



وزارة البحث العلمي والتعليم العالي
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique



Département de Génie Électrique

Université Abdelhamid Ibn Badis Mostaganem

كلية العلوم والتكنولوجيا

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جامعة عبد الحميد بن باديس مستغانم

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Lakhdari AbdelHalim

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. Study, modeling and simulation of the NDT eddy currents by finite element software in 2D and 3D

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devant le jury composé de :

Président :	Benaouali Mohamed	MAA	Université de Mostaganem
Examineur :	Chaouch Abdellah	Pr	Université de Mostaganem
Rapporteur :	Omari Hamza	MAA	Université de Mostaganem

“Intellectuals solve problems, geniuses prevent them”.
-Albert Einstein-

Acknowledgement

I would like to thank Allah for letting me through all the difficulties. I have experienced your guidance day by day. I will keep on trusting you for eternity.

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ملخص

اختبار تيار إيدي (ECT) هو تقنية غير مدمرة معروفة NDT بقدرتها على اكتشاف العيوب السطحية وتحت السطحية في المواد الموصلة دون التسبب في تلف أو تغيير.

يعتمد اختبار تيار إيدي على مبدأ الحث الكهرومغناطيسي، حيث يولد التيار المتردد مجالات مغناطيسية مختلفة.

في هذه الدراسة، تم استخدام برنامجين حاسوبيين للمحاكاة "Femm" و "COMSOL Multiphysics" لمحاكاة وظيفة تقنية "ECT" في بعدين مختلفين: ثنائي وثلاثي الأبعاد.

الكلمات الدالة:

اختبار غير مدمر, اختبار التيار الدوامي , الحث الكهرومغناطيسي , برامج المحاكاة , طريقة العناصر المحدودة , الكهرومغناطيسية.

Abstract

Eddy current testing (ECT) is a well-known NDT technique known for its ability to detect surface and subsurface defects in conductive materials without causing damage or alteration.

Eddy current testing is based on the principle of electromagnetic induction, where alternating current generates different magnetic fields.

In this study, two computer programs (Femm and COMSOL Multiphysics) were used to simulate the functionality of his ECT technique in two different dimensions: 2D and 3D.

Keywords:

Non-destructive testing, eddy current testing, electromagnetic induction, simulation programs, finite element method, electromagnetism.

Résumé

Les tests par courants de Foucault (ECT) sont une technique CND bien connue pour sa capacité à détecter les défauts de surface et souterrains dans les matériaux conducteurs sans causer de dommages ou d'altérations.

Les tests par courants de Foucault sont basés sur le principe de l'induction électromagnétique, où le courant alternatif génère différents champs magnétiques.

Dans cette étude, deux programmes informatiques (Femm et COMSOL Multiphysics) ont été utilisés pour simuler la fonctionnalité de sa technique ECT dans deux dimensions différentes : 2D et 3D.

Mots clés:

Contrôles non destructifs, contrôles par courants de Foucault, induction électromagnétique, programmes de simulation, méthode des éléments finis, électromagnétisme.

List of symbols

Symbol	Quantity	Unit
E	Electric field intensity	[V/m]
H	Magnetic field intensity	[A/m]
D	Electric flux density	[C/m²]
B	Magnetic flux density	[T]
J	Current density	[A/m²]
A	Magnetic vector potential	[Tm]
V	Electric potential	[V]
ϵ	Electric permittivity	[F/m]
μ	Magnetic permeability	[H/m]
σ	Electric conductivity	[S/m]
f	Frequency	[s⁻¹]
ω	Angular frequency	[s⁻¹]
Z	Impedance	[Ω]
L	Inductance	[H]
R	Resistance	[Ω]

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General introduction

The main goal of this master thesis is to acknowledge and study non-destructive testing using eddy current technology and show its importance in the world of maintenance in various domains such as mechanical engineering, structural engineering, aerospace engineering, electrical engineering, etc.

We elaborated on the concept of how this technology works and functions by using the neat equations of Maxwell's that describe electromagnetism.

In Chapter One, Nondestructive testing (NDT) plays a critical role in ensuring the safety, reliability, and quality of materials and components in a variety of industries. Eddy current testing (ECT) is a well-known NDT technique known for its ability to detect surface and subsurface defects in conductive materials without causing damage or alteration. This abstract provides an overview of ECT and highlights its principles, applications, and importance in modern engineering and manufacturing.

In Chapter Two, Eddy current testing is based on the principle of electromagnetic induction, where alternating currents generate different magnetic fields. When these magnetic fields interact with conductive materials, eddy currents are induced, creating a unique magnetic field. Discontinuities such as cracks, cavities, and corrosion interrupt the flow of eddy currents and change the magnetic field. Highly sensitive sensors can detect these changes, allowing inspectors to accurately identify and characterize defects.

In Chapter Three, Finite element methods are used to predict the interaction of defects and eddy currents. The complex nature of this method requires a deeper understanding that can potentially be gained using mathematical models (magneto-dynamic formulation).

In Chapter Four, we were able to simulate the function of the ECT technique using two computer programs (Femm and COMSOL Multiphysics) in two different dimensions "2D and 3D."

The simulation helped us gather important information on the technique and get results similar to real inspections.

Chapter One

State of the art on NDT and general
information on sensor

I.1 Definition

Non-destructive testing (NDT) is a testing and analysis technique used by industry to evaluate the properties of a material, component, structure or system for characteristic differences or welding defects and discontinuities without causing damage to the original part. NDT also known as non-destructive examination (NDE), non-destructive inspection (NDI) and non-destructive evaluation (NDE).

In the field, NDT is often used as an umbrella term to refer to non-destructive inspection methods, inspection tools, or even the entire field of non-destructive inspections.

Inspection and Analysis of Engineering Materials and Structures imply an imperative need for a thorough examination of all the properties without invading the structural integrity of the materials as the conventional destructive techniques i.e., Harness testing, and tensile testing to name a few, would require destruction of test specimens leading to obstruction of functionality in Factory or In-situ settings.

Non-Destructive Testing (NDT/ NDT testing) Techniques or Methodologies allow the investigator to carry out examinations without invading the integrity of the engineering specimen under observation while providing an elaborate view of the surface and structural discontinuities and obstructions. The personnel carrying out these methodologies require specialized **NDT Training** as they involve handling delicate equipment and subjective interpretation of the NDT inspection/NDT testing results.

For commercial applications, the goal of NDT is to ensure that critical infrastructure is properly maintained in order to avoid catastrophic accidents.

While NDT methods are typically associated with industrial use cases, like inspecting weak points in a boiler at an oil refinery, uses in medicine are actually some of the most common.

For example, an expecting mother getting an ultrasound to check on the health of her baby would be considered an NDT use case, as would getting an X-ray or MRI to learn more about an injury.

But it's important to note that NDT does not necessarily require the use of special tools, or any tools at all.

For instance, when inspectors in industrial settings review the outside of a pressure vessel with their naked eye that would fall under the NDT designation, since they are collecting data on the status of the boiler without damaging it. On the other hand, using a sophisticated tool like an ultrasonic sensor to look for defects in a certain material or asset would also be called NDT.

Regardless of the specific use case, the underlying commonality among all these examples is the collection of data in a non-intrusive manner.

I.2 History of NDT

The history of non-destructive testing (NDT) can be traced back to ancient times when early civilizations used visual inspection to assess the quality and integrity of materials and structures. However, the formal development of NDT as a discipline began in the late 19th and early 20th centuries with the advancements in industrialization and the need for reliable and safe infrastructure.

Here is a brief overview of the key milestones in the history of NDT:

Late 1800s: The discovery and understanding of X-rays by Wilhelm Conrad Roentgen in 1895 laid the foundation for radiographic testing. X-rays were initially used for medical purposes but quickly found applications in industrial inspection.

Early 1900s: Ultrasonic testing emerged in the early 1900s with the development of piezoelectric transducers and the understanding of sound wave propagation. Ernst Florenz Friedrich Ruska is credited with the invention of the electron microscope in 1931, which significantly advanced the capabilities of ultrasonic testing.

Mid-1900s: World War II played a significant role in advancing NDT technologies as the demand for reliable materials and structures increased. Radiographic testing, magnetic particle testing, and dye penetrant testing saw significant advancements during this period.

1950s-1960s: Eddy current testing gained prominence as a technique for detecting surface and near-surface flaws. The development of electromagnetic coils and the understanding of electromagnetic induction contributed to the growth of this technique.

1970s-1980s: The use of digital radiography and the development of computed radiography (CR) and digital radiography (DR) transformed radiographic testing by providing faster image acquisition and analysis.

1990s-Present: The advancement of technologies such as phased array ultrasonics (PAUT) and guided wave ultrasonics (GWUT) enhanced the capabilities of ultrasonic testing, enabling faster inspections and improved flaw detection. Additionally, advancements in laser-based techniques, thermography, and remote inspection technologies have expanded the scope of NDT applications.

Historic event

The year of 1854 for Hartford, the capital city of the U.S. state of Connecticut, proved to be fatal to the lives of 21 workers and left 50 injured, amongst the 300 employed at Railroad-Locomotive Factory located at Fales and Grey Car works. The fatalities were attributed to an explosion from a newly installed 50-HorsePower Boiler with an operation time of under a month.

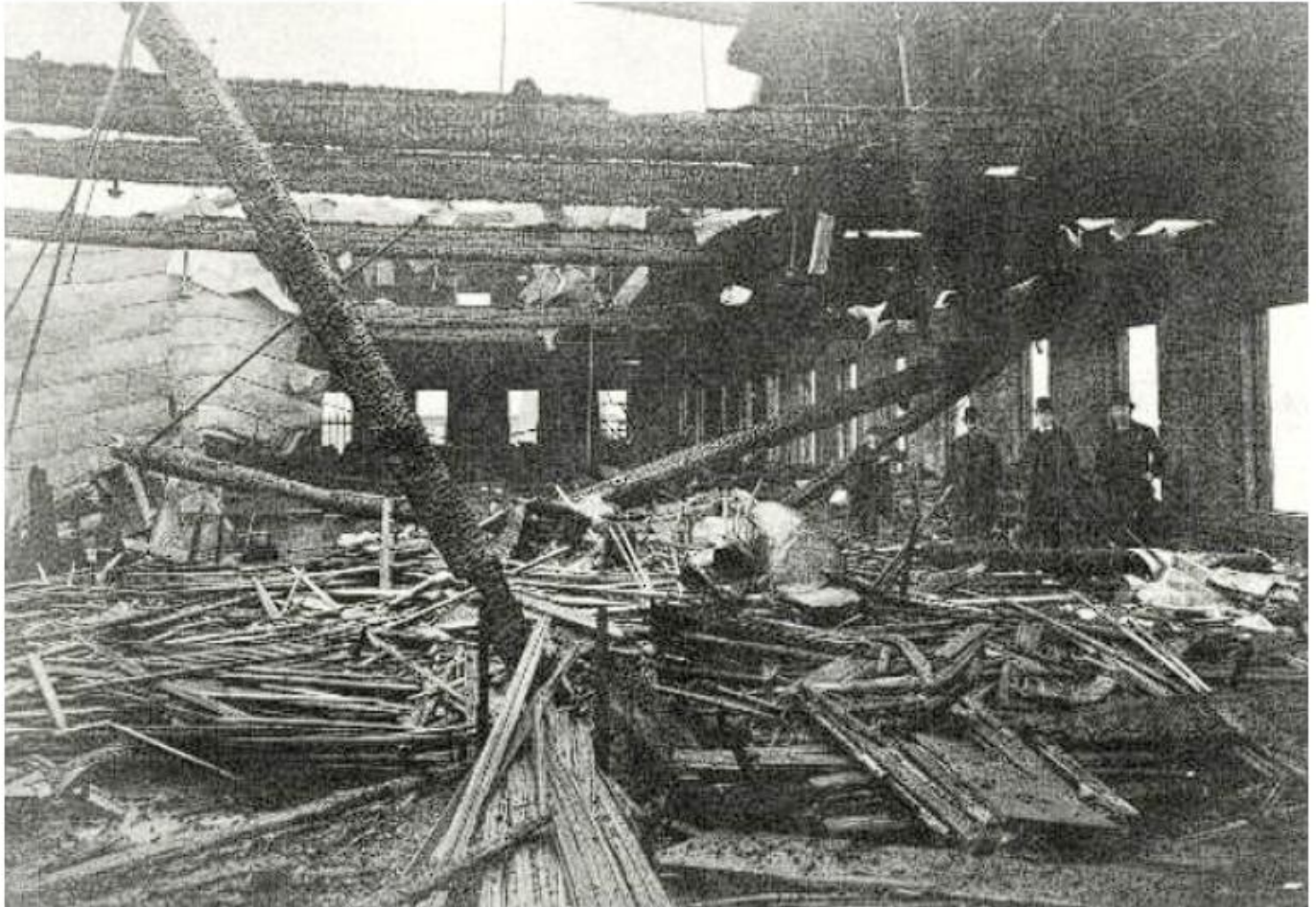


Figure I.1: In Hartford, Connecticut, The Boiler feeding the machinery at Fales and Grey Car Works Exploded on 2nd March 1854, with several casualties. (Image credits: Connecticut Historical Society)

The investigators concluded that the explosion was caused due to an overload of steam in the boiler because of the negligence of the personnel in charge. In Nearly a decade, Hartford officials made Boiler inspections and rigorous training for Engineers allocated mandatory. The inspections at that time relied on Visual examinations of the machinery without invading the integrity or functionality of its operation in the factory which ensured safety without any obstruction during production and served to be precursors to the modern-day Non-Destructive Inspection techniques of visual examination. The Non-Destructive Testing (NDT Testing) techniques and methodologies in their most contemporary form, are discussed in the successive sections.

Today, NDT continues to evolve with the advancements in technology, including robotics, artificial intelligence (AI), and machine learning. These technologies are being integrated into NDT systems to improve inspection speed, accuracy, and data analysis capabilities.

Overall, the history of NDT reflects the ongoing efforts to ensure the safety, reliability, and quality of materials and structures across various industries.

I.3 Types of NDT

There are several types of non-destructive testing (NDT) methods, each with its own principles and applications.

Test method names often refer to the type of penetrating medium or the equipment used to perform that test. The selection of an appropriate NDT method is unique to each application and material (for example, whether it is metallic, magnetic, massive, or irregularly shaped) and the potential problems of interest. NDT may be done in a cursory one-step manner or use a multistep process for reaching detailed conclusions regarding material conditions.

Here are some of the most commonly used NDT techniques:

I.3.1 Visual NDT (VT)

As the name **suggests**, visual **inspection** (VT) involves **visually observing** the surface of a test object to **assess** the presence of discontinuities or **steps** during manufacturing. VT is the most **commonly** used **inspection** method in **the industry** because most **inspection** methods require **an operator to** visually inspect **the** surface of **the** part prior to inspection. **Ultrasound** and **X-ray examinations** typically require visual **inspection before** performing the method. **Inspection of liquid penetrants** and magnetic **particles is** a visual inspection once the penetrant or magnetic particles **are** applied. **Film** or digital **images of the part are** evaluated using visual inspection.



Figure I.2: Visual testing

VT Techniques

Direct Visual Testing

When VT is treated as a standalone inspection method rather than supporting other methods, it is performed using one of two techniques. First, VT can be performed by **looking directly at an angle of less than 30 degrees using a partial line of sight, typically** at a distance of no more than 24 inches. Evaluation items include **welding, surface coating, dimensional measurements, etc.** Tests can be improved by using optical instruments such as magnifying glasses, optical comparators, mirrors, **rulers**, and **additional lighting in the test area.**

Remote Visual Testing

The second technology for VT is remote visual inspection. This includes visual inspection using endoscopes, cameras, and computer-assisted observation systems that allow remote viewing. Remote visual inspection detects corrosion, misaligned parts, internal physical damage, and cracks. The use of drones is becoming increasingly common for petrochemical and structural inspections. Some specialized drones are designed to immerse themselves in large tanks to evaluate products, valves, and corrosion. Field visual inspectors can now perform visual inspections of welds one day and fly a drone the next to assess areas that previously could not be visually inspected without special access.

I.3.2 Ultrasonic NDT (UT)

Ultrasound testing (UT) uses the same principles as marine sonar and fish finders. Introduces ultra-high frequency sound to the area to be inspected. When sound hits a material with a different acoustic impedance (density and speed of sound), some of the sound may be reflected back to the transmitting unit and displayed on the image display. By knowing the speed of sound passing through the part (sound velocity) and the time

it takes for the sound to return to the transmitting unit, you can determine the distance to the reflector (a display with different acoustic impedance). The most commonly used sound frequencies in UT are between 1 and 10 MHz, which are too high to be heard and to not propagate through air. Lower frequencies have more penetrating power, but less sensitivity (ability to "detect" small signs). Higher frequencies, on the other hand, do not penetrate as deeply, but can detect small signs. The two types of sound waves most commonly used in industrial inspection are compression waves (longitudinal waves) and shear waves (transverse waves), as shown in the following diagram. Compression waves cause the atoms in the part to vibrate back and forth parallel to the direction of sound, while shear waves cause atoms to vibrate perpendicular to the direction of sound (left and right). Transverse waves travel at about half the speed of longitudinal waves. Sound is introduced into the part using an ultrasonic transducer ("probe"). Ultrasonic transducers ("probes") convert electrical pulses from the UT device into sound waves, and the returned sound into electrical pulses that can be displayed digitally or as a visual representation on an LCD. Screen (CRT screen on older devices). If the machine is properly calibrated, the operator can determine the distance from the transducer to the reflector, and an experienced operator can often determine the type of discontinuity (slag, porosity, weld cracks, etc.). . Because ultrasound cannot travel through air (the atoms in air molecules are too far apart to transmit ultrasound), a "couplant" is used between the front of the transducer and the surface of the part to transmit the ultrasound. A liquid or gel called. To allow sound to travel inside the parts.

UT Techniques

Straight Beam

Straight beam testing uses longitudinal waves to inspect the specimen, as shown to the right. When sound hits an internal reflector, the distance from the transducer is shorter, so the sound from that reflector is reflected back to the transducer faster than the sound coming back from the back wall of the part. This will display a screen like the one shown on the right. Digital thickness gauges use the same process, but the output is a digital numeric display rather than a slide show.

Angle Beam

The angled beam test shown above uses the same type of transducer but is mounted on an angled wedge (also called a "probe") designed to send an acoustic beam to the part at a known angle. I am. The most commonly used test angles are 45°, 60°, and 70°, where the angle is calculated using a line through the thickness of the part (not through the surface of the part). If the frequency and wedge angle are not specified in the applicable code or specification, it is the operator's responsibility to select a combination that will adequately inspect the part being inspected.

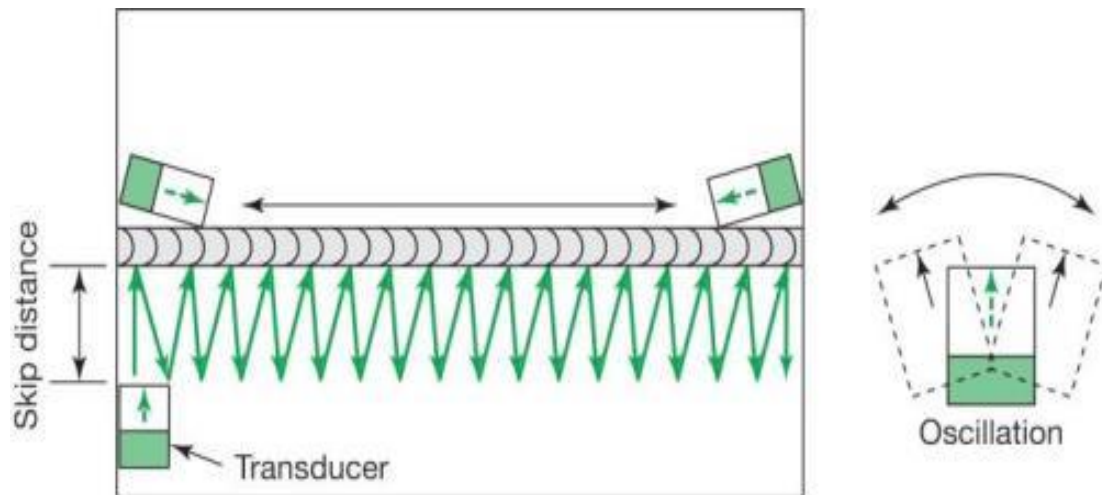


Figure I.3: Ultrasonic testing

In angle beam inspections, the transducer and wedge combination (also referred to as a "probe") is moved back and forth towards the weld so that the sound beam passes through the full volume of the weld. As with straight beam inspections, reflectors aligned more or less perpendicular to the sound beam will send sound back to the transducer and are displayed on the screen.

Immersion Testing

Immersion testing is a technique in which the part is immersed in a tank of water and an acoustic beam is passed between the transducer and the part using water as the coupling medium. The UT machine is mounted on a movable platform ("bridge") on the side of the tank and can be moved along the entire length of the tank. The transducer is pivotally attached to the bottom of the waterproof tube and can be raised, lowered, and moved within the tank. The movement of the bridge and tube allows the transducer to move on its X, Y, and Z axes. All directions of motion are gear-driven, allowing precise incremental movement of the transducer in any direction, and a swivel joint allows the transducer to be reoriented so that the sound beam enters the part at the desired angle. Circular inspection parts are often mounted on powered rollers that allow the part to rotate as the transducer moves along its length, allowing the entire circumference to be inspected. Multiple transducers can be used simultaneously, allowing multiple scans to be performed.

Through Transmission

Gear inspection is performed using two transducers, one on each side of the part. The transmitting transducer transmits sound through the part, and the receiving transducer receives the sound. Reflectors within the part reduce the amount of sound reaching the receiver, so the screen display shows a lower amplitude (screen height) signal. The figure on the right shows a passage in a plunge pool (top) and an example of how the water column is used (bottom).

