenz's law, it can be seen how inductance reduces the flow of current in the circuit. In the image below, the direction of the primary current is shown in red, and the magnetic field generated by the current is shown in blue. The direction of the magnetic field can be determined by taking your right hand and pointing your thumb in the direction of the current. Your fingers will then point in the direction of the magnetic field. It can be seen that the magnetic field from one loop of the wire will cut across the other loops in the coil and this will induce current flow (shown in green) in the circuit. According to Lenz's law, the induced current must flow in the opposite direction of the primary current. The induced current working against the primary current results in a reduction of current flow in the

-21-
circuit.

It should be noted that the inductive reactance will increase if the number of winds in the coil is increased since the magnetic field from one coil will have more coils to interact with.

![Diagram of induced current](image)

**Fig. 2.3 Schematic illustration of induced Current**

Since inductive reactance reduces the flow of current in a circuit, it appears as an energy loss just like resistance. However, it is possible to distinguish between resistance and inductive reactance in a circuit by looking at the timing between the sine waves of the voltage and current of the alternating current. In an AC circuit that contains only resistive components, the voltage and the current will be in phase, meaning that the peaks and valleys of their sine waves will occur at the same time. When there is inductive reactance present in the circuit, the phase of the current will be shifted so that its peaks and valleys do not occur at the same time as those of the voltage.
2.1.4 Mutual Inductance

The magnetic flux through a circuit can be related to the current in that circuit and the currents in other nearby circuits as shown in Fig. 2.4.

![Fig. 2.4 Mutual inductance between two circuits](image)

The magnetic field produced by circuit 1 will intersect the wire in circuit 2 and create current flow. The induced current flow in circuit 2 will have its own magnetic field which will interact with the magnetic field of circuit 1. At some point between the two circuits the magnetic field consists of a part due to \( I_1 \) and a part due to \( I_2 \). These fields are proportional to the currents producing them.

The two self inductances of the two coils are represented as \( L_1 \) and \( L_2 \), respectively. The values of \( L_1 \) and \( L_2 \) depend on the geometrical arrangement of coil and the conductivity of the material. The mutual inductance of the two circuits expressed as \( M \) is dependent on the geometrical arrangement of both circuits. In particular, if the circuits are far apart, the magnetic flux linkage through circuit 2 due to the current \( I_1 \) will be small and then the mutual inductance will be small.

We can calculate the magnetic flux linkage \( \Psi_1 \) through circuit 1 and the magnetic flux linkage \( \Psi_2 \) through circuit 2 as the sum of two parts.
\[ \psi_1 = L_1 I_1 + M_{21} I_2 \]  \hspace{1cm} (2.11)

\[ \psi_2 = L_2 I_2 + M_{12} I_1 \]  \hspace{1cm} (2.12)

Though it is certainly not obvious, it can be known that the mutual inductance is the same for both circuits.

\[ M_{12} = M_{21} \]  \hspace{1cm} (2.13)

In eddy current inspection, the eddy currents are generated in the test material due to mutual induction. The test probe is basically a coil of wire through which alternating current is passed. Therefore in test the probe is basically represented by circuit 1, and the circuit 2 can be any piece of conductive material.

### 2.2 Equivalent Circuit of Eddy Current Testing

When alternating current is passed through the coil, a magnetic field is generated in and around the coil. When the probe is brought in close proximity to a conductive material, such as aluminum, the probe's changing magnetic field generates current flow in the material. The induced eddy currents flow in closed loops in planes perpendicular to the magnetic flux.

The eddy currents produce their own magnetic fields that interact with the primary magnetic field of the coil. By measuring changes in the resistance and inductive reactance of the coil, information can be gathered about the test material. This information includes the electrical conductivity and magnetic permeability of the material, the amount of material cutting through the coils magnetic field, and the condition of the material, such as whether it contains cracks or other defects.

The equivalent circuit of ECT probe is obtained by circuit analysis as shown in
Fig. 2.5. The primary circuit is the ECT probe circuit flowed with exciting alternating current. The secondary circuit is the eddy current loop circuit induced in test material. Based on the Kirchho’s voltage laws, we will obtain two equations of the two loop circuits shown in equations (2.8) and (2.9), respectively. [68-69]

\[ R_0 I + j2\pi frL_0 I - j2\pi fMI_e = U \]  
(2.14)

\[ R_e I_e + j2\pi frL_e I_e - j2\pi fMI = 0 \]  
(2.15)

Where \( R_0, L_0 \) is the original resistance and inductance of coil of ECT probe, respectively; \( R_e, L_e \) is the equivalent resistance and inductance of the eddy current loop in test surface, respectively. \( U \) is the alternating excitation voltage of ECT probe; \( I \) is the alternating current in coil of ECT probe and \( I_e \) is in induced eddy current in test surface. \( M \) is the mutual inductance between the coil of ECT probe and the eddy current loop. Where \( \omega=2\pi f \) is the angular frequency, and \( f \) is the excitation frequency of ECT probe.

The original impedance of coil \( Z_0 \) is shown in equation (2.16). To substitute the
eddy current $I_e$ in equation (2.15) for that in equation (2.14), we can get the equivalent impedance $Z_{eq}$ of ECT probe loaded with eddy current circuit shown in equation (2.17).

$$Z_0 = R_0 + j\omega L_0 \quad (2.16)$$

$$Z_{eq} = \frac{U}{I_{eq}} = \frac{U}{R_0 + j\omega L_0 + \frac{\omega^2 M^2}{R_e + j\omega L_e}} = \frac{Z_0 + \frac{\omega^2 M^2}{R_e + j\omega L_e}}{\omega} \quad (2.17)$$

By simplifying equation (2.17), the equivalent impedance $Z_{eq}$ can be expressed as a complex number in two dimensions shown in equation (2.18).

$$Z_{eq} = \frac{U}{I_{eq}} = \left( R_0 + \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2} R_e \right) + j\omega \left( L_0 - \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2} L_e \right) \quad (2.18)$$

The equivalent impedance $Z_{eq}$ contains two parts: the real part of the complex number is the equivalent resistance expressed as $R_{eq}$, and the imaginary part of the complex number is the equivalent inductance expressed as $L_{eq}$ in equations (2.19) and (2.20), respectively. Then the equivalent impedance $Z_{eq}$ can be expressed as equation (2.21) and its module is calculated in equation (2.22).

$$R_{eq} = R_0 + \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2} R_e \quad (2.19)$$

$$L_{eq} = L_0 - \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2} L_e \quad (2.20)$$

$$Z_{eq} = R_{eq} + j\omega L_{eq} \quad (2.21)$$

$$|Z_{eq}|^2 = R_{eq}^2 + (\omega L_{eq})^2 \quad (2.22)$$

Because induced eddy currents generate calories and exhausts energy, the induced eddy current results in that the real part of impedance of ECT probe increases and the image part decreases. It means that the equivalent resistance $R_e$
gets greater than the original resistance $R_0$ of coil, and the equivalent inductance $L_e$ gets less than the original inductance $L_0$ of coil.

