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A review of miniaturised Non-Destructive Testing technologies for in-situ inspections

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Abstract

Non-destructive testing (NDT) techniques have become attractive trends of product manufacturing, installation and post-maintenance in the aerospace, automotive and manufacturing industry, because of its benefits such as cost saving, easy to use and high efficiency etc. With the industrial products becoming large-scale, high integration and complication, developing the NDT miniaturisation technique for in-situ inspections is highly demanded and becoming an inevitable trend. However, in-situ inspection using NDT have been limited by a number of factors, such as the heavy weight, large size or complex structure etc. This paper aims to systematically identify and analyse the current state-of-the-art of NDT miniaturisation techniques in research and innovation, and discuss the challenge and prospect of miniaturisation of the commonly used NDT techniques.

Keywords: Miniaturisation; Low-cost; In-situ; Magnetic Particle Inspection; Ultrasonic Testing; Infrared thermography; Radiographic Testing

1. Introduction

Non-destructive testing (NDT) is a practical technique for detecting, locating, recognising, and measuring the internal hetero-structure of the material or component without causing damage for effectiveness or reliability. The most commonly used NDT techniques include: Ultrasonic-testing, X-rays testing, magnetic particles testing, penetrant testing, eddy currents testing, infrared thermography and so on [1][2]. 'In-situ' is a term that is widely used to define the location of sensors as part of the system with the capability to provide functional measurements when the system is in its natural working environment [3]. Because engineering systems need to be maintained regularly to prevent any catastrophic failure as a result of regular wear and tear, NDT technology for in-situ inspection has been widely used in aerospace, automotive, and manufacturing industries [4][5]. It has been

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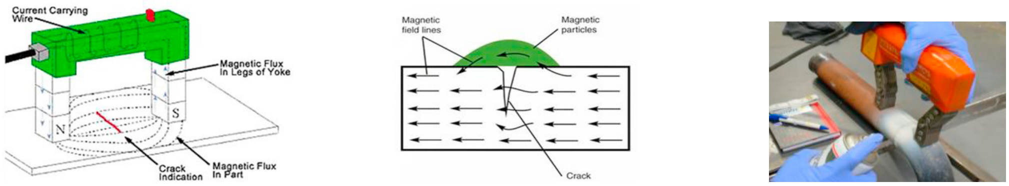
supporting maintenance activities for over a century and industries still continue to rely on such technologies for effective degradation assessment. The practical applications include honeycomb structures and bonding structural on the aircrafts, structural components and inboard piping systems on the ships, automotive parts, wind turbine blades, boilers and various types of pressure equipment in the petrochemical companies etc [6][7]. NDT technique has also become an indispensable part of product manufacturing, installation, and maintenance, due to its characteristics on convenience, high-efficiency, and low-cost. However, with the increase of the functionalisation, integration, complexity of industrial products and increasing use of advanced materials into complex systems, the deployment of NDT devices in in-service inspection has been limited by various factors such as weight, large size, and complex structures. Developing lightweight and miniaturised NDT testing equipment to inspect multiple materials for degradation assessment of inaccessible area becomes more and more important [8]. Additionally, the serviceability of the components or systems to be inspected has now become challenging, particularly in determining their maintenance requirements as disassembly and inspection is very expensive [9]. This paper aims to systematically identify and analyse the current state-of-the-art of NDT miniaturisation techniques in research and innovation, and discuss the miniaturisation prospects of commonly used NDT techniques[10]–[12].

2. Commonly used NDT techniques

Before reviewing the state-of-the-art of miniaturised NDT technique, this section introduces the principles of commonly used NDTs. It will directly determine the feasibility of miniaturisation for NDTs.

2.1. Magnetic Particle Inspection (MPI)

Magnetic particle inspection is one of the conventional detection methods, and is one of the oldest and most mature NDT technologies. It is widely used in the surface and near surface detection of ferromagnetic components in various industries [13]. When the ferromagnetic material and the workpiece are magnetised, due to the presence of discontinuity, the magnetic lines of force on the surface and the near surface of the workpiece are locally distorted to generate a leakage in the magnetic field, and the magnetic powder applied on the surface of the workpiece is adsorbed to form a visible magnetic material under suitable illumination, traces showing the position, shape, and size of discontinuities. Fig.1 illustrates the principle and deployment example of this technique.