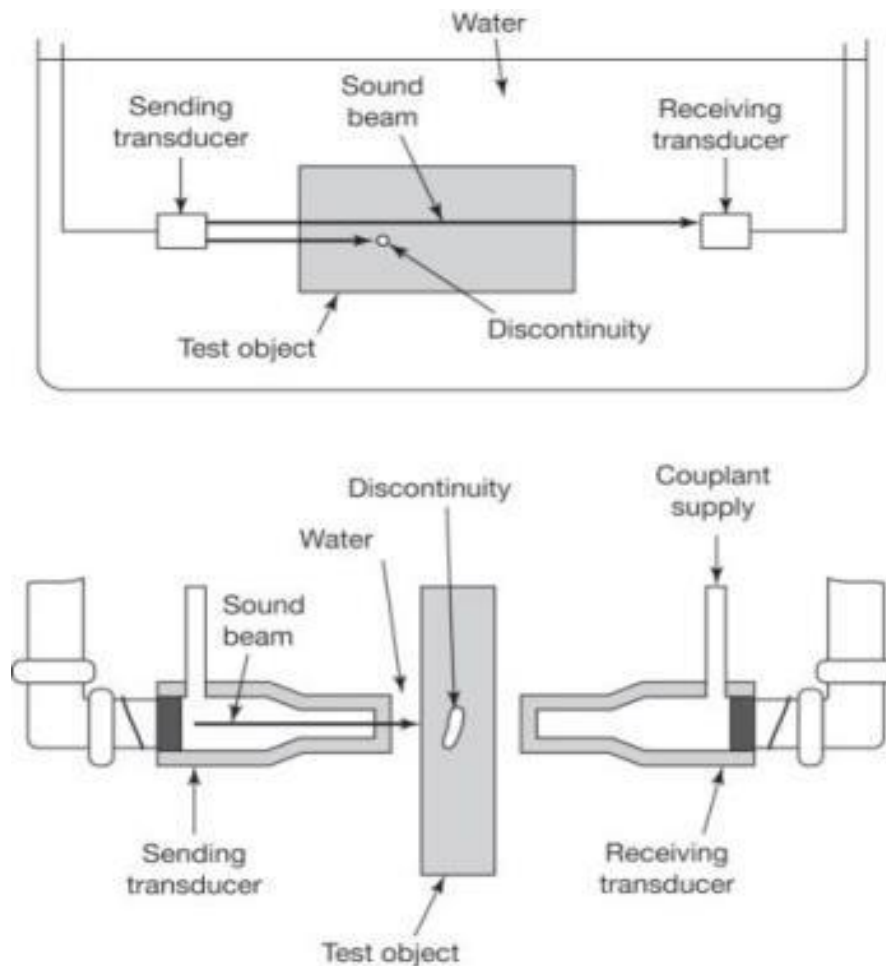


Figure I.4: Ultrasonic testing through transmission

Phased Array

Phased array inspections are done using a probe with multiple elements that can be individually activated. By varying the time when each element is activated, the resulting sound beam can be "steered," and the resulting data can be combined to form a visual image representing a slice through the part being inspected.

Time of Flight Diffraction

Time of Flight Diffraction (TOFD) uses two transducers located on opposite sides of a weld with the transducers set at a specified distance from each other. One transducer transmits sound waves and the other transducer acting as a receiver. Unlike other angle beam inspections, the transducers are not manipulated back and forth towards the weld, but travel along the length of the weld with the transducers remaining at the same distance from the weld. Two sound waves are generated, one traveling along the part surface between the transducers, and the other traveling down through the weld at an angle then back up to the receiver. When a crack is encountered, some of the sound is diffracted from the tips of the crack, generating a low strength sound wave that can be picked up by the receiving unit. By amplifying and running these signals through a computer, defect size and location can be determined with much greater.

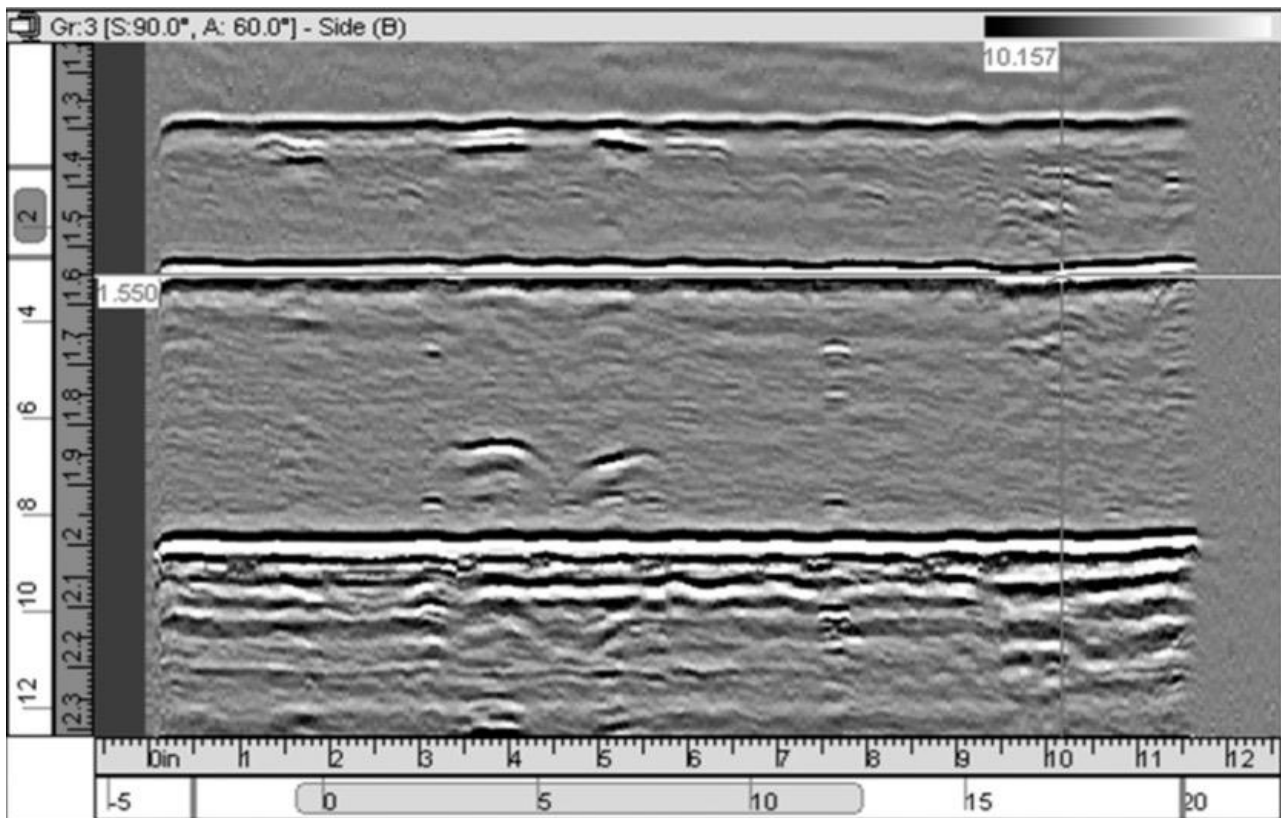


Figure I.5: accuracy than by conventional UT methods. The figure at right shows a TOFD display of weld indications.

I.3.3 Radiography NDT (RT)

Industrial radiography, or radiographic testing (RT), involves exposing an object to be inspected to penetrating radiation such that the radiation passes through the object and a recording medium is placed on the opposite side of the object. will appear. For thinner or less dense materials, such as aluminum, electrically generated X-rays (X-rays) are commonly used; for thicker or denser materials, gamma rays are commonly used. Masu. Gamma rays are emitted by the decay of radioactive materials, and the two most commonly used gamma ray sources are iridium-192 (Ir-192) and cobalt-60 (Co-60). Ir-192 is typically used for steels up to 2.5 to 3 inches thick, depending on the Curie strength of the source, and Co-60 is typically used for thicker materials due to its higher penetration ability. The recording medium can be industrial X-ray film or one of several types of digital radiation detectors. In both methods, the media is exposed to radiation passing through the test object, resulting in dark areas where more radiation has passed through the part and bright areas where less radiation has passed through the part. If there are voids or defects in the part, more radiation will pass through, resulting in a darker image on the film or detector, as shown in the image below.

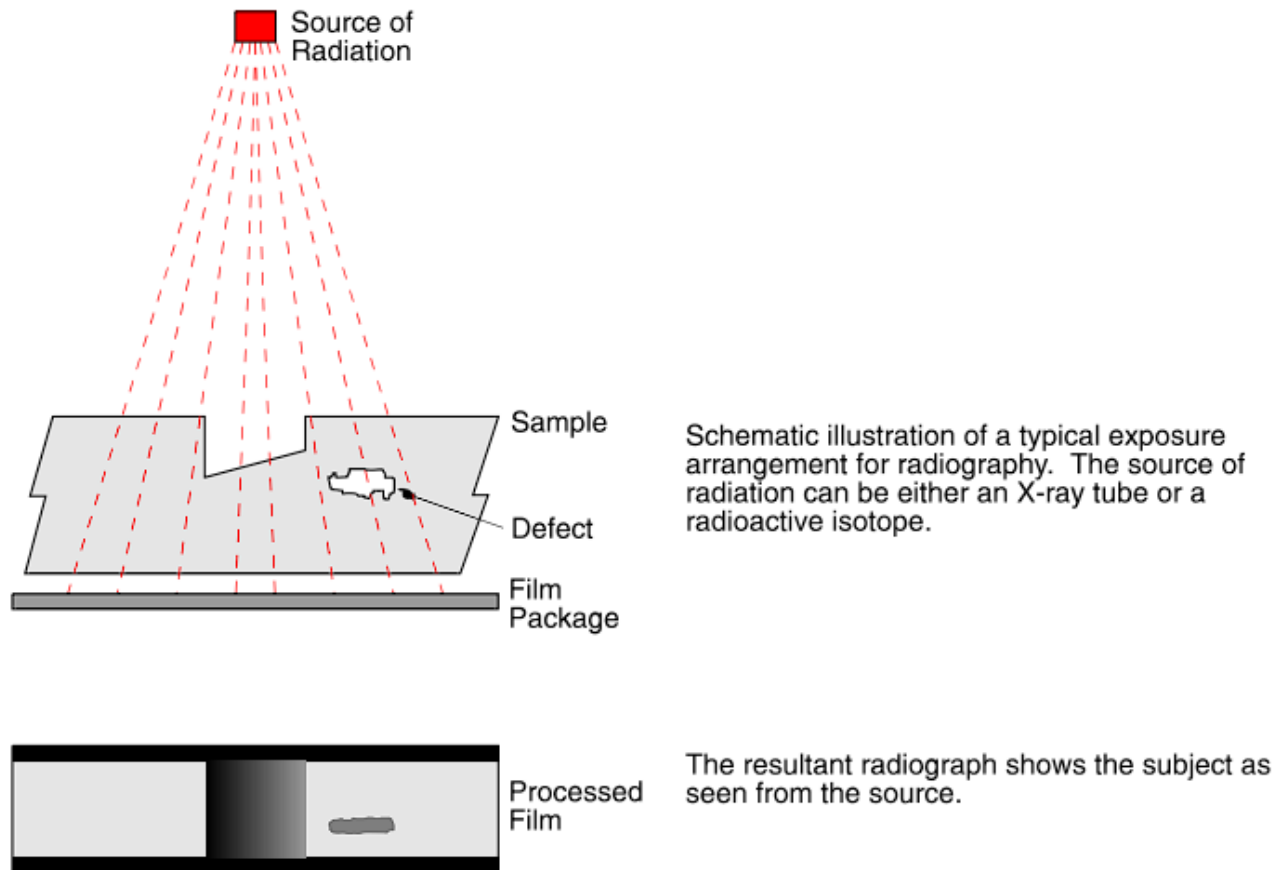


Figure I.6: Radiography testing

RT Techniques

Computed Radiography

Computed radiography (CR) is a transitional technology between film radiography and direct digital radiography. The technique uses reusable, flexible photostimulable phosphor (PSP) plates that are loaded into a cassette and exposed in a manner similar to traditional film radiography. The cassette is then placed in a laser reader and scanned into a digital image. This will take 1–5 minutes. Images can be uploaded to a computer or other electronic medium for interpretation and storage.

Computed Tomography

Computed tomography (CT), unlike traditional X-rays, uses a computer to reconstruct images of cross-sections of objects. CT images are created from multiple views taken at different times. Viewing angle reconstructed using a computer. Conventional radiography cannot accurately determine the location of internal discontinuities unless photographs are taken from multiple angles to localize the object through

triangulation. In computed tomography, a computer performs triangulation by observing each point in a plane from different directions.

Digital Radiography

Digital radiography (DR) directly digitizes the radiation that passes through an object, producing an image that can be displayed on a computer monitor. The three main technologies used in direct digital imaging are amorphous silicon, charge-coupled devices, and complementary metal-oxide semiconductors. These images can be viewed and analyzed in seconds compared to the time it takes to scan a computed radiography image. The increased processing speed is due to the unique structure of the pixels. This configuration also allows for higher resolution than in computer radiography and most film applications.

Film Radiography

Film radiography uses a film made of thin, clear plastic and coats one or both sides of the plastic with a thin layer of silver bromide. When these crystals are exposed to radiation, a reaction occurs that turns them into black metallic silver as they grow. This silver is "fixed" to the plastic during the development process and becomes the finished X-ray film after drying. For a film to be usable, the area of interest on the film (such as a weld area) must be within a certain density range (darkness range) and have sufficient contrast to make discontinuities in the object visible. and sensitivity. These factors depend on the intensity of the radiation, the distance from the film to the source, and the thickness of the part being tested. If any of these parameters are not met, another exposure ("shot") must be made for that area of the part.

I.3.4 Magnetic Particle NDT (MT)

Magnetic particle testing (MT) uses one or more magnetic fields to identify surface and near-surface discontinuities in ferromagnetic materials. The magnetic field can be applied using permanent magnets or electromagnets. When using electromagnets, the magnetic field is only present when a current is applied. When the magnetic field encounters a discontinuity across the direction of the magnetic field, the magnetic flux lines create their own leakage flux field, as shown in the diagram below (note the change in magnetic polarity). Because the magnetic flux lines do not spread much through the air, very fine-colored ferromagnetic particles are applied to the surface of the part. As a result of this process, particles are drawn into the stray magnetic field created by the discontinuity, creating a visible indication on the surface of the part. The magnetic particles may be a dry powder or suspended in a liquid solution and colored with a visible dye or a fluorescent dye that fluoresces at an ultraviolet wavelength of 365 nm.

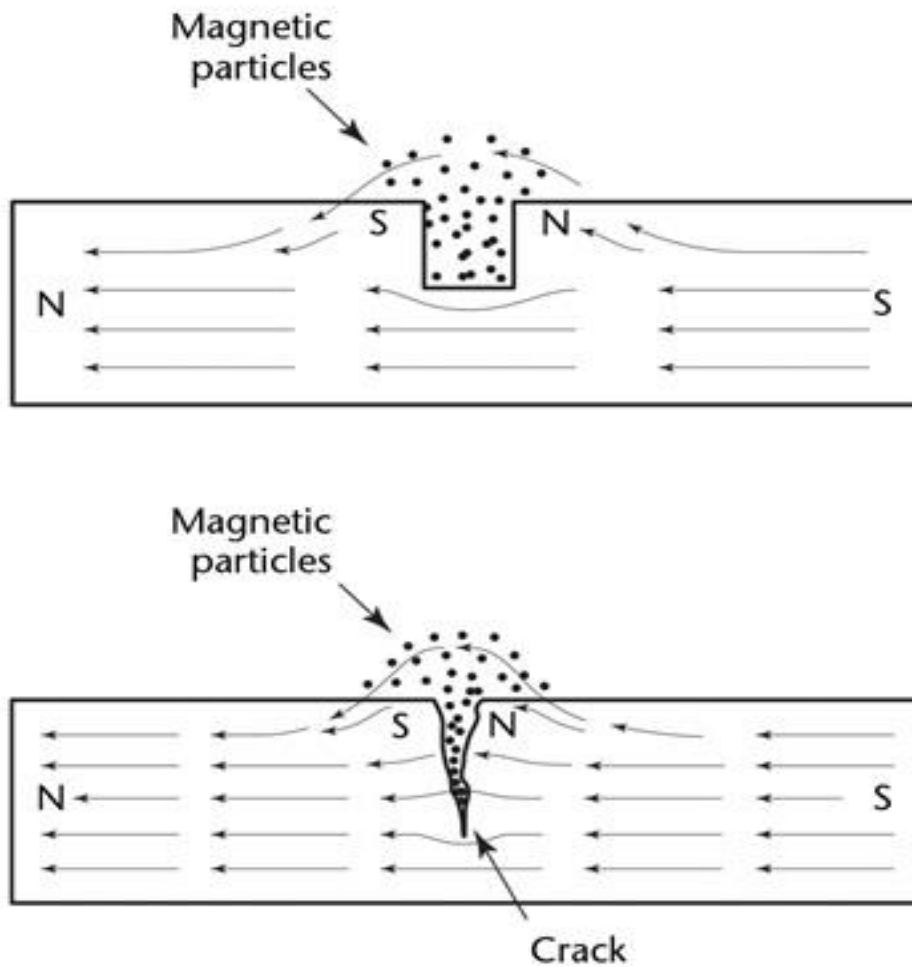


Figure I.7: Magnetic Particle testing

MT Techniques

Yokes

Most field inspections are performed using a yoke as shown to the right. As shown in the diagram below, an electrical coil is wrapped around a central core, and when a current is applied, it creates a magnetic field that extends from the core through the hinge legs and into the part. This is called longitudinal magnetization because the lines of magnetic flux flow from one leg to the other. When the legs are placed on top of a ferromagnetic component and power is applied to the yoke, a magnetic field is introduced into the component. Because the flow line extends from one leg to the other, there is a discontinuity perpendicular to the line drawn between the legs. To make sure you don't miss any of the displays, use the yoke once in the position shown, then rotate the yoke 90 degrees and use it again to ensure you don't miss any of the displays. This type of application is called indirect induction because all of the current is contained within the yoke and only the magnetic field penetrates the yoke.

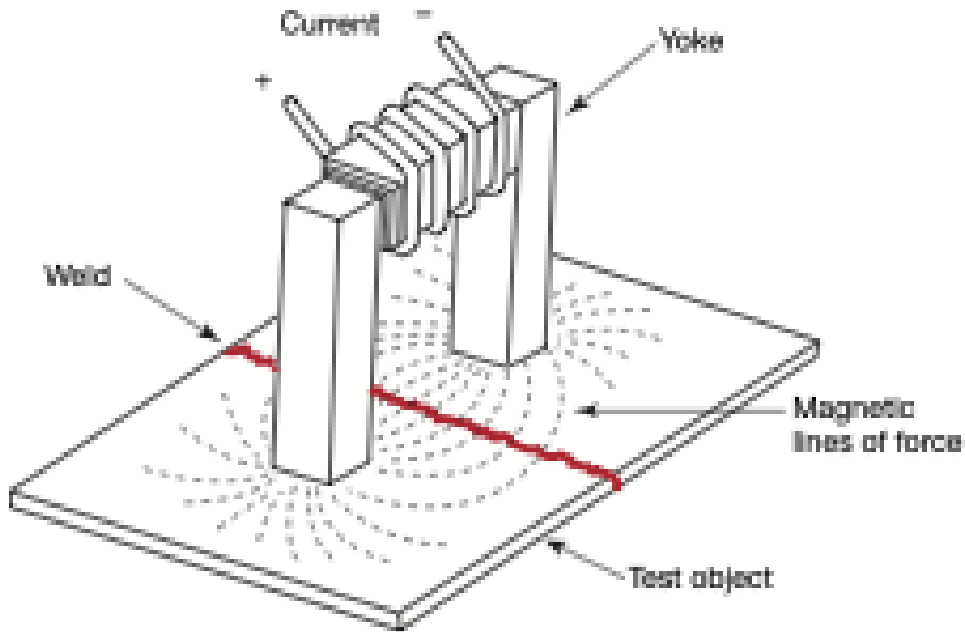


Figure I.8: MT yokes

Prods

The manufacturing unit uses direct induction, where an electric current is passed through the part and creates a circular magnetic field around the legs, as shown below. The magnetic field propagates between peaks perpendicular to the lines drawn between the peaks, so the display appears aligned parallel to the lines drawn between the peaks. As with the yoke, two tests are performed. The second test is performed with the tip oriented at 90° to the first application.

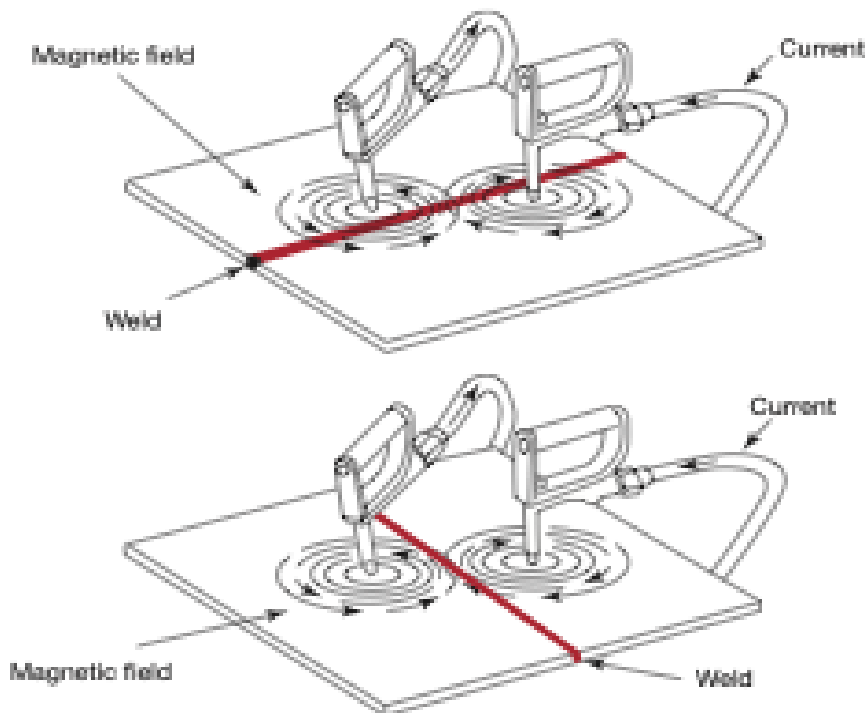


Figure I.9: MT prods

Coils

Electric coils (shown on the right) are used to generate a longitudinal magnetic field. When energized, the current creates a magnetic field around the wires that make up the coil, and the resulting lines of magnetic flux align within the coil as shown to the right. Due to the vertical magnetic field, the display is placed in coiled sections and aligned transversely with respect to the vertical magnetic field.