According to (2.19) and (2.20), we obtain the quality factor $Q$ with the affect of induced eddy current shown in equation (2.23). The quality factor of coil without the affect of induced eddy current is $Q_0$ in equation (2.24). It can be seen that the quality factor $Q$ decreases because of the effect of eddy currents.

$$Q = \frac{\omega L_e}{R_e} = \omega \cdot \frac{L_0 - L_e \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2}}{R_0 + R_e \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2}} = Q_0 \cdot \frac{1 - \frac{L_e}{L_0} \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2}}{1 + \frac{R_e}{R_0} \frac{\omega^2 M^2}{R_e^2 + \omega^2 L_e^2}} \quad (2.23)$$

$$Q_0 = \frac{\omega L_0}{R_0} \quad (2.24)$$

We define the inductance coupling coefficient $K$ in equation (2.25). The equivalent impedance $Z_{eq}$ can be expressed as equation (2.26) to substitute equation (2.25) for the mutual inductance $M$ in equation (2.18).

$$K = \frac{M}{\sqrt{L_0 \cdot L_e}} \quad (2.25)$$

$$Z_{eq} = R_0 + \frac{R_e \frac{L_0}{L_e} \cdot K^2}{1 + \left(\frac{R_e}{\omega L_e}\right)^2} + j\omega L_0 \left[1 - \frac{K^2}{1 + \left(\frac{R_e}{\omega L_e}\right)^2}\right] \quad (2.26)$$

When the excitation frequency $f$ is high frequency, there is an approximation shown in equation (2.27). Then the equivalent impedance expression (2.26) can be simplified to be equation (2.28). Then the equivalent inductance $L_{eq}$ is simplified shown in equation (2.29).

$$R_e \ll \omega L_e \quad (2.27)$$
From equation (2.29) we see that the equivalent inductance $L_{eq}$ is not dependent on the electrical resistivity of test metallic plate and only dependent on the coupling coefficient $K$. So when the coupling coefficient $K$ varies, the equivalent inductance $L_{eq}$ will vary with it. In my study, based on this principle we propose a new multifunctional ECT probe composed of double uneven distributing coils, and it can detect crack location and width in static test mode. In crack detection by employing the proposed ECT probe the coupling coefficient $K$ varies with crack position and width. Then according to the two output equivalent inductances, the crack position and width can be evaluated.

### 2.3 Current Density and Standard Depth of Penetration

Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux. They normally travel parallel to the coil's winding and flow is limited to the area of the inducing magnetic field. Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil as shown in the image. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect.

The skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases. Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field, thereby weakening the magnetic field at greater depths and reducing induced currents.

The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current and the electrical conductivity and magnetic permeability of the specimen as shown in equation (2.30). The depth of
penetration decreases with increasing frequency and increasing conductivity and magnetic permeability. The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called the standard depth of penetration [70]. The word 'standard' denotes plane wave electromagnetic field excitation within the test sample (conditions which are rarely achieved in practice). Although eddy currents penetrate deeper than one standard depth of penetration, they decrease rapidly with depth. At two standard depths of penetration, the eddy current density has decreased to 1/e squared or 13.5% of the surface density. At three depths, the eddy current density is down to only 5% of the surface density.

\[
\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu \cdot \sigma}} \tag{2.30}
\]

Where:
- \(\delta\): standard depth of penetration (m)
- \(\pi\): 3.14
- \(f\): test frequency (Hz)
- \(\mu\): magnetic permeability (H/m)
- \(\sigma\): electrical conductivity (S/m)

![Eddy Current Depth of Penetration](image)

Fig. 2.6 Eddy current depth of penetration
Since the sensitivity of an eddy current inspection depends on the eddy current density at the defect location, it is important to know the strength of the eddy currents at this location. When attempting to locate flaws, a frequency is often selected which places the expected flaw depth within one standard depth of penetration. This helps to assure that the strength of the eddy currents will be sufficient to produce a flaw indication. Alternately, when using eddy currents to measure the electrical conductivity of a material, the frequency is often set so that it produces three standard depths of penetration within the material. This helps to assure that the eddy currents will be so weak at the back side of the material that changes in the material thickness will not affect the eddy current measurements.

2.4 Probes

2.4.1 Operation Mode of Probe

Eddy current probes are available in a large variety of shapes and sizes. In fact, one of the major advantages of eddy current inspection is that probes can be custom designed for a wide variety of applications. Eddy current probes are classified by the configuration and mode of operation of the test coils. The configuration of the probe generally refers to the way the coil or coils are packaged to best "couple" to the test area of interest. An example of different configurations of probes would be bobbin probes, which are inserted into a piece of pipe to inspect from the inside out, versus encircling probes, in which the coil or coils encircle the pipe to inspect from the outside in. The mode of operation refers to the way the coil or coils are wired and interface with the test equipment. The mode of operation of a probe generally falls into one of four categories: absolute, differential, reflection and hybrid. Each of these classifications will be discussed in more detail below.

(1) Absolute Probes

Absolute probes generally have a single test coil that is used to generate the eddy currents and sense changes in the eddy current field. As discussed in the
physics section, AC is passed through the coil and sets up an expanding and collapsing magnetic field in and around the coil. When the probe is positioned next to a conductive material, the changing magnetic field generates eddy currents within the material. The generation of the eddy currents take energy from the coil and this appears as an increase in the electrical resistance of the coil. The eddy currents generate their own magnetic field that opposes the magnetic field of the coil and this changes the inductive reactance of the coil. By measuring the absolute change in impedance of the test coil, much information can be gained about the test material.

![Coil Diagram]

**Fig. 2.7 Absolute mode probe**

Absolute coils can be used for flaw detection, conductivity measurements, liftoff measurements and thickness measurements. They are widely used due to their versatility. Since absolute probes are sensitive to things such as conductivity, permeability lift-off and temperature, steps must be taken to minimize these variables when they are not important to the inspection being performed. It is very common for commercially available absolute probes to have a fixed "air loaded" reference coil that compensates for ambient temperature variations.

(2) Differential Probes

Differential probes have two active coils usually wound in opposition, although they could be wound in addition with similar results as shown in Fig. 2.8 [71-72]. When the two coils are over a flaw-free area of test sample, there is no differential signal developed between the coils since they are both inspecting identical material. However, when one coil is over a defect and the other is over good material, a differential signal is produced. They have the advantage of being
very sensitive to defects yet relatively insensitive to slowly varying properties such as gradual dimensional or temperature variations. Probe wobble signals are also reduced with this probe type. There are also disadvantages to using differential probes. Most notably, the signals may be difficult to interpret. For example, if a flaw is longer than the spacing between the two coils, only the leading and trailing edges will be detected due to signal cancellation when both coils sense the flaw equally.

![Differential mode probe](image)

**Fig. 2.8** Differential mode probe

(3) Reflection Probes

Reflection probes have two coils similar to a differential probe, but one coil is used to excite the eddy currents and the other is used to sense changes in the test material [73-75]. Probes of this arrangement are often referred to as driver–pickup probes. The advantage of reflection probes is that the driver and pickup coils can be separately optimized for their intended purpose. The driver coil can be made so as to produce a strong and uniform flux field in the vicinity of the pickup coil, while the pickup coil can be made very small so that it will be sensitive to very small defects.
(4) Hybrid Probes

An example of a hybrid probe is the split D, differential probe shown to the right. This probe has a driver coil that surrounds two D shape sensing coils. It operates in the reflection mode but additionally, its sensing coils operate in the differential mode. This type of probe is very sensitive to surface cracks. Another example of a hybrid probe is one that uses a conventional coil to generate eddy currents in the material but then uses a different type of sensor to detect changes on the surface and within the test material. An example of a hybrid probe is one that uses a Hall effect sensor to detect changes in the magnetic flux leaking from the test surface. Hybrid probes are usually specially designed for a specific inspection application.
(a) Probe composed of a driver coil and two D shape sensing coils

(b) Section view of probe

(c) Driver coil

(d) Two D shape sensing coils

Fig. 2.10 Hybrid probe composed of a driver coil and two D shape sensing coils
2.4.2 Configuration of Probe

As mentioned on the previous page, eddy current probes are classified by the configuration and mode of operation of the test coils. The configuration of the probe generally refers to the way the coil or coils are packaged to best "couple" to the test area of interest. Some of the common classifications of probes based on their configuration include surface probes, bolt hole probes, inside diameter (ID) probes, and outside diameter (OD) probes.

(1) Surface probes

Surface probes are usually designed to be handheld and are intended to be used in contact with the test surface [75-76]. Surface probes generally consist of a coil of very fine wire encased in a protective housing. The size of the coil and shape of the housing are determined by the intended use of the probe. Most of the coils are wound so that the axis of the coil is perpendicular to the test surface. This coil configuration is sometimes referred to as a pancake coil and is good for detecting surface discontinuities that are oriented perpendicular to the test surface. Discontinuities, such as delaminations, that are in a parallel plane to the test surface will likely go undetected with this coil configuration.

