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A Review on the Study of Non Destructive Testing Methods

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Abstract: *This abstract brings together advances and strategic changes in Non-Destructive Testing (NDT) in modern engineering. Applications of NDT have become a key component of the transition of industrial sectors to pro-active maintenance in order to guarantee structural integrity and operational safety in the aerospace, oil and gas, and manufacturing industries. This review discusses the existing methodologies, such as ultrasonic, radiographic, electromagnetic and visual testing, as well as emphasizing a paradigm change to "Condition Based Maintenance" (CBM). Key findings show that the combination of the solid-state sensors (GMR/TMR) and the Machine Learning architectures (CNNs/RNNs) has contributed to a significant improvement in diagnostic accuracy, with results up to 99% in complex signal processing. In addition, the transition from the traditional harmonic systems to Pulsed Eddy Current (PEC) and automated surface inspection shows an improvement towards more detailed and objective data characterization. Future paths highlight the importance of Industry 4.0, Digital Twins and autonomous robotic systems in developing a high level of integration for an inspection framework. In addition to strengthening safety measures, NDT also helps to promote circular economy models and material reuse, thereby contributing to global sustainability goals. This synthesis offers a holistic framework to develop NDT sensitivity and automation in high-stakes engineering application areas.*

Keywords: A Review on the Study of Non Destructive Testing Methods

I. Introduction

Within the field of engineering and industrial applications, the importance of quality control and material inspection cannot be overstated, as it plays a crucial role in maintaining structural integrity, operational safety, and economic viability. The buildings, whether sky-crusting skyscrapers or supersonic airplanes, are equipped with materials that must resist extreme conditions without causing catastrophic failure. The resulting failures can have dramatic consequences including loss of life, environmental damage and significant economic losses if the material quality is deficient due to cracks, voids, corrosion, or inclusions. The Challenger space shuttle accident in 1986, for example, showed that safety protocols must be strict and that flaws in the properties of the O-ring materials caused mission failure. Quality control processes includes systematic evaluation techniques to ensure that the product meets the design requirements, reduce risks, and increase service life. A critical subset of the material inspection category is that of being able to inspect for surface and subsurface anomalies without actually touching the material, which is important in industries that are subject to strict requirements such as ASME, ASTM and ISO.

Non-Destructive Testing (NDT) is another name for Non-Destructive Evaluation (NDE) or Non-Destructive Inspection (NDI), which refers to a collection of analytical techniques used to assess the properties and integrity of materials, components or structures without causing damage. The main goal of NDT is to locate defects, determine properties of materials and evaluate performance parameters, and maintain the test object's function and value. NDT recognises that samples are not sacrificed like traditional inspection methods, but enables in-service inspections, thereby minimising downtime and costs. This ability can come in handy when replacing the components is too costly or impractical, like turbine blades in jet engines or pipelines in distant oil fields. NDT provides quantitative information about the size, location and severity of a flaw, which can be used to guide decisions on repair or replacement based on physical principles such as wave propagation, electromagnetic fields, and particle interactions.

There are a number of well-known NDT techniques that are the foundation of industrial inspection arsenals, each of which is appropriate to a certain type of material, defect morphology, and environmental factors. In Ultrasonic Testing (UT), high-frequency sound waves are sent through the material and the pattern of echoes and the time they take to travel through the material is used to identify internal discontinuities like voids or delaminations; it is highly sensitive and has a high penetration depth for thick metallic parts. Despite the concern of radiation hazard, Radiographic Testing (RT) which involves the use of X-rays or gamma rays, is indispensable for weld inspection because it produces shadowgraphs that show volumetric faults such as porosity or inclusions. Magnetic Particle Testing (MPT) magnetizes ferromagnetic materials and utilizes the iron particles to see the cracks under magnetic flux leakage on the surface and near surface of the components, such as crankshafts, which are subjected to the test. This cost-effective liquid-based technique, Dye Penetrant Testing (DPT), is based on capillary action of the dye to fill surface breaking defects and developer to reveal the dye, and is applicable to non-porous materials regardless of whether they are magnetic or not. Alternating magnetic fields create currents in conductive materials (Eddy Current Testing, or Eddy Current Testing – ECT) that measure the differences in conductivity, cracks, or reductions in thickness; suitable for heat exchanger tubes and aircraft skins. Visual Testing (VT) is the most common and basic method, using visual (or remote) aids (such as borescopes) to detect anomalies on the surface, typically as an initial screening method. Such approaches, frequently used in combination in multi-technique protocols, offer complementary insights, augmenting the reliability of detection.

