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# Autonomous systems thermographic NDT of composite structures

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## ABSTRACT

Transient thermography is a method used successfully in the evaluation of composite materials and aerospace structures. It has the capacity to deliver both qualitative and quantitative results about hidden defects or features in a composite structure. Aircraft must undergo routine maintenance – inspection to check for any critical damage and thus to ensure its safety. This work aims to address the challenge of NDT automated inspection and improve the defects' detection by suggesting an autonomous thermographic imaging approach using a UAV (Unmanned Aerial Vehicle) active thermographic system. The concept of active thermography is discussed and presented in the inspection of aircraft CFRP panels along with the mission planning for aerial inspection using the UAV for real time inspection. Results indicate that the suggested approach could significantly reduce the inspection time, cost, and workload, whilst potentially increase the probability of detection of defects on aircraft composites.

**Keywords:** Thermography, composites, CFRP, UAS, imaging, aerospace.

## 1.0. Introduction

Since the increase demand for composite materials, researchers within the aerospace industry are investing in the new development of testing and evaluation methods of this complex material. Transient thermography is a well-established non-destructive inspection technique that is crucial for a cost-effective method for reducing manufacturing cost and out of service aircraft due to maintenance [1]. Transient thermography is based on capturing the temperature difference data through a series of images when an external source of heat is applied to a subject. When the surface of a material is subjected to a rapid heat pulse, the surface temperature will be raised, as time passes, the surface starts to cool due to the heat pulse propagating through the material. The purpose of this external source of energy is to induce a temperature difference between defective and non-defective areas of the material. For example, where there is a homogeneous material the radiation from the excitation source will pass through the material uniformly, however if there is a subsurface defect such as delaminations, these will create a higher thermal impedance to the passage of the radiation. When a defect is close to the surface it restricts the rate that the material cools which will then be visible through a thermal camera due to the temperature difference [2].

The work in this paper will focus on two forms of excitation, optical and mechanical and propose integrating an NDT method onto an autonomous unmanned aerial vehicle. The optical external source of energy in this experiment is a flash lamp, however other optical excitations are widely used such as halogen or LED. Whereas the mechanical excitation is an ultra-sonic transducer which excites the specimen by means of mechanical oscillations [3]. Infrared Thermography (IRT) is commonly used in industry to detect damages subsurface in several mechanical systems consisting of a plethora of different materials, this method is popular due to its low-cost and minimal manpower which allows more frequent inspections [4] [5]
The Airbus A380 is the largest passenger aircraft in the world, it has better fuel consumption per passenger than a family car [6] this is made possible due to consisting of up to 25% in composite materials which has

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resulted in saving 15 tonnes of weight [7]. Composites usage has increased in commercial aircraft due to the high strength-to-weight ratio which ultimately leads to lower operating cost. For contrast, in 1985, the A310-300 consisted of around 5 percent composite materials, 18 years after and the materials used to manufacture the next generation A350XWB are made up of around 53 percent composites [8] [5]. The materials of an aircraft structure are required to consistently resist many intense loads and remain free from damage, delamination, fatigue and corrosion after each cycle [5].

To put into perspective the scale of the NDT industry. It is estimated there are more than 120,000 inspectors worldwide which has an estimated turnover of 5.2 billion [9]. At the moment, within the aircraft industry the NDT has been predominately focused on inspecting metals such as aluminium, however this material when damaged does not react the same as a composite material would. Composite material damages are more difficult to identify due to the complexity of the material. This demand calls for cost/time-efficient inspection methods which gives qualitative and quantitative information about this complex material to keep up with the importing growing NDT industry [5].

Unmanned Aerial Vehicles are the pinnacle of recent technology, they are increasingly integrating into our everyday lives. The idea of inspecting aircraft structures came from an ongoing project at Cranfield University in collaboration with Airbus, where a commercially available UAV is performing a non-destructive inspection (i.e. dye penetrants testing). A liquid paint substance is added to a metallic wing panel and a UAV equipped with a UV light inspected the aircraft in a dark room, the primary objective is to execute the algorithms in order to display, classify and log defects [10]. IRT is a fast-non-contact method and is well-suited for testing large areas of complex geometry [11]. Nevertheless, the traditional thermographic systems are bulky and inconvenient for use on many applications. Therefore, it is necessary to develop a more versatile thermographic system suitable to work in combination with UAV technology [5].