![Fig. 2.11 Surface probe](image-url)
Wide surface coils are used when scanning large areas for relatively large defects. They sample a relatively large area and allow for deeper penetration. Since they do sample a large area, they are often used for conductivity tests to get more of a bulk material measurement. However, their large sampling area limits their ability to detect small discontinuities.

Pencil probes have a small surface coil that is encased in a long slender housing to permit inspection in restricted spaces. They are available with a straight shaft or with a bent shaft, which facilitates easier handling and use in applications such as the inspection of small diameter bores. Pencil probes are prone to wobble due to their small base and sleeves are sometimes used to provide a wider base.

(2) Bolt hole probes

Bolt hole probes are a special type of surface probe that is designed to be used with a bolt hole scanner. They have a surface coil that is mounted inside a housing that matches the diameter of the hole being inspected. The probe is inserted in the hole and the scanner rotates the probe within the hole.

(3) Inside diameter or bobbin probes

Inside diameter (ID) probes, which are also referred to as Bobbin probes or feed-through probes, are inserted into hollow products, such as pipes, to inspect from the inside [77-78]. The ID probes have a housing that keeps the probe central in the product and the coil(s) orientation somewhat constant relative to the test surface. The coils are most commonly wound around the circumference of the probe so that the probe inspects an area around the entire circumference of the test object at one time.

![Fig. 2.12 Inside diameter probe](image)
(4) Outside diameter or encircling coils

Outside diameter (OD) probes are often called encircling coils. They are similar to ID probes except that the coils encircle the material to inspect from the outside. OD probes are commonly used to inspect solid products, such as bars.

![Diagram](image)

Fig. 2.13 Outside diameter probe

2.5 Scanning System of Eddy Current Testing

Eddy current data can be collected using automated scanning systems to improve the quality of the measurements and to construct images of scanned areas. The most common type of scanning is line scanning where an automated system is used to push the probe at a fixed speed. Line scan systems are often used when performing tube inspections or aircraft engine blade slot inspections, where scanning in one dimension is needed. The data is usually presented as a strip chart recording. The advantage of using a linear scanning system is that the probe is moved at a constant speed, so indications on the strip chart can be correlated to a position on the part being scanned. As with all automated scanning systems, operator variables, such as wobble of the probe, are reduced.
Two-dimensional scanning systems are used to scan a two-dimensional area [79-80]. This could be a scanning system that scans over a relatively flat area in a X-Y raster mode, or it could be a bolt hole inspection system that rotates the probe as it is moved into the hole. The data is typically displayed as a false-color plot of signal strength or phase angle shift as a function of position, just like an ultrasonic C-scan presentation.

There are some advantages of automated scanning shown in below:

1. Minimizes changes in liftoff or fill factor resulting from probe wobble, uneven surfaces, and eccentricity of tubes caused by faulty manufacture or damage
2. Accurate indexing
3. Repeatability
4. High resolution mapping

### 2.6 Summary

In this chapter, firstly the author presents several basic laws of electromagnetic. Then the electromagnetic induction phenomenon and the principle of eddy current testing are discussed. The self inductance and mutual inductance is studied. The author analyses the equivalent circuit of eddy current testing, and discusses the equivalent impedance and the fact quality. The author also presents the lift-off and standard depth of penetration of eddy current testing. The ECT probe is introduced, and the operation modes and configurations of probe are presented. Finally the author introduces the scanning system of ECT.
3 Eddy Current Testing Probe Composed of Double Uneven Step Distributing Coils for Crack Position Detection

3.1 Introduction

Eddy current testing is one of several non-destructive testing methods that use the principle of electromagnetism as the basis for conducting examinations. Eddy currents are created through a process called electromagnetic induction. When alternating current is applied to the conductor, such as copper wire coil, a magnetic field develops in and around the conductor. If another electrical conductor gets close to this changing magnetic field, current will be induced in this second conductor. The induced currents flow in closed loops in planes perpendicular to the magnetic flux. They are named electrical eddy currents because they are thought to resemble the eddy currents that can be seen swirling in streams. The eddy currents concentrate near the surface adjacent to the excitation coil called the skin effect [81-82].

As a NDT tool the ECT can perform in a variety of inspections and measurements. In the proper circumstances, eddy currents can be used for: crack detection, material thickness measurements, coating thickness measurements, conductivity measurements and so on. The crack detection of metallic structural frames is an important application of ECT. At present the crack position is usually detected by using ECT probe to scan the test metallic surface point by point. Obviously the scanning detection is the dynamic detection that performs a mass of measurement work. So we research a novel ECT probe composed of double uneven step distributing planar coils applied in crack detection. Because of the novel coil structure, the probe can directly and quickly detect crack position in measurable range of test metallic surface beneath probe in non-
scanning detecting mode. This static detection for crack can advance test efficiency and reduce test work greatly compared with traditional dynamic scan detection. Furthermore this ECT probe itself has the resolution for defect position which is expected [83].

Because of these advantages, the novel ECT probe can be used to detect the long defect as crack in wide aircraft fuselages, long railway, and long tubes. Also it can be used to inspect a batch of metallic workpieces. Furthermore the probe can still detect crack in some instances when the ECT probe is fixed or can’t be moved in high resolution.

3.2 Uneven Step Distributing Coil

3.2.1 Prototype of Uneven Step Distributing Coil

The structure of uneven step distributing planar coil is shown in Fig. 3.1. The wire of coil is not wound evenly in all directions of each turn, and there is always a step distance in the same direction. So it is called uneven step distributing coil.

(1) The uneven step distributing coil is a thin and long planar coil of trapezoid shape. It is long along the $x$ axis and short along the perpendicular direction of the $x$ axis.

(2) The uneven step distributing planar coil satisfies reflection symmetry with
respect to the $x$ axis.

(3) The uneven step distributing planar coil is made up of many wire turns with similar shape. Whereas the coil turns are unevenly distributed along the $x$ axis, and the coil turn density decreases along positive direction of the $x$ axis. There is a spacing expressed as $s_1$ between two adjoining turns in positive direction of the $x$ axis. But in negative direction of the $x$ axis there is no spacing between two adjoining turns, where the wire swirls closely in each turn. In each turn there is a same width expressed as $s_2$.

3.2.2 Basic Principle of Crack Position Detection by Using Uneven Step Distributing Coil

When the planar coil is kept away from the test metal, the original inductance of coil is expressed as $L_0$. When the planar coil carrying alternating current detects the test material, the induced eddy currents flow in the material surface. Then the loaded inductance of coil increases and decreases respectively for paramagnetic material and for diamagnetic material. When there is no defect and any defect existing in the material surface beneath coil, the loaded inductances are respectively expressed as $L_{EC}$ and $L_{ECD}$. For diamagnetic material, there is a relation as shown in inequality (3.1).

$$L_{EC} < L_{ECD} < L_0 \quad (3.1)$$

We can see that the maximum coil inductance is the original inductance $L_0$ and the minimum coil inductance is the equivalent inductance $L_{EC}$.

Because of the step distributing structure of coil, the coil turn density decreases along the positive direction of the $x$ axis, and correspondingly the magnetic field intensity $B$ produced by the coil also decreases along the positive direction of the $x$ axis. For a series of positions along the $x$ axis of the uneven step distributing planar coil as shown in Fig. 3.2, the value relation of the magnetic field intensity $B$ is easily known in inequality (3.2).

$$B_{p_3} < B_{p_2} < B_{p_1} \quad (3.2)$$
Fig. 3.2 One crack existing at a series of different positions

When no defect exists in test surface beneath coil, the primary circuit of coil closely couples with the induced loaded circuit of test surface in detection. But when any defect exists, the coupling between two circuits will get loose. The existence of defect influences the eddy current distribution in test surface and the coupling between two circuits.