The application of NDT is seen in a variety of industries, ensuring the reliability and safety of vital infrastructure and operations in high-stakes environments. In the aerospace field, UT and ECT guarantee the perfectly compliant composite components and airframes, meeting with FAA requirements to avoid-in-flight failures. RT and MPT are used in manufacturing for quality assurance of welds for pressure vessels and structural steel to maximize production. Automated UT crawlers are a key to the integrity of oil and gas pipelines, ensuring leak risk is reduced for pipelines in subsea and arctic conditions. Applications to the automotive industry include DPT and VT of castings and forgings as well as just in time manufacturing. RT and UT are useful for construction in bridge girders and prestressed concrete and can be used for construction lifecycle assessment according to ACI codes. For reactor vessels and Steam generators, as used in power plants, especially nuclear power plants, detailed NDT suites are required by ASME Section XI for radiatio containment.

One of the main benefits of NDT vs destructive testing (DT) is that 100% inspection can be achieved without destroying the test specimen. While the DT methods such as tensile testing or charpy impact do give reliable mechanical properties, they also destroy the sample, and therefore can only be used for statistical sampling (and post mortem) analysis. NDT, on the other hand, provides repeatability, portability, and results that are available in real time, and for large inventories can yield cost savings on a per unit basis. The effectiveness of NDT is shown by quantitative data, including probability of detection (POD) curves, such as POD >90% for 2 mm defects in welds with phased-array UT. Furthermore, NDT allows for in-situ evaluations under operational conditions, without the need to disassemble— a critical advantage in industries that rely on assets. Although DT is essential for the validation of material models, NDT due to its non-invasive approach is available for continuous monitoring and thereby enables a transition from reactive to proactive engineering. The growing significance of NDT has great implications for current-day engineering fields such as safety, reliability, and maintenance, driven by the changes in regulations, miniaturization of technology, and sustainability considerations.

The purpose of this literature review is to compile scholarly research on NDT techniques, their historical development, effectiveness, and their combination with information technologies. The focus is on peer-reviewed research on AT, UT, RT, MPT, DPT, ECT, and VT conducted between 2000 and 2026, paying particular attention to the performance capabilities of the techniques, their shortcomings, and new variants including laser ultrasonics and thermography. After assessing more than one hundred papers, possible areas for further research, such as developing standards suitable for Industry 4.0, will be proposed.

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III. LITERATURE REVIEW

1. Evolution of NDT Methods

Non-Destructive Testing provides invaluable techniques for examining materials—particularly those used in pressure vessels and metals—with zero damage done to them. Both articles emphasize its importance in ensuring there is no accident, such as an explosion, and preventing any pollution while improving safety standards and extending product lifespans.

The development of non-destructive testing has progressed from basic flaw detection to complete materials assessment. Through the use of data fusion, digital twins, and real-time surveillance, non-destructive testing today allows for a predictive maintenance system that cuts downtime and improves structural robustness (Bond, 2015). As we progress towards 2026, the combination of sophisticated sensing equipment and artificial intelligence will continue to revolutionize safety and efficiency.

2. Visual optical Test

VIT, alternatively termed VI, represents the easiest form and one of the most frequently used NDT techniques. Generally, it becomes a standard procedure preceding other NDT methods. Essentially, it involves examining the outer surface of an object in search of visible defects such as cracks, corrosion, deformations, surface irregularities, and other obstructions. In this respect, visual inspectors either make use of the naked eye or employ optical instruments such as magnifiers, microscopes, and borescopes. The primary objective of VOT consists in detecting surface discontinuities without damaging the part under analysis. In many industrial facilities, VOT serves as the first-level quality inspection, since many defects become obvious from careful observation. Adequate lighting becomes necessary for improving surface visibility. When dealing with microscopic defects not visible to the naked eye, visual inspection becomes possible with the help of magnifiers or microscopes.