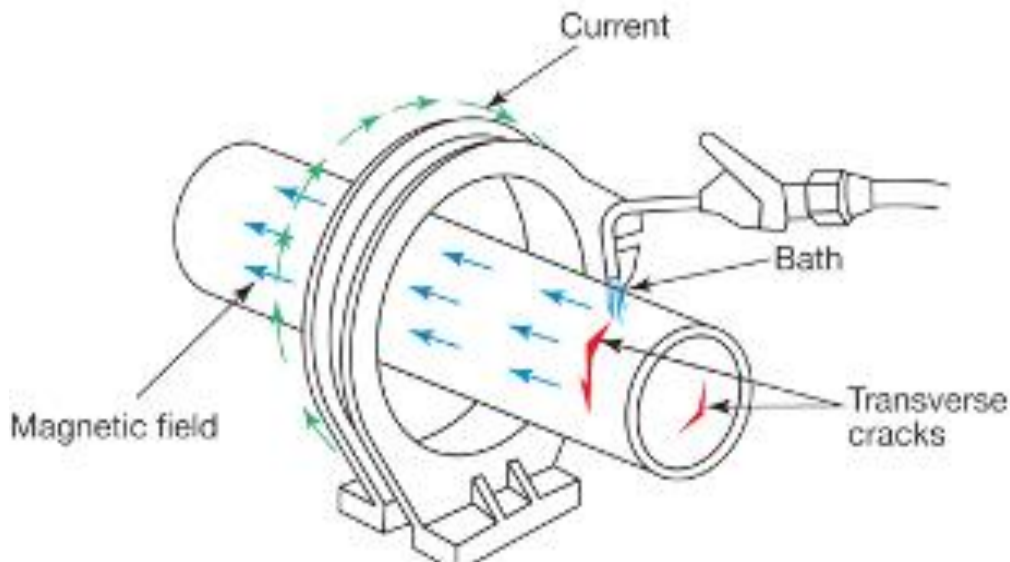


Figure I.10: MT coils

Heads

Most horizontal wet bath machines ('benchtop units') have both a coil and a series of heads that can carry an electric current and generate a magnetic field. In most cases, fluorescent magnetic particles in a liquid solution are used, hence the name "wet bath". When inspecting a part between the heads, the part is placed between the heads, the movable head is raised to firmly hold the part to be inspected between the heads, and the part is wetted with a bath liquid containing magnetic particle current. Applied as particles flow over the part. The current flows from head to head, and the magnetic field is oriented at 90° to the current, resulting in a display that is aligned parallel to the line between the heads. This type of test is commonly referred to as a "headshot."

Central Conductor

When testing hollow parts such as pipes, tubes, and fittings, place a conductive round rod between the heads and suspend the part (the "center conductor") from the rod, as shown in the image below. The parts are then wetted with bath liquid and an electric current is applied. The current flows through the center conductor, not through the components. You can check the inner and outer diameters of parts. Like a headshot, the magnetic field wraps around the specimen perpendicular to the flow of current, and the technique can find cues that run axially along the length of the part.

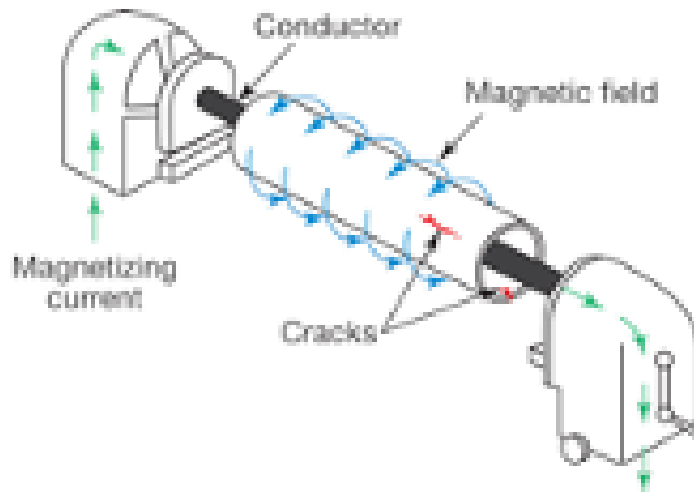


Figure I.11: MT central conductor

I.3.5 Acoustic Emission NDT (AE)

Acoustic emission (AE) testing involves applying localized external forces to the part under test, such as sudden mechanical loads or sudden changes in temperature or pressure. The resulting stress waves generate short-lived high-frequency elastic waves in the form of small material displacements or plastic deformations on the part surface, which are detected by sensors attached to the part surface. Using multiple sensors allows you to evaluate the resulting data to identify component discontinuities.

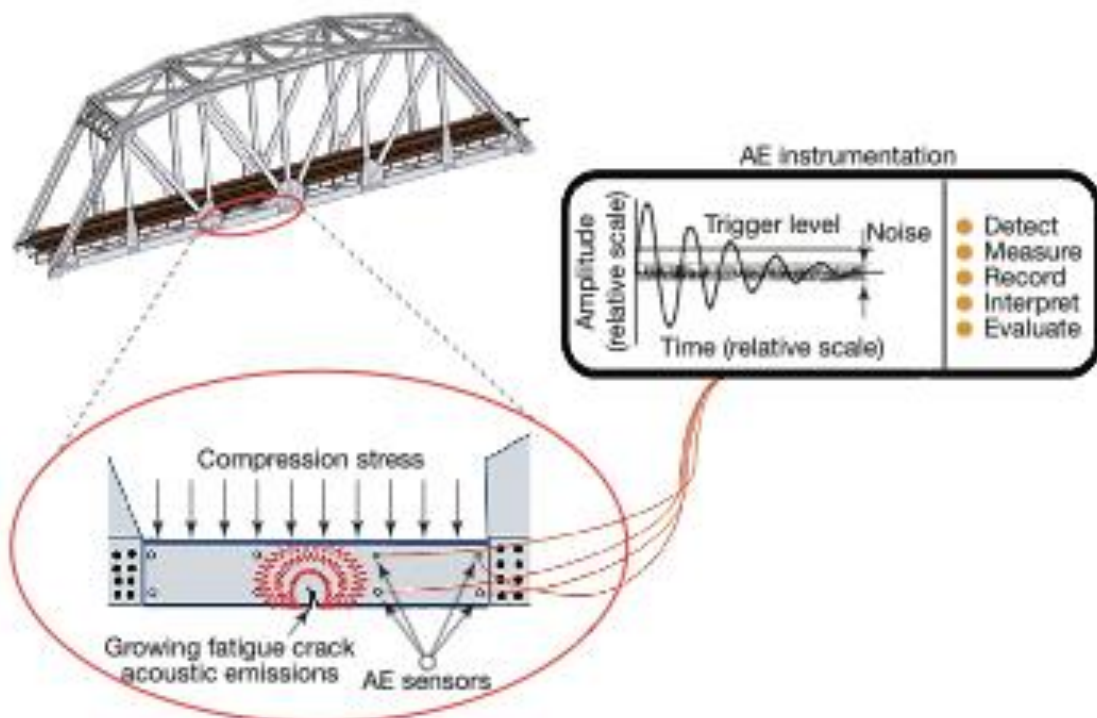


Figure I.12: Acoustic Emission testing

I.3.6 Dye Penetrant NDT (PT)

The basic principle of liquid penetration testing (PT) is that a very low-viscosity (very liquid) liquid (a penetrant) applied to the surface of a part will penetrate into cracks and voids opened in the surface. Once the excess penetrant is removed, the penetrant trapped in these cavities flows back and creates a display. PT can be performed on both magnetic and non-magnetic materials, but it does not work well on porous materials. Penetrants can be “visible,” meaning visible in ambient light, or fluorescent, which requires the use of an ultraviolet excitation light source at a wavelength of 365 nanometers. The visible color penetration process is shown on the right. When performing a PT test, it is essential that the surface being tested is clean and free of foreign objects or liquids that could prevent the penetrant from penetrating into the voids and cracks on the part surface. After the penetrant is applied, it is allowed to act on the surface for a certain period of time (the "penetrant residence time"). The parts are then carefully cleaned to remove excess penetrant from the surfaces. When removing the permeate, care must be taken not to remove the permeate that has flowed into the cavity. A thin layer of developer is then applied to the surface and left for a period of time until the penetrant penetrates into the developer through the voids and cracks and visible signs appear ('developer residence time'). After the developer reaches the specified exposure time, the part is visually inspected. When using fluorescent penetrants, ambient temperatures should be minimized, and a UV excitation source should be used. Most developers are fine-grained, white, talc-like powders that increase the size of the viewing area and provide color contrast to the penetrant used.

The image below shows the process of infiltrating a surface discontinuity with a penetrant. Infiltrate surface discontinuities with a liquid penetrant: First, apply the penetrant. The surface penetrant is then removed. After 30 seconds, a deep, narrow crack appears. And after 10 minutes, a deep and narrow crack finally appears.

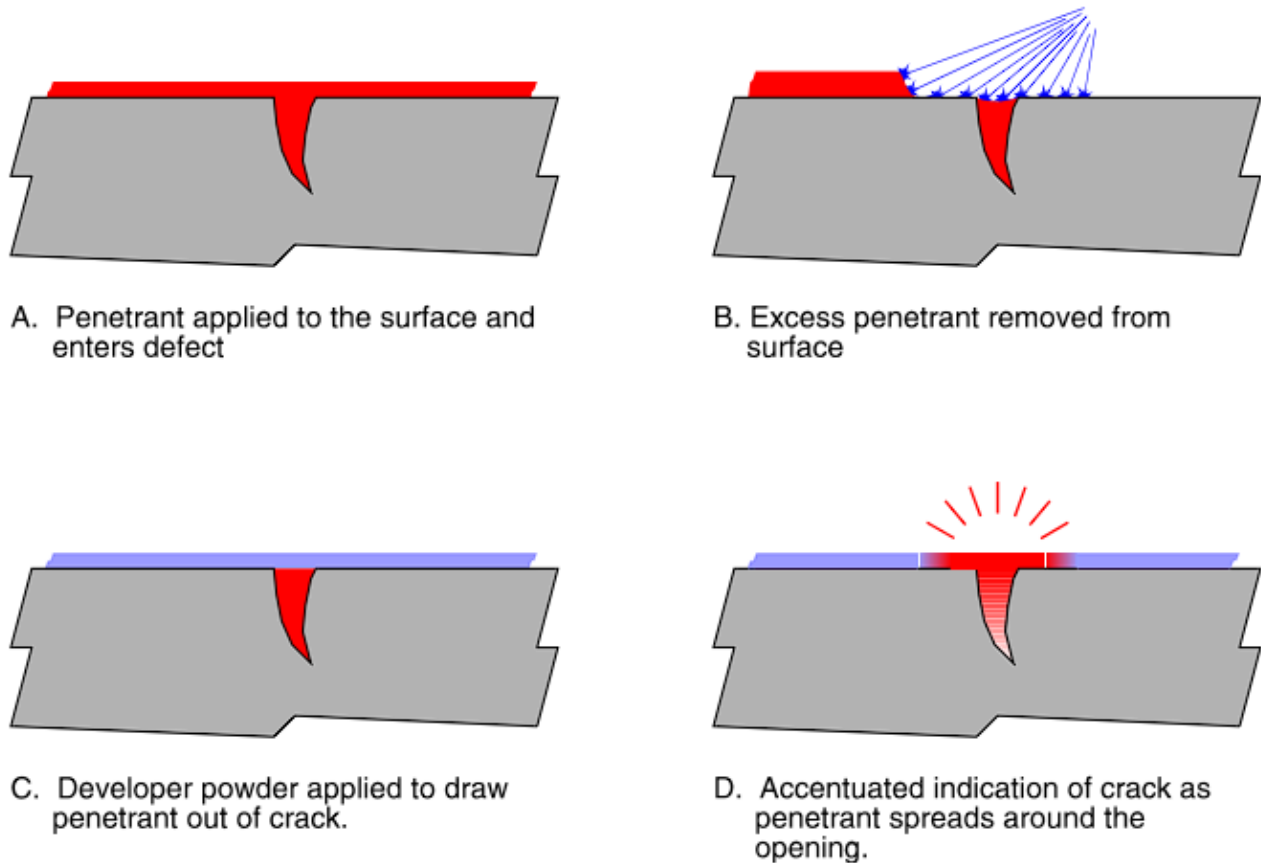


Figure I.13: Penetrant testing

PT Techniques

Solvent Removable

Solvent-removable penetrants are penetrants that require a solvent other than water to remove excess penetrants. These penetrants are usually visible in nature and are usually bright red in color, contrasting well with the white developer. Penetrants are typically sprayed or brushed onto the part. Once the penetration time has elapsed, wipe the part with a cloth dampened with penetration cleaner and apply developer. After applying the developer, inspect the part for leaks from the developer.

Water-washable

Water-washable penetrants contain emulsifiers in the penetrant, and the penetrant can be removed with a water spray. Penetrant is most commonly applied by dipping the part into a container of penetrant, but for larger parts, penetrant can also be applied by spraying or brushing. Once the part is fully covered with penetrant, it is placed on a draining platform until the penetrant is retained, then taken to a rinse station where it is washed with a powerful stream of water to remove excess penetrant. After removing excess penetrant, place the part in a hot air dryer or in front of a gentle fan until the moisture is removed. The part can then be placed in a dry developer tank and coated with developer, or left for the remaining dwell time before inspection.

Post-emulsifiable

Post-emulsifiable penetrants are penetrants that do not contain emulsifiers in their chemical composition, as is the case with water-washable penetrants. Post-emulsifiable penetrants are applied in a similar manner, but before the water washing step, an emulsifier is applied to the surface for a predetermined period of time (emulsifier residence time), and excess penetrants are removed. Once the emulsifier residence time has elapsed, the part is exposed to the same wash and development process used for washable penetrants. Emulsifiers can be lipophilic (oil-based) or hydrophilic (water-based).

I.3.7 Leak Testing (LT)

Leak Testing, as the name implies, is used to detect through leaks using one of the four major LT techniques: bubble, pressure change, halogen diode, and mass spectrometer testing. These techniques are described below.

LT Techniques

Bubble Leak Testing

As the name suggests, bubble leak testing is based on the visual detection of gas (usually air) escaping from a pressurized system. Small parts can be pressurized and immersed in a liquid tank, while larger containers can be inspected under pressure by spraying a soap solution onto the inspection area that creates fine bubbles. For flat surfaces, you can apply a soap solution to the surface and use a vacuum box to create negative pressure from the inspection side. If there is a continuous leak, bubbles will form to indicate the location of the leak. The image on the right shows a diagram of the bubble leak test, showing how the bubbles are forced out (by pressure) from the leak.



Figure I.14: Leak testing

Pressure Change Testing

Pressure swing tests can only be performed in closed systems. Leak detection is done by pressurizing the system or applying a vacuum and monitoring the pressure; loss of pressure or vacuum over a period of time indicates a leak in the system. Temperature changes within the system can cause pressure changes, so measurements may need to be adjusted accordingly.

Halogen Diode Testing

When testing halogen diodes, the system is pressurized with a mixture of air and a halogen-based test gas. After a set amount of time has elapsed, use a halogen diode detection device, or "sniffer," to locate the leak.

Mass Spectrometer Testing

Mass spectrometer testing can be performed by pressurizing the test part in a test chamber with helium or a mixture of helium and air and inspecting the surface with a sniffer that sends a sample of the air back to the spectrometer. Another technique creates a vacuum within the test chamber, and gases in the pressure system are sucked into the chamber through a leak. A mass spectrometer is then used to take a sample from the vacuum chamber, and the helium present is ionized, making trace amounts of helium easily detectable.

I.4 The difference between Destructive testing & NDT

This table represents the difference between destructive testing & NDT

Aspect	Destructive Testing (DT)	Non-Destructive Testing (NDT)
Objective	Destroys or alters the specimen to assess its properties.	Does not harm or alter the specimen; assesses properties without damage.
Purpose	Primary purpose is to evaluate material properties, including strength, toughness, and durability.	Primary purpose is to inspect and assess the integrity of materials or components without causing damage.
Sample Size	Typically requires a dedicated sample, which is usually destroyed during testing.	Requires access to the material or component itself, but the specimen remains intact.
Material Alteration	Results in material alteration or destruction.	Does not alter or damage the material being tested.
Speed	Often time-consuming, especially for destructive tests, as they may require extensive preparation and analysis.	Generally faster as it involves using various non-invasive techniques.
Cost	Can be expensive due to the need for specialized equipment and replacement of tested specimens.	Can be cost-effective in terms of equipment and labor, especially for routine inspections.
Applicability	Commonly used for material qualification, quality control, and research purposes.	Widely used in various industries for quality control, maintenance, and safety inspections.
Examples of Techniques	Tensile testing, impact testing, hardness testing.	Radiographic testing, ultrasonic testing, eddy current testing.
Safety Concerns	Safety precautions are necessary due to the destructive nature of tests.	Generally safer as there is no risk of material damage or harm to the operator.
Material Wastage	Results in material wastage as specimens are destroyed.	No material wastage since the specimens remain intact.
Extent of Information	Provides extensive information about material properties.	Provides information about the presence of defects or anomalies but may not provide detailed material properties.
Field of Application	Commonly used in material science, metallurgy, and research.	Used in a wide range of industries, including aerospace, automotive, manufacturing, and construction.

I.5 Conclusion

In this chapter we get the general idea of NDT with its applications in many domain and fields. NDT has many techniques which they use different ways to assess the conditions of materials and detect defect in components for better and more accurate results than the destructive testing.

NDT is an important way to maintain the functionality of materials and machines.

Chapter Two:

Theorem on inductive eddy current
sensors

II.1 Eddy current testing (ECT)

Eddy current technology, also known as eddy current testing (ECT), is a non-destructive testing (NDT) technique that uses electromagnetic induction to detect and evaluate defects at or near the surface of conductive materials. An alternating magnetic field is generated and the resulting induced currents, so-called eddy currents, are measured within the material under test. Eddy current technology is particularly suitable for testing components made of non-ferromagnetic materials such as aluminum, copper, and stainless steel. It is widely used in applications such as surface crack detection, material sorting, conductivity measurement, layer thickness measurement, and heat treatment verification. Eddy current inspection allows inspectors to find very small defects that are invisible to the naked eye. Eddy current testing is one of several electromagnetic testing methods used for non-destructive testing (NDT). These tests are conducted with the aim of performing tests without damaging the test object.

II.2 The history of ECT

The eddy current phenomenon was first observed by researcher François Arago in 1824, but it is the inventor “Léon Foucault” who is actually credited with its discovery.

Foucault’s discovery happened in 1855, and was based in part on research conducted by Michael Faraday, who discovered the principle of electromagnetic induction in 1831.

This principle describes the relationship between electric currents and magnetic fields, and was the result of Faraday observing that a magnetic field will pass through a conductive material in a manner that varies over time as an electric current flows through it.



Figure II.1: A Faraday Cage, which was invented by Michael Faraday to study electromagnetism

Despite these early observations, it wasn't until 1879 that scientist David Hughes discovered the potential use of eddy currents. Hughes was able to show that the properties of a coiled conductive wire change when it comes into contact with different types of conductive materials. Eddy current testing was not used until World War II, when German professor Friedrich Förster began researching industrial applications. After the war, Förster founded a company called Förster Group, which manufactured equipment for eddy current testing, further developing the technology and expanding its applications.

Currently, ECT is one of the most commonly used NDT techniques by examiners and has a long track record of providing reliable data.

II.3 The principle of Eddy current

When a conductor (usually a copper coil) is connected to a circuit and an alternating current flows through it, a magnetic field is generated around the coil based on the principle of self-inductance. The right-hand rule determines the direction of the magnetic field. The strength of the magnetic field is determined by the magnitude of the excitation current in the coil and its frequency, which corresponds to the alternating frequency of the excitation current. When a coil is placed near a metal sample, eddy currents are induced within the material. Eddy currents in materials are similar to eddy currents in liquids, hence the name. During electromagnetic induction, eddy currents flow in the opposite direction of the coil current, and a counterforce, a "secondary" magnetic field, is also created. The ECT system circuit is normalized (also called "balanced") to this opposing secondary field. Moving the coil to the location of the defect on the sample interrupts the flow of eddy currents and changes the eddy current path and eddy current density. Subsequent changes in the strength of the secondary magnetic field change the equilibrium state of the system, which is recorded as a change in impedance within the coil. Typical ECT systems represent this change as a voltage measurement.

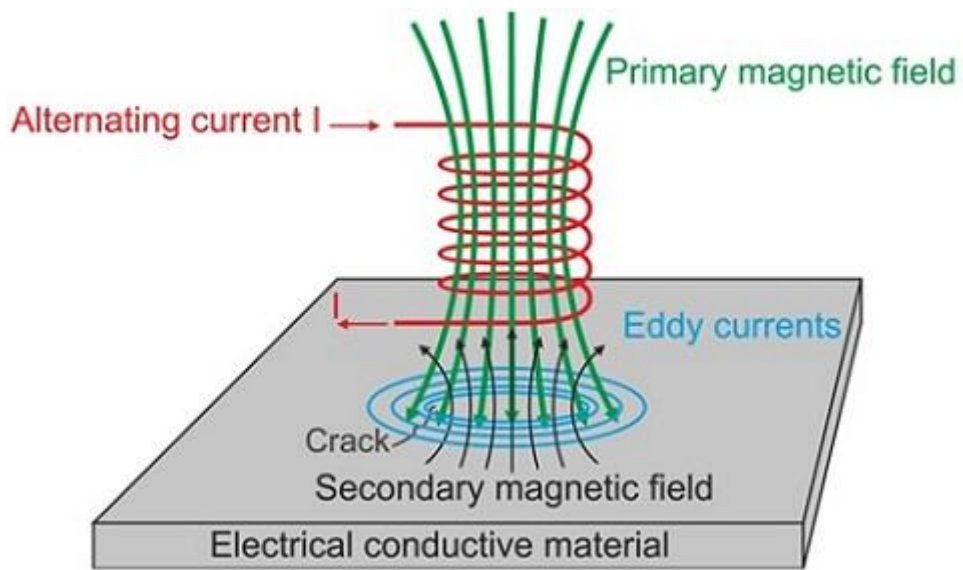


Figure II.2: Eddy current principle

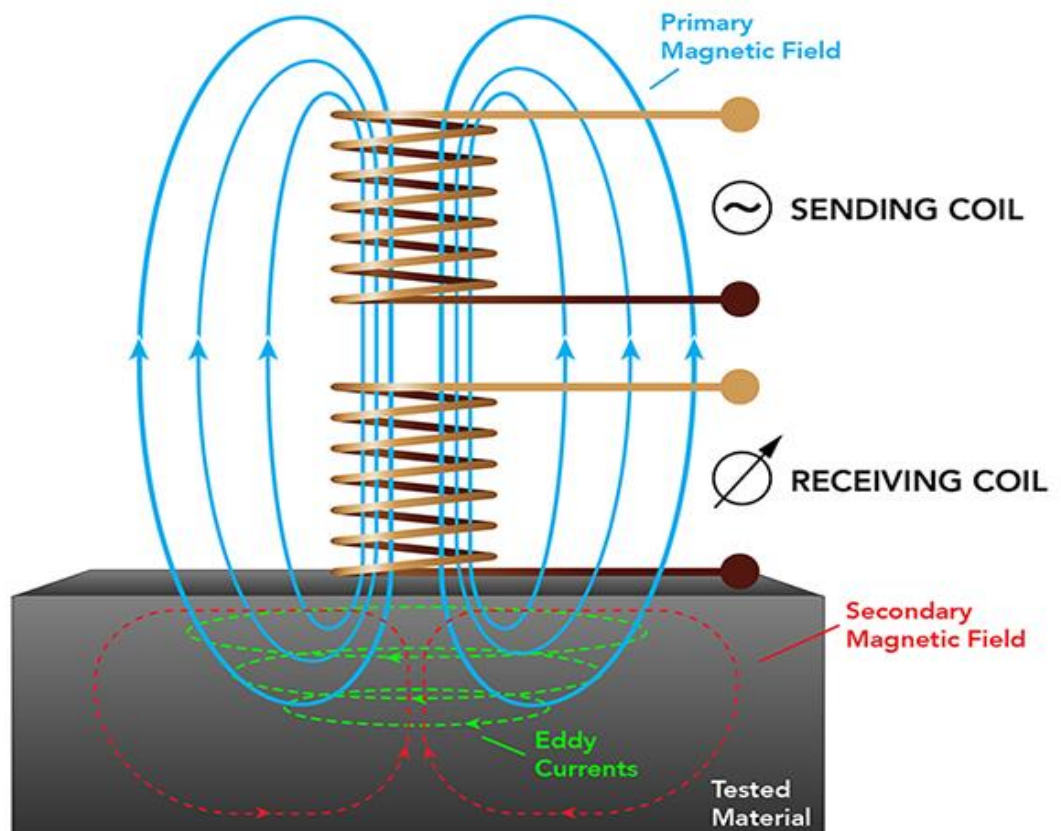


Figure II.3: ECT principle with two coils

II.4 Block diagram of the device

The chain of non-destructive testing by eddy current essentially comprises a generator supplying the sensor, the sensor itself, the product to be checked, including possibly the presence of defects and finally the observation system which displays a derived quantity eddy currents. The following paragraphs describe each element of this installation.

