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A confidence map based damage assessment approach using pulsed thermographic inspection

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ABSTRACT

In the context of non-destructive testing, quantification of uncertainty caused by various factors such as inspection technique, testing environment and the operator is important and challenge. This paper introduces a concept of contour-based confidence map and an application framework for pulsed thermography that offers enhanced flexibility and reliability of inspection. This approach has been successfully applied to detect three flat-bottom holes of diameter 32, 16 and 8 mm drilled onto a 5 mm thick aluminium plate with a high accuracy of damage detection ($R > 0.97$). Its suitability and effectiveness in assessing impact damage occurring in composites have also been demonstrated.

1. Introduction

Non-destructive testing (NDT) has been the front-runner in estimating the health of a component over the last few decades with specific emphasis on damage detection and quantification without causing further damage to the material. Pulsed thermography inspection has now been established as a reliable thermal NDT technique to detect near and sub-surface damage occurring in various materials. Pulsed thermography offers an effective alternative where damage detection and quantification is much faster and robust in comparison with traditional NDT methods such as ultrasonic testing and 3D X-radiography computed tomography methods [1,2]. The users of pulsed thermography are frequented with questions such as 'How do you estimate the accuracy of defect measurement? Or what is your confidence level of damage characterisation and how the confidence level affects the decision making?'. There is very limited reported research addressing these issues directly. Understanding the uncertainty of defect/damage characterisation is important because that is the only way to mitigate the uncertainty associated with the inspection and improve the accuracy of the measurement through identifying the source of errors followed by corresponding actions. Thermal data acquisition is a challenging process where the technique's dependence is heavily based on primarily the infrared detection system followed by an appropriate heat excitation source. Most of the current state-of-the-art systems still employ equipment such as flash lamps. These optical units are heavily dependent on capacitor bank systems where there is a level of uncertainty that exists in determining the flash initiation and end of flash and can only be monitored by a high frame rate infrared acquisition system. Further, the influence of environmental parameters such as the background temperature and humidity levels together with the inspected material, its type, surface finish and the data synchronisation all add uncertainty to the acquired measurement data, which adds disparity between inspection rendering repeatability as a challenging aspect [3]. Therefore, there is a strong demand to build the confidence level in results obtained from the thermographic inspection which becomes a driving factor to help establish and exploit the active thermal inspection method in the main stream inspection scenarios.

The use of Probability of Detection (POD) curves to quantify NDT reliability is common in the aeronautical industry [4]. There are studies that have been conducted to determine the POD for anomalies occurring in composite materials where traditional NDT techniques such as ultrasonic testing, radiography, and eddy current have been used [5–7]. Minkina and Dudzik [3] and Lane et al. [8] investigated the errors and uncertainties in infrared thermography in the passive mode, where it is mentioned that errors of temperature measurement with the infrared camera are typically classified into errors of the method, errors of calibration, and errors of the electronic path. However, manufacturing test pieces with representative flaws in sufficient numbers to draw statistical conclusions on the reliability of the NDT system being investigated is costly. The application of active thermography in detecting damage of metallic components and composites has been well established over the last few years but associated reliability research is limited. A few POD studies have been conducted to improve the applicability of pulsed and

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lock-in into main stream inspection activities [9–11]. However, with the uncertainties and errors associated with the inspection process itself, it is important that a relative measure of confidence with limited trials needs to be addressed and established to make sure that pulsed thermography can be used to discriminate the health of the part being inspected. This paper is an effort to answer the very challenge described and thus develops a method to compute a unique confidence map that quantifies the confidence level of damage detection for each pixel statistically, and then introduces a confidence-map-based assessment routine to further exploit the applicability of pulsed thermography inspection technique to perform material degradation assessment.

2. Methods

In order to develop a contour-based confidence map and the associated assessment toolsets, this paper starts from the improvement of existing theory of defect characterisation, which is then integrated with the statistical theory to construct a new concept of representative of defect. This section presents the various concepts that support the development of the Adaptive Peak Temperature Contrast method (APTC), together with a proposed inspection framework that will enhance and highlight the merits of the pulsed active thermography system.