Obviously when the defect exists at where the primary magnetic field intensity produced by coil is greater, the influence on the coupling between two circuits is greater. For three different crack positions at P1, P2, and P3, the simple value relation about the equivalent inductance of coil can be obtained as shown in inequality (3.3).

\[ L_{P3} < L_{P2} < L_{P1} \]  

(3.3)

Because the uneven step distributing structure of planar coil, the uneven magnetic field intensity produced by coil influences the induced eddy current intensity in test surface. During crack detection the equivalent inductance of coil varies with the crack position beneath it, and reversely the crack position can be estimated according to the loaded inductance.
3.3 Eddy Current Testing Probe Composed of Double Uneven Distributing Coils

The ECT probes are available in a large variety of shapes and sizes. In fact, one of the major advantages of eddy current inspection is that probes can be custom designed for a wide variety of applications. The proper ECT probe should fit the geometry of the testing surface and must produce eddy currents that will be disrupted by crack.

The ECT probes are classified by configuration and operation mode of the test coils. The probe configuration generally refers to the way that the coils are packaged to best couple to the test area of interest. The operation mode refers to the way that the coils are wired and interface with the test equipment. The operation mode of a probe generally falls into one of four categories: absolute, difference, reflection and hybrid.

3.3.1 Prototype of Eddy Current Testing Probe

The prototype of ECT probe terminal is composed of double uneven step distributing planar coils as shown in Fig. 3.3. The double trapezoid shape coils make up of a parallelogram shape probe terminal.

Fig. 3.3 Prototype of ECT probe terminal
First the ECT probe is a surface one based on its configuration. In detecting processing, the ECT planar probe is in contact with the test surface, which is good for detecting surface defects [84-85]. The size of the coil is determined by the intended use of the ECT probe. The probes composed of the wide surface coils are used to test large areas for relatively large defects, and test a bulk material. However, usually the large testing area limits the ability to detect small defects. So the size of the ECT planar probe should be designed properly, and the resolution of the ECT probe for defect should match the size of the defects.

Second the ECT probe is a hybrid one based on its operation mode. The double coils of ECT probe respectively test in the absolute mode, and moreover they both make up of a difference mode probe. As an absolute mode probe, when testing the metal surface, the double uneven step distributing coils both alternately induce eddy currents in the metal surface, and the inductance variations of the double coils are alternately measured. As a difference mode probe, the novel ECT probe is composed of double uneven step distributing planar coils that are not connected together. For the double planar coils, the trends of the inductance variation to crack position are inverse due to the novel structure of probe. So in order to reduce the nonlinear items of the inductance variation, we establish the dependence of difference inductance variation on crack position.

The probe configuration satisfies the rotation symmetry with respect to the centre point O. The rotation symmetry can ensure a good linear dependence of the difference inductance of double coils on the crack position.

3.3.2 Three-layer Configuration of Eddy Current Testing Probe

The ECT probe contains three layers including magnetic layer, coil layer and bottom protection layer as shown in Fig. 3.4.
(1) Magnetic layer
The magnetic layer is made of ferromagnet which can assemble the magnetic field generated by coil and enhance the magnetic field intensity. It also can shield coils from external noise and advance the resolution for defect.

(2) Coil layer
The coil layer is composed of double uneven step distributing planar coils that are both wired in 19 turns by copper wire whose diameter of cross section is $\Phi 0.2\text{mm}$. The lift-off of the coil layer is 1.9mm.

The shape of uneven step distributing planar coil is like a trapezoid whose two bases are 4mm and 16mm and altitude is 100mm. The double trapezoids make up of a parallelogram with two opposite sides that are 20mm long and perpendicular to the $x$ axis. The two distances $s_1$ and $s_2$ shown in Fig. 1 are respectively 5mm and 4mm.

(3) Bottom protection layer
The bottom protection layer is made of plastic material. It can protect the coil layer from touching the test surface directly, and also provide a lift-off distance.

3.4 Experiment of Crack Position Detection

3.4.1 Measurement System of Experiment

The measurement system is carried out to detect crack as shown in Fig. 3.5. We
aim to find the dependence of the crack position on the variation of equivalent inductances of double planar coils. In the experiment we use the split of two aluminum plates to simulate the crack in the surface of aluminum plate. The thickness of aluminum plate is chosen as 1.5mm.

In test the inductance variations of two coils are measured by LCR meter. But the resolution of LCR meter for inductance variation limits the measuring resolution for crack position and width. During detecting surface defects, the drive frequency of ECT probe should be high to get the required high resolution and sensitivity. Here the measure frequency of LCR meter is chosen as 100 kHz.

In order to avoid the coupling of double planar coils in the generated magnetic field, they must alternately work in test. So the LCR meter alternately measures the inductance variations, and it is controlled by a switch as shown in Fig. 3.5.

The crack is set to be perpendicular to the $x$ axis of probe. The center point $O$ of probe is called zero position, and actualy the crack position $x$ is a relative position.
In test the inductance variations of the double planar coils mainly depend on two factors of the crack: the crack position $x$ and the crack width $d$. Therefore when the crack of width $d$ exists at position $x$, the two equivalent inductances are expressed as $L_1(x, d)$ and $L_2(x, d)$. In the experiment six cracks are detected whose widths are 1mm, 2mm, 3mm, 4mm, 5mm and 6mm, respectively. The six cracks locate at a series of positions varying from -30mm to 30mm by step 5mm. Finally there are 78 sets of two equivalent inductances including $L_1(x, d)$ and $L_2(x, d)$ obtained by measurement.

Because the induced eddy currents sharply decrease in the periphery of coil, the crack can only be estimated in a measurable range beneath probe. We define a coefficient expressed as $r$ which is the proportion of the absolute measurable range of crack position to the probe length along the $x$ axis. The experiment data prove that when the crack exists in the range from -30mm to 30mm it can be estimated as shown in Fig. 3.5. Then the absolute measurable range is 60mm and the probe length is 100mm, so the coefficient $r$ is 3:5 for this probe. The coefficient $r$ mainly depends on the structure of probe and reflects the relative measurable range of probe for crack position which is expected to be as great as possible.

### 3.4.2 Experiment Results

The experiment of crack detection presents the results of inductance variations. When the ECT probe is kept away from the aluminum plate, the measured inductances of two coils are respectively $L_{01}=25.4\mu H$ and $L_{02}=25.0\mu H$. When testing the surface, if no crack exists beneath probe, the two measured inductances are respectively $L_{EC1}=15.37\mu H$ and $L_{EC2}=15.33\mu H$; if a crack exists in the testing surface of aluminum plate beneath the ECT probe, the two equivalent inductances are expressed as $L_1$ and $L_2$, respectively. According to inequality (3.1) we know that the value ranges of two inductances are respectively shown in inequalities (3.4) and (3.5).

\[
15.37\mu H < L_1 < 25.4\mu H
\]  

(3.4)
Because the structure of probe terminal satisfies the rotation symmetry, the inductances $L_1(x,d)$ and $L_2(x,d)$ should mutually satisfy a reflection symmetry with respect to $x$ presented in equation (3.6).

\[ L_1(x,d) = L_2(-x,d) \]  

(3.6)

In the experiment we test six cracks with different widths $d$ varying from 1mm to 6mm. So for the six cracks the six curves of the inductance $L_1$ to the crack position $x$ are drawn as shown in Fig. 3.6, and the six curves of the inductance $L_2$ to the crack position $x$ are drawn as shown in Fig. 3.7.

The two figures show that the two inductances $L_1$ and $L_2$ are not in linear dependence on crack position $x$, and the two dependences of inductance $L_1$ to crack position $x$ and inductance $L_2$ to crack position $x$ both approximately satisfy the reflection symmetry shown in equation (3.6).