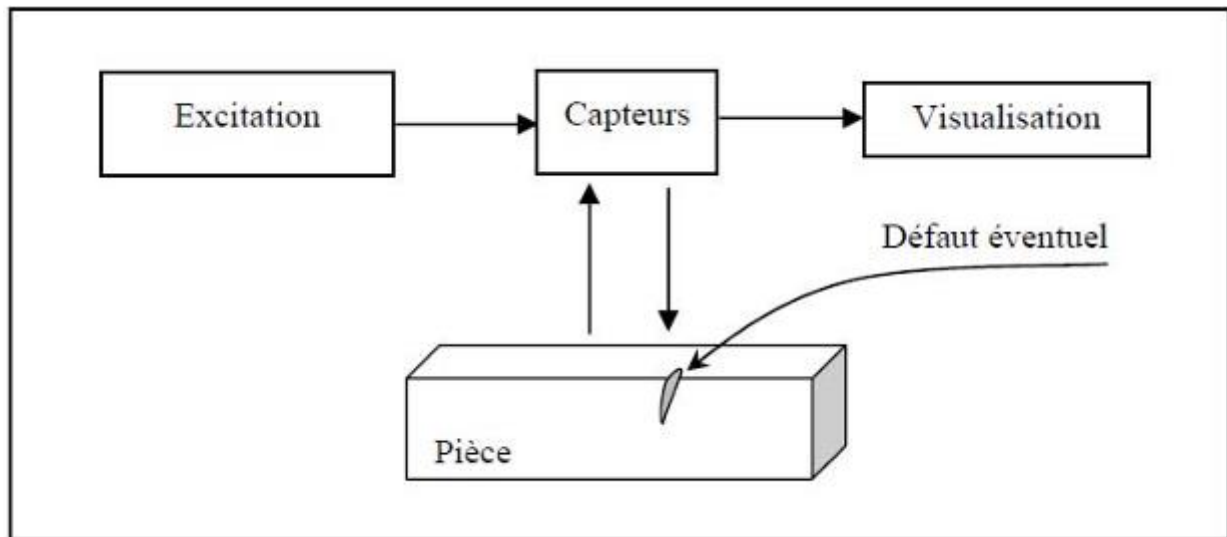


Figure II.4: Block diagram of the control chain

II.5 Electromagnetic Testing Procedure

There are several different eddy current testing methods.

Here are some of the most common ones:

II.5.1 Eddy Current Array

Eddy current array inspection uses a series of charged coils to create a sensitivity profile that can identify defects in materials. In this type of test, the tester must be careful to avoid mutual inductance between individual coils.

II.5.2 Heat Exchanger Testing

Heat exchanger testing is one of the most common applications of eddy currents. In this type of test, the inspector uses eddy currents to detect defects in metal pipes and provides instant data after just one pass of the eddy current test probe.



Figure II.5: Heat exchanger tubes

II.5.3 Lorentz Force ECT

Lorentz eddy current testing is a new NDT method that uses multiple DC magnets to overcome the skin effect (i.e., the current flowing in the center of the conductor is canceled out by a corresponding gain in the skin). In addition to the use of multiple magnets, Lorentz force eddy current testing utilizes relative motion to allow inspectors to perform fast and accurate eddy current testing.

II.5.4 Surface Array Testing

Surface array testing is commonly used in the aerospace industry to help measure conductivity and corrosion/wall thickness with high precision. This type of test is very versatile and can find defects in hard-to-reach locations where other testing methods may not work.

II.6 Probes

Constructing a suitable probe is a process that has a major impact on understanding the operating principles of eddy current applications. The object to be inspected is typically placed under the probe for inspection on an open surface (some differences in the discussion apply to inspecting pipes, wires, or similar). Therefore, it is desirable to direct the magnetic field to the surface below the probe. This means that the current-carrying element of the probe is usually coiled, and ferromagnetic material can be used to shield magnetic fields in other directions. A ferromagnetic material placed within the coil causes a focusing effect on the applied magnetic field. Ferrite is also often used to increase the magnetic field strength within the probe and increase the signal-to-noise ratio. A ferromagnetic core may also serve better against wear as the probe is scanned over a test object surface. Polytetrafluoroethylene (PTFE) tape is also widely used as a protective and replaceable layer. The copper coil is usually placed inside an epoxy body, and the winding has a thin isolating layer for protection against currents flowing between the wound layers of the coil. The coil that is carrying the external current can also serve as a sensor for changes in impedance. In that case, it was called an absolute probe, "see figure down below". However, it is also common to use another coil for sensing or to measure the impedance difference between two or more coils. This can be extended to the construction of array or matrix probes to gain larger coverage in a single scan (Grimberg et al. 2006). Specialized probes may have complex geometries and can also be sensitive to the direction of the scan, for example, when optimized for the detection of defects below the surface (Stepinski 2002; Uchanin 2001). There are also probes that are developed for specialized inspections, for example, welds (Noritaka et al. 2006). The sensing element, which is usually a coil, can be replaced by a Hall or giant magnetoresistive (GMR) sensor to achieve higher sensitivity, especially at low frequencies (Dogaru and Smith 2001). Probes manufactured as printed circuits and specific assemblies offering the possibility of adapting to curved surfaces (Marchand et al. 2010) or so-called serpentine-wound magnetometers (Goldfine et al. 2005) have also been developed. The magnetic field exciter and receiver elements must be included in the mathematical model of the EC test and may require complex probe descriptions. [11]

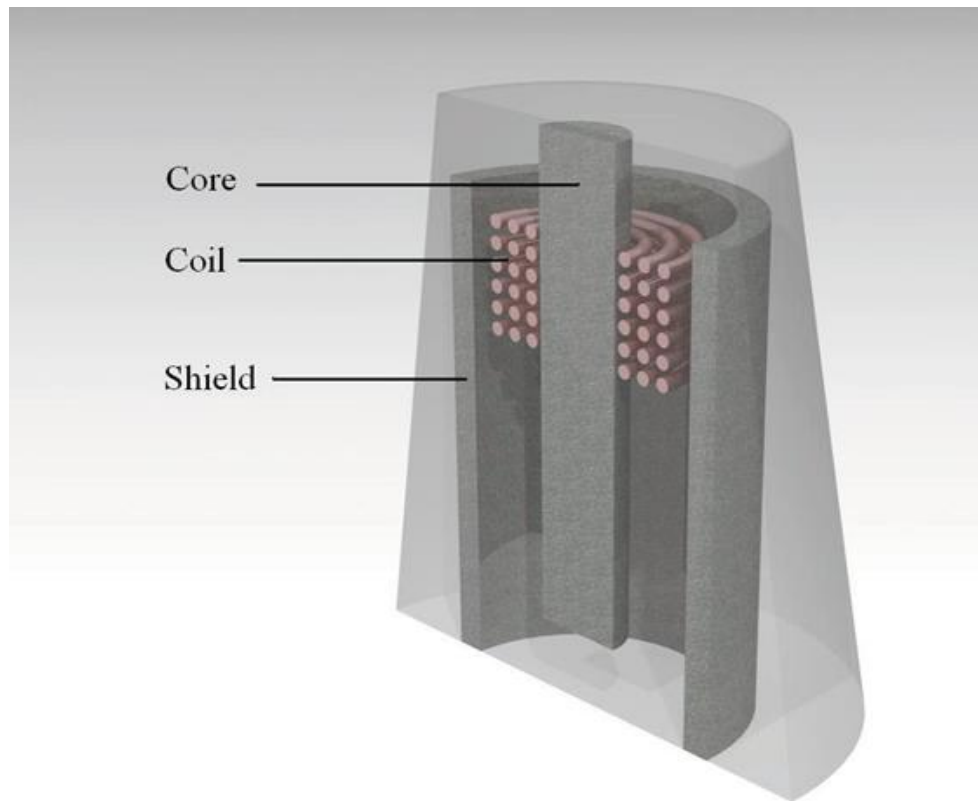


Figure II.6: Cross section of an absolute eddy current probe with ferrite core and shielding.

II.7 Purpose of Eddy Current Testing

Eddy Current Testing is used for various purposes; here are some of the objectives of Eddy Current Testing:

- Detection of flaws, material identification.
- Heat treatment analysis of specific elements.
- Measurement of the thickness of the material surface coating.

II.8 Factors that may impact Eddy Current Testing

There are multiple factors that may have an impact on the accuracy of an eddy current testing procedure. For example:

II.8.1 Electrical conductivity

Electrical conductivity is often described as the ease with which electrons flow within a material. Conductivity is the reciprocal of resistivity, and the commonly used symbol is σ . The SI unit of conductivity is the Siemens meter. The previously used metric unit was meter/ Ω mm². However, the unit most commonly used by NDT users is the International Annealed Copper Standard (IACS), which compares the conductivity of metals as a percentage of the conductivity of pure copper (for example, the IACS content of aluminum is approximately 37%).

II.8.2 Magnetic Permeability

The magnetic permeability of the material under test has a decisive influence on the strength of the eddy current flow. “Noise” caused by changes in the magnetic permeability of ferrous materials complicates eddy current testing of carbon steel welds, and strong signals from the steel supports of cupronickel-nickel heat exchanger tubes obscure signs of failure. Permeability effects can be eliminated by magnetic saturation, multifrequency testing, or differential coil placement. Transmittance measurements are the basis for bridge material selection.

II.8.3 Frequency

The frequency of the alternating current passing through the eddy current test coil affects the depth of penetration of the eddy current field in the test material. This is also known as the skin effect. The intensity of the eddy current flow will decrease exponentially with increasing depth into the material.

The SDP can be calculated using the formula:

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{1}{\mu\pi f\sigma}} \quad (\text{II.1})$$

Where:

δ = SDP (m)

f = frequency (Hz)

σ = conductivity (S/m)

μ_r = relative permeability

II.8.4 Lift-off/Stand-off distance

This term is used to describe the proximity between the coil and the test surface. Small lifts have a large effect on signal amplitude. When analyzing eddy current signals using an impedance plane representation, the lift-off signal has a different phase angle than the crack signal or conductivity change.

The lift-off effect is used to measure non-conductive coating thickness.

II.9 Eddy Current Testing pros and cons

ETC allows inspectors to find defects on the surface and subsurface level of an object easily and with a high degree of accuracy—but that’s just one of the reasons inspectors commonly use it to look for defects in a material.

Here’s a list of pros and cons for ECT:

II.9.1 Pros

- It is incredibly versatile in terms of accuracy and portability/ease of use).
- Its results are highly reliable, providing data of a high quality.
- It is highly sensitive, allowing inspectors to identify defects as small as .5mm.
- It is effective on surfaces that have paint or some other type of coating on them.
- It can be used on high-temperature and underwater surfaces.
- It provides immediate data.
- It takes a relatively short amount of preparation time to perform (i.e., not much pre-cleaning or couplant is needed).
- It can be automated for testing uniform parts, such as boiler tubes or wheels.

II.9.2 Cons

- It only works with a current.
- ECT current always runs parallel to the surface of a material, so a defect that doesn’t come in direct contact with the current can’t be detected—and this means that some defects may go undetected.
- It’s not ideal for inspecting large areas.
- It’s efficacy for different depths can vary.
- It can be subject to changes in magnetic permeability, which can make it hard to use it for inspecting parts of ferromagnetic materials. It’s also non-conductive with ferromagnetic materials, as ECT equipment is subject to permeability changes on the welds.
- Interpreting signals correctly can be difficult, since it may require weeding out non-relevant data points.

II.10 Conclusion

In this chapter I explained pretty much everything about NDT technique “Eddy current” based on a bibliographic research.

Eddy current testing is a fast, reliable, and cost-effective method of non-destructive testing. It is widely used in the aerospace, automotive, and power generation industries, and can be used to detect flaws, measure thickness, and measure conductivity.

Eddy current testing is not without its limitations and external factors such as temperature, humidity, and the presence of other metals can affect the accuracy of the test. However, it is still a great option for companies that need to test large numbers of components quickly and accurately.

Chapter Three

Numerical modeling by FEM of an
inductive eddy current sensor

III.1 Introduction

The aim of this chapter is to define electromagnetism and its history of discovery, also elaborate Maxwell's equations of electricity and magnetism that describe the electromagnetic phenomena involved in the Non-Destructive Testing using Eddy current.

The goal of this work is to use mathematical modeling to characterize the reliability and capacity of eddy current technique to detect and characterize defects embedded in the system's pieces and components.

The numerical model studied in this chapter enables to predict and evaluate important parameters act directly on the impedance responses of eddy current testing.

III.2 Electromagnetism

III.2.1 Definition

In physics, electromagnetism is an interaction that occurs between particles with electric charge via electromagnetic fields. The electromagnetic force is one of the four fundamental forces of nature. It is the dominant force in the interactions of atoms and molecules. Electromagnetism can be thought of as a combination of electrostatics and magnetism, two distinct but closely intertwined phenomena.

III.2.2 History

Development of the eddy current method was based on certain discoveries made during the early nineteenth century about the relationship between electricity and magnetism. In fact, the relevant electromagnetic principles were discovered in the same sequence in which they occur during an eddy current test. In 1820, Hans Christian Oersted, a Dane, discovered electromagnetism -the fact that an electrical current flowing through a conductor causes a magnetic field to develop around that conductor. Oersted discovered electromagnetism accidentally. While demonstrating that heat is developed when an electric current passes through a wire, Oersted observed that the needle of a magnetic compass deflected perpendicular to the wire while the current was passing through it. Electromagnetism is the principle on which eddy current coils operate. Whereas Oersted was using direct current developed from a battery voltage when he discovered electromagnetism, an eddy current instrument employs alternating electric current flowing through the test coil in order to develop an alternating magnetic field around the coil.

In 1831, an Englishman, Michael Faraday, discovered electromagnetic induction-the fact that relative motion between a magnetic field and a conductor induces a voltage in that conductor, causing an electric current to flow. Consequently, when the alternating magnetic field of an eddy current instrument's coil is brought in contact with a conducting test object, a voltage is developed, causing a current to flow in the test object. Thus, electromagnetic induction is considered to be the operating principle

of eddy current testing. Joseph Henry also independently discovered electromagnetic induction in the United States at about the same time. In fact, the unit of measure for induction is named after him. [1]

III.3 Maxwell's equations

Maxwell's equations represent one of the most elegant and concise ways to state the fundamentals of electricity and magnetism. From them one can develop most of the working relationships in the field. Because of their concise statement, they embody a high level of mathematical sophistication and are therefore not generally introduced in an introductory treatment of the subject, except perhaps as summary relationships. [8]

III.4 Mathematical Modeling: Magneto-dynamic formulation

Mathematical modeling of eddy currents testing provides a good basis for allowing an early evaluation of part inspection. The equations governing the general time varying fields in section include magnetic and conducting isotropic materials can be derived from the Maxwell equations:

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \frac{\partial(\epsilon \mathbf{E})}{\partial t} \quad \text{Ampere-Maxwell law} \quad (\text{III.1})$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{Faraday's law} \quad (\text{III.2})$$

$$\nabla \cdot (\mu \mathbf{H}) = 0 \quad \text{Gauss's law for magnetism} \quad (\text{III.3})$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon} \quad \text{Gauss's law} \quad (\text{III.4})$$

Where \mathbf{E} and \mathbf{H} are the electric and magnetic fields, and $\rho, \sigma, \epsilon,$ and μ are respectively the volume density of electric charges, conductivity, permittivity, and permeability of the medium.

Conductivity ranges vary from zero in insulators to $> 10^6$ (S/m) in metals.

Permittivity ranges vary from the value ϵ_0 [$\epsilon_0 = 10^{-9}/36 \pi$ (SI)] in vacuum to up to $100 \epsilon_0$ in some dielectric materials.

The range for permeability is from μ_0 [$\mu_0 = 4 \pi 10^{-7}$ (SI)] in vacuum to about $5000 \mu_0$ in soft iron.

Potentials must be introduced as usual in 3D eddy current finite element formulations. Thus, the flow field can be constructed by introducing two potentials, the magnetic vector potential \mathbf{A} and the electric scalar potential Φ :

– The magnetic vector potential \mathbf{A} is linked with the magnetic flux density \mathbf{B} by:

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (\text{III.5})$$

– The relation between the electric field and the magnetic vector potential can be derived as:

$$\mathbf{E} = -\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t} \quad (\text{III.6})$$

Substituting (5) and (6) in (1) and (4), and using the constitutive relation ($\mathbf{B} = \mu\mathbf{H}$), (1) becomes:

$$\nabla\mathbf{x}\nabla\mathbf{x}\mathbf{A} = \mu\sigma\left(-\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t}\right) + \mu\epsilon\left(\frac{\partial(-\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t})}{\partial t}\right) \quad (\text{III.7})$$

After simplification by the curl-curl relationship (i.e.: $\nabla\mathbf{x}(\nabla\mathbf{x}\mathbf{A}) = -\nabla.(\nabla\mathbf{A}) + \nabla(\nabla.\mathbf{A})$).

Equation (8) is given by:

$$-\nabla.(\nabla\mathbf{A}) + \nabla(\nabla.\mathbf{A}) - \mu\sigma\left(-\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t}\right) = \mu\epsilon\left(\frac{\partial(-\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t})}{\partial t}\right) \quad (\text{III.8})$$

Using the Coulomb gauge ($\nabla.\mathbf{A} = \mathbf{0}$) and the relation ($\nabla\Phi = \mathbf{0}$) “there is no gradient of a scalar potential in (8) if there is no initial static charge on the medium”. Equation (8) is written as:

$$-\nabla^2\mathbf{A} + \mu\sigma\left(\frac{\partial\mathbf{A}}{\partial t}\right) = \mu\epsilon\left(\frac{\partial(-\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t})}{\partial t}\right) \quad (\text{III.9})$$

Or

$$\nabla^2\mathbf{A} = \mu\sigma\left(\frac{\partial\mathbf{A}}{\partial t}\right) - \mu\mathbf{J}_{source} \quad (\text{III.10})$$

The gradient of Φ is implicit in \mathbf{J}_{source} .

The eddy current problem can be described mathematically by the following equation in terms of the magnetic vector potential:

$$\nabla^2\mathbf{A} + \mathbf{K}^2\mathbf{A} = -\mu\mathbf{J}_{source} \quad (\text{III.11})$$

Where \mathbf{A} represents the magnetic vector potential, μ is the magnetic permeability, \mathbf{J}_{source} is the excitation current density,

$$\mathbf{K}^2 = \omega\mu(\mathbf{j}\sigma + \omega\epsilon), \quad (\text{III.12})$$

ω is the angular frequency of the excitation current (rad).

The magnetic vector potential can be found by solving (10) with appropriate boundary conditions attached to the studied configuration, and once this potential is given, other physical parameters can be deduced from it. [12]

III.5 Finite element method

The finite element method (FEM) is a popular method for numerically solving differential equations arising in engineering and mathematical modeling. Typical problem areas of interest include the traditional fields of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential.

The FEM is a general numerical method for solving partial differential equations in two or three space variables (i.e., some boundary value problems). To solve a problem, the FEM subdivides a large system into smaller, simpler parts called finite elements.

This is achieved by a particular space discretization in the space dimensions, which is implemented by the construction of a mesh of the object: the numerical domain for the solution, which has a finite number of points. The finite element method formulation of a boundary value problem finally results in a system of algebraic equations. The method approximates the unknown function over the domain.

Indeed, the complexity of the geometries of the studied problems induced that the analytical solution exists only for limited simple cases, and obviously, our interest is directed towards the search for the approximate numerical solutions.

Based on the Galerkin's method, the finite element formulation of (III.10) can be developed. The studied configuration is discretized into a number of tetrahedrons and the nodal shape functions defined on this mesh are the basis functions. The vector and scalar functions are approximated by the sets of these basis functions, as:

$$A = \sum_{i=1}^K N_i A_i \quad (\text{III.13})$$

Where k is the number of nodal points in the element (in this case $K = 4$), N_i and A_i : are the nodal interpolation functions and the value of potential function corresponding to the i^{th} node respectively of the element.

The approximation for the magnetic vector potential in (III.13) is substituted into the Galerkin weighted residual technique to set up the finite element equations. After some usual mathematical manipulations, the approximation of nodal values results in equations which in matrix form can be written as:

$$([S^e] + j[R^e])\{A^e\} = \{Q^e\} \quad (\text{III.14})$$

$[S^e]$ is the $k \times k$ real part of the elemental matrix, $[R^e]$ is the $k \times k$ imaginary part, $\{Q^e\}$ is the $k \times 1$ vector of contributions at the nodes of the element from the current densities, and $\{A^e\}$ is the $k \times 1$ vector of unknown values of the magnetic vector potential at the nodes of the element.

The elemental contributions of the solution can be calculated and summed into a global system of equations:

$$[K]\{A\} = \{Q\} \quad (\text{III.15})$$

Where $[K]$ is the $N \times N$ banded symmetric complex global matrix (N is the total number of nodes), and $\{Q\}$ and $\{A\}$ are respectively the $N \times 1$ complex source matrix and the $N \times 1$ complex vector of unknowns.

The system is solved using a developed code. Special techniques are used to the storage of the global matrix elements by the elimination of zero elements and storage of nonzero elements as a $1D$ array. And the Gauss elimination method is chosen like method of resolution. [12]

III.6 Conclusion

One of the important benefits of finite element method is that complex geometries can be studied. In the field of modeling and simulation of eddy current technique this feature enables the study of impedance responses on complex parts as well as using defects and probes with complex shapes. There are also possibilities to implement complex material properties in 3D finite element models.

The finite element method was applied successfully since it adapts for any chosen section.