## 2.0. Test specimens and experimental procedures I

### 2.1. Material

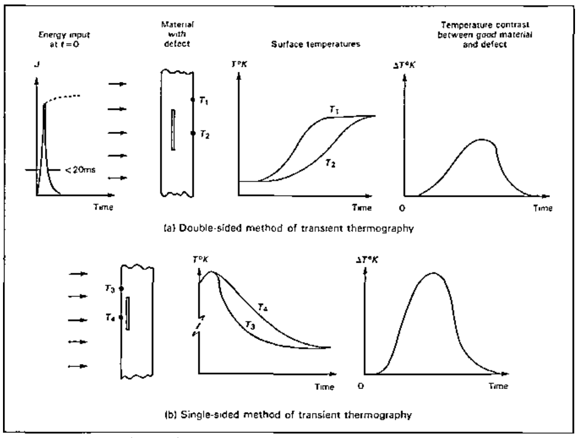
The specimens studied in this work were made of Carbon Fibre Reinforced polymer (CFRP) (composite laminate). Sample A4 was manufactured via manual woven and the other two samples where unidirectional. The composites consist of laying up pre-preg piles to form a laminate stack, the material is then autoclave processed at 180C and 7 bars for a few hours suitable for the thermoset resin cure, this is according to the supplier's specification (Hexcel). There were three specimens, one that was undamaged, and two that had been impacted with a force of 15J and 20J of energy [5].

### 2.2. Equipment

The equipment required to perform a PT test falls into two separate areas: the heat source and the thermal imaging/analysis system. The heat source needs to be an adequate fast pulse of energy, in this experiment the CFRP was excited using two separate Balcar Xenon flash lamps, which provide 6.400 J per flash with a pulse duration of 2 ms at FWHM (full width half maximum). As time elapses heat will travel through the specimen and will decrease uniformly if the specimen is without a defect. On the contrary, subsurface defects, such as delaminations, fibre breakage or any other composite flaws will ultimately affect the uniform heat flow resulting in abnormal temperature patterns, this thermal response is captured by an infrared camera and recorded for further analysis later. The infrared camera used in this experiment was a FLIR Phoenix, with inSb sensor material, 3–5 mm, 640 × 512 pixels and allows data acquisition at 50 Hz [5]. These camera needs to be cooled to 77 K (i.e. −196.15 °C) during testing. Cooled cameras work by collecting photons of infrared energy that pass through the optic. The photons are converted into electrons that are stored in an integration capacitor. After a certain period (integration time), the charge is read out to a digital count calibrated to temperature, assigned a colour or greyscale value and then presented as a viewable infrared image [12]. To obtain an accurate result, a synchronisation unit was used so that the initial thermal pulse excitation and the recording of the data happen simultaneously. The acquired data is stored as a 3D matrix where t is the time and x and y are the spatial coordinates [5].

Active thermography uses external heating dissipation to create thermal contrast, once excited the thermal waves propagate through the heated specimen, and when they reach inhomogeneities caused by a medium with different thermal properties, the diffusivity coefficient changes. These inhomogeneities could be defects, such as cracks, surface cracks, air/water/material inclusions, delamination's and debonding damages.

Mathematical processing techniques are the key to gather the necessary data from the raw thermogram and help visualise the damages within the material [13] [5].



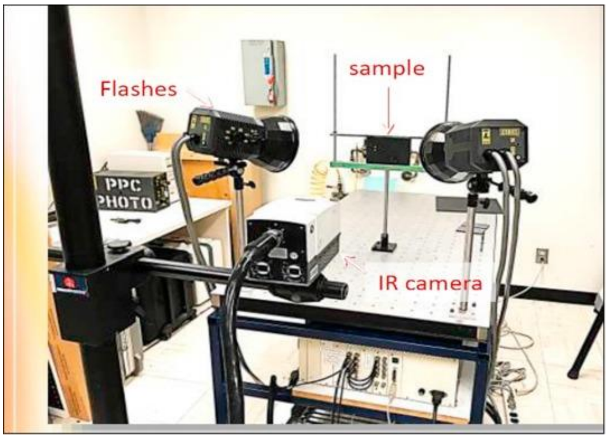




FIGURE 1 (LEFT): THE IMAGE REPRESENTS TRANSIENT THERMOGRAPHY AND HOW THE TEMPERATURE DIFFERS WHEN THERE IS A DEFECT PRESENT. (A) THE TRANSMISSIVE MODE (DOUBLE-SIDED) AND (B) THE REFLECTIVE METHOD (SINGLE-SIDED) [2]. FIGURE 2 (RIGHT): EXPERIMENTAL SET UP [5].