Fig. 3.6 Curves of inductance $L_1$ to crack position $x$
3.5 Evaluation of Crack Position

In order to estimate the crack position according to the inductance variation, the dependence of inductance variation on crack position should be established. Then the inverse dependence of crack position on inductance variation can be obtained.

The difference inductance of two coils of ECT probe is defined in equation (3.7). From equations (3.6) and (3.7) we can know that the dependence of difference inductance $\Delta L(x,d)$ on crack position $x$ itself satisfies the odd symmetry with respect to crack position $x$. The conclusion in equation (3.8) is an ideal deduction.
Fig. 3.8 Curves of difference inductance $\Delta L$ to crack position $x$

$$\Delta L(x, d) = L_1(x, d) - L_2(x, d)$$ \hfill (3.7)

$$\Delta L(-x, d) = -\Delta L(x, d)$$ \hfill (3.8)

The six curves of difference inductance $\Delta L$ to crack position $x$ are drawn in Fig. 3.8. They are all approximately linear and odd symmetric curves. The experiment results satisfy the ideal deduction shown in equation (3.6).

In order to establish the dependence of difference inductance $\Delta L$ on crack position $x$, we do curve fitting for the six curves based on the least square principle. We choose the simple linear polynomial in equation (3.9) to fit the six curves.

$$\Delta L = k \cdot x$$ \hfill (3.9)
Where, $k$ is the slope of linear polynomial.

The results of curve fitting are shown in Fig. 3.9. The six fitting curves of six different crack widths are drawn as the six real lines, respectively. The experiment data of difference inductance $\Delta L$ to crack position $x$ are also marked and drawn as the six dashed flexional lines, respectively.

Fig. 3.9 Fitting curves for dependence of difference inductance $\Delta L$ on crack position $x$

Consequently the six slopes are obtained and shown in Table 3.1. The results show that the slope $k$ is also approximately linear dependence on the crack width $d$. Hence we also use a linear polynomial as shown in equation (3.10) to do curve fitting for the dependence of the slope $k$ on the crack width $d$ based on the least square principle.

$$k(d) = A \cdot d + B \quad (3.10)$$
Table 3.1 Slope $k$ to crack width $d$

<table>
<thead>
<tr>
<th>Crack width $d$ (mm)</th>
<th>Slope $k$ ($10^{-3}$H/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.03168</td>
</tr>
<tr>
<td>2.0</td>
<td>0.04027</td>
</tr>
<tr>
<td>3.0</td>
<td>0.04781</td>
</tr>
<tr>
<td>4.0</td>
<td>0.05710</td>
</tr>
<tr>
<td>5.0</td>
<td>0.06377</td>
</tr>
<tr>
<td>6.0</td>
<td>0.07132</td>
</tr>
</tbody>
</table>

The results of curve fitting present that the two constants are respectively $A=7.942 \times 10^{-3}$H/m² and $B=2.420 \times 10^{-5}$H/m. In Fig. 3.10 the linear fitting curve is drawn and the six slopes $k(d)$ ($d=1$mm, 2mm, 3mm, 4mm, 5mm, 6mm) are also marked.

Fig. 3.10 Curve fitting of dependence $k(d)$
Finally by curve fitting method we get a dependence of difference inductance $\Delta L$ on crack position $x$ as shown in equation (3.11). Then inverse dependence of crack position $x$ on difference inductance $\Delta L$ can be deduced in equation (3.12).

$$\Delta L = (A \cdot d + B) \cdot x$$  \hspace{1cm} (3.11)

$$x = \frac{L_1 - L_2}{A \cdot d + B}$$  \hspace{1cm} (3.12)

Then in crack detection by measuring the two equivalent inductances $L_1$ and $L_2$ of two coils of ECT probe we can evaluate the relative crack position $x$ in the measurable range beneath ECT probe according to equation (3.12).

### 3.6 Error Estimation of Crack Position Detection

The estimation of crack position $x$ expressed as $x'$ is calculated by equation (3.12) which is deduced from the curve fitting based on the least square principle. As we know, the fitting method will bring error for the estimated crack position $x$. The estimation error of the crack position $x$ expressed as $error_x$ can be calculated by equation (3.13). When the crack position is $x$ and the crack width is $d$, the estimation error is expressed as $error_x(x,d)$ as shown in Fig. 3.11.

$$error_x = x' - x$$  \hspace{1cm} (3.13)

In the testing experiment we measure to get 78 sets of inductance data $L_1$ and $L_2$. The crack position $x$ varies from -30mm to 30mm that means the full scale $X_{FS}$ is 60mm, and the crack width varies from 1mm to 6mm. The results of error estimation present that for these inductance data the maximum error of crack position $x$ expressed as $\text{max}(error_x)$ is 2.2mm. Then the linearity expressed as $\delta L$ of the crack position estimation based on equation (3.12) can be calculated by
formula (3.14) to be 3.7% for the used probe.

\[
\delta_L = \frac{\max(\text{error}_x)}{X_{FS}} = \frac{2.2}{60} = 3.7\%
\]  

(3.14)

Certainly the linearity may be different with respect to the different fitting curves for the same experiment data. Additionally the linearity also depends on the structure of probe.

![Fig. 3.11 Estimation error of crack position](image)

The statistics of error estimation are presented in Table 3.2. When the intervals include or don't include the border values, the square brackets or the round brackets are respectively used. The statistic results present that: among the 78 experiment data, for the absolute value of \(\text{error}_x\), there are 88.4% errors within the interval \((0,1]\), 9.0% errors within the interval \((1,1.5]\), and only 2.6% errors within the interval \((1.5,2.2]\). From Fig. 3.11 we can know that the absolute values of
error_x within (1,2.2) mainly appears at the crack position x within [25,30]. By analysing the statistic result we conclude that when the crack position x is within [-30,25] the precision of the crack position estimation is 1.1mm, whereas when the crack position x is within [25,30] it is 2.2mm.

Table 3.2 Statistics of error estimation

<table>
<thead>
<tr>
<th>Absolute value of error_x (mm)</th>
<th>Number of data</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>error_x ∈ (0,0.5]</td>
<td>37</td>
<td>47.4%</td>
</tr>
<tr>
<td>error_x ∈ (0.5,1]</td>
<td>32</td>
<td>41.0%</td>
</tr>
<tr>
<td>error_x ∈ (1,1.5]</td>
<td>7</td>
<td>9.0%</td>
</tr>
<tr>
<td>error_x ∈ (1.5,2]</td>
<td>1</td>
<td>1.3%</td>
</tr>
<tr>
<td>error_x ∈ (2,2.2]</td>
<td>1</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

The results present that the estimation errors are greater at some points, which mainly comes from two reasons. One reason is that the curve fitting brings the estimation error; the other reason is that the double planar coils of the ECT probe are manufactured in low precision and not symmetric well, which brings the system error in crack position detection. Because the probe structure of double planar coils is complex, they are handmade and artificially wired by copper wires, which results in that the precision of manufacture is low. Certainly during testing the random error always exists in measurement data. In conclusion, the estimation error, the system error and the random error together affect the estimation x' for the real crack position x.

3.7 Summary

In this chapter, the new planar coil with uneven step distributing structure is proposed. The basic principle of crack position detection by using the uneven step distributing coil is discussed. The new ECT probe composed of double uneven step distributing coils is proposed. The characteristics of the probe
terminal are represented and the ECT probe contains three layers. The measuring system of experiment for crack detection is introduced. Through analysing the experiment results, the dependence of equivalent inductance on crack position is established by curve fitting method based on the least square principle. Finally the error estimation of crack position detection is studied.
4 Multifunctional Eddy Current Testing Probe for Crack Detection

4.1 Introduction

Eddy current testing is a non-destructive testing (NDT) method using the principle of electromagnetism. An important application of ECT is to detect cracks in metallic structure, and generally a traditional probe detects crack in test metallic surface by point-by-point scan mode [86-90] that performs a mass of measurement work. Furthermore recently more detail information of defect by ECT technique are wanted including its position, shape, length, direction, and material parameters.