(a) (b) (c)

Fig. 1. The schematic of Magnetic Particle Inspection: (a) shows the magnetic field lines are formed between north and south poles when Legs of Yoke touch with the ferromagnetic material under power condition. The magnetic powder builds up to form a line which can be observed when there is an internal defect (Crack indication, red line in this picture); (b) is an enlarged view that the magnetic powder is piled up at the defect area. (c) In-situ inspection using Magnetic Particle Inspection technique [14].

2.2. Ultrasonic Testing

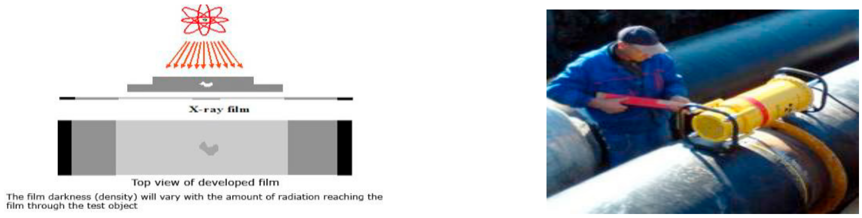
Ultrasonic testing uses special equipment to send high frequency sound waves to penetrate a material's thickness, and then uses other special equipment to receive these sound waves. According to how the high frequency sound waves are returned to the recording equipment, the determinations about material condition and discontinuities can be made [15]. It is commonly used to inspect and evaluate the specific application of macroscopic flaw detection, geometrical characteristics measurement, characterisation of changes in mechanical structure and mechanical properties of the test piece [16]. The principle and deployment example of this technique are demonstrated in Fig. 2. With the increasing level of electronics, computer and software technology, digital ultrasonic testing instruments are being put into largely use. High-precision, effective control and judgment capabilities reduce human error and enhance the reliability and stability of detection. It promotes the automation and intelligent development of ultrasonic testing and evaluation.

(a) (b)

Fig. 2. (a) The schematic of Ultrasonic Testing: When the ultrasonic wave (black line) emitted from an ultrasonic probe (transducer) passes through an object, reflected waves formed at the defect and the back of the object, are displayed by the wave spectrum (green line), further to judge the position, size and depth of the defect. (b) In-situ inspection using Ultrasonic Inspection technique [17].

2.3. Radiographic Testing

A variety of electromagnetic (EM) spectral waves pass through a material. Whilst, only wavelengths pertaining to the visible spectrum of the EM spectrum are visible, rays between the wavelengths of 0.01 to 10nm penetrate the material identifying its internal structure. These rays, generally termed as radiographic rays or X-Rays, irradiate the film. Rays can penetrate the material that the naked eye cannot penetrate to make the film sensitive. When X-rays or r-rays irradiate the film, like ordinary light, it can make the silver halide in the film emulsion layer produce a latent image because of the different density of the material to the radiation. Since the absorption coefficient is different, the intensity of the radiation irradiated to the film will produce differences. The defects can be detected based on the difference between the darkness of the film after treatment in the dark room [18]. The ray detection has high accuracy, it can clearly display the position and contour of defects. However, because of its inherent radioactivity, the requirements for the personnel and detection environment are extremely strict to ensure safety. Therefore, most ray detection technique requires the testing process undertaken in a confined space. Fig.3 demonstrates the principle and deployment example of this technique. Meanwhile, with the development of digital radiography, digital X-ray sensors will be used instead of traditional photographic film, less radiation can be used to produce an image of similar contrast to conventional radiography, the detection environment will change as well [19].



(a) (b)

Fig. 3. (a) The schematic of Radiographic Testing: Red represents the source of the radiation, transmitted the test object shines on the X-ray film, forming a dark spot that indicates the defect, icon is top view (b) In-situ inspection using Radiographic Inspection technique [20].