Factors such as the type of material, surface finish and condition of the material, the design of the probe, and many other factors can affect the sensitivity of the inspection.

Further investigations have to be done in order to verify: the detection of defects, the influence of the various parameters on the control of the impedance responses and the increasing of analysis, which enables to minimize errors and benefit more of the performance of the finite element analysis.

Chapter Four:

2D & 3D Simulation and analysis
of results

IV.1 Introduction

In this Chapter, I am going to demonstrate the process of crack detection using eddy current testing as part of an electromagnetic problem with FEMM (2D) & COMSOL multiphysics software (3D) that is a leading simulation software platform that enables students “as me”, engineers, scientists, and researchers to model, simulate, and optimize complex physical systems. It provides a versatile environment for solving multiphysics and multiscale problems, making it a valuable tool in various fields, including engineering, physics, and the sciences.

FEMM is a light software mainly for 2D simulations that includes magnetic problem solving.

COMSOL provides great imaging performance, easement in building geometries in all spacial dimensions and it has an optimized FEM (Finite Element Method) in which the latter is used in solving mathematical complex problems in electromagnetics or fluid dynamics, heat transfer, acoustics....etc.

IV.2 2D simulation: (using Femm)

IV.2.1 Simulation steps

Femm software is so basic and very easy to handle when simulating any problem, as I do have a magnetic problem to solve, I first start a new file, then define the problem type “planar” and then, click “ok”.

We start creating the geometry of the coil and the specimen by selecting the “dot” icon from the tool bar and link the dots with the “segment” icon.

After making the geometry, we must define our materials and boundary setting from the “properties” icon.

Material settings:

Copper:

Relative magnetic permeability $\mu_r=1$

Electric conductivity $\sigma= 58 \text{ MS/m}$

Coil:

Relative magnetic permeability $\mu_r=1$

Electric conductivity $\sigma= 58 \text{ MS/m}$

Source current density $\mathbf{J}=3 \text{ MA/m}^2$, the other coil $\mathbf{J}=-3 \text{ MA/m}^2$

Air:

Relative magnetic permeability $\mu_r=1$

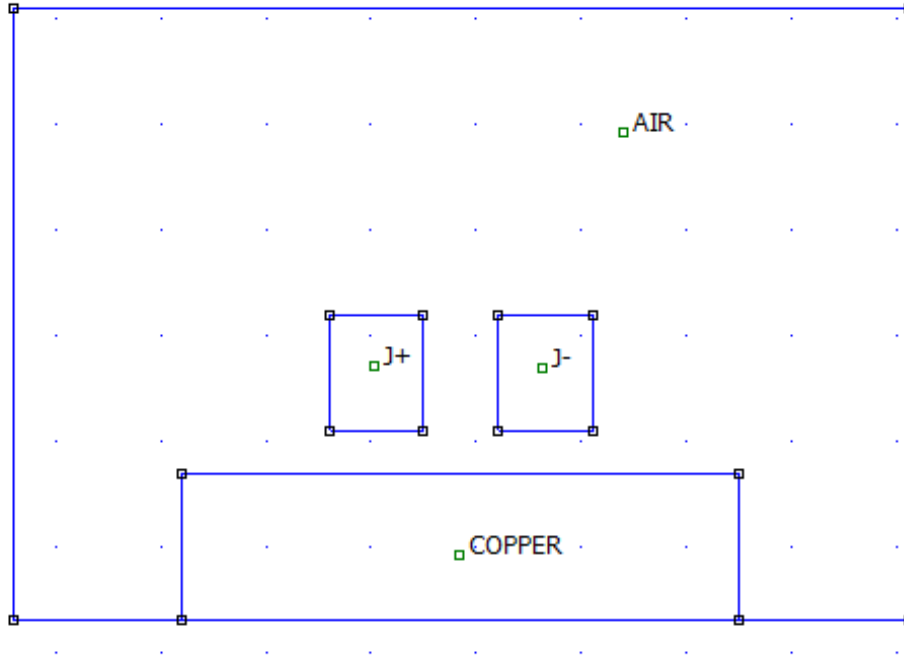
Electric conductivity $\sigma= 0 \text{ MS/m}$

Limited conditions:

We limit our domain by imposing dirichlet type boundary conditions ($A=0$) on the boundaries

IV.2.2 Results

IV.2.2.1 No defect case



FigureIV.1: 2D geometry of the ECT experiment using Femm without defect

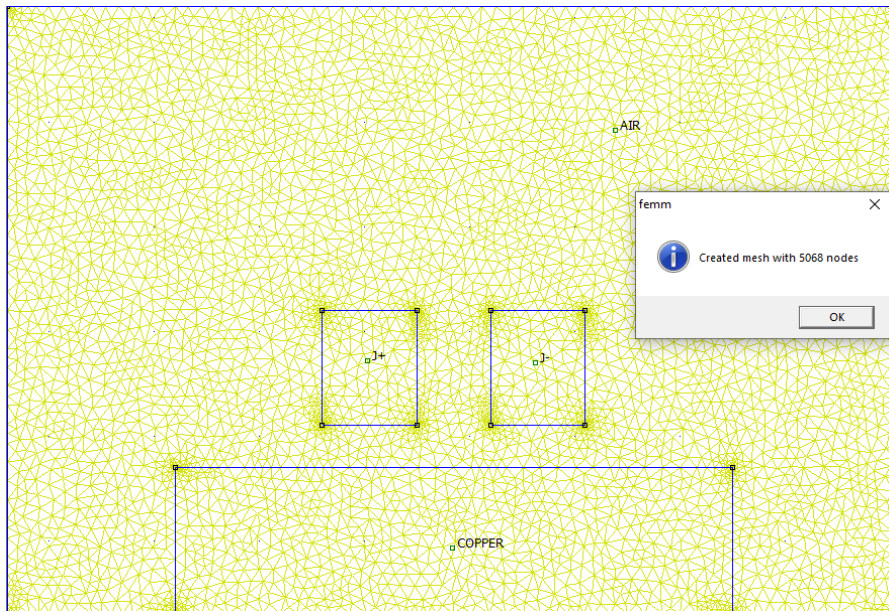


Figure IV.2: mesh of the geometry without defect

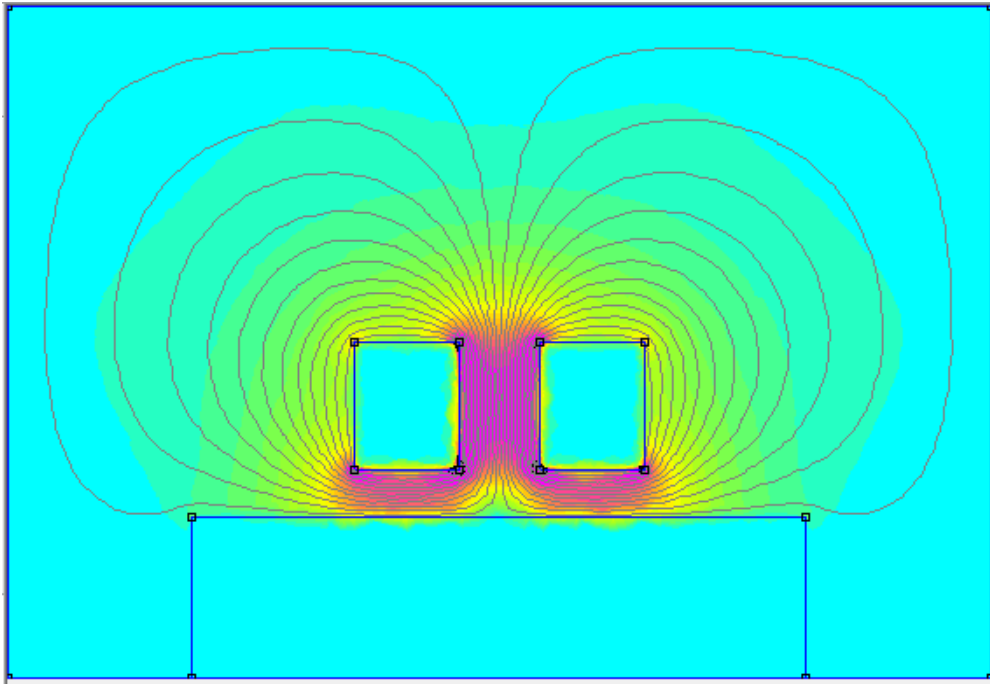


Figure IV.3: magnetic field lines (no defect)

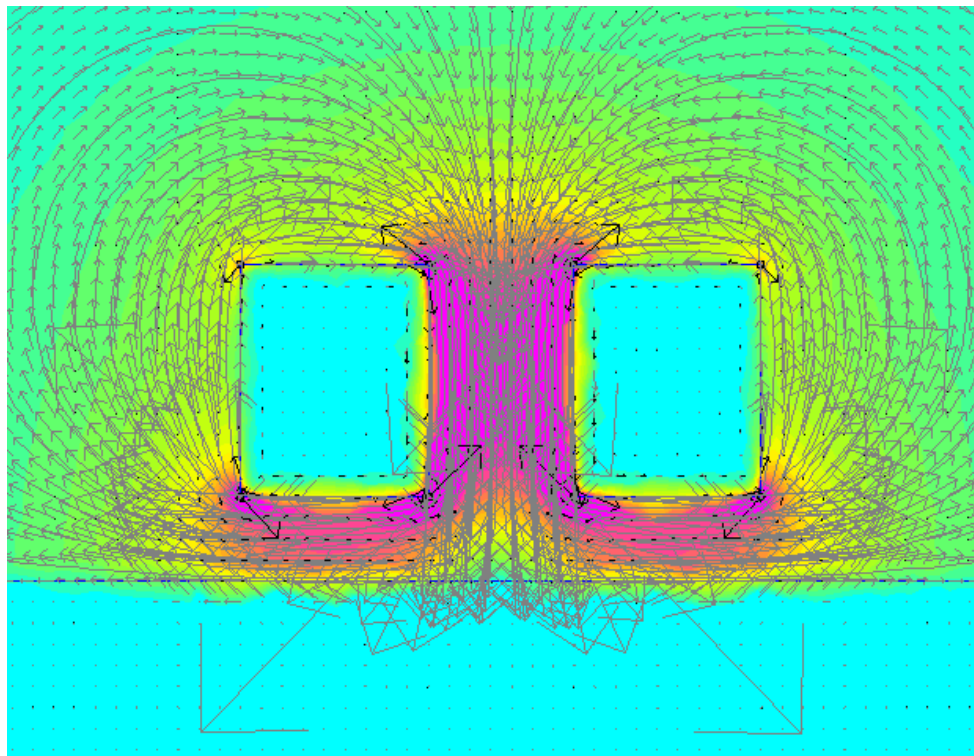


Figure IV.4: magnetic field vectors (no defect)

Length Units: Millimeters

2-D Planar (Depth: 1 mm)

Frequency: 100000 Hz

5068 Nodes

9857 Elements

IV.2.2.2 Defect case

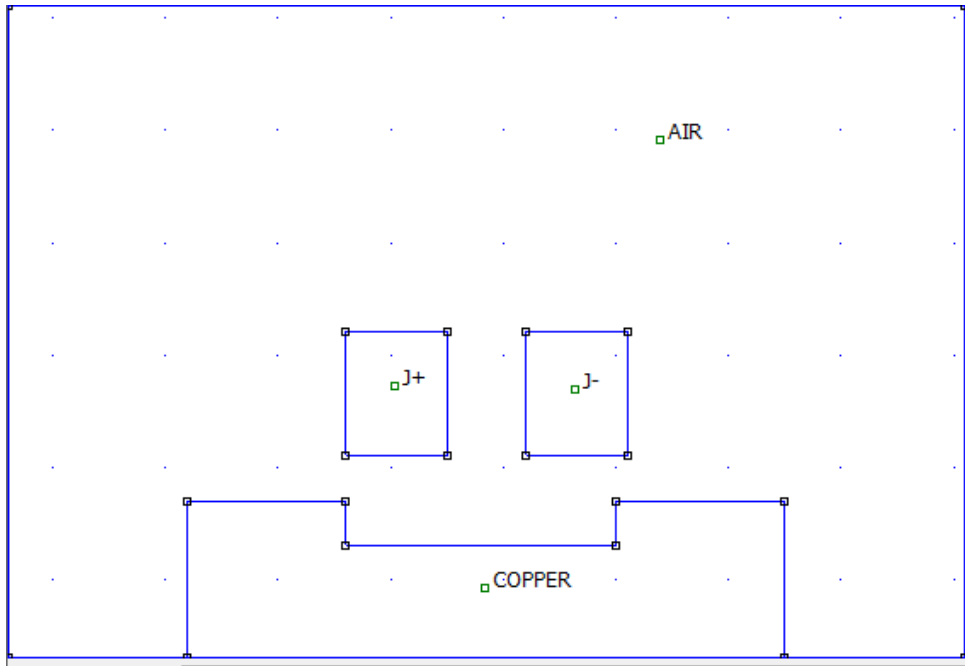


Figure IV.5: 2D geometry of ECT with crack defect

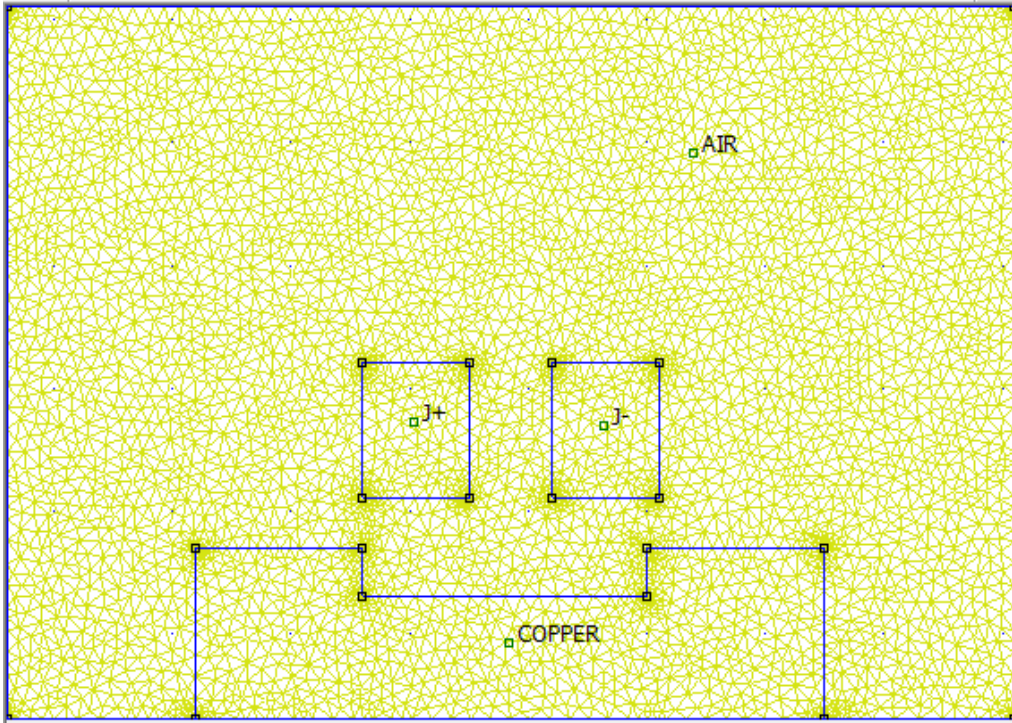


Figure IV.6: mesh of the geometry with defect

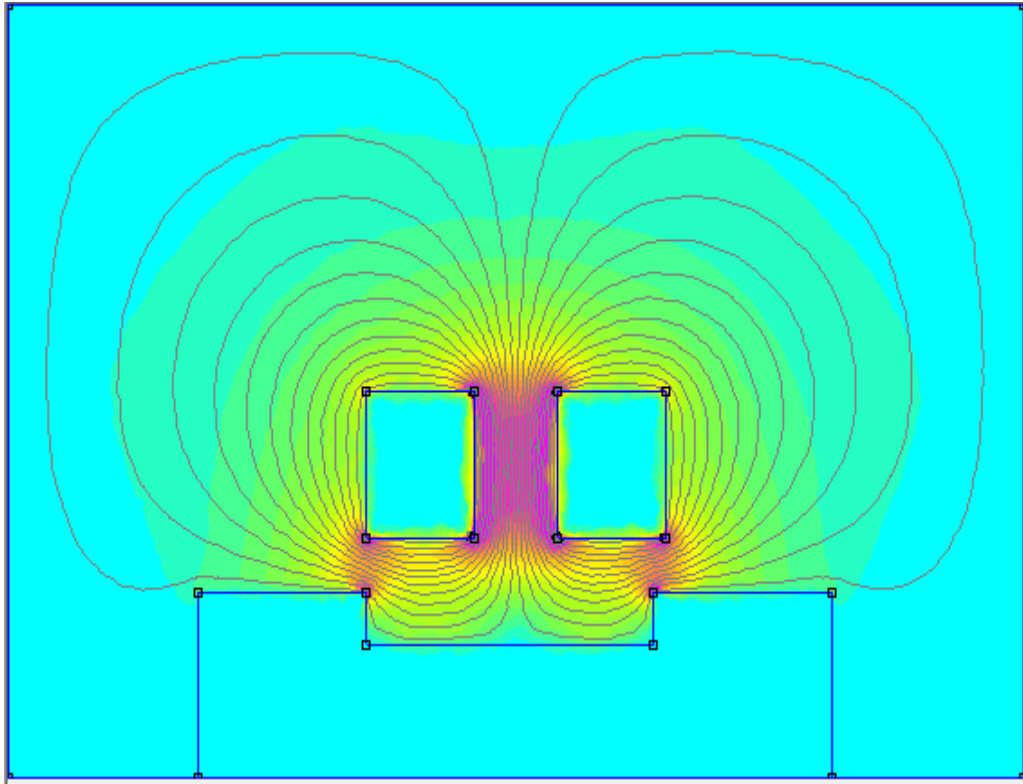


Figure IV.7: magnetic field lines (with defect)

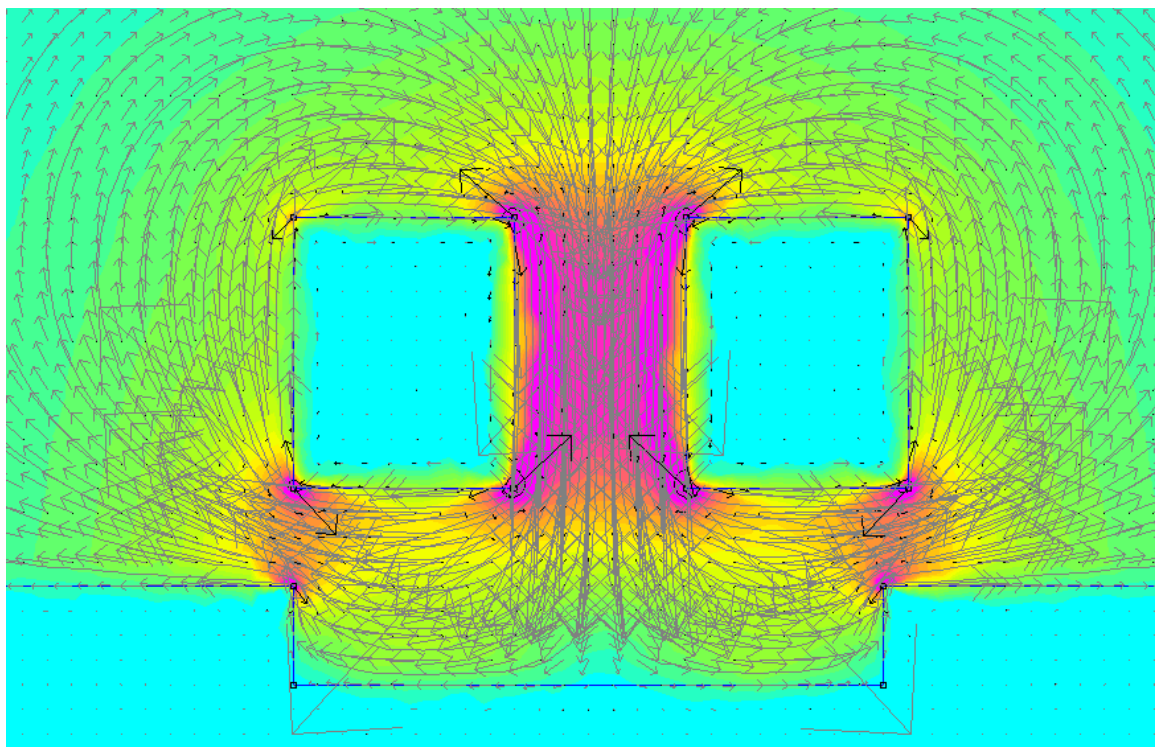


Figure IV.8: zoom on magnetic field vectors

Length Units: Millimeters

2-D Planar (Depth: 1 mm)

Frequency: 100000 Hz

5296 Nodes

10307 Elements

IV.2.3 Interpretation of results using Femm “2D simulation”

The 2D simulation by Femm is as simple as it appears in the figures above in case of a “defect” and “No defect”. The nodes increase in the presence of a crack defect. Therefore the mesh increases and the number of elements.

The magnetic field lines interact with the specimen and distort when passing over the crack defect that is on the non-ferromagnetic metallic place.

When there is no defect the interference pattern is normal (*figure IV.3 & IV.4*) but when the coil passes over the crack defect we notice a distortion in the magnetic field lines “a shifting in the paradigm” (*figure IV.7 & IV.8*).

IV.3 3D Simulation: (using COMSOL multiphysics)

IV.3.1 Simulation steps

Simulating a 3D model of eddy current crack detection in COMSOL Multiphysics involves several specific steps tailored to the physics of eddy currents and crack detection. Here's a step-by-step guide to simulate such a model:

IV.3.1.1 Open COMSOL Multiphysics

- Launch COMSOL Multiphysics on your computer.

IV.3.1.2 Create a New Model

- Click on "File" > "New" > "Model" to create a new simulation model.

IV.3.1.3 Select Physics Interfaces

- In the "Model Builder" window, choose the relevant physics interfaces for your eddy current crack detection model. Typically, this involves selecting the "Electromagnetic Waves" or "Electromagnetic Fields" physics interface.

IV.3.1.4 Define the 3D Geometry

- Create or import the 3D geometry that represents the cracked object you want to analyze. Ensure that the geometry includes the crack's location, dimensions, and surrounding materials.

IV.3.1.5 Set Up Material Properties

- Specify the material properties for different regions in your geometry. Define the electrical conductivity of the materials involved, especially the conductive material (e.g., a metal) and the non-conductive material (e.g., air or a non-metallic solid).

IV.3.1.6 Define Boundary Conditions

- Set boundary conditions to represent the excitation source (e.g., a coil) and the behavior of the electromagnetic fields at boundaries. Specify conditions like the coil current, frequency, and boundary conditions for the electromagnetic fields.