The proposed uneven step distributing coil is a planar induction coil. When alternating current is applied to the induction coil, because of uneven step distributing structure of coil, the produced magnetic field intensity also distributes unevenly. When the induction coil detects crack in test surface, the equivalent inductance of coil will vary with crack position and width.

The new multifunctional ECT probe containing double uneven step distributing coils can simultaneously detect out the position and width of one crack in static mode. This static detection can advance test efficiency and reduce test work greatly compared with traditional dynamic detection by point-by-point scan. The new ECT probe can detect crack in wide metallic surface by line scan advanced to traditional point scan. So the ECT probe can detect the long defect as crack in wide aircraft fuselages, long railway, and long tubes. Furthermore the probe itself has a high resolution for crack, so it can detect crack in some special situations when the probe is fixed or can not move in high resolution.
4.2 Multifunctional Sensing Technology

4.2.1 Principle of Multifunctional Sensing Technology

Multifunctional sensing has been researched and developed in last decade [91-93]. In order to sense different variables simultaneously, usually different sensors are used independently. Improved from the popular independent sensing technique, the multifunctional sensing technology has been researched known as the compound sensing. Because one measured variable can affect more than one output signal of sensor, a multifunctional sensing system can sense more independent variables than one variable. For multifunctional sensing, each output of multifunctional sensor is the fusion of the input measurands, but the data processing for reconstructing different measurands is needed.

Fig. 4.1 Multifunctional sensing system

The general structure of multifunctional sensor is shown in Fig. 4.1. The variables $X_1, X_2, ..., X_n$ are measurands of the tested object. The outputs of multifunctional sensor are $Y_1, Y_2, ..., Y_n$. By processing data the evaluated results are obtained as $X'_1, X'_2, ..., X'_n$. In conventional works, the sensors with the characters as $Y_1=f_1(X_1), Y_2=f_2(X_2), ..., Y_n=f_n(X_n)$ are combined for measurement. Although the data processing of this way is simple, their corresponding measuring system that combines several separated sensors may cause a complicated structure. So comparing with conventional works, the structure of multifunctional sensing system can be compacted and simplified, furthermore the function of sensor is enhanced and the measure efficiency is advanced.
Multifunctional sensing system is mainly composed of two sections. The first section is to measure quantities by multifunctional sensor. The input measured quantities are mutually independent, and the output signals vary with one input variable or simultaneously several input variables. The second section is data processing. By analyzing the multifunctional sensor and the relation between input and output signals, the functional dependence of the measured quantities on the output signals can be established.

4.2.2 Principle of Multifunctional Eddy Current Testing Probe for Crack Detection

The new multifunctional sensing system is researched to detect crack position and width simultaneously in static mode by using the new ECT probe shown in schematic Fig. 4.2. In measuring section two independent input variables are crack position \( x \) and width \( d \), and the two output signals are inductances \( L_1 \) and \( L_2 \) of two coils. According to the two inductances, the evaluation of crack position and width are obtained as \( x' \) and \( d' \), respectively. Here the non-destructive evaluation is an inverse problem [94].

![Fig. 4.2 Multifunctional ECT probe for crack detection](image-url)
4.3 Multifunctional Eddy Current Testing Probe Used in Crack Detection

4.3.1 Structure of Eddy Current Testing Probe

The uneven step distributing planar coil is shown in Fig. 4.3. The configuration is similar to trapezoid shape and satisfies the reflection symmetry with respect to the x axis. The coil is wound by copper wire in 19 turns. The same step spacing $s_1$ between two adjoining turns is 5mm and the same top width $s_2$ of each turn is 4mm.

The terminal of ECT probe consists of two uneven step distributing planar coils that mutually satisfy the rotation symmetry with respect to the centre point O that is defined as the zero position of crack as shown in Fig. 4.4.

Fig. 4.3 Uneven step distributing planar coil

Fig. 4.4 Probe containing two uneven step distributing planar coils
The ECT probe consists of three layers: magnetic layer, coil layer and bottom layer. The magnetic layer is made from ferrite that can concentrate the magnetic field generated by coil, enhance the magnetic field intensity, and advance the resolution for defect. The coil layer is composed of double uneven step distributing planar coils, and its lift-off is 1.9mm which is provided by the bottom layer.

In test the probe is in contact with the test surface, so it is manufactured as a planar probe that is good for detecting surface defects. In once measurement the probe is an absolute probe based on the operation mode. Because the two coils alternately inspect the metallic surface, and in once measurement each coil acts as the exciting coil and the pick-up coil simultaneously. The probe is also a differential probe used for nondestructive evaluation. But it is different from the general differential probe that has two active coils usually wound in opposition, and the two coils are not connected as one coil. For the two coils the respective trends of $\Delta L/\Delta x$ the ratio of differential inductance to differential crack position are inverse due to the rotation symmetry of probe. For a crack existing in the measurable range, the coil 1 and coil 2 is sensitive to the crack existing in the positive position and the negative position, respectively. So the two coils of probe together can advance the sensitivity for crack in the whole measurable range. Also in crack evaluation the dependence of difference inductance $\Delta L$ on crack position $x$ is approximately linear, because its nonlinear items are reduced greatly.

### 4.3.2 Detection Principle of the Eddy Current Testing Probe

From the equivalent circuit of ECT probe shown in Fig. 2.5, based on the Kirchhoff’s voltage laws, we will obtain two Equations (2.14) and (2.15). Then in test the equivalent inductance $L$ of coil will decrease due to the induced eddy current $I_e$ as shown in equation (2.20). When the excitation frequency $f$ increases to be the high frequency, an approximation for the equivalent inductance $L$ can be used shown in equation (4.1) [95].
\[ L \approx L_0 - \frac{M^2}{L_e} \]  \hspace{1cm} (4.1)

Obviously the original inductance \( L_0 \) is the maximum inductance. In test the life-off of coil is a fixed distance. If no crack exists beneath coil, the inductance of coil will decrease to be \( L_E \) that is the minimum inductance. If a crack exists beneath coil, the equivalent inductance of coil will vary in range of \( L_E < L < L_0 \). The existence of crack can affect the coupling between the coil of ECT probe and the eddy current loop. The coupling is indicated by the mutual inductance \( M \). Because the configuration of planar coil is uneven step distributing, the mutual inductance \( M \) indicating the coupling is dependent on crack position and width. Therefore the equivalent inductance of coil \( L \) will vary with crack position \( x \) and width \( d \) simultaneously. In test the crack position \( x \) and width \( d \) can both be evaluated according to the equivalent inductances \( L_1 \) and \( L_2 \) of two coils, which is to solve an inverse problem.

4.3.3 Measurement of the Eddy Current Testing Probe

In experiment the probe detects one crack in surface of aluminium plate whose thickness is \( 1.5 \)mm. The two planar coils alternately detect the metallic surface in order to avoid the coupling of the generated magnetic field. Then the inductance variations of two coils are alternately measured by LCR meter controlled by switch. The test frequency of ECT probe is chosen as \( 100kHz \) that is high frequency to get the high resolution and sensitivity for crack. The resolution of LCR meter for inductance variation can affect the resolution for crack.

For aluminium material the electrical conductivity \( \sigma \) is \( 3.8 \times 10^7 \)S/m, and the magnetic permeability \( \mu \) is \( 1.24 \times 10^6 \)H/m. When the test frequency \( f \) is \( 100kHz \), the standard depth of penetration \( \delta \) is calculated to be \( 0.26 \)mm.

In experiment the crack is perpendicular to the \( x \) axis of probe. Because the induced eddy currents sharply decrease in the periphery of coil, the crack can
only be detected in a measurable range beneath the ECT probe. There are five
cracks detected whose widths are 2mm, 3mm, 4mm, 5mm and 6mm, respectively.
The five cracks locate at a series of positions differing from -30mm to 30mm by
step 5mm. Finally there are 65 sets of two inductances including $L_1(x,d)$ and
$L_2(x,d)$ obtained by measurement.

