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Through transmission thermography- A review of the state-of-the-art

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Abstract

Nondestructive Testing (NDT) covers a wide range of testing methods in which a component can be inspected without affecting its functionality. Infrared thermography is an NDT technique that has gained rapid popularity in recent years for structural integrity assessment, especially in the aerospace and oil & gas industries. Pulsed thermography, a subset of IR thermography is one of the active thermography techniques that uses flash lamps to thermally excite the specimen under observation. Thermal measurements can be taken in the reflection, or the transmission mode based on the positioning of the IR Camera and the flash lamps with respect to the specimen. Currently, estimating the defect depth using IR thermography remains a challenge as the reflection mode cannot accurately characterise defects that are deeper than 3mm. A major advantage of the through-transmission technique lies in its ability to detect defects that are deeper than the 3mm depth with higher levels of precision and accuracy. This makes through-transmission a suitable candidate for measuring defect depths using IR thermography. However, unlike the reflection mode, through-transmission has a limited number of image post-processing algorithms for defect detection and characterisation. This paper presents the state-of-the-art in the development of through-transmission thermography together with the technique's know-how and limitations currently available in the scientific committee.

Keywords: through-transmission thermography; pulsed thermography; image post processing; defect characterisation;

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1. Introduction

Nondestructive testing (NDT) is an extremely useful method as it allows for the inspection of components while maintaining their functionality. Inspections can be carried out throughout a component's life cycle for both defects that may occur during the manufacturing stages and in-service damage that could be caused by the various conditions the component has been exposed to. It offers a vast range of inspection techniques, each governed by a different set of physical principles that produce results relevant to the physical properties of the specimen under observation [1]. NDT provides a cost-effective solution for testing a single sample as part of an individual investigation or an entire production line [2]. Furthermore, it is also used to test whether the manufactured product complies with the design specification. Some of the most commonly used NDT techniques are visual inspection, ultrasonic testing, microscopy, radiography, electromagnetic and infrared thermography [3].

The need for NDT extends across various industries. Metal alloys such as aluminium, titanium, and nickel alloys for example have numerous applications in the construction, energy, transportation, and aerospace industries [4]–[8]. They have also garnered a lot of attention in the defence industry where aluminium alloys are used to enhance ballistic resistance in armours [9]. Their popularity can be attributed to their resistance to fatigue and corrosion when compared with steels and ferritic alloys [10], [11] Similarly, owing to their high strength to weight ratio, Composite materials such as Carbon Fibre Reinforced Polymers (CFRPs) are widely used in building ships, aircraft components, sports equipment, and manufacturing vehicles [12]. Many of these alloys are used in the manufacturing of critical components in various industries which means that their failure may result in catastrophic damage. For instance, nickel superalloys are used to manufacture airplane turbine blades and are required to withstand extremely high temperatures. To ensure that the component can withstand those temperatures, it needs to go through rigorous testing and qualification during the manufacturing stages to qualify its structural integrity. Furthermore, they also need to be assessed regularly to check for any deformities throughout its life cycle. Which is why it is extremely important to have reliable NDT techniques for this purpose. In the oil & gas industries various NDT methods such as infrared thermography and ultrasound have already shown promise in detecting pipeline leaks [13].

Of the various methods mentioned above, Infrared (IR) Thermography is a non-contact, non-intrusive technique that measures, and records the thermal radiation emitted by a specimen and analyses its characteristics and state with reference to its temperature patterns. It is a technique that primarily came to light in the early 1970s as an experimental technique resulting from the use of military infrared imagers [14]. Infrared thermography measurements can be carried out either in the active, or passive mode. In the passive mode, the camera or the infrared radiometer captures the existing heat/thermal profile of the specimen as emitted from its surface. The active mode in IR thermography operates by observing the surface temperature decay profile when subjected to an external thermal excitation over a period of time. The thermal excitation can be carried out by several means. Table 1 provides a summary of the various thermal excitation methods and the types of defects that can be detected using them.

Table 1 Summary of the active IRT methods and the types of defects that they can detect