The surface of the specimens where positioned parallel to the camera lens as depicted in Fig. 2. The data was acquired for 40 s with a 1.5 ms integration time, that includes 10 frames before the flashes, plus 1990 frames during cooling a total of 2000 frames where recorded. The software used to acquire the data was RDac from FLIR. For signal processing MATLAB and Ir_view from Visiooimage inc were employed. Two advanced processing techniques where used; PCT (principal component thermography) and PPT (pulsed phase thermography) [5].

### 2.3. Results & Discussion I

The figures below (Figures 3-8) are all the processed results. A reflection test means that the camera and the excitation source are on the same side (as seen in Figure 4). Generally, reflection is more suited to detect defects closer to heated surface. PPT (pulsed phase thermography) was one of the methods used, with the acquired temperature data it varies with time and is transferred to phase data, which varies with frequency, the frequencies which show adequate data are below each image in hertz. PCT (principal component thermography) was the other, method used, the data is re-ordered by variance, this method finds both time series and spatial patterns, most of the variability is contained in the first component: EOF1 (empirical orthogonal function). Usually, EOF1 shows thermal variations related to surface heating. Later EOFs are typically related to surface and subsurface damage. Comparing both techniques, for this specific data set in figure 5 it seems that the PCT technique displays the damage clearer [5].

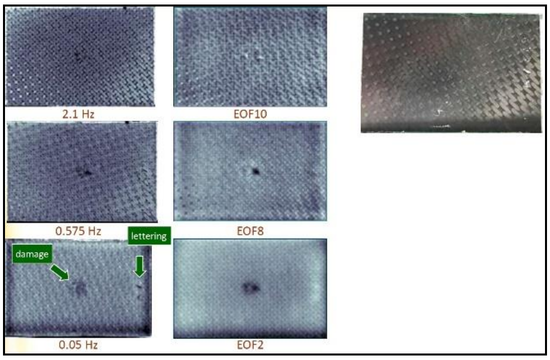



***Figure 3: Sample A4 (15 J woven), front face (impacted side), PPT and PCT****. The damage is barely visible in the original image of the composite (Far right image), the white marks are lettering from labelling the specimen*. *The 0.05Hz PPT image, shows clear subsurface damage* [5].

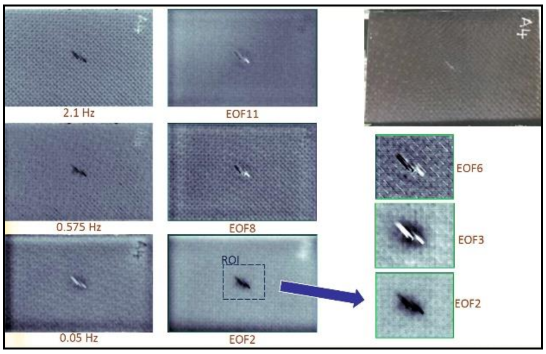



***Figure 4: Sample A4 (15 J), Reflection rear face PPT and PCT****. The rear surface is cracked, this is interesting because this side is significantly more damaged than the impacted side. This is a prime example of barely visible impact damage* [5].

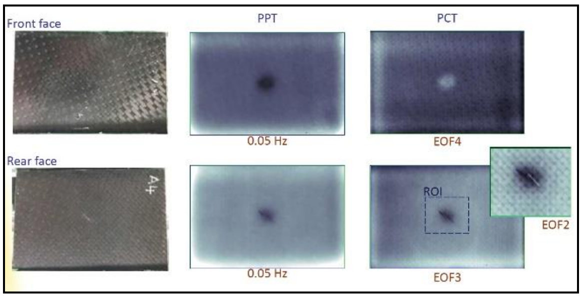



***Figure 5: Sample A4 (15 J).*** *Transmission is where the one side of the composite is excited, and the other side is observed by the camera and captures the data* [5].