VIT plays a critical role when analyzing objects that cannot be accessed directly. In this regard, borescopes represent special optical instruments incorporating a lighted tube, objective lens, and eyepiece. The borescope head moves to inaccessible locations such as bolt holes, pipe interiors, hollow shafts, and engine housings, allowing images to be transmitted to the operator through the lenses or fiber optics and makes the inspection accurate.

VOT is an important technology in sectors such as aerospace, manufacturing, power plants, rail transportation, and electronics. Borescopes regularly inspect the inside of bolt holes, turbines, aircraft engines, pipes, and micro-circuit boards that cannot be physically accessed.

Despite being inexpensive and simple to use, there are limitations in the VOT inspection technology. The method only detects surface defects, not those which may exist internally. In addition, the results are influenced by the quality of light, accessibility, skills of the person performing the inspection, and the efficiency of the equipment used. For this reason, VOT is commonly used in conjunction with other testing methods, including penetrant inspection, ultrasound, and X-ray.

In conclusion, VOT continues to be an important inspection technique used as part of the NDT process for fast and low-cost inspections of manufactured components.

3. Liquid(dye) Penetrant Test

The DPT technique is non-invasive and utilizes the phenomenon of capillarity to uncover surface anomalies. Here, the process involves applying a dye (often red) to the surface in question and letting it seep through the crack or pore before being sucked up by a developer.Several factors hinder automated processing, according to the authors, such as differences in the developer coating thickness, uneven surface texture, and illumination, which make identifying defects more difficult.This article concentrates on binarization, which entails transforming an elaborate image with color into a binary mask, highlighting defective areas.

The researchers compared three categories of methods:

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a) Traditional Single-Channel Methods: Applied to grayscale images, these include global thresholding, adaptive thresholding, and histogram-based methods like Otsu's, Triangle, and Yen thresholding

b) Multi-Channel Color Methods: These extend traditional methods to RGB or HSV color spaces. The HSV space is particularly useful because it decouples color information (Hue and Saturation) from brightness (Value), allowing for more targeted detection of the red dye.

c) Novel Machine Learning-Assisted Methods: The authors developed three new approaches:

1.Soft Binarization (SoBin): IT Uses a Random Forest regressor to estimate optimal thresholds for Saturation and Value channels based on the statistical features of the red channel histogram.

2.Delta Binarization (DeBin): It Adjusts the binarization strength based on a regulator (δ) that is automatically estimated using machine learning from the saturation channel's histogram.

3.Convolutional Autoencoder Binarization (AutoBin): It Utilizes a neural network architecture to perform binarization.

4. Magnetic Particle Testing

Magnetic Particle Inspection is a well-established form of non-destructive testing technology that can identify cracks and other flaws in ferromagnetic metal surfaces or subsurfaces. It plays an important role in damage tolerance airworthiness techniques.

1) Principle of Magnetic Particle Testing

* Mechanism: MPT depends on magnetic flux leakage. When a ferromagnetic part is magnetized, discontinuities in it such as cracks distort the magnetic lines of force, causing them to leak outside the surface.

*Indication: Fine ferromagnetic particles applied over the magnetized surface are attracted to these leakage fields, creating a visible "indication" of the flaw.

*Orientation: For the most favorable detection, the magnetic field should ideally be oriented 90° to the defect.

2) Reliability of MPT

Repeatability of MPT is determined from the parameter a_{NDI}, which is the smallest size of cracks that could be repeatedly measured.

Probability of Detection (POD): The a_{NDI} value is generally set as $a_{90/95}$, indicating that there is 90% probability of detection with 95% statistical confidence.

Standard Limitations: The RAAF provides a standard limitation value of 2.0 mm for wet fluoroscent MPI performed continuously.

Research into MPT reliability has seen a "gap" between the late 1970s and the early 1990s, with most foundational data coming from four major sources that were later reanalyzed using modern statistical methods:

Packman et al. (1968/1976): Initial studies found that MPT could not "consistently" detect cracks smaller than 2.54 mm. Reanalysis of their D6ac steel plate data yielded an a_{90} of 2.32 mm.

Southworth et al. (1975): Investigated various geometries and found that magnetisation methods (portable yokes vs. stationary benches) had negligible effects on a_{90} for external flaws.

