Classification of Non-Destructive Evaluation

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Inspection methods, also known as non-destructive evaluation (NDE), is a process for inspecting materials, products, and facilities to identify flaws, imperfections, and malfunctions without destruction or changing the integrity of materials, structures, and mechanisms.

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1. Introduction

Overall testing, inspection, and certification services have been continuously carried forward along with INDUSTRIAL revolutions. The testing, inspection, and certification market is projected to grow from $221 billion in 2022 to $268.9 billion by 2027 [1]. Testing, inspection, and certification services help manufacturers improve productivity, meet global standards, and enhance product and service quality for any product, service, or process. Part of that has been due to testing, inspection, and maintenance developments to keep up the production and service processes and ensure infrastructure health and safety regardless of the sector in which the company operates. Of all these developments, non-destructive evaluation methods (NDE) are of great importance because of their detection and characterization capabilities. Non-destructive evaluation is a set of techniques that do not destroy materials during inspection [2]. NDE is the evaluation and analysis technique that enables inspecting materials or components without causing any damage to the part [3] in a safe and reliable manner. Moreover, NDE methods are cost-effective and safe for workers. These methods are mainly used in aerospace and manufacturing industries [3] and vary from visual inspection performed by engineers specialized in the field to chemical and liquid penetration tests, alternative current, acoustics, etc. [4].

However, the contemporary industry is struggling with new challenges that prohibit modernization and synchronization. Due to the large volume of data and innovative technologies that are emerging exponentially and in response to the need for better and faster production, the world has entered a new stage of the industrial revolution, which is also called Industry 4.0. Industry 4.0, defined as the digital transformation of the business [5], is a relatively new concept that includes the most important technological developments in the fields of automation, control and information technology applied to production processes. It incorporates concepts ranging from physical-cyber systems to the Internet of Things (IoT) and Internet services, and production processes are becoming more efficient, autonomous and adjustable [6]. Driven by a large amount of available data [7], Industry 4.0 is transforming manufacturing into smarter automation in many ways, including the installation of intelligent robots, sensors, the use of collaborative robots, and the use of manufacturing simulations [8]. An Industry 4.0 typical example is the introduction of a monitoring system that monitors equipment in real-time by the means of AI algorithms to automatically detect and identify defects [9].

2. Classification of NDE Methods

In general, NDE methods can be classified based on various factors, including the type of physical field, type of defect, and performance characteristics. In order to classify NDE methods based on physical fields, electric, magnetic, thermal, and mechanical fields can be highlighted. Defects can also be classified into surface and subsurface defects. Accuracy, efficiency, safety, and cost are the most important determinative parameters. **Table 1** presents an overview of some of the NDE methods.

Table 1. An overview of the NDE methods and their advantages and disadvantages.

Methods Criteria	Visual Evaluation	Eddy Current	Ultrasonic	Thermographic Inspection	Radiographic Testing	Laser 3D Scanning	Laser Spot Thermography
Source	-	Eddy current	Acoustic vibration	Thermal emissivity	X-ray/Gamma-ray	Laser beam	Heat distribution
Material	All	Conductive materials	All	All	All	All	Metals
Contact requirements	Non-contact	Non-contact	Contact/Non-contact	Non-contact	Non-contact	Non-contact	Non-contact
Advantage	Easy to implement, low cost	Low-cost, no surface treatment	Great depth penetration, high resolution	Full-field, fast, high resolution, high sensitivity	High resolution	Full-field, fast, high resolution	High surface temperature, hazardous environments, high resolution
Disadvantage	Surface defects, safety problems, time-consuming, low reliability	Scanner required	Sound attenuation, time-consuming, 2D measurements	Scanner required, detection of false positives, limitation due to thermal properties of materials	Radiation hazards, relatively slow, scanner required	Surface defects	Surface defects, time-consuming

2.1. Visual Evaluation (VE)

Visual evaluation is the process of collecting data visually. This type of inspection requires a team of trained and experienced inspectors and usually does not require a special set of tools. It is effective to capture macroscopic defects, bad joints, incorrect dimensions, inadequate surface finish, large cracks, and non-compliant parts. It is also used to detect defects in composite structures [3]. Optical-based NDE techniques, as the major subset of VE methods, offer many advantages compared to other NDE methods. In addition to resistance to electromagnetic interference, optical NDE is not limited to a specific type of material and can be used in various cases. Although the use of optical approaches is expensive, these advantages lead to a wide range of applications [10]. That being said, the VE inspection methods cannot be limited in number, where any technique using vision can be considered in the mentioned scope. However, robust and efficient implementations of VE can be obtained in the literature, such as the example provided in [11]. Researchers presented a vision measurement system that was designed to track the complete field deformations of specimens, and a quad ocular vision system to calculate the concrete column deformations. In this context, the state-of-the art of the VE system in infrastructure and concrete can be studied in detail in article [12].