Means of excitation	Heat Source	Active IRT Terminology		Types of defects detected (Maximum Defect depth detected)
Optical	Photographic flashes, lasers, and lamps	Optically Stimulated Thermography (OST)	Lock-in Thermography (LIT) [15]–[19]	• Disbonding in coatings • Delaminations • Corrosion (3mm) • Defects in weld roots • Cracks (surface/subsurface)
			Pulsed Thermography (PT) [15], [20]–[23]	• Pitting • Corrosion • Delaminations • Cracks (Surface/near surface) (6mm) • Defects in weld roots
			Frequency Modulated Thermography (FMT) [24]	• Pitting • Corrosion • Delaminations • Cracks (Surface/subsurface) (4.5mm) • Defects in weld roots • Flat bottom holes
			Pulsed Phase Thermography (PPT) [25]	
			Step-Heating Thermography (SHT) [26]	• Pitting • Corrosion • Delaminations • Cracks (Surface/near surface) (3.5mm) • Defects in weld roots • Flat bottom holes
			Long Pulse Thermography (LPT) [27]	• Pitting • Corrosion • Delaminations • Cracks (Surface/near surface) (4.25mm) • Defects in weld roots • Flat bottom holes
			Laser-Line Thermography (LLT) [28]–[30]	• Cracks (Surface/near surface) (5mm)
			Laser-spot Thermography (LST) [30]–[32]	• Cracks (Surface/near surface) (10mm) • Defects in weld roots
Ultrasonic	Ultrasonic horn/Acoustic, air-coupled transducers, piezo-ceramic sensors,	Nonlinear Ultrasonic Stimulated Thermography (NUST)[33], [34]		• Cracks (Surface/subsurface) (8mm)
		Thermosonics, Sonic IR Thermography and Vibro-thermography. (Ultrasonic Stimulated Thermography) (UST) [35], [36]		• Cracks (Surface/near surface) • Internal delaminations (5mm)
Electromagnetic	Microwaves	Microwave Thermography (MWT) [37], [38]		• Cracks (Surface/subsurface) • Voids • Delaminations (38mm) • Material debonding
	Eddy Current Induction	Pulsed Eddy current thermography (PEC) [39]–[42]		• Delaminations • Cracks (Surface/near surface) (4mm)
Thermo-resistive radiation (for composites)	Embedded shape memory alloy wires with electric current	Indirect Material-based Thermography (IMT)	Shape Memory Alloys-based Thermography (SMArT)[43]	• Cracks (Surface/subsurface) (1.25mm)
	Embedded steel wires with electric current		Metal-based Thermography (MT) [44]	• Delaminations • Cracks (Surface/subsurface) (8.25mm) • Material deformations
	Embedded carbon nanotubes with electric current		Carbon-nanotubes-based Thermography (CNTT) [45]	• Cracks (Surface/near surface) • Holes (1mm)
	Electrical current running through carbon fibres	Direct Material-based Thermography	Electrical Resistance Change Method (ERCM) coupled to thermography [46]	• Cracks (Surface/near surface) • Indentation damage (6.5mm)

To ensure that the manufactured component will not fail while in use, the testing phase needs to test material behaviour before going to failure. This requires the component to be tested under certain conditions to examine its behaviour. At present using a single NDT technique on its own is not sufficient to detect all the various types of defects that can affect a component which is why a combination of techniques are generally used to provide a comprehensive assessment of the structural assessment. In the aerospace industry, for example, components are often exposed to conditions where the loads cause them to undergo fatigue without any noticeable surface changes. It is important to ensure during the manufacturing stages that the components can withstand those conditions. However, NDT methods such as thermography and ultrasound have shown to be quite useful in identifying potential discontinuities in the internal structure due to low energy impacts. One of the solutions to combat this challenge is to introduce hybrid technologies that employ one or more existing advanced NDT techniques along with digital imaging and 3D printing technology. Furthermore, the existing technologies can be enhanced with intelligent automated systems that use machine learning and deep learning providing more sophisticated image processing algorithms [47]. This paper provides an overview of infrared thermography with specific focus on the current state-of-the-art in through transmission thermography. The rest of the paper is organised as follows. Section 2 talks about pulsed thermography and introduces the knowledge gap that currently exists. Section 3 provides a review of some of the current state-of-the-art in through transmission thermography. Section 4 discusses the findings and Section 5 provides a summary and discusses future possibilities in through transmission thermography.

2. Pulsed thermography

As mentioned in the previous section, active IR thermography requires a thermal excitation of the specimen for data capture. Pulsed thermography also known as flash thermography is a subset of active IR thermography which uses flash lamps to thermally excite the specimen. Measurements can be either taken in the reflection mode, where the IR camera and the flash lamps are on the same side of the specimen or in the transmission mode where the IR camera and the flash lamps are on the opposite sides of the specimen. Figure 1 illustrates the setup in both reflection and transmission modes. The figure below shows the dimensionless temperature quantity V on the y-axis which is the ratio of the temperature T in °C to the maximum back wall temperature T_M and the dimensionless time quantity ω on the x-axis which is π^2 multiplied by the Fourier number ($\alpha t/L^2$) where α is the thermal diffusivity in m^2/s, t is the time in seconds and L is the thickness in mm. To further enhance the images obtained from IR thermography, several signal processing techniques have been developed over the years. One of the most commonly used technique is the Thermographic Signal Reconstruction (TSR) introduced first by Shepard et al. [48]. The method operates by taking every pixel in the field of view and comparing its time history to a model in the logarithmic domain. This allows for the deviations from the ideal behaviour to be easily identified. Other processing methods include Differential Absolute Contrast [49], Pulsed phase thermography (PPT) [25] Absolute Peak Slope Time (APST) [50], and Nonlinear Least-Squares Fitting (NLSF) Method [51].