Rummel et al. (1976): Highlighted the critical impact of surface condition, showing that a_{90} improved from 4.02 mm in "as-machined" specimens to 2.01 mm after etching and proof loading.

Meta-analysis findings:-

A meta-analysis of these studies concluded that the median a_{90} for MPT is 2.2 mm. While performance varies between organizations, the data supports the current 2.0 mm standard limitation but does not suggest it should be reduced. The largest a_{90} consistent with most implementations was found to be 2.6 mm.

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5. Eddy Current Testing

ECT is one of the basic non-destructive techniques employed in examining pipelines in industries such as oil, gas, and petrochemicals. It involves the principle of electromagnetic induction, whereby an alternating current flowing through the excitation coil creates a primary magnetic field. As this primary magnetic field approaches the material under test, it causes eddy currents, which then create another magnetic field that is opposite the initial field. Variations in this process can be determined as variations in coil impedance, providing insights into defects or material thickness.

Recent studies have focused on PEC NDT to circumvent the deficiencies associated with harmonic-based ECT methods. While the conventional sine-wave excitation method used in harmonic ECT limits the range of inspection depths and resolution, PEC uses square-wave or step signals containing many frequencies. The high frequencies detect surface defects, whereas the low frequencies detect subsurface defects through materials like metal cladding or thick insulations. The effectiveness of inspection is heavily dependent on probe architecture. The review highlights several key design categories:

a) Encircling Coil Systems: These include differential and absolute probe designs (ECDP and ECAP). While encircling coils ensure a uniform magnetic field around a pipe's circumference, they can struggle with identifying defects on outer walls compared to inner walls.

b) Magnetic Sensor Integration: To improve sensitivity, researchers are increasingly replacing traditional induction coils with solid-state magnetic sensors.

c) Giant Magnetoresistance (GMR): These sensors offer superior accuracy and a small form factor, making them ideal for high-resolution data collection in confined spaces.

d) Tunnel Magnetoresistance (TMR) and Hall Sensors: These are also explored for their ability to provide detailed imaging of longitudinal cracks and deeper material penetration.

e) Electromagnetic Field Models: These solve Maxwell’s equations to understand the spatial and temporal distribution of fields. Numerical methods like the Finite Element Method (FEM) are particularly valued for their ability to simulate complex sensor geometries and irregular defect shapes.

f) Circuit Models: These simplify the physics into equivalent electrical components (resistors, inductors, and capacitors) for faster, engineering-focused analysis, such as the "eddy current ring theory".

6. Acoustic Emession

Acoustic Emission (AE) refers to an NDT technique that involves the detection of the high-frequency elastic wave emitted by a stressed material during the emission process. The acoustic emissions are brought about by irreversible internal phenomena such as micro-cracks, corrosion, or the breaking of fibers. Unlike active NDT techniques that add external energy to the structure, AE takes advantage of the energy released during the damage process in determining its occurrence. Even though conventional techniques focused on the qualitative analysis of the acoustic emissions, today's advances in technology permit their quantitative analysis through high-tech sensors and fast data capture.

The inherent complexity involved in AE signals, made even more difficult by the presence of noise, has necessitated the application of machine learning algorithms in AE-based analysis. Through machine learning, the system can automatically learn from data without necessarily being programmed for specific tasks.

a) Core Methodologies and Architectures

There are various machine learning (ML) types used to process AE data to detect faults and localize them:

* **Clustering Algorithms:** Methods such as Fuzzy C-means and K-means are often applied for damage classification in both composites and concrete without supervision. Despite being computationally efficient, clustering algorithms have high errors and bias.

* **Artificial Neural Network (ANN):** The popular technique widely used to perform classification of faults. It employs three types of layers – input, hidden, and output – based on the signal feature extraction performed. The main advantages include high accuracy and fault-tolerance but require rigorous training process.

*** Convolutional Neural Network (CNN):** One more innovation is represented by CNNs allowing for "feature-extraction-free" monitoring. They automatically find informative traits among raw data and time-frequency images providing high efficiency in terms of processing big data and separating noise in situ.
*** Recurrent Neural Networks (RNN):** Another type of network designed to analyze sequential data to predict structure's remaining lifetime and to remove noise in time series AE data.

b) Comparative Performance and Future Outlooks

According to existing studies, deep learning architectures (CNNs and RNNs) tend to produce more accurate results (70% to 99%) than conventional clustering algorithms (80% to 90%), owing to their capacity for automated extraction of knowledge from vast amounts of data.