2.2. Eddy Current Evaluation

Eddy-current testing offers a high degree of sensitivity for material identification and microstructure characterization [13]. As the name suggests, eddy current evaluation is based on introducing an alternating current into a conductor through a process called electromagnetic induction [3]. The interaction between the magnetic field source and the test material induces eddy currents in the test piece [14]. Inspectors can detect the presence of very small cracks by monitoring changes in the eddy current. Eddy current allows detecting cracks in a variety of conductive materials, both ferromagnetic and non-ferromagnetic. It is applied without any contact between the test object and the sensor [15]. Eddy current inspection has proven its effectiveness in defect detection. Its implementations are seen in different domains such as the aeronautics industry [16][17], nuclear industry [18][19], metallurgical industry [20][21], and transportation [22].

2.3. Ultrasonic Evaluation

Ultrasonic evaluation is based on the propagation of ultrasonic waves into an object. These high-frequency sound waves are radiated into the material to characterize the material and detect defects. It consists of several functional units such as pulser-receivers, piezoelectric transducers, and display devices. A pulsar is an electronic device used to generate high voltage electrical pulses. Using pulses, the transducer generates high-frequency ultrasonic energy. Sound energy is introduced that propagates through the material like a wave. If there is a discontinuity in the wave path such as a crack, some of the energy will be reflected by the flat surface. The reflected wave signal is converted into an electrical signal using a piezoelectric transducer and the output is displayed on the screen [23]. Surface cracks can also be detected using ultrasonic evaluation. It uses the same concept as naval SONAR. In ultrasonic evaluation, information about the ultrasonic wave, such as its reflection and scattering, is used to detect flaws in materials. The two most common forms of sound waves used in industrial inspections are the longitudinal wave and the shear wave. The traveling speed of shear waves is almost half of longitudinal waves. It was found that Rayleigh waves, which are one of the surface waves that are travelling along the solid surface, are more suitable for surface flaw detection due to their physical properties [24]. In literature, there are several implementations of ultrasonic inspection. In [25], for example, the authors suggested a system model for ultrasonic examination of smooth planar fractures in ferritic steel employing pulse-echo probes. Their suggested model predicts echo amplitudes and ranges as functions of probe location, and is implemented as a suite of adaptable and user-friendly computer programs suited for usage by practical NDE engineers, backed up by a thorough user manual. Similarly, in [26], the authors introduced Laser-EMAT (ElectroMagnetic Acoustic Transducer), an ultrasonics technology appropriate for on-line surface and interior fault detection in a steel mill. The device is designed to autonomously check steel as it travels through the steel production process at temperatures above 700 degrees

Celsius. Because of its non-contact nature, it is one of the few ultrasonic systems that could ever be employed in the rigorous working environment of a steel mill.

2.4. Thermal Inspection

Thermal inspection is a method of mapping and measuring surface temperatures. It is known for its use of thermal measurements of an object and its response to a stimulus. The most commonly used tools for temperature measurements are thermal cameras. Thermal cameras have been used to diagnose electrical junctions in power transmission networks [27], monitor the thermal state of other electrical installations automatically [28], assess particular qualities in various materials, and to assess the erosion resistance of silicon rubber composites as in [29]. It has proven to be an effective and economical method for evaluating concrete [3]. Thermal non-destructive evaluation is most likely applied due to its underlying physical principles. Infrared/thermal, X-ray, electromagnetic, and ultrasonic tests use the injection of some form of energy and detect the residual energy not absorbed by the object. Defects are detected when the energy intensity varies because of the presence of defects. Its results can be affected by thermal noise, but with sufficient combination with other NDE methods, more efficient and productive results can be achieved [30].

2.5. Laser Spot Thermography

Laser spot thermography (LST) is a new infrared evaluation method for surface crack inspection. The LST method uses a laser to produce a highly localized heating spot near the crack and an infrared camera to detect the perturbation of the round lateral heat flow to reveal crack information. Fiber-guided LST systems have been developed to inspect surface cracks in metal structures. A high-power laser, a fiber delivery unit, and a specially designed optical head are used to generate a heat source for the nine-by-nine laser array points on the sample surface. Combined with an improved image processing method that uses multiple background-free images, this system was able to successfully detect and extract cracks from measured thermal images [31].

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