4.3.4 Experiment Results

The original inductances of two coils are $L_1=25.4\mu H$ and $L_2=25.0\mu H$,
respectively. In test when no crack exists beneath probe, the equivalent
inductances of two coils vary to be $L_1=15.37\mu H$ and $L_2=15.33\mu H$, respectively,
which are the minimum inductances of respective coils in test. So during
detecting crack the range of varying inductance is $15.37\mu H < L_1 < 25.4\mu H$ and
$15.33\mu H < L_2 < 25.0\mu H$, respectively.

![Fig. 4.5 Experiment data of equivalent inductance $L_1(x,d)$](image)

-63-
Because the structure of probe satisfies the rotation symmetry, the inductances $L_1(x,d)$ and $L_2(x,d)$ should mutually satisfy a reflection symmetry with respect to $x$ presented in equation (4.2). This ideal deduction is proved by the experiment data of $L_1(x,d)$ and $L_2(x,d)$ that are drawn in Figs. 4.5 and 4.6, respectively.

$$L_1(-x,d) = L_2(x,d)$$  \hspace{1cm} (4.2)

### 4.4 Evaluation of Crack Position and Width

For the multifunctional sensing system the two output inductances $L_1$ and $L_2$ are both dependent on crack position and width. Firstly the dependence of inductance on crack position $x$ and width $d$ should be established. Here the difference and sum inductance is defined in equations (4.3) and (4.4), respectively. According to equation (4.2) the function $\Delta L(x,d)$ is an odd function
and the function $\Sigma L(x,d)$ is an even function with respect to crack position $x$. The two ideal deductions are shown in equations (4.5) and (4.6), respectively.

$$\Delta L(x, d) = L_1(x, d) - L_2(x, d) \quad (4.3)$$

$$\Sigma L(x,d) = L_1(x,d) + L_2(x,d) \quad (4.4)$$

$$\Delta L(-x,d) = -L(x,d) \quad (4.5)$$

$$\Sigma L(x,d) = \Sigma L(-x,d) \quad (4.6)$$

The Figs. 4.7 and 4.8 show that for a crack of width $d$ approximately the dependence $\Delta L(x,d)$ is a linear odd function, and the dependence $\Sigma L(x,d)$ is an even function, which correspond with the deduced ideal conclusion as shown in equations (4.5) and (4.6).

Fig. 4.7 Surface of difference inductance $\Delta L(x,d)$
According to the experiment results we use data fitting method based on the least square principle to establish two functions with two variables that are $\Delta L(x,d)$ and $\Sigma L(x,d)$. Here we do curve fitting in one dimension twice to realize surface fitting in two dimensions.

Firstly two supposed functions shown in equations (4.7) and (4.8) are used to do curve fitting for $\Delta L(x,d)$ and $\Sigma L(x,d)$. The equation (4.7) is a linear polynomial and has odd symmetry with respect to variable $x$. The equation (4.8) is a quadratic polynomial and has even symmetry with respect to variable $x$.

\[
\Delta L(x,d) = k(d) \cdot x \quad (4.7)
\]
\[
\Sigma L(x,d) = m(d) \cdot x^2 + n(d) \quad (4.8)
\]

Here $k(d)$, $m(d)$ and $n(d)$ are three functions on crack width $d$. The results of first curve fitting present that they are all approximately linear dependence on crack width $d$ as shown in Figs. 9, 10 and 11, respectively.
Fig. 4.9 Dependence $k(d)$

Fig. 4.10 Dependence $m(d)$
Then secondly three linear polynomials shown in equations (4.9), (4.10) and (4.11) are used to do curve fitting for $k(d)$, $m(d)$ and $n(d)$, respectively.

\[ k(d) = A_2 \cdot d + A_1 \]  \hspace{1cm} (4.9)

\[ m(d) = B_3 \cdot d + B_2 \]  \hspace{1cm} (4.10)

\[ n(d) = B_1 \cdot d + B_0 \]  \hspace{1cm} (4.11)

There are six constant coefficients $A_1$, $A_2$, $B_0$, $B_1$, $B_2$ and $B_3$. The results of second curve fitting present that the values are $A_1=2.483\times10^5\text{H} \cdot \text{m}^{-1}$, $A_2=7.806 \times10^3\text{H} \cdot \text{m}^{-2}$, $B_0=3.143\times10^5\text{H}$, $B_1=1.830\times10^4\text{H} \cdot \text{m}^{-1}$, $B_2=3.591\times10^4\text{H} \cdot \text{m}^{-2}$, and...
By curve fitting method we finally obtain two functions of $\Delta L(x,d)$ and $\Sigma L(x,d)$ shown in equations (4.12) and (4.13), respectively. They together make up of systems of two equations with two variables $x$ and $d$.

\[
\Delta L(x,d) = (A_2 \cdot d + A_1) \cdot x \quad (4.12)
\]

\[
\Sigma L(x,d) = (B_3 \cdot d + B_2) \cdot x^2 + B_1 \cdot d + B_0 \quad (4.13)
\]

As we know the curve fitting method will bring error. The fitting value of inductance $\Delta L$ and $\Sigma L$ are $\Delta L'$ and $\Sigma L'$, respectively. Then the estimating error of $\Delta L' - \Delta L$ and $\Sigma L' - \Sigma L$ is shown in Figs. 4.12 and 4.13, respectively.

Fig. 4.12 Estimating error $\Delta L' - \Delta L$
The crack position $x$ can be calculated by equation (4.14) deduced from equation (4.12). We substitute equation (4.14) for $x$ in equation (4.13), and a cubic equation with one variable crack width $d$ can be obtained as shown in equation (4.15).

$$x = \frac{\Delta L}{A_2 \cdot d + A_1}$$ (4.14)

$$A_2^2 B_1 \cdot d^3 + \left(2 A_2 A_1 B_1 + A_2^2 B_0 - A_2^2 \cdot \Sigma L\right) \cdot d^2$$
$$+ \left(A_1^2 B_1 + 2 A_2 A_1 B_0 - 2 A_2 A_1 \cdot \Sigma L + B_1 \cdot \Delta L^2\right) \cdot d$$
$$+ A_1^2 B_0 - A_1^2 \cdot \Sigma L + B_1 \cdot \Delta L^2 = 0$$ (4.15)

According to the measurement results of equivalent inductance $L_1$ and $L_2$, firstly the estimating value of crack width expressed as $d'$ can be calculated out.
by solving equations (4.15). Then the estimating value of crack position expressed as $x'$ can be calculated to substitute the estimating value of crack width $d'$ for the variable $d$ in equation (4.14). The solution must satisfy that the estimating values of crack position $x'$ and width $d'$ are both reasonable and close to their respective evaluable ranges.

4.5 Error Estimation

The estimating error of crack position and width is $error_x$ and $error_d$ in equations (4.16) and (4.17). The results are shown in Figs. 4.14 and 4.15, respectively.

$$error_x = x' - x$$ (4.16)

$$error_d = d' - d$$ (4.17)

Fig. 4.14 Estimating error $error_x(x,d)$
The statistic results of the estimating error of crack position and width are shown in Tables 4.1 and 4.2, respectively. Among the 65 sets of experiment data, the 91% results of the absolute value of error\(_x\) are less than 2mm and the 88% results of the absolute value of error\(_d\) are less than 0.3mm. The results of the absolute value of error\(_x\) and error\(_d\), which are greater than 2mm and 0.3mm respectively, mainly occur when the crack position is near 30mm. It implies that the probe terminal near position 30mm doesn’t satisfy a good symmetry.