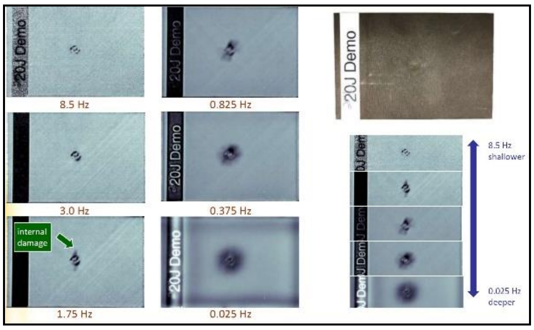



***Figure 6: Sample 20 J Demo, Reflection front face, PPT.*** *The damage is visible on the front face, how, it's clear that the damage is much worse subsurface and spreads further than the impacted area* [5].

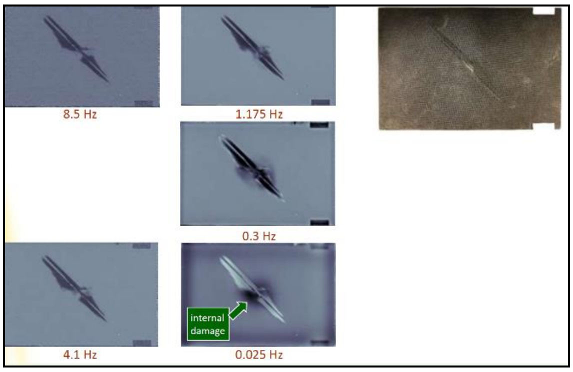



***Figure 7: Sample 20 J Demo, Reflection rear face****. PPT. The rear face has some substantial damage. The PPT locates the surrounding internal damage* [5].

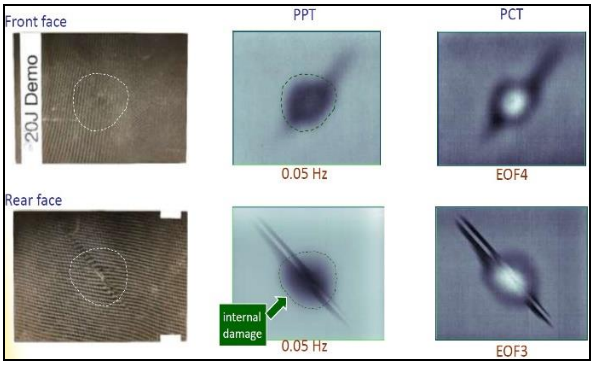



***Figure 8: Sample 20 J Demo, Reflection front face, Transmission.*** *The test has adequately located the internal damage* [5].

## 3.0. Test specimens and experimental procedures II

### 3.1. Vibrothermography

VT is another non-destructive testing method, it uses vibration and/or ultrasonic excitation to evaluate the structural health of the specimen. The mechanisms of vibration energy dissipation on damage are not widely understood however they depend on the material parameters and defect characteristics similarly to most NDT techniques [14]. It is certain that generated heat depends on frequency and position of the excitation source [14] [5].

Ultrasonic waves vibrate between 20kHz and 1 MHz which is beyond humans' audible capabilities, although the transducers that are usually used in VT inspections operate between 15 and 50 kHz. Mechanical elastic waves such as sonic and ultrasonic require a medium to travel, the waves travel faster through solids and liquids than air [3]. The VT approach consist of using a coupling media such as a piece of moisten fabric, water-based gels or aluminium, between the transducer and the specimen to improve contact [3].

### 3.2. VT Data Acquisition

During this VT inspection a transducer is placed in contact with the specimen, assisted by a coupling media (material, gel, etc.). The ultrasonic waves flow through the specimen and will travel without disruption through a homogenous material, however if there is an internal defect present this will disrupt the usual flow of the waves producing a compilation of effects such as the waves being absorbed, scattered, and dispersed, this is present in the form of heat. An IR camera can observe the surface of the specimen because the heat that is generated will travel by conduction in all directions and a defect signature data can be captured. VT is ideal for detecting crack and delamination's, the ultrasonic waves assist in discovering both internal and surface defects [15].