IV.3.1.7 Define Mesh Settings

- Generate a suitable mesh for your 3D geometry. Mesh settings should be refined near the crack region to capture the details of the eddy currents accurately.

IV.3.1.8 Define Eddy Current Equations

- Set up the equations governing eddy currents. In COMSOL, this typically involves defining the electromagnetic field equations and incorporating terms that account for the eddy currents induced by the coil.

IV.3.1.9 Set Up Study

- Define the type of study you want to perform. Depending on your goals, you might choose a frequency-domain, time-domain, or parametric study.

In this case I used 2 studies: One with no defect (no crack) and the other one with a defect (with a crack), in order to make a difference between them.

IV.3.1.10 Specify Solver Settings

- Configure solver settings, such as the solver type, convergence criteria, and time-stepping parameters if you're performing transient simulations.

IV.3.1.11 Run the Simulation

- Click the "Run" button to start the simulation. COMSOL will solve the electromagnetic field equations and calculate the eddy current distribution within the 3D object.

IV.3.2 Simulation

First, we begin by drawing the geometry of the coil, the specimen (*conducting plate*), and the crack.

Then specify the material properties (*both of the coil and specimen are set to be of a copper material*) and boundaries of the existing materials as shown in the figure below:

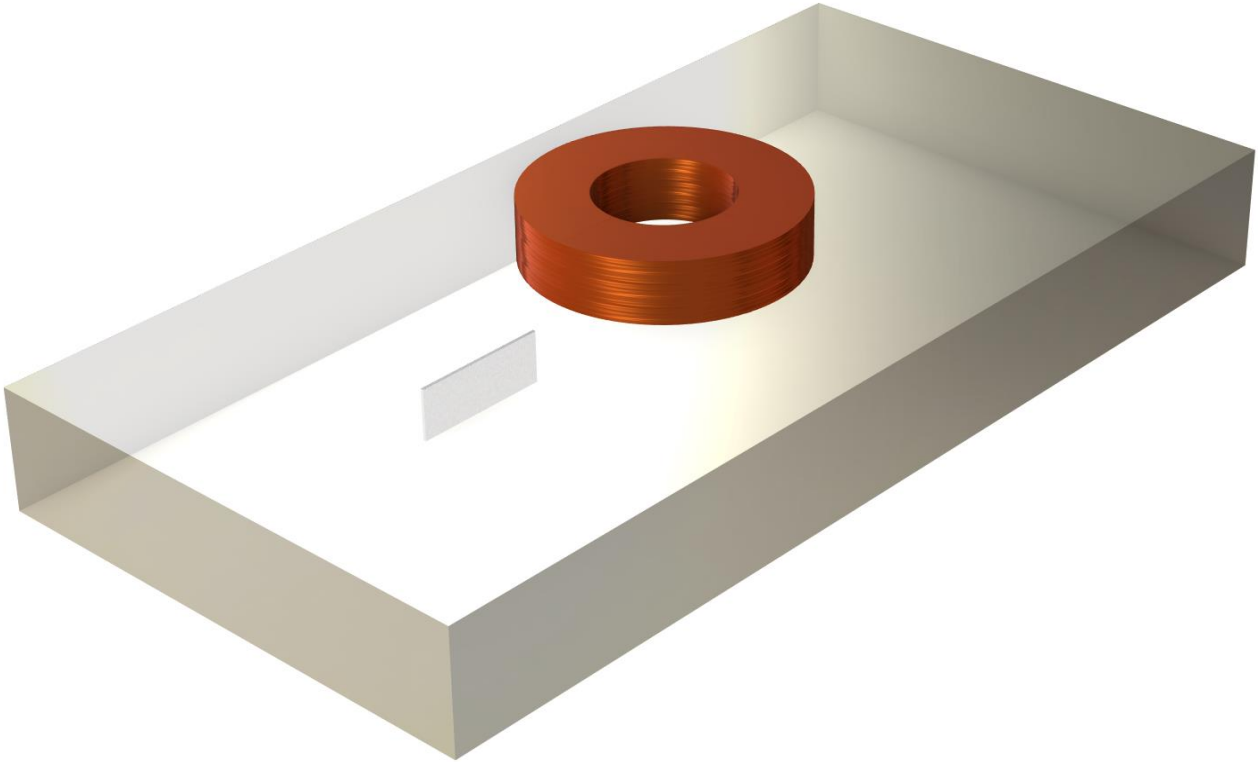


Figure IV.9: the test subject

IV.3.2.1 Input Parameters

We've taken the liberty to set the parameters of the geometry and material properties as we desire as shown in the figure below:

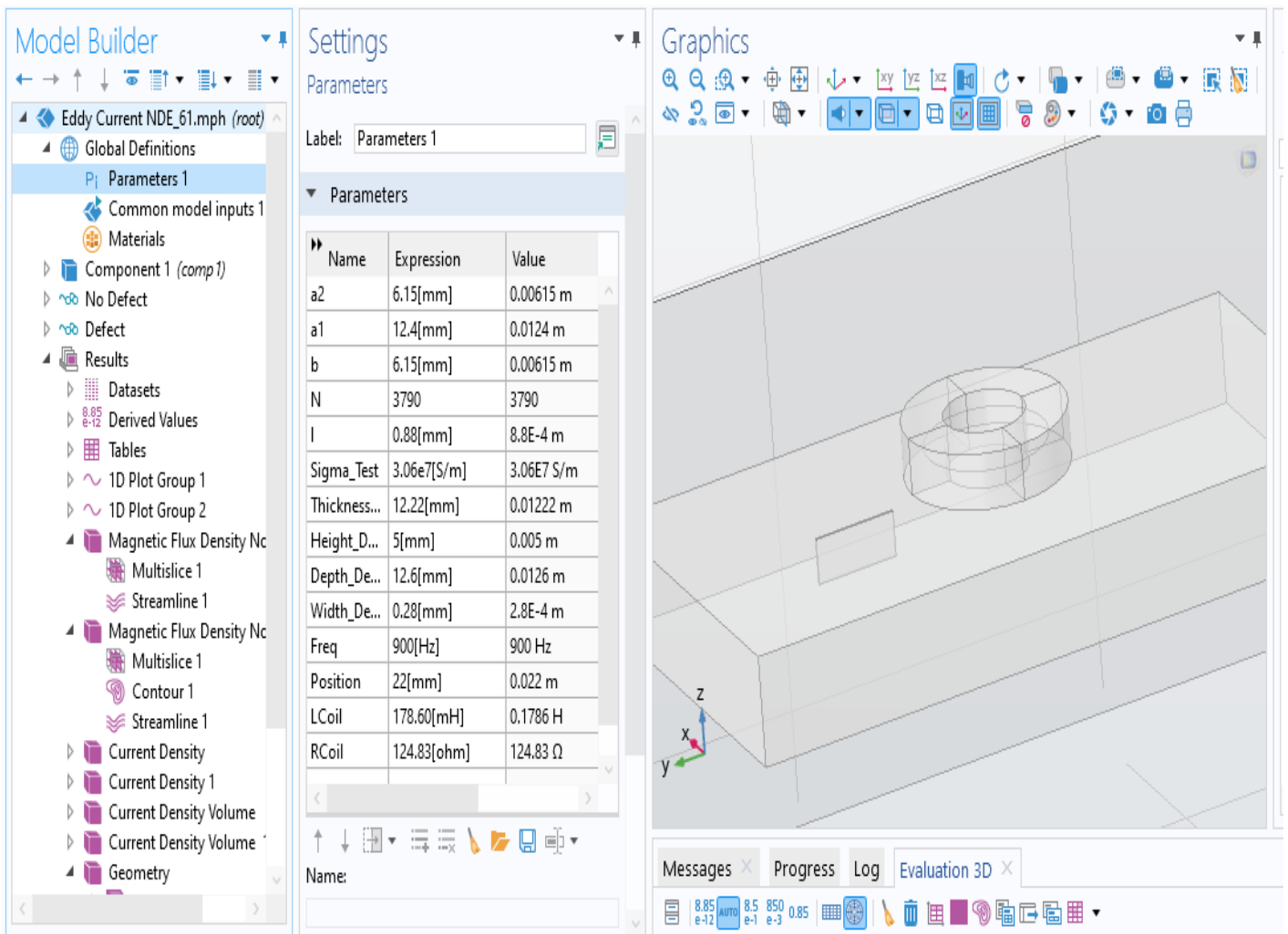


Figure IV.10: the input parameters of the subject of study

- Number of turns: 3790
- Frequency: 900 [Hz]
- Conductivity of plate: 3.06e7 [S/m]
- Defect parameters
 - Length: 12.60 [mm]
 - Depth: 5.00 [mm]
 - Width: 0.28 [mm]
 - Lift off: 0.88 [mm]

IV.3.2.2 Model Setup

Since our study of Eddy current crack detection is purely a problem of electromagnetism, we must work with Maxwell's equations in order to solve the problem.

- Magnetic Fields interface
- Frequency Domain study
- Defect is modelled by assigning the material properties of air to it.
- Non-zero conductivity to air domain for numerical stabilization
- Parametric sweep to change coil position

The following figure shows the settings of the test subject:

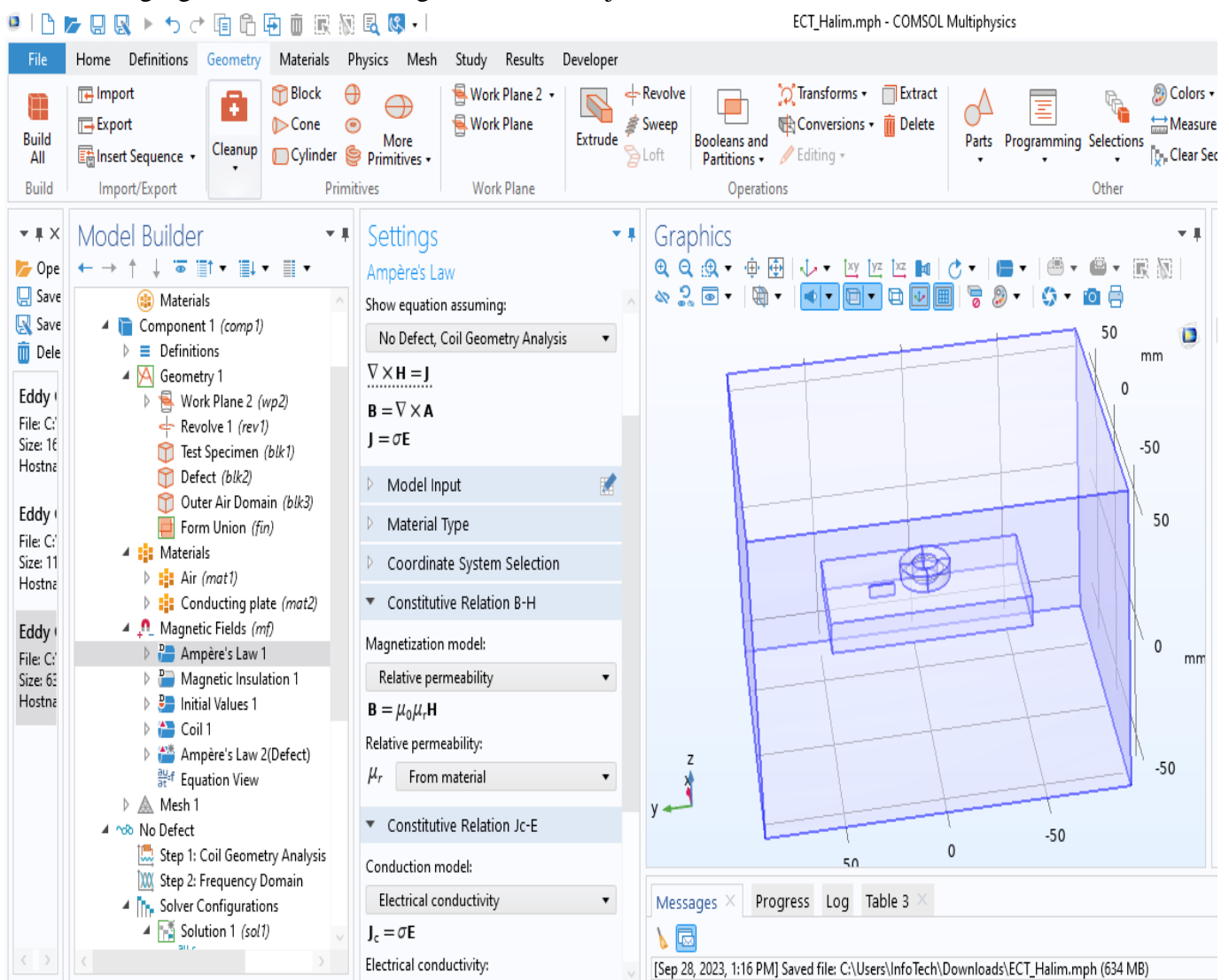


Figure IV.11: settings of the model

IV.3.2.3 Coil Setting

As established before, the coil is made of copper.

Its setting is:

- Homogenized Multi Conductor
- Geometry analysis
- Input

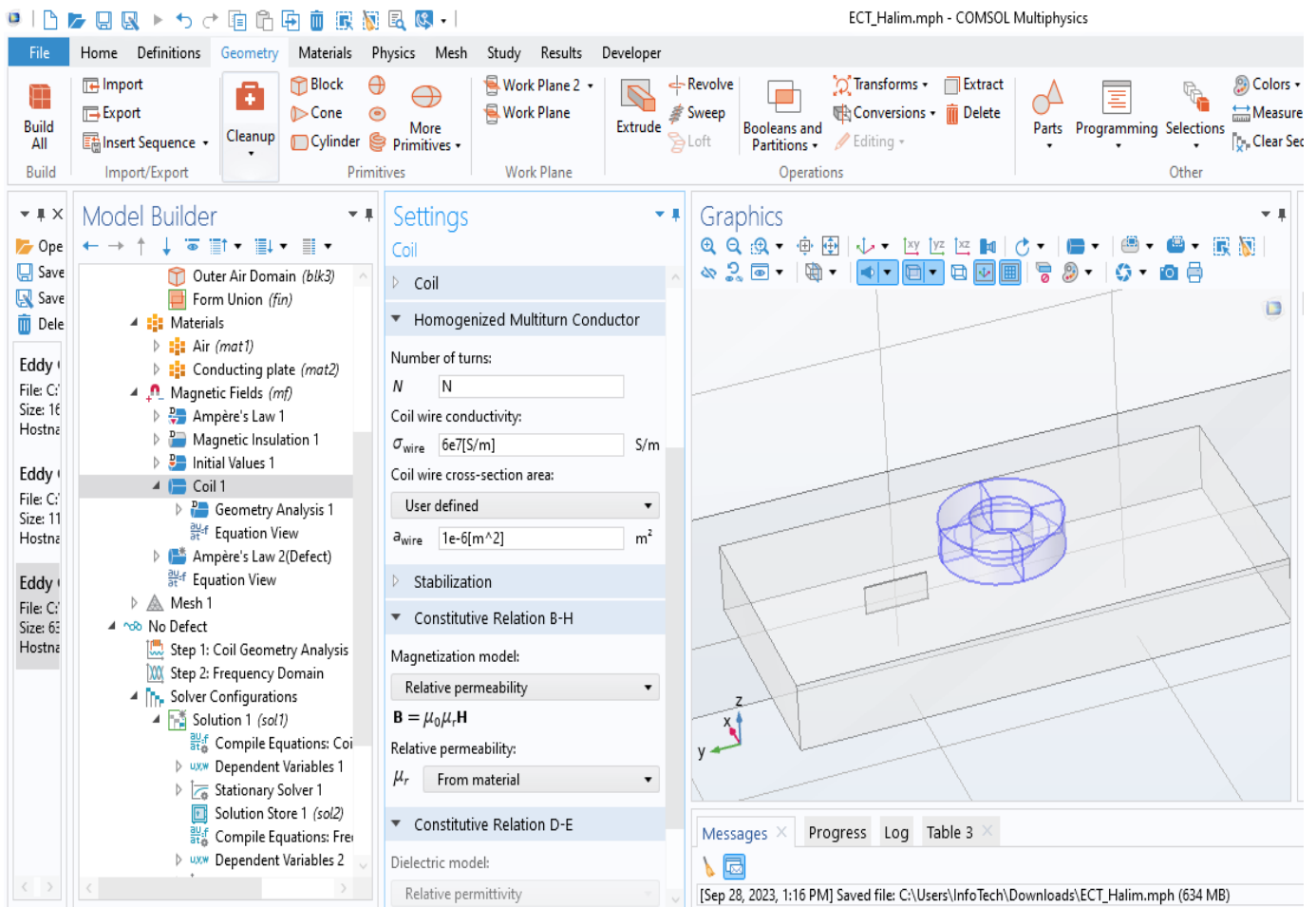


Figure IV.12: coil setting

$$I_{coil} = 1 \text{ A}$$

IV.3.2.4 Study Setup

We have two study cases here with a defect and without.

- Without defect: Defect part takes material properties of conducting plate
- With defect: Defect part takes the properties of air.
- Change in Coil Position
 - Defect part takes material properties of air
 - Parametric sweep is used to the coil position

IV.3.3 Results

Meshing display:

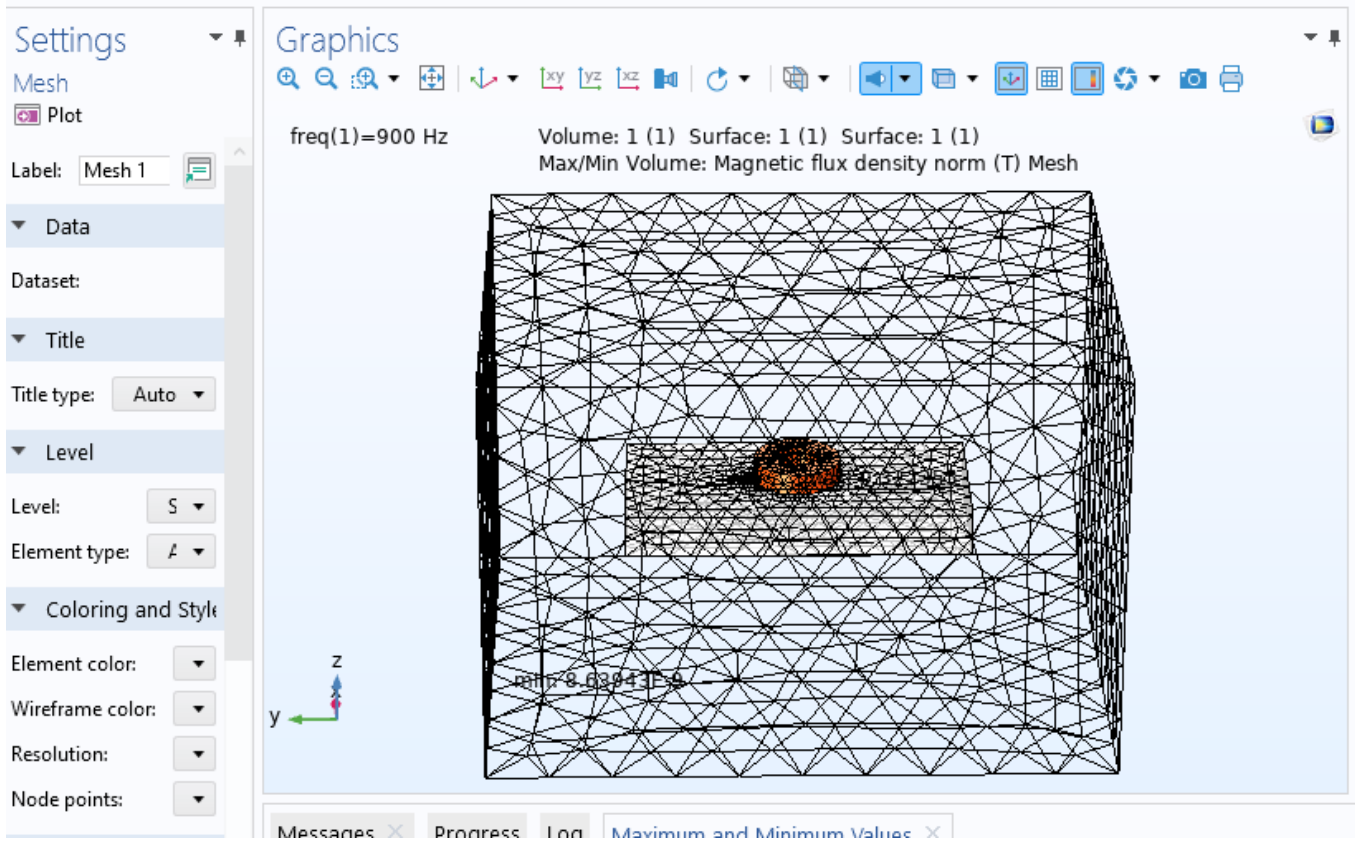


Figure IV.13: Geometry mesh of the test subject

MESH STATISTICS

Description	Value
Status	Complete mesh
Mesh vertices	3233
Tetrahedra	17597
Triangles	2467
Edge elements	328
Vertex elements	44
Number of elements	17597
Minimum element quality	0.08918
Average element quality	0.639
Element volume ratio	7.0572E-6
Mesh volume	3.024E6 mm ³