An emerging trend in this area involves the use of transfer learning (TL) techniques that permit the deployment of pre-trained algorithms on novel structures unrelated to the original training tasks, especially useful when the quantity of data is insufficient. Future investigations will likely concentrate on creating foolproof and quantitative rules for specific geometric shapes.

7. Ultrasonic testing

Ultrasonic Testing (UT) is one of the most important methods of non-destructive evaluation which uses ultrasonic waves in order to test and evaluate the material under study, especially for its mechanical properties. UT is based on the principle of wave propagation through a medium. By measuring the time taken for the ultrasonic pulse to travel to the other end and then bounce back to the point of emission, the speed of longitudinal and transverse waves is determined.

UT-NDT is better than other testing methods in many ters such as:

***Accuracy:** UT-NDT methods have lesser deviation from theory .

***Precision:** The information obtained from the ultrasonic wave method is almost twice as precise as that obtained through simulations.

***Convenience:** With UT-NDT, a clean lab experience is guaranteed since there is no need for sample deformations or destructions.

Though tensile testing is still an important way to observe the actual performance of materials subjected to enormous stress, UT-NDT is the best way to accurately measure properties. It is essential for such techniques to be taught in engineering curriculums in order to prepare future engineers to use them widely.

8. Radiographic testing

Radiographic Testing is one of the key techniques of Non-Destructive Testing, which employs high-energy electromagnetic radiation in the form of X-rays or gamma rays to inspect the internal structure of a material. RT is extremely important in areas that require utmost reliability as failures could be disastrous, including aviation and oil and gas exploration. The technique of RT rests on the principles of differential absorption as radiation passes through the object under test; depending on the thickness and density of the material, radiation is captured differently by the film.

The methods involve two main forms of radiation sources:

i) X-ray Machines: The use of electrically generated X-rays involves the production of X-rays through the collision of high-speed electrons with a tungsten target. The operators have the capability to regulate the strength and wavelength of radiation emitted using a filament temperature adjustment and voltage.

ii) Gamma Ray Sources: This makes use of the natural decay process of unstable isotopes such as Cobalt-60 and Iridium-192. Unlike X-ray machines, gamma rays are not electricity-driven and therefore more portable.

*** Procedural Framework and Industry Standards**

A standardized six-step protocol ensures the reliability of RT results: initial surface preparation to remove misleading irregularities, selection of appropriate radiation sources and films based on material density, use of penetrameters for quality control, execution of the chosen exposure technique, thorough defect inspection, and meticulous data recording.

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Compliance with global standards from organizations such as ASTM, ASME, ISO, API, and CEN is mandatory to guarantee workmanship quality and operational safety.

* **Advantages and Constraints**

Radiography offers the unique benefit of providing a permanent, visual record of a material's internal state without requiring structural disassembly. However, it is constrained by significant safety and logistical challenges.

* **Safety Hazards:** The ionizing radiation used is inherently dangerous to living tissue, necessitating strict adherence to safety protocols and the use of personal protective equipment.

* **Operational Requirements:** Effective RT requires access to both sides of the sample and significant investment in specialized facilities for exposure and film processing.

* **Source Comparison:** While X-rays provide higher image resolution and adjustable energy levels, gamma rays are favored for their superior penetrating power through thick materials and their cost-effective, robust equipment.

IV. COMPARITIVE ANALYSIS

Method	Defect type	Material	speed	Cost
VT	SURFACE	ALL	FAST	VERY-LOW
PT	SURFACE	NON-POROUS	FAST	LOW
MT	SUBSURFACE	FERROMAGNETIC	MEDIUM	MEDIUM
ET	SUBSURFACE	CONDUCTIVE	MEDIUM	MEDIUM
AT	SBSR+ INTERNAL	METALS & COMPOITES	REAL-TIME	COSTLY
UT	INTERNAL	MOST SOLIDS	REAL-TIME	COSTLY
RT	INTERNAL	ALL	VERY-SLOW	VERY COSTLY

TABLE 3.1

Non-destructive testing (NDT) comprises a diverse suite of evaluative techniques essential for ensuring structural integrity without compromising component functionality. These methods are generally categorized by their ability to detect surface-level or volumetric irregularities.