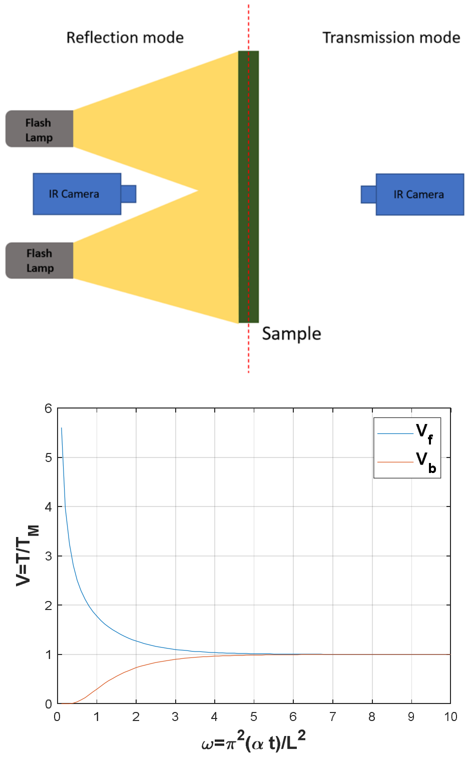

Figure 1 (Top) Reflection and transmission configurations of pulsed thermography (Bottom) Dimensionless plot of the front (Vf) and back (Vb) wall temperatures according to Parker's equations [52]

While there have been numerous signal processing algorithms for signal processing, most of these equations have been used using the front wall temperature decay curves. In other words, the mode for the data capture was the reflection mode. Our review shows that there has been limited research using through-transmission in pulsed thermography. This could possibly be attributed to the lack of motivation to explore transmission mode since in most practical settings, the back wall is not accessible to conduct measurements. Moreover, the lack of development in mathematical and real time models for heat transmission is also a potential obstacle for the through transmission technique. The transmission mode, like the reflection mode makes use of the temperature profile to calculate material properties. The difference arises from the fact that unlike the reflection mode, the transmission mode measures the temperature rise on the back wall to measure properties such as thermal diffusivity and thermal conductivity. Since the material under inspection is the same, both reflection and transmission modes can be used for material and defect characterisation. The reflection mode is better suited for detecting surface and near surface defects of up to 3mm. Combined with its various image processing algorithms, the reflection mode has become an established technique for defect detection. However, in terms of defect depth, existing literature has shown that the transmission mode can detect deeper defects compared to the reflection mode [53]. The next section elaborates on this further and provides an overview of the current state-of-the-art in through transmission thermography.

3. State-of-the-art in through transmission thermography

The transmission mode in thermography as shown in the figure above (Figure 1) places the camera at the back of the specimen with the flash lamps heating the sample's front surface. The camera can then record the temperature rise of the back wall post pulse excitation. In order to compare and contrast the strengths of active thermography, Maierhofer et al. [53] characterised damage in CFRP structures using both the reflection and transmission modes of pulsed thermography. The study concluded that the transmission configuration was able to detect the lateral size of the defects as well as defects that were deeper into the specimen for up to a material thickness of 5.9mm. A similar study was conducted by Prakash and Maharana [54] for carbon-flax fibre hybrid composite and concluded that the transmission mode is more applicable for the detection of deeper defects. Moreover, another takeaway from the study is that for specimens that are damaged due to impact, heating the damaged area and taking readings in the transmission configuration produces a clearer indication of damage.

Montinaro et al. [55] used the PPT approach in the transmission mode to inspect the dispersion quality of nanoparticles in a nanocomposite material. It was determined that the proposed NDT technique was effective in studying the inner structure of nanocomposites which contain various kinds of filling materials. Pan et al. [39] used pulsed eddy current as the thermal excitation source to assess impact damage and delaminations in CFRP laminates. Image reconstruction to enhance the raw images was produced using principal component analysis (PCA) independent component analysis (ICA). The study showed that the two types of defects have different detection mechanisms. Kalyanavalli et al. [56] used long pulse thermography to estimate the defect depths of a basalt fibre composite in the transmission mode. The composite was first modelled on COMSOL before moving on to physical experiments. The depth estimation was done using the peak contrast derivative method and Parker's [52] method. They were able to predict and characterise defect depths of up to 3mm and it was observed that the peak contrast derivative method fared better than Parker's method in determining defect depths.