IV.3.3.1 No Defect case

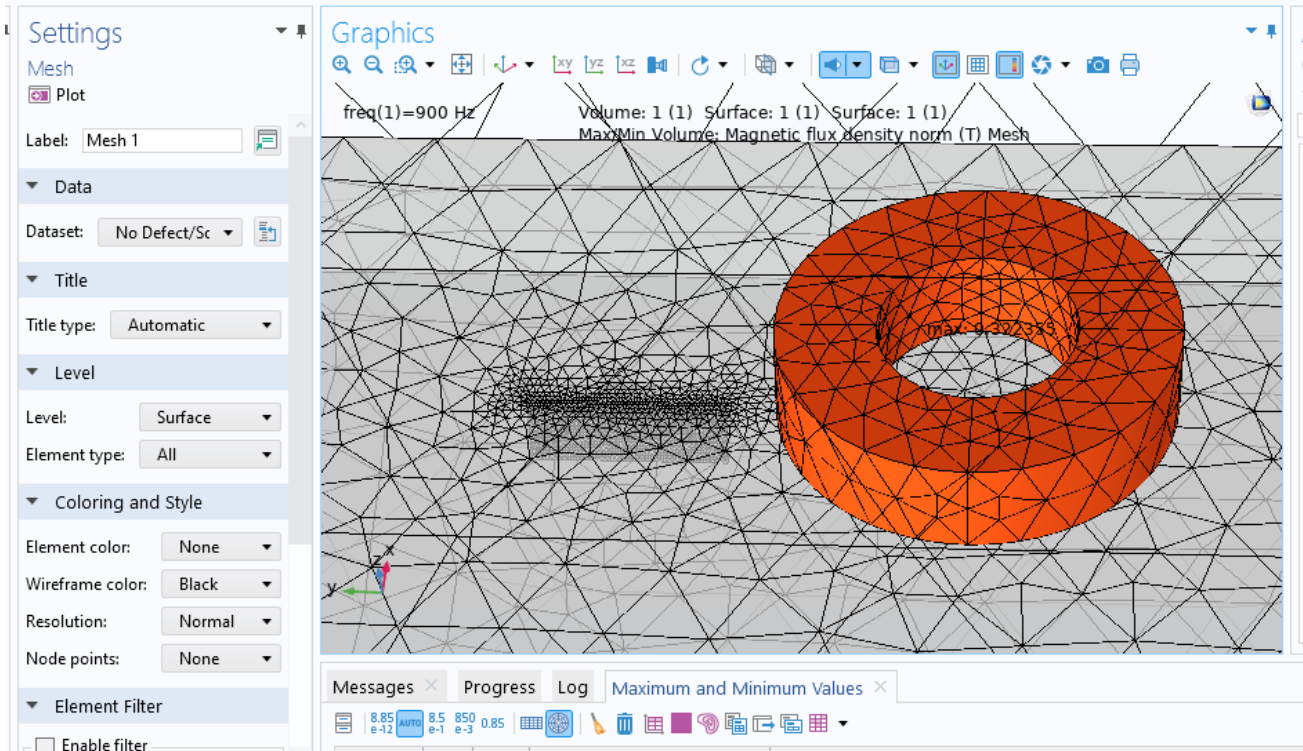


Figure IV.14: No defect mesh

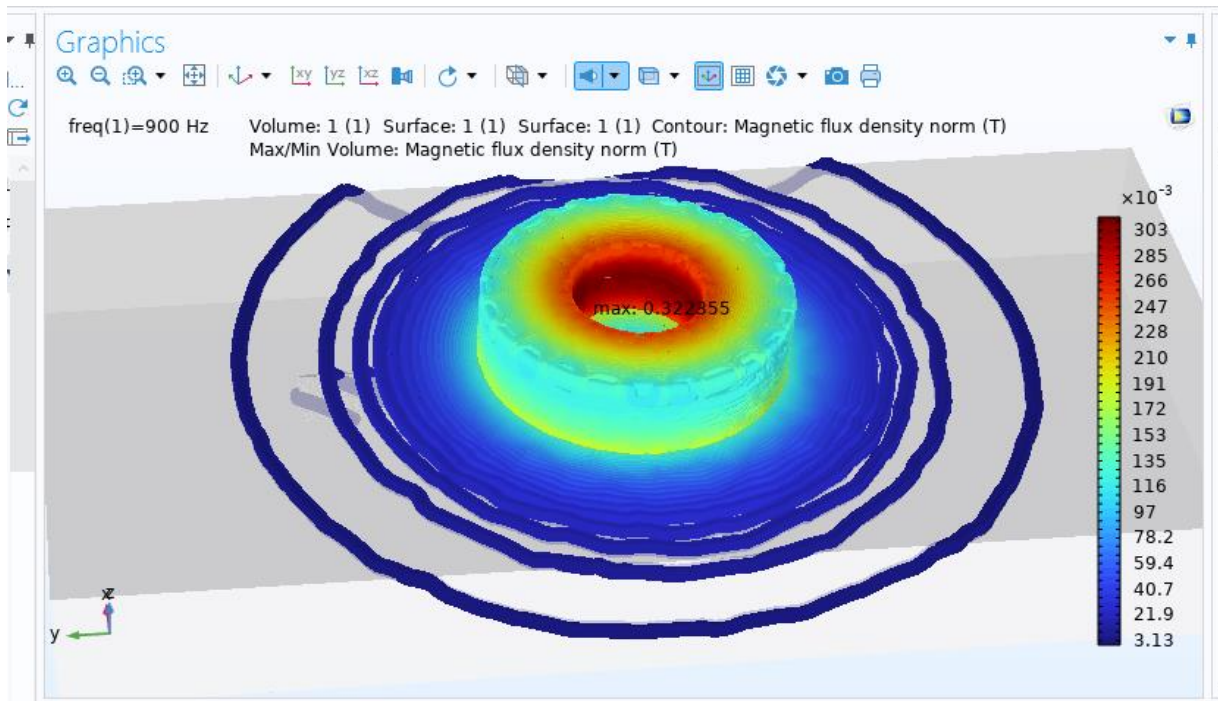


Figure IV.15: No defect contour display

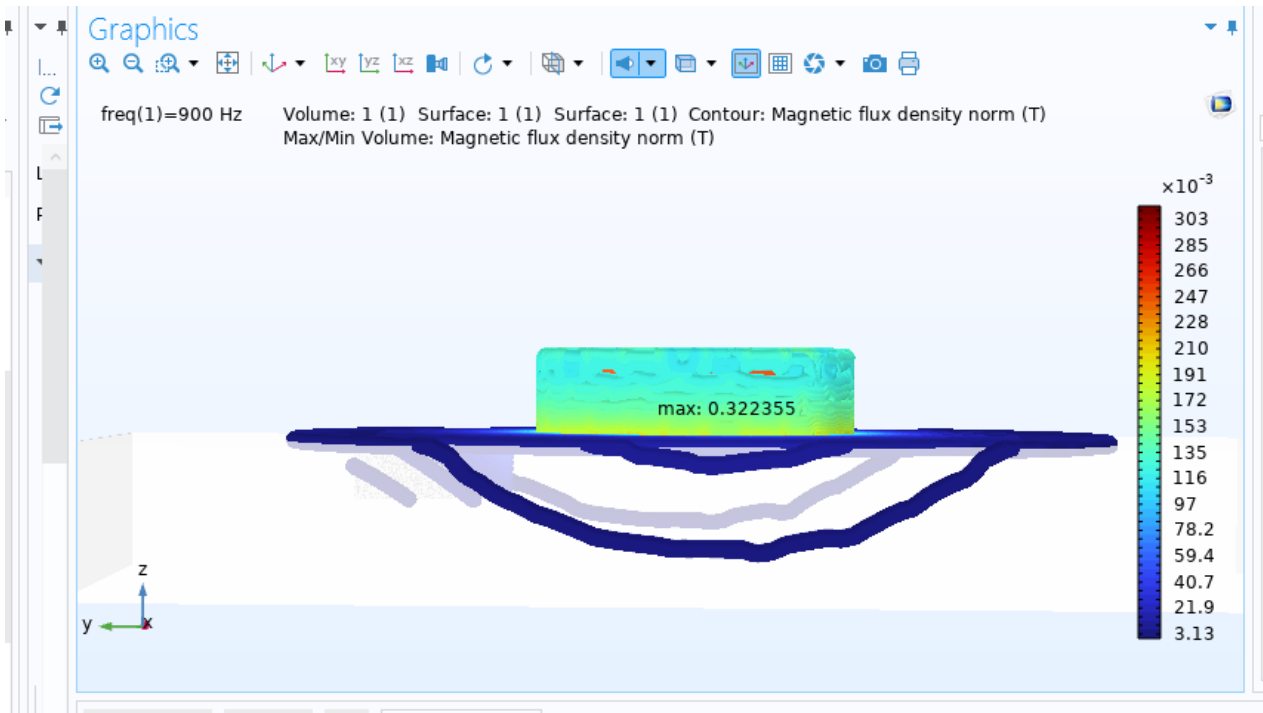


Figure IV.16: No defect contour from a different angle

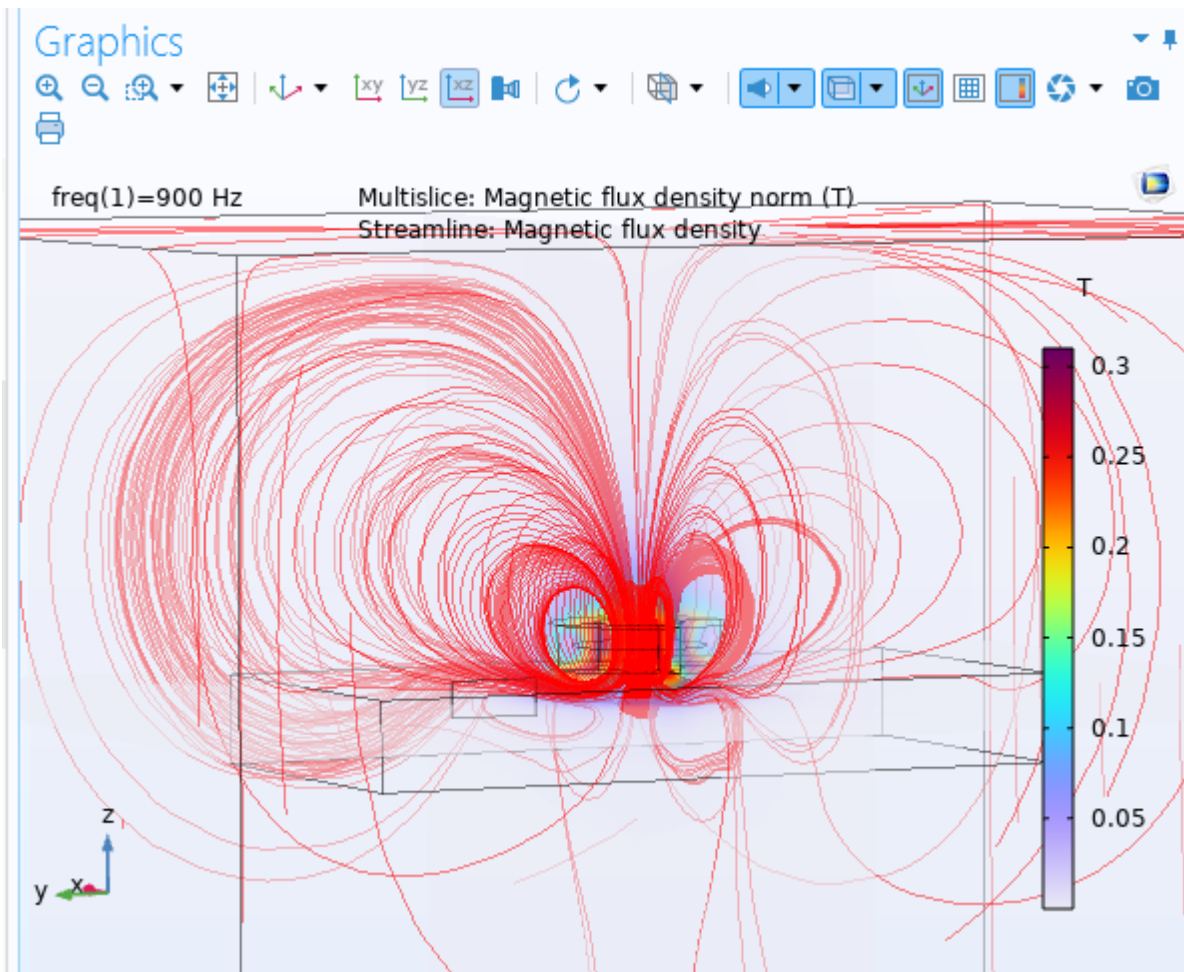


Figure IV.17: stream lines

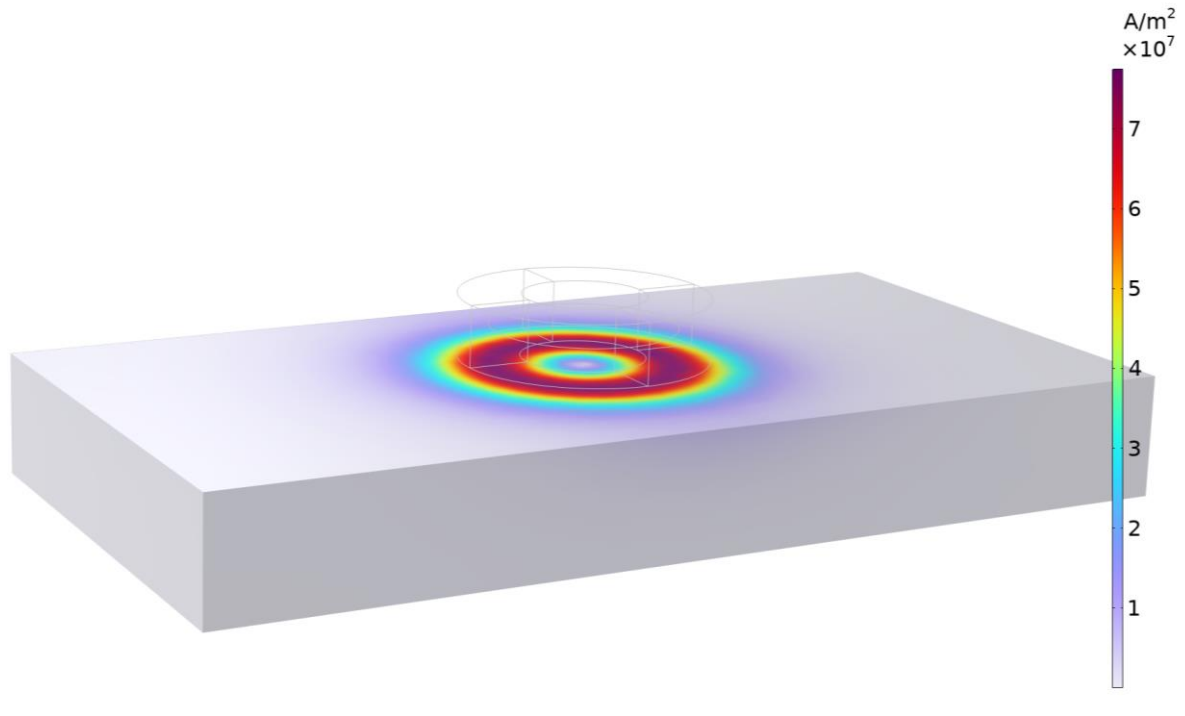


Figure IV.18: Current density without crack defect

The mesh (figureIV.14), contour (figureIV.15 & IV.16) and the stream lines (figure IV.17) display represent the magnetic flux density B and its interaction with the specimen in the case with no defect.