1) Surface and Subsurface Inspection

Traditional methods like Visual Testing (VT) and Penetrant Testing (PT) have been widely applied for their economic value when it comes to open-to-surface discontinuities. Although VT continues to be the first step in all inspections, PT increases the sensitivity of detection of cracks. For the detection of near-surface defects in metals, Magnetic Particle Testing (MT) and Eddy Current Testing (ET) can be used effectively, depending on the type of metal used. ET is especially known for its high sensitivity to cracks and thin coatings.

2) Volumetric and Advanced Inspection

If the defect is of an embedded nature, then for such flaws, UT and RT are standard practice. UT allows precise subsurface imaging and is now coupled with artificial intelligence technology, increasing the precision of flaw detection by up to 30% . On the other hand, RT uses radioactive rays and gives permanent films of the inner structure. However, RT comes with many safety issues . AT is used as a dynamic testing method and can detect real-time flaw growth through stress waves (Tosti, 2025).

V. KEY FINDINGS

•**Shift towards Proactive Maintenance Strategy: It** is evident that there is a shift in the maintenance paradigms within the realm of engineering from the reactive to the proactive approach of "Condition-Based Maintenance". The main data

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provider in this context is the use of the NDT methodology. The application of this approach results in a decrease of the number of unplanned industrial stops up to 50 percent.

•**Efficiency of Quantitative NDT compared to Destructive Tests:** Although destructive test (DT) method is inevitable for the preliminary verification of the material, NDT offers an efficient substitute for further control of the quality. According to research, ultrasonic wave velocity analysis could lead to almost double efficiency in comparison with simulations in terms of defining elasticity modulus (E) and Poisson's ratio (ν).

• **PEC Testing:**□There is evidence of the replacement of traditional harmonic sine wave tests with the pulsed eddy current testing (PEC). This innovative development facilitates multi-frequency testing, providing information not only about the surface but also the sub-surface damages regardless of the insulating or metallic coverings.

• **Incorporation of Artificial Intelligence in Acoustic Emission (AE):** The study of spontaneously generated elastic waves is now gaining more automation due to Machine Learning. CNNs (Convolutional Neural Networks) and RNNs (Recurrent Neural Networks) exhibit much greater diagnostic effectiveness, up to 99%, than conventional unsupervised clustering approaches by virtue of their ability to automatically extract features.

• **Progress Made in Automation of Surface Inspection:** Conventional surface inspection techniques such as liquid penetrant testing (LPT) have been upgraded using machine learning-based binary techniques (for example, SoBin and AutoBin). These techniques tackle issues in automation that have persisted for quite some time now, including lighting and surface texture variations, which enable a better distinction of red dye from the surroundings.

• **Reliability and Standardization of Magnetic Particle Testing (MPT):** A meta-analysis reveals that the standard detection limit ($a_{90/95}$) for MPT is consistent at 2.0 mm for ferromagnetic materials. Although surface preparation (e.g., etching) plays a critical role in lowering detection limits, the existing industry standards have robust statistical backing.

• **Complementarity of Radiographic Testing:** Radiographic Testing (RT) is established as the standard testing method for volumetric internal inspection. Analysis indicates a strategic consideration where X-rays are used due to their higher resolution and adjustability while gamma-ray systems (Cobalt-60/Iridium-192) are employed for better portability and high penetrative power for thicker walls.

• **The Effects of Modern Solid-State Sensors on Probes:** The incorporation of advanced solid-state sensor technologies, such as Giant Magnetoresistance (GMR) and Tunnel Magnetoresistance (TMR), in non-destructive test (NDT) probes has been instrumental in enhancing the resolution capacity within the tight constraints of NDT testing.

• **Non-destructive Testing (NDT) and Sustainable "Second Life" of Parts:** Apart from being a crucial method of ensuring safety, NDT has the potential to play an important role in sustaining the environment by non-invasive certification of reusability.