Oswald et al. [57] explored the detection of subsurface cracks i.e., cracks that are concealed below the surface using eddy current induction heating using both the reflection and transmission mode of thermography. For the transmission mode, the sample was heated where the crack was open to the surface and the camera was placed at the opposite end of the heat source behind the sample. Using this mode defects that are open to the back surface can be detected in a wide range of excitation frequencies regardless of whether the material is non-magnetic or ferro-magnetic. Pawl and Henryk [58] investigated the use of active thermography to detect defects in building partitions and units that have high heat capacity. A major conclusion from this study is that it is sufficient to heat up the surface to about 60ºC to locate defects present 22mm below a thick layer of construction material. Yang et al. [59] performed Induction infrared thermography and thermal-wave-radar analysis to diagnose CFRP blades and compared the results with existing eddy current pulsed thermography (ECPT) and eddy current pulsed phase thermography (ECPPT). The method was able to detect 36mm^2 delaminations with their thickness varying from 1.0 to 3.5mm. To improve depth penetration for detecting deeper defects, an adaptation of the truncated-correlation photothermal coherence tomography (TC-PCT) algorithm was suggested for future work.

To detect interfacial defects in thermal barrier coatings Zhu et al. [60] used eddy current thermography (ECT) combined with adaptive carrier algorithm as a post processing algorithm. The proposed method can overcome the uneven temperature distribution associated with the inspection method and highlights the thermal response characteristics of the defects with greater efficiency. Furthermore, this method can be applied with the heating phase in which the resulting thermal images exhibit a substantially high thermal contrast. Finally, the method unlike traditional post-processing algorithms, does not require both defective and non-defective images to compare. While transmission mode is better suited for detecting defects that are deeper into the surface when compared to the reflection mode, in-field applications may not always provide access to both sides of a structure. For transparent and semi-transparent composites such as glass fibre reinforced polymers, Exarchos et al. [61] proposed the Near-Infrared Double-Transmission Mode (NIR DTM) to overcome this challenge. The method utilises a reflector surface placed behind the specimen while the NIR sensor picks up the thermal signal reflecting of that surface. This method compared to the NIR in reflection mode yielded more accurate results for defect detection and characterisation.

4. Discussion on the current state-of-the-art

From the literature review conducted in the previous section, it is evident that the image processing techniques for the transmission mode are not as well developed compared to the reflection mode. However, through transmission shows a lot of promise for detecting subsurface defects. For pulsed thermography using optical flashes, the 6mm defect depth limitation could be attributed to the lack of more sophisticated image processing algorithms to measure defect depth. More complex processing techniques such as PCA, ICA and PPT are being developed for images obtained using through-transmission, but the studies conducted using these methods are limited. Longer heating times using infrared radiators have shown to detect defects even as deep as 22mm below the surface. Furthermore, more recently developed heating methods such as FMT and PPT which combine the benefits of both pulsed and lock-in thermography can be leveraged in the transmission mode to evaluate its ability to detect subsurface defects. One of the reasons through transmission has not been explored as much as reflection could be due to the back side of the specimen not being accessible in most practical settings. Nevertheless, the through transmission's ability to detect deeper as well as lateral defects provide enough reason for more research to be conducted with various heating sources to better understand the capabilities of through transmission for material and defect characterisation

5. Conclusion

NDT is an extremely convenient technique for determining the structural integrity of materials as it does not reduce or alter material functionality during its inspection process. Not only does it help in manufacturing defect-free components, but it also helps in maintaining their quality during the in-service stages via periodic assessments. One of the major trends in NDT is developing hybrid systems coupled with 3D printing, machine and deep learning to produce more advanced and automated systems for nondestructive evaluation. Infrared thermography, which is one of the more popular NDT techniques has seen a lot of advancements in the field of signal processing to better characterise defects that may occur in materials. While pulsed thermography, which is one of the optical excitation techniques in active infrared thermography has numerous image processing algorithms, many of these are limited to the reflection mode with very little development being reported in the literature supporting the transmission mode. This paper addresses this knowledge gap and presents an overview of the current state-of-the-art in through transmission thermography. Our research suggests that the through transmission has the potential to deliver more accurate results than the reflection mode in determining the defect depth of a component. However, further research is required to fully assess the overall strength of the through transmission pulsed thermography technique in detecting subsurface defects. This initial assessment provides motivation to further explore through transmission as a viable candidate for defect depth estimation especially when the defect is not visible on the surface.

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