2.1. Defect detection using pulsed thermography

In pulsed thermographic inspection, the typical experimental setup of which is illustrated in Fig. 1(a), a short and high energy light pulse from the flash lamps is projected onto the sample surface. Heat conduction then takes place from the heated surface to the interior of the sample, leading to a continuous decrease of the surface temperature [12]. An infrared radiometer controlled by a PC captures the time-dependent response of the sample surface temperature. In areas of the sample surface above a defect (see point 2 in Fig. 1) the transient flow of heat from the surface into the sample bulk is wholly or partially obstructed, thus causing a temperature deviation from the sound areas (see point 1 in Fig. 1). Most of the defect detection methods are based on the classification of the temperature decay curve (see Fig. 1(b)). The time when the temperature deviation occurs can be used to estimate the defect depth. The surface temperature due to a defect at depth L for a plate is given by Ref. [13].

$$T(t) = \frac{Q}{\sqrt{\pi \rho c k t}}\left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2 L^2}{\alpha t}\right)\right] \tag{1}$$

where $T(t)$ is the temperature variation of the surface at time t, Q (unit: J) the pulse energy, ρ (unit: kg/m^3) the material density, c (unit: J/kgK) the heat capacity, k (unit: W/mK) the thermal conductivity of the material and α (unit: m^2/s) it's the thermal diffusivity.

The most widely used method to differentiate sound areas and defective areas is using the thermal/temperature contrast technique. Various temperature contrast definitions exist [14] but they share the need for specifying a sound area A_s as the reference. For instance, the absolute temperature contrast $\Delta T(t)$ is defined as

$$\Delta T(x, y,\ t) = T(x, y, t) - T_{A_s}(t) \tag{2}$$

where $T(x, y, t)$ denotes the temperature of a pixel at the location (x, y) at time t, and $T_{A_s}(t)$ denotes the temperature at time t for the pre-defined sound area A_s. Practically, the definition of A_s is important as issues such as non-uniform heat application and surface finish can cause considerable variations on the results and the same can be observed when changing the location of A_s [15]. A frame of absolute temperature contrast at a certain time is usually selected to represent the result of defect detection. For example, the Peak Temperature Contrast method (PTC) [14] calculated the thermal contrast between the defective/damaged region and an adjacent sound or non-defective region, and the frame where the maximum contrast between the sound and defective areas is chosen even though the defect peak occurs much later in time. Because of the 3D heat conduction effect, the temperature contrast first increases with time and then decreases. The time at which the temperature difference rises to its maximum value is approximately proportional to the square of the defect depth, and the proportionality coefficient depends on the size of the defect. Therefore, it should be noted that PTC is a defect detection method and only provides an approximation for defect depth measurement.

One limitation of PTC is that when the selected region of interest (ROI) includes multiple defects with a variety of sizes and depths, the selection of the optimal frame to visualise all defects in a single image is a challenge. The most common approach in defect characterisation in such cases is by considering defects occurring at similar depths and truncating the sampling time accordingly to achieve best contrast, and the same repeated for the remaining defects [16]. However, automating such a dynamic assessment approach to detect and quantify all defects at the same time is challenging. This paper proposes an Adaptive Peak Temperature Contrast (APTC) method to detect defects before estimating the confidence map. For each pixel on the image plane, the peak of temperature contrast is computed and a map of these peaks is constructed to represent the detection result, by which means, defects with different sizes or depths can be visualised with maximal contrast in a single image. To reduce the noise, the Thermographic Signal Reconstruction (TSR) algorithm [17] is employed to fit the raw data before the application of APTC. The estimation of APTC can then be written as

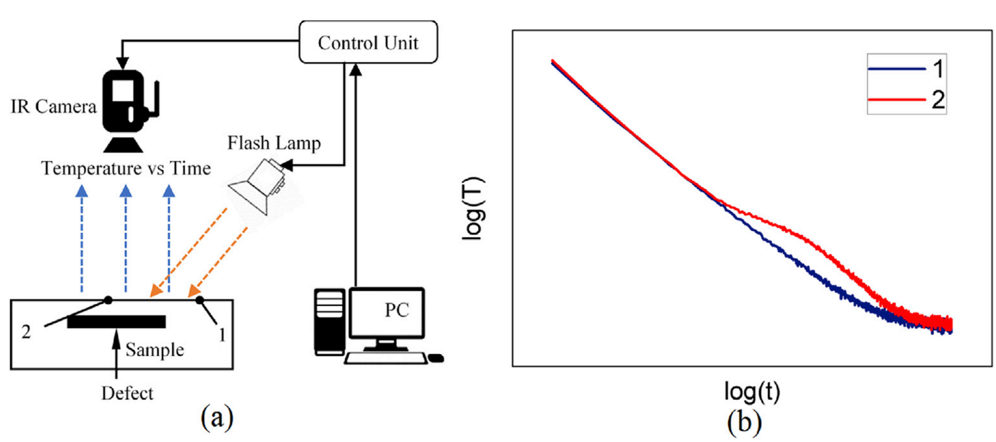

Fig. 1. (a) Experimental configuration of the pulsed thermographic inspection, where point 1 denotes a sound area on the sample surface and point 2 denotes a position with defects underneath; (b) Typical observed time-temperature decay curves in the logarithmic domain for the point 1 and 2, respectively.