2.4. Infrared Thermography Testing

Infrared thermography technology is divided into passive (without external excitation) and active (with external excitation) modes [21]. Passive infrared thermography is a detection method based on the relationship between the surface temperature of an object and the intensity of infrared thermal radiation energy generated by the object. Based on the types of excitations, the active infrared thermography can be divided into Pulsed thermography, Lock-in thermography, Vibro-thermography, Eddy current thermography and Laser spot thermography [22]–[25]. Pulsed thermography is a well-established form of active thermography technique. The working principle of this technique is as follows (see Fig. 4): the surface temperature of the component is increased briefly with the help of a uniform optical excitation source (e.g., flash pulse or hot gun). An IR camera or radiometer controlled by a computer (PC) records the response of the surface temperature due to the thermal excitation over a known period of time. In a homogeneous material, the transient heat flow from the surface into the component will be uninterrupted. As soon as a thermal discontinuity appears, there is a break in the transient heat flow characteristics which shows on the surface as a hot or a cold spot indicating the presence of a foreign body in the bulk of the material [8].It will be using test results of thermogram or an infrared image to determine defects.

(a) (b)

Fig 4. (a) The schematic of active thermography testing: Using excitation source to heat sample, using infrared (IR) camera to capture the change of temperature; (b) using pulsed thermography technique in the lab [26].

3. The state-of-the-art of NDT miniaturisation for in-situ inspection

Although there are many other NDT methods, such as eddy current testing, acoustic emissions/EMATs, 3-D imaging/ part of visual inspection and phased array/ full matrix capture (FMC), which have attracted more and more investigation, as the first attempt on this topic, this paper will only focus on four selected NDTs.

3.1. MPI

MPI employs either electromagnets or permanent magnets. The former generally uses electrical current to produce the magnetic field, lifting power therefore can be controlled easily through controlling the current. However, it cannot be used in underwater environments or explosive environments [27]. The permanent magnet can be made small enough to fit into tight areas where electromagnet based one might not be able to because permanent magnet has no requirement of power source and battery. However, a limitation of permanent magnet is that it is difficult to remove the magnets from the component being inspected after the inspection. The rapid development and innovation has promoted a number of global magnetic particle equipment manufacturers, such as Italian CGM, German Karl Deutsch, US Magnaflux, French Srem, and British Johnson & Allen. Recent development includes the pulse technology for magnetic testing and demagnetisation of steel components proposed by Peter Hirsch of Germany [28] and cross and additional orthogonal magnetic coils application in components of large dimensions technology proposed by Rainer Link and Nathanael Riess of Germany [29]. The new frequency conversion and non-contact magnetisation technology proposed by Michitaka Hori and Arihito Kasahara of Japan enables non-contact stereo composite magnetisation for workpiece [30]. The improvement of magnetic particle detection technology gradually adapts to the increasingly complex detection environment, but the miniaturisation degree of magnetic particle testing equipment has not changed significantly. Taking US MAGNAFLUX as an example, its magnetic particle detector Y-7 (see Fig. 5 (a)) is the most advanced high-strength electromagnets based device at present. Solid-state controls allow the operator to use Alternating Current magnetic fields for surface indications or Direct Current magnetic fields for sub-surface indications to meet all inspection needs, but this kind of equipment is still kept in the combination of traditional power supply and magnetic yoke [31]. YM-5 (see Fig. 5 (b)) is a representative product of permanent magnets produced by the company, it can find sub-surface indications during magnetic particle testing with no power supply. It also features with 40-pound dead-weight lift strength [32]. The enhancement of lifting force increases the degree of magnetisation of the object being inspected, which in turn increases the detection rate. Although it is optimised in the design of the overall equipment, the output of large lifting force still affects the optimisation of the equipment volume, and due to the permanent magnet, the control is not very convenient. Similar products also include RPNSS and RPNSL permanent magnets equipment manufactured by Johnson & Allen Company (see Fig. 5 (c)). These two products are relatively small, with the smallest pole gap of 37mm and the cross section of 20mm x 25mm, but the lifting force is only 18kg [33]. So according to the current state of the art, the degree of miniaturisation of magnetic particle testing is relatively low.