VI. FUTURE SCOPE

The evolution path of non-destructive testing (NDT) is going towards an integrated, smart, and autonomous platform. With respect to recent technological advancements, the following can be taken as the main domains for future endeavors:
* **Standardization of Industry 4.0 and Digital Twin Technology:** A major area requiring further investigation is the standardization of NDT data in "Industry 4.0." In the future, researchers will probably concentrate on developing "Digital Twins," which are virtual replicas of the physical components, updated dynamically by NDT sensors' data. Such

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integration will facilitate the creation of accurate lifecycle projections and enable the simulation of structural stress conditions virtually before their appearance.

* **Implementation of Transfer Learning (TL) Methodology in Machine Learning Algorithms:** Despite the success of deep learning techniques for Acoustic Emission (AE) and Eddy Current Testing methods, the next important development will probably be associated with "transfer learning." The transfer learning methodology is necessary for transferring knowledge gained from one type of material/geometry to another completely different object without any additional data.

* **NDT Methods Hybrids:** In future inspection methods, there will be a tendency toward hybridizing various NDT techniques that combine the best characteristics of several physical phenomena into a single system. For example, "laser ultrasonics" can use both optical and acoustic waves to eliminate inherent "blind zones" in inspections conducted by only one method. Similarly, pulse thermography combined with eddy current sensors can provide additional information about the test object.

* **NDT Sensors Minimization and Robotics:** With further advancements in solid-state sensors, like Giant Magnetic Resistance (GMR) or Tunneling MagnetoResistance (TMR), there is potential for further reduction in size. Future studies will focus on mounting these sensors on automated crawling devices or drones that can access hazardous locations without human assistance.

* **Quantitative NDT for Additive Manufacturing (3D Printing):** As companies incorporate metal 3D-printed components into their production processes, new types of defects will arise, such as "lack-of-fusion" porosity or anisotropic grains. The task for future researchers is to develop specific Probability of Detection (POD) curves for additive manufacturing inspections.

* **Green NDT and Sustainability Certification:** In support of global net-zero goals, NDT will play a pivotal role in the circular economy. Future frameworks will focus on "Life Extension Certification," using non-invasive testing to formally validate that decommissioned components (such as wind turbine blades or structural steel) are safe for a second life, significantly reducing industrial waste and carbon footprints.

* **Advanced Data Fusion and Cloud-Based Diagnostics:** The massive volume of data generated by modern high-speed NDT sensors necessitates advanced data fusion algorithms. Future systems will likely utilize cloud-based platforms where inspection data from around the globe can be synthesized to identify universal patterns in material degradation, leading to more robust global safety standards.

VII. CONCLUSION

The extensive review of existing literature reveals that Non-Destructive Testing (NDT) has transformed from a secondary approach to quality assurance to a first-line resource for safeguarding industrial facilities. With the rise of expectations regarding the durability and robustness of global infrastructure, the switch from conventional destructive testing to non-destructive monitoring becomes a prerequisite of the modern technological landscape.

In summary, although such classical approaches as Visual Observation Technique (VOT), Radiographic Testing (RT), and Magnetic Particle Testing (MPT) serve as the cornerstones of NDT, the current advancements in the field have been driven by digitalization and automation processes. Specifically, the shift from the conventional manual inspection process to the sensor-driven data collection process has greatly enhanced the sensitivity of detecting flaws within the infrastructure system. Besides, the recent implementation of deep learning technologies and convolutional neural networks has enabled the replacement of expert knowledge in NDT applications.

Conclusions drawn from the comparison between NDT and conventional mechanical testing demonstrate that ultrasonic and electromagnetic modern technologies can provide comparable or superior accuracy compared to destructive tests for material characterization. Moreover, the possibility of conducting non-destructive inspections in situ, without interrupting production, is a key advantage making NDT the cornerstone of Condition-Based Maintenance (CBM).

Concluding, the future success of non-destructive testing will be contingent on the technology's capacity to evolve in tandem with new manufacturing paradigms, including additive manufacturing and composites, as well as support international sustainable development initiatives by extending the life span of vital equipment. For this purpose, it is necessary to focus on data standardization and developing multi-modal inspection platforms. Overall, the integration of sound physical theory and advanced algorithms.will remain the core of the next era of engineering integrity and reliability.

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