The estimating error of crack position mainly comes from two aspects. One aspect is that the curve fitting method brings the method error. The other aspect is that the two coils of ECT probe are handmade and wired artificially by copper wires, so the manufacture precision is low and the symmetry is not good, which brings the system error for estimation.
Table 4.1 Statistics of the estimating error of crack position

<table>
<thead>
<tr>
<th>Value range of error_x (mm)</th>
<th>Number of results</th>
<th>Percent</th>
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<tr>
<td>0&lt;</td>
<td>error_x</td>
<td>&lt;1</td>
</tr>
<tr>
<td>1&lt;</td>
<td>error_x</td>
<td>&lt;2</td>
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<tr>
<td></td>
<td>error_x</td>
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Table 4.2 Statistics of the estimating error of crack width

<table>
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<th>Value range of error_d (mm)</th>
<th>Number of results</th>
<th>Percent</th>
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<td>0&lt;</td>
<td>error_d</td>
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</tr>
<tr>
<td>0.1&lt;</td>
<td>error_d</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>0.2&lt;</td>
<td>error_d</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>0.3&lt;</td>
<td>error_d</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>0.4&lt;</td>
<td>error_d</td>
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</tr>
<tr>
<td></td>
<td>error_d</td>
<td>&gt;0.5</td>
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4.6 Summary

In this chapter, the author studies the new ECT probe based on the multifunctional sensing technology. The new ECT probe can detect crack position and width simultaneously due to the novel probe terminal that consists of double uneven step distributing planar coils. The multifunctional sensing system has two input variables including crack position x and width d, and two output signals including two equivalent inductances $L_1$ and $L_2$. By curve fitting method based on the least square principle we establish two functional dependences of $\Delta L_1(x,d)$ and $\Sigma L_2(x,d)$. So in crack detection according to the two output varying inductance $L_1$ and $L_2$, the crack position x and width d can be
evaluated by solving the systems of two equations. Finally the error estimation of crack position and width are studied.
5 Conclusion

5.1 Introduction

The overall goal of this thesis is to develop an eddy current testing probe for crack detection based on the multifunctional sensing technology. The author research on the new ECT probe composed of double uneven step distributing coils. During inspecting the metallic surface, the position and width of crack can both be evaluated simultaneously by the two equivalent inductances of two coils of the ECT probe. The understanding and applications of the multifunctional sensing technology in the field of measurement of eddy current testing are extended substantially by this work. Although a brief summary for each chapter is provided at the end of corresponding chapter, this chapter deals with the comprehensive discussions of the overall work on chapter basis. Possible future research works that can be extended from this study are also mentioned in this chapter.

5.2 Conclusions and Discussions

In chapter 1, the author briefly introduces the necessity of nondestructive testing in assuring that structural components and systems perform their function in a reliable and cost effective fashion. There are a lot of NDT methods used to inspect components and make measurements. Particularly the eddy current testing as an important NDT method is introduced. The advantages, limitations and present state of eddy current testing are represented.

In chapter 2, the author introduces the principle of eddy current testing. The equivalent circuit of eddy current testing is studied. The results show that because of the generation of eddy current the equivalent resistance gets greater and the equivalent inductance gets less, and then the equivalent quality factor decreases. When the excitation frequency of probe is high, the equivalent
inductance is not dependent on the electrical resistivity of test metallic plate and only dependent on the coupling coefficient. So when the coupling coefficient varies, the equivalent inductance will vary with it. Based on this principle the author proposes a new multifunctional ECT probe to detect crack location and width in static detection mode.

In chapter 3, the author firstly proposes the new uneven step distributing planar coil. Because the novel structure of the coil, the coil is sensitive to the crack in metallic surface beneath it without scanning the test surface point by point. Then the new ECT probe composed of double uneven step distributing coils is proposed. It is a different ECT probe for detecting the surface crack. The new ECT probe can realize the static detection for crack which can advance the test efficiency and reduce the test work compared with the traditional dynamic detection by scanning the test surface in point by point mode.

The measuring system of experiment is made to detect crack by using the new probe. In experiment the six cracks of different widths are detected. Each crack is vertical to the x axis of the ECT probe and located at a series of positions in the measurable range. The experiment results of the two equivalent inductances are obtained. It shows that the difference of two inductances is approximately linearly dependent on the crack position for one crack. Then the estimation formula of crack position is deduced by curve fitting method based on the least square principle. The estimation error is analysed which mainly comes from the method error and the system error.

The novel ECT probe has some advantages for detecting crack presented in above, whereas there are still some problems to deal with. The ECT probe presently is handmade, which brings the system error and makes the probe size greater. Also the measuring precision of LCR meter for inductance variation limits the resolution for crack size. The ECT probe is sensitive to the cracks that disrupt the ECT probe in the perpendicular direction of the x axis, and then the detection length of crack must be greater than the length along the perpendicular direction of the x axis for the ECT probe. So in the testing experiment, the simulated cracks are long because of the big size.

For crack detections in the different scales, the ECT probe is emphasized
particularly on different functions. If the ECT probe is manufactured to be a microscale probe by the MEMS technique, it could detect the defects in microscale and moreover itself has the high resolution for the defect position. If the ECT probe is used to detect long defects in wide testing surface or in a batch of metallic workpieces, it can inspect in the static state with an advanced efficiency.

In chapter 4, based on the multifunctional sensing technology, the author does the further research on the new ECT probe. The ECT probe can realize the multifunctional detection for crack position and width simultaneously. The multifunctional sensing system has two input variables including crack position and width, and two output signals including two equivalent inductances.

By analysing the experiment results of equivalent inductances, it shows that the function of difference inductance and sum inductance is an odd and an even function with respect to crack position, respectively. Then base on the least square principle the curve fitting in one dimension is employed twice for fitting crack position and width, respectively, to realize the surface fitting in two dimensions. Finally the dependence of the difference inductance on crack position and width, and the dependence of the sum inductance on crack position and width are both established. So in test according to the two equivalent inductances, the crack position and width can both be evaluated by solving the systems of two equations with two variables. Finally the error estimation of crack position and width are both studied. The statistics of the estimating error prove that the multifunctional sensing system for crack detection is feasible.

In experiment the crack is vertical to the x axis of the ECT probe, actually even a crack not vertical to the x axis can also be detected. If the planar coil could be manufactured to be a thin one with the small width in the perpendicular direction of the x axis, the ECT probe could actually realize the line detection for defect in metallic surface that is advanced to the traditional point detection for defect. The ECT probe can be employed to scan test surface along the vertical direction of the x axis, and then a series of defect positions and widths will be obtained by analysing the measurement results. So the 2D image of defect can be drawn, and more shape details of the defect such as length and trend direction
can also be known.

5.3 Recommendations for Future Work

This thesis has achieved the new ECT probe that is valuable for the crack detection based on the multifunctional sensing technology. For the new ECT probe there are still some aspects to study and make improvement for the actual practical use. Following are some recommendations for extending this thesis work.

The manufacture technique of the uneven step distributing coil should be improved. If the ECT probe is manufactured by the printed circuit board (PCB) technique, firstly the manufacture precision and symmetry of double coils can be advanced and improved, which will reduce the estimation error for crack position. Secondly the coil turns can be increased and then the spacing $s_1$ of the ECT probe can be reduced, so the resolution of the ECT probe for the crack position and width can be advanced. Thirdly the length along the perpendicular direction of the x axis for the ECT probe can be shortened, and then the ECT probe can detect the cracks with short length.

To enhance the magnetic density generated by probe, the coil layer of ECT probe can be manufactured to be the multi-layer with same structure in each layer. Then the resolution for defect can also be enhanced and the noise in measuring results can be reduced.

In actual measurement, for the output of measuring system it is convenient to measure the voltage variation rather than to measure the inductance variation. So the ECT probe should be improved to be a reflection mode probe with two coil layers. The driver coil layer is used to excite the eddy currents in test metallic surface and the pickup coil layer is used to sense changes in the test metallic surface. Then the driver and pickup coil layers are separately optimized for their intended purpose.
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