(Figure IV.18) shows the current density J

IV.3.3.2 Defect case

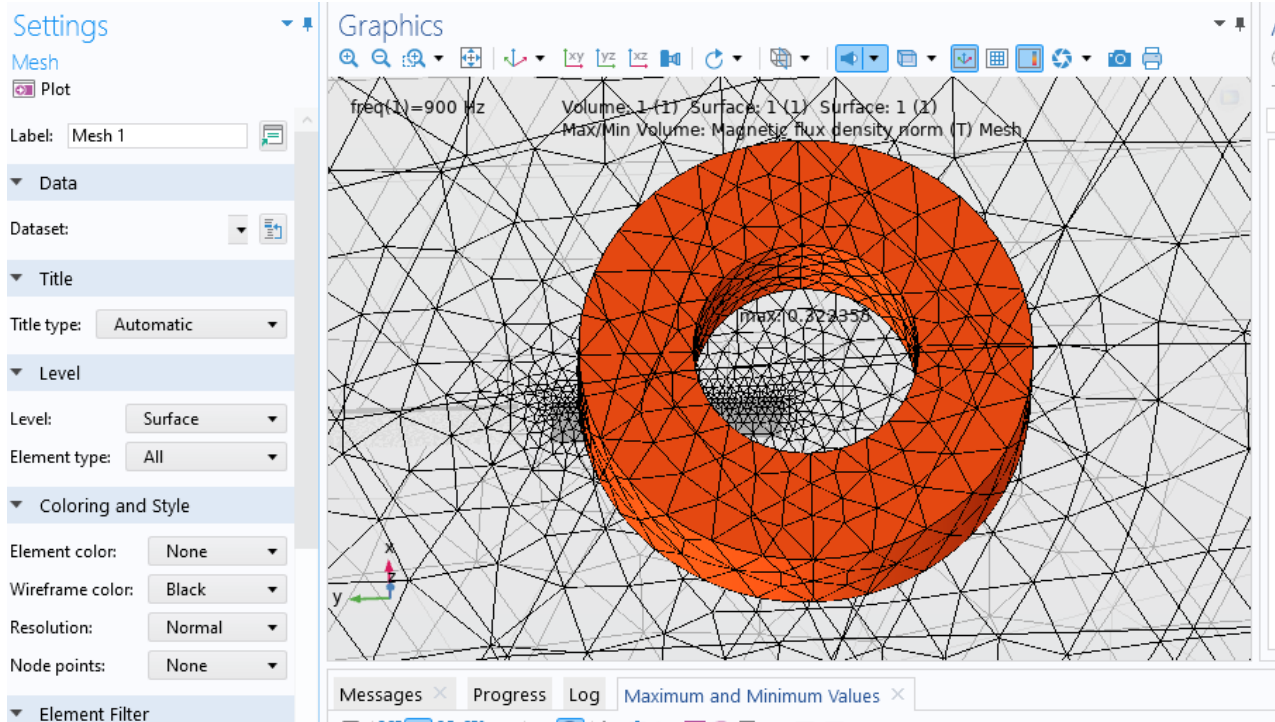


Figure IV.19: Defect mesh of magnetic flux density

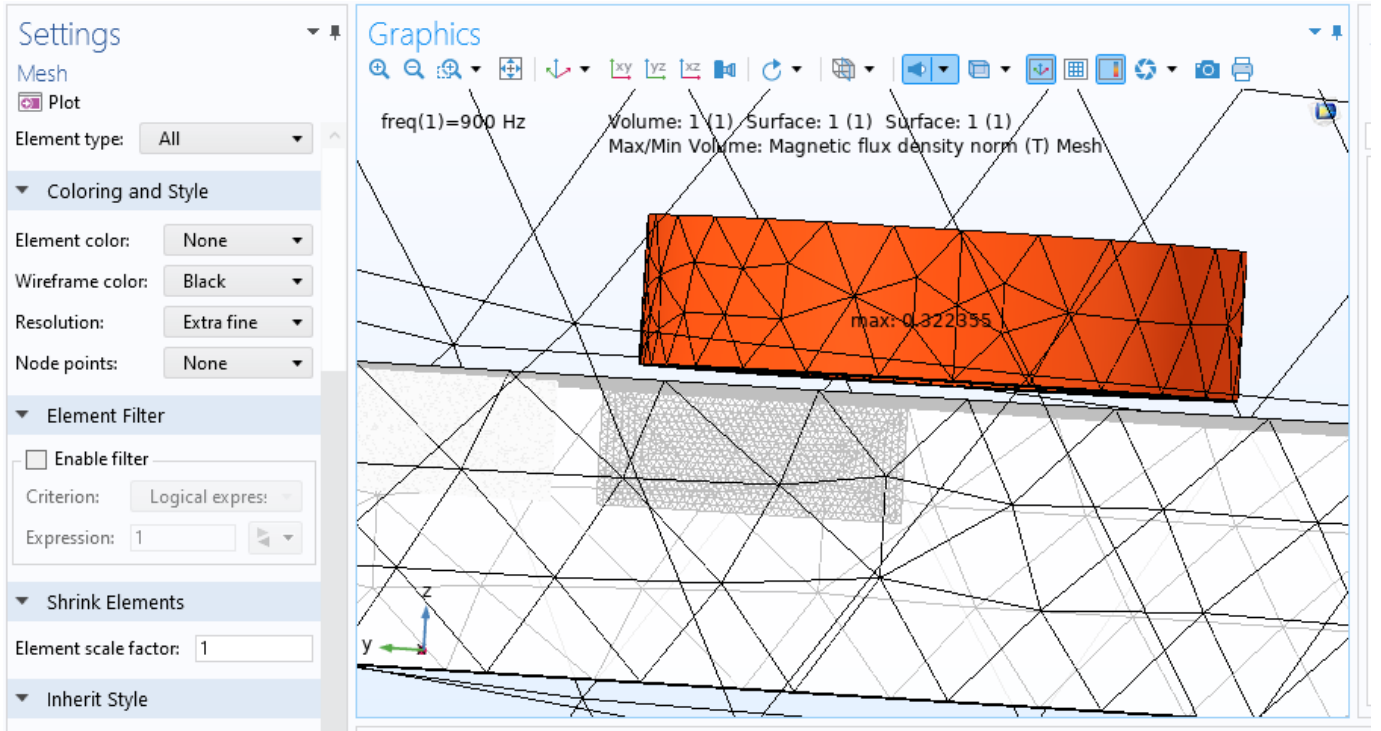


Figure IV.20: Defect mesh from a different angle

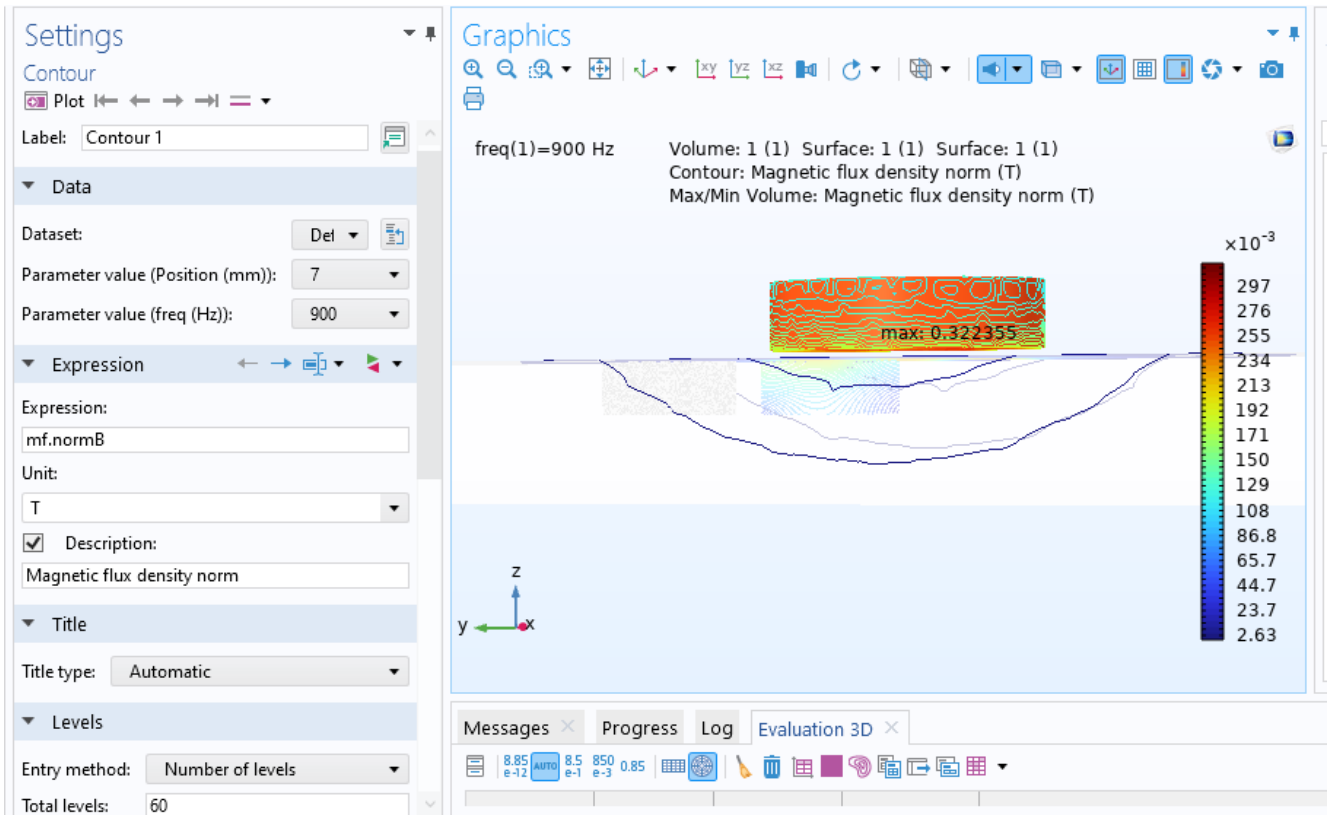


Figure IV.21: Defect contour (line type) of magnetic flux density

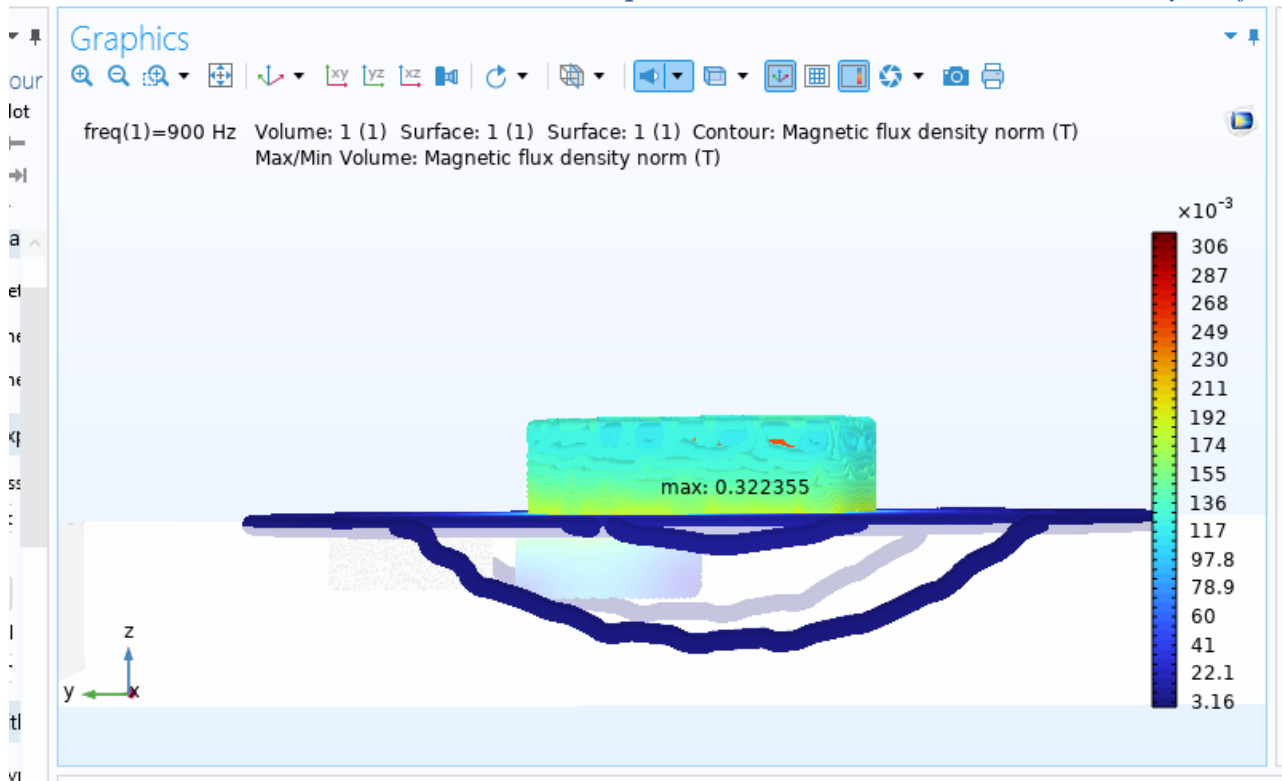


Figure IV.22: Defect contour (tube type)

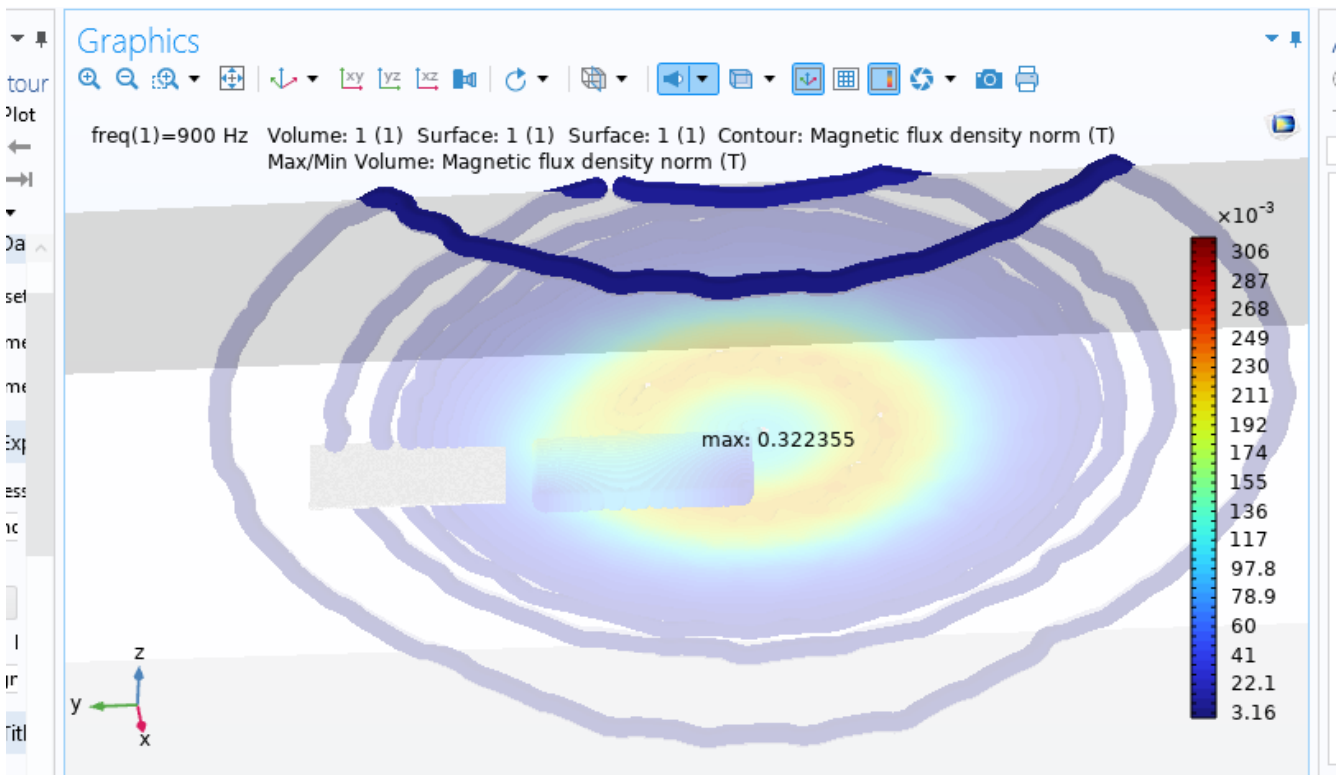


Figure IV.23: Defect contour from a different angle (tube type)

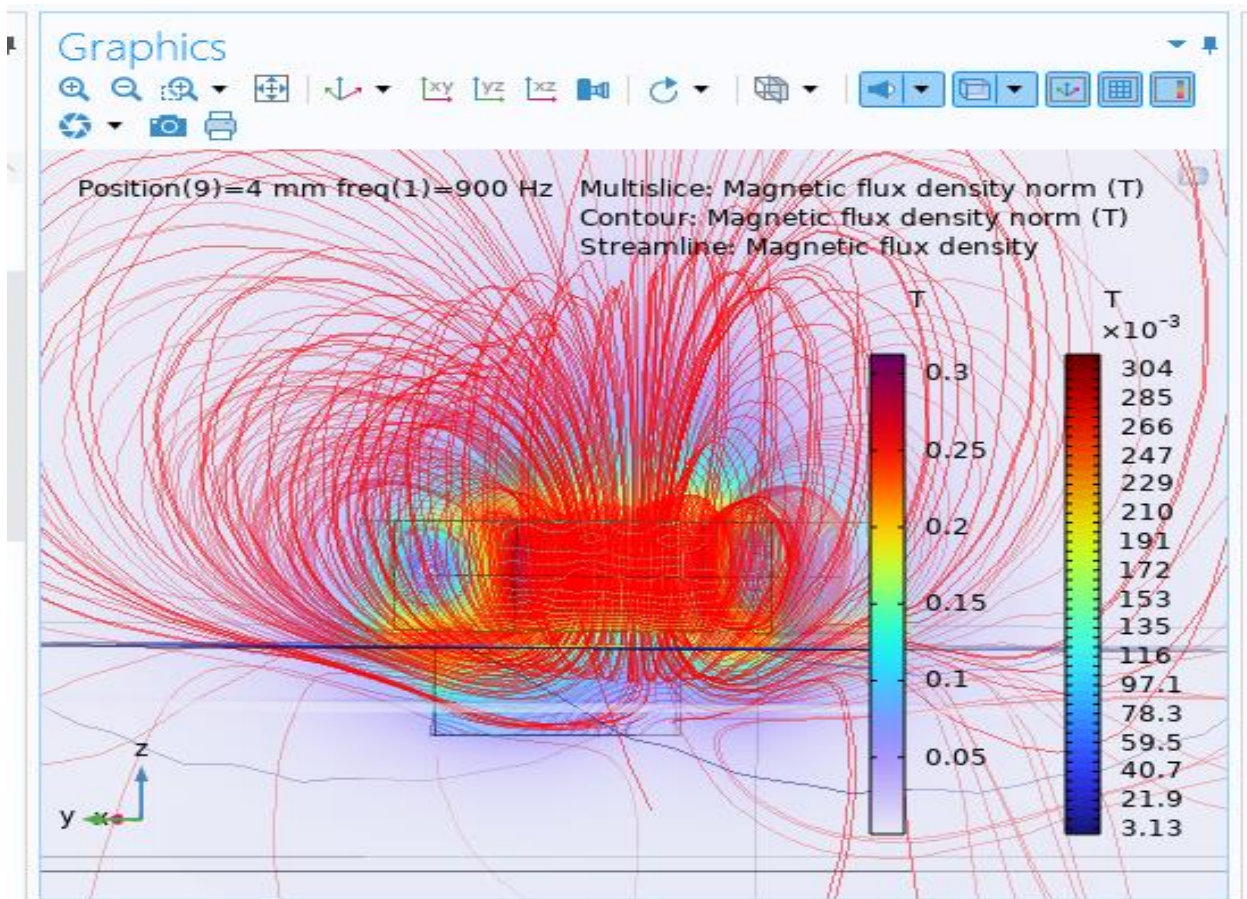


Figure IV.24: stream lines

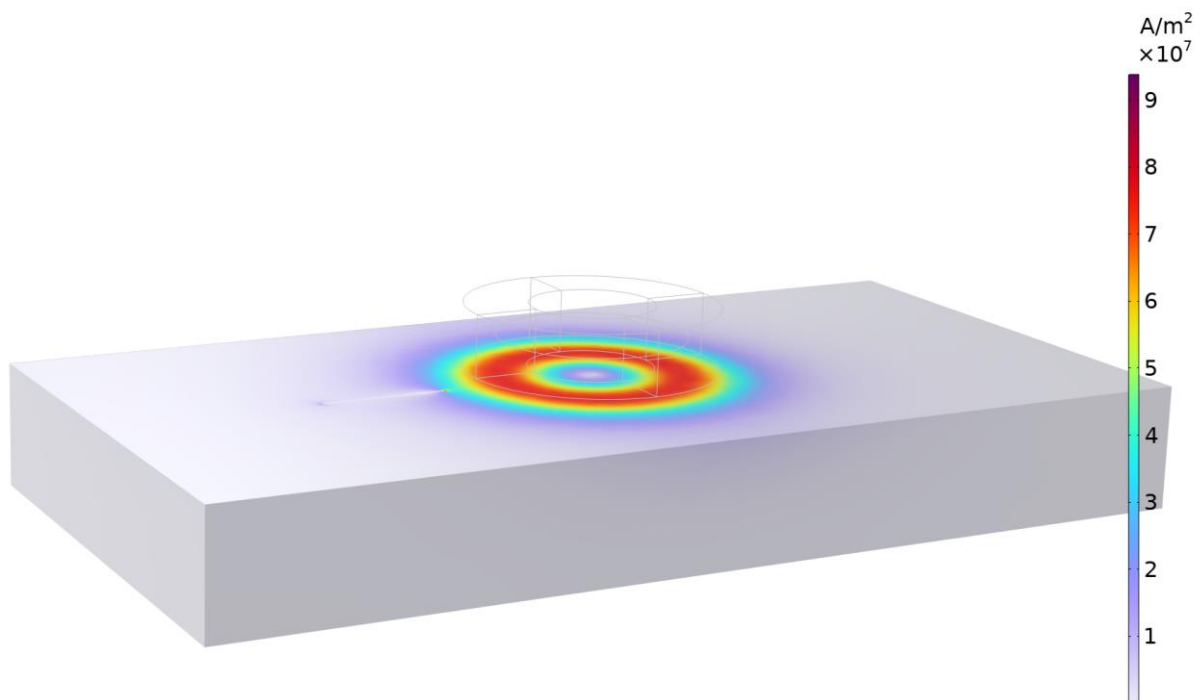


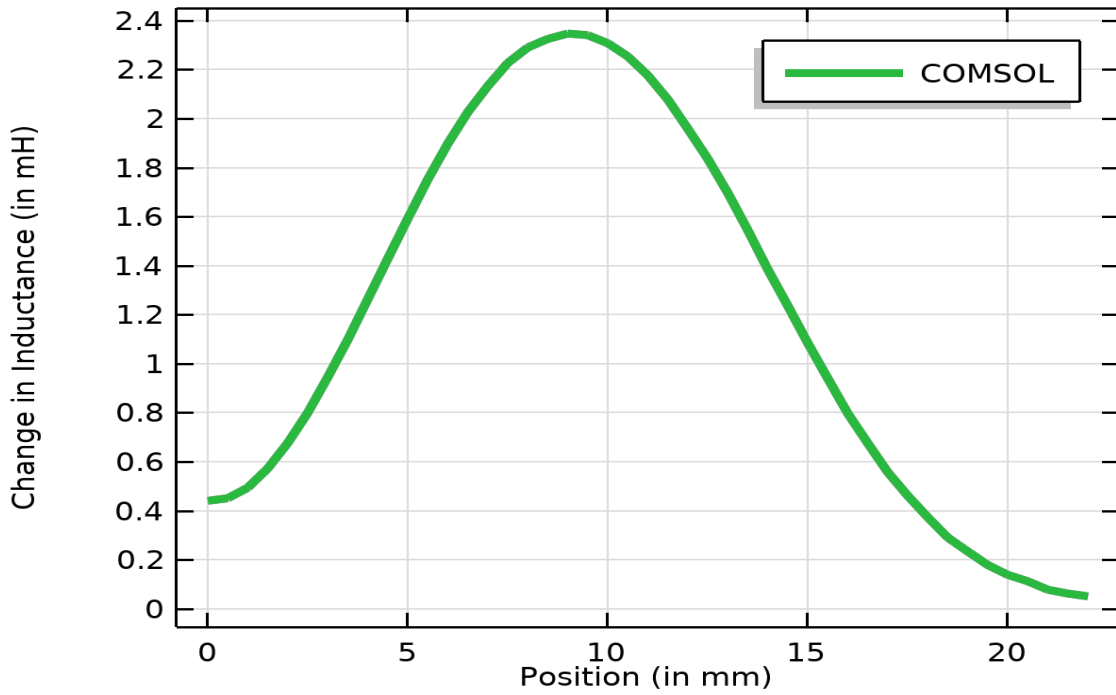
Figure IV.25: Current density with crack defect

The figures above represent the mesh, contour and stream lines of the magnetic flux density B in case of the existence of a crack.

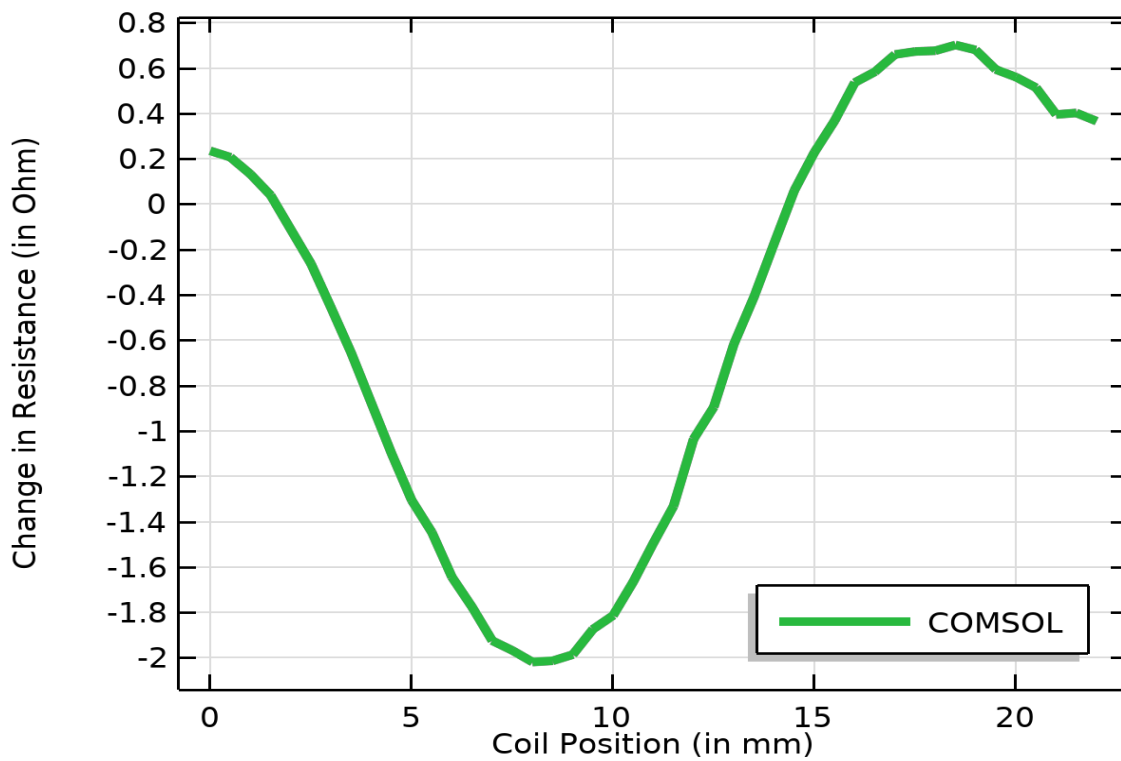
Also (figure IV.25) is for the current density J

IV.3.4 Plots

Plot 1 represents the change in inductance as the coil passes over the crack defect.



Plot 2 represents the change in resistance as the coil passes over the crack defect



IV.4 Interpretation of the results: (3D)

As shown above in the results provided by COMSOL multiphysics software when studying Eddy current testing crack detection using the electromagnetic induction, we notice that the simulation was a success because when comparing the test results in both cases (*with crack defect and without*), we see differences in the pattern of scattering magnetic flux density \mathbf{B} and current density \mathbf{J} over the conducting copper plate in many forms including (*Mesh, Contour, stream lines and the field density map*) i.e. In case of no crack defect the interaction paradigm of the field density appears to be normal without flaws in the testing specimen. Hence, in case of a crack defect there was some distortion when there's a coil sweep or in other words, whenever the field density passes over the crack defect (*which its material property in this condition is air*), magnetic flux density leaks in the crack making a distortion and an interference pattern in the field density like we have seen in the comparable figures earlier.

COMSOL multiphysics simulate successfully the issue of crack defect detection 3D

Note:

I used a non-ferromagnetic material as a tested object (Copper), but it is also fine to use a ferromagnetic material as (Iron) in the simulation. The only difference between the ferromagnetic and non-ferromagnetic materials is that the relative magnetic permeability changes extensively.

When using the non-ferromagnetic specimen, it won't be necessary to calculate the difference between the relative permeability of copper and air (in the crack defect when making a sweep) because their μ_r is somehow similar and equals to 1.

In the other hand, if Iron was the tested object for surface cracks, the relative magnetic permeability should be taken into consideration because:

$$\mu_r(\text{iron})=5500$$

$$\mu_r(\text{air})=1$$

IV.5 Conclusion

COMSOL Multiphysics is used extensively in academia, research institutions, and industry to solve complex engineering and scientific challenges. Its versatility, combined with comprehensive documentation, tutorials, makes it a valuable tool for advancing innovation and solving real-world problems.

Also, it helped me simulate ECT with easement and proper results.

In this chapter we discovered Femm & COMSOL multiphysics and their functionality that enabled us to simulate 2D & 3D model of ECT and see how it does work in the absence and present of a defect in a non-ferromagnetic conducting material.

The data given by Femm & COMSOL multiphysics are accurate due to the definition of properties in materials.

COMSOL also contains Finite Element Method library in its system which makes it even more adequate for engineers and scientists to solve complex math problems.

General Conclusion

In conclusion, this research includes the general information about NDT and more specifically ECT “eddy current testing”. ECT is a versatile technique that uses electromagnetic induction; it also proved its value in maintenance and assessing the condition of materials and machines without compromise their structural integrity.

The mathematical modeling used to solve the mathematical issues regarding ECT is based on the development of Maxwell’s equations in which they describe electrodynamics.

Finite element method is the method reliable to solve complex partial differential equations and to simulate physical phenomena in various fields of science such as what we have studied in this thesis (an electromagnetic problem).

There are many computer softwares that can use FEM (Finite Element Method) like what we chose to work with in this research “Femm” & “COMSOL multiphysics”, these two programs have FEM library integrated in them specifically for solving those issues.

The simulation of the technique was successful and the results were accurate somehow when compared to real testing measures.

Lastly, as technology continues to advance, ECT techniques have also evolved with increased sensitivity, automation, and real-time data analysis capabilities. Additionally, ECT is a non-invasive and environmentally friendly testing method, contributing to a cost-effective quality assurance process.

Taking into account the non-linearity of electromagnetic phenomena and the magnetic saturation of materials.

Study, modeling and thermal simulation of an eddy current inductive sensor by finite element software in 2D.

Study, modeling and thermal simulation of an eddy current inductive sensor by finite element software in 3D.

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