(a) (b) (c)

Fig. 5. Examples of magnetic particle detector (a) Y-7 (Electromagnet) produced by MAGNAFLUX [31]; (b) YM-5 (Permanent magnets) produced by MAGNAFLUX [32]; (c) RPNSS&RPNSL Permanent Magnets equipment manufactured by Johnson & Allen Company [33].

3.2. Ultrasonic Testing

Ultrasonic testing (UT) is widely used and is generally divided into Ultrasonic Thickness Gauges and Ultrasonic Flaw detectors according to the function division. Cygnus Dive Wrist-Mountable Underwater Thickness Gauge (see Fig. 6(a)) can measure through coatings up to 20 mm thick in the 300 meters depth water, developed by Cygnus instruments Company, and accuracy is ±0.1 mm [34]. VEO+ is produced by Sonatest (see Fig. 6(b)) combines with phased array probes, it can display S, L, A, B, C, TOFD Scan and integrate real-time imaging and 3D scanning, enable a device to have both UT and ultrasonic Time-of-flight-Diffraction detection capabilities [35]. Although miniaturisation has not been achieved yet, it is already going forward in the process of functional intensification. Another product EPOCH® 6LT portable flaw detector (see Fig. 6(d)) also produced by Olympus, the weight is just 1.95 pounds (890 g) with a grip-oriented weight distribution for one-handed operation with minimal wrist fatigue, and contains wireless LAN connectivity [36]. The RollerFORM Scanner (see Fig. 6(c)) uses phased array wheel probe and zero-degree ultrasonic beams for manufacturing and maintenance inspections. Common applications include delamination sizing and porosity quantification in composite core material, as well as wall-loss monitoring in aluminium panels, the compact and lightweight form integrates powerful detection functions [37]. However, there is also a factor that restricts the development of ultrasound miniaturisation, which is the use of a coupling agent. The traditional ultrasonic detection process requires the participation of the coupling agent, which requires the probe close to the surface of the object to be inspected during the detection process. This is mainly to remove any attenuation caused by gaps between the detector and the material surface, which brings inconvenience to detect the narrow area. The non-contact ultrasonic transducer methods that have been successfully developed and put into use include: laser ultrasonic method, air coupling method, electrostatic coupling method, and electromagnetic sound method. The Non-Contact Air Coupled Ultrasonic Testing technology invented by Japan Probe has largely changed the coupling agent and the contact restriction conditions [38]. Due to the use of a combination of mobile handheld devices, embedded processors, digital signal processors and Field－Programmable Gate Array, ultrasonic testing instruments are gradually being developed toward low power consumption and miniaturisation, easier to carry and use.

(a) (b) (c)_ (d)

Fig. 6. Examples of miniaturised UT devices (a) Cygnus Dive Wrist-Mountable underwater thickness gauge [34]; (b) Sonatest's VEO+ Smart Portable Phased Array Solution device [35]; (c) RollerFORM Scanner produced by Olympus [37]; (d) Olympus's EPOCH® 6LT Portable Flaw Detector [36]

3.3. Radiographic Testing

X-ray detection and Gamma rays (γ-ray) detection are most used in in-situ inspections. The X-ray inspection time is short, but the penetrating ability is weak, and it is not suitable for thick-scale work piece inspection, such as XXQ-3005 produced by RSTAR, when the maximum voltage is 300 KV, the maximum thickness of Penetrability is 50mm for A3 steel [39]. The portable γ-ray device is small and portable, but it has a long projection time and is not easy to control. Versatile Industrial CT Scanner (see Fig. 7(a)) has been widely used in laboratories. These devices generally have features such as high accuracy, high resolution, and high precision 3D metrology, but they are bulky and unsuitable for portable and in-situ detection [40]. Traditional in-situ X-ray inspections use a combination of X-ray machines and film (see Fig. 7(b)). GE developed a product called DXR250C-W/DXR250U-W Wireless Digital X-ray Detector (see Fig. 7(c)), which is an upgrade equipment for in-situ inspection. In a sense, it replaces the X-ray films used in traditional ray detection and integrates portable, wireless and robust features through on-site X-ray photographing, and direct wireless transmission to the computer terminal. The DXR250C-W8”×8” detector weighs 3.5 kg (7lb) with a thickness of only 25 mm (0.98”), and ideal for places which offers difficult access and where most portability is needed [41]. Although such devices still do not have the characteristics of miniaturisation, its cutting-edge sense of technology and convenient design concept is the vane of the future ray detection miniaturisation.