The transducer is made of a stack of pie piezoelectric elements and concentrated in a titanium horn that acts like a hammer [15]. The specimen must be firmly restraint without damage, the immobilized specimen seeks to avoid cantilever effects, clapping, and sliding of the transducer [15]. For maximum performance the coupling of the ultrasound into the specimen needs to be improved, to do this the transducer horn should be pressed against the specimen. It is recommended to add some sort of material between the transducer and the specimen to avoid damage to the specimen, to improve contact and to eliminate any possible misalignment [15]. In the event of bad coupling it can result in poor ultrasound transmission, the specimen will then be subject to unwanted heat at the injection point, which can ultimately affect the inspection results [16] [5].

VT is a fast inspection technique, slightly faster than PT, within seconds the defect usually appears therefore the acquisition will then end. The fast inspection is necessary because longer inspections will result in an excess of heat and increase the probability of the specimen getting damaged. The experiment is controllable, this is because the heat is generated selectively at the location of defects, and if certain parameters of excitation need changing, repeat experiments can be made in quick success. However, the intensity of the vibrations has to be carefully managed or else the subject could be damaged [5].

### *3.3.* VT Equipment

The data processing is usually easier to manage when using VT, this is since the source of the heat is the damage itself [16]. The IR camera used to capture the data, is the same as used in the PT experiment explained in 2.2. Figure 9 displays the VT testing equipment and the experimental set up, the transducer used is a 20 kHz ultrasound generator (BRANSON 2000). The experiment will consist of inspecting three different specimens to search for defects but more specifically concentrating on kissing bond defects [5].
The three inspected specimens are all composite material with artificial defects (see fig.10,11,12,13)

- ***Specimen N-D-F4P*** *is composed of one layer of adhesive sandwiched by two layers of adherent (carbon fiber) and contains no defect, it was purposely used for reference only.*
- **Specimen W-DA-F4** is similar to N-D-F4P but with an adhesive film release semi-circular ("thumb nail") shape defect, simulating a kissing bond defect.

- **SpecimenW-DC-F2** is similar to W-DA-F4 but with an additional adhesive film on top of the one with the simulated defect.

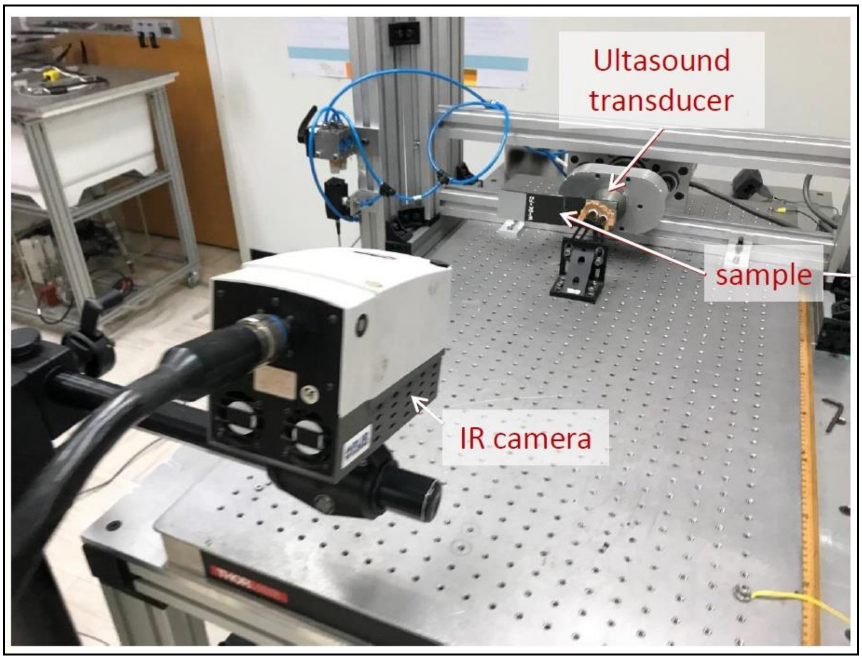



***Figure 9:*** *Experimental set up* [5]

Kissing bonds can be defined as a kind of defect in which surfaces are in intimate contact but with little bonding if any. Detection of kissing bonds defects is challenging for all NDT techniques given that, unlike other type of defects such as delamination's there is no significant separation between adherent and/or adhesive surfaces. These types of defects can considerably reduce the impact strength and the fatigue life of the material causing premature failure [5].