(a) (b) (c)

Fig 7. (a) Versatile Industrial CT Scanner [40]; (b) Portble X-ray device and X-ray film [39]; (c) DXR250C-W/DXR250U-W Wireless Digital X-ray Detector produced by GE [41].

3.4. Active Thermography Testing

The miniaturisation development of active thermography needs to consider the selection of IR camera and the excitation source. Current portable IR cameras include FLIR ONE from FLIR (see Fig. 8(a)), Seek Compact from SEEK Thermal (see Fig. 8(b)), and Therm-App TH (see Fig. 8(c)) [42]–[44]. All these IR cameras benefit from the appearance of miniaturised infrared sensors. The Lepton series produced by FLIR is one of the miniaturised infrared sensors. Lepton 3 (see Fig. 8(d)) features with a size of 11.8 x 12.7 x 7.2 mm, a weight of only 0.9 grams, an array format of 160 x 120, a pixel size of 12 µm, and an acquisition frame rate of 8.8Hz [45]. Cranfield University has been developing an NDT device that combines an infrared camera with an endoscope, which offers visible-spectrum and infrared views to detect the inside diameter of the tube and other narrow openings space that are hard to access [8]. Active thermography uses a variety of thermal excitation sources, such as flash/pulse, lock-in, ultrasonic and laser. The main challenge of its miniaturisation is the selection of a portable and effective heating source, integration with the current existing miniaturised infrared sensors, as well as associated software development [46][47].

(a) (b) (c) (d)

Fig. 8 (a) FLIR One Infrared Thermography Camera; (b) Seek Compact IR Thermography Camera; (c) Therm-App TH IR Thermography Camera (d) Lepton 3 IR sensor [42]–[45]

4. Conclusions

This paper reviews a number of widely used NDT techniques, particularly on the state-of-the-art of their miniaturisation. The feasibility and prospect to apply them on the in-situ inspection has also been discussed. The review draws the following conclusions:

- Due to its own detection characteristics, the miniaturised design of magnetic particle detection will reduce the lifting force at the time of its detection, which will affect the detection rate of its defects and affect the detection results. Therefore, with the current level of technology, magnetic particle testing will have to undergo major changes and may not be miniaturised over the next decade. Such as one of current smallest permanent magnet product can keep the lifting force 18kg and the pole gap is only 37mm, if its volume keeps reducing, the lifting force will be reduced, and then it will not meet the test requirement.
- Portable and pocket-type ultrasonic testing equipment have become more and more popular. Meanwhile, ultrasonic testing is widely used due to its versatility, high level of function integration and intelligence. If the coupling technology can be more mature, the development of its miniaturisation will be just around the corner. The viewing screen will evolve into smart phone size and weight will be reduced more than EPOCH® 6LT which is 890 g so far.
- Due to the influence of radioactivity and its strict requirements on the detection environment, miniaturisation of radiographic inspection is a challenge even though there are evidences that create miniature prototypes. It is envisaged that the technology will continue to reform over the next decade where nano-CT will be further developed into miniature systems.
- The excitation source and the infrared sensor in the active thermography system can be individually designed and explored in miniaturisation. According to the current existing excitation source and the development of micro-sensors, the prospect of the development of infrared thermography miniaturisation is promising. It will combine micro IR camera (such as FLIR one) with smart phone, meanwhile, if the excitation source volume can be small enough, the thermography NDT system can be small like a smart phone.

It is concluded from this paper that ultrasonic testing and active thermography have a great prospect of miniaturisation for in-situ inspection of complex components and systems, with radiography being potentially reduced to bench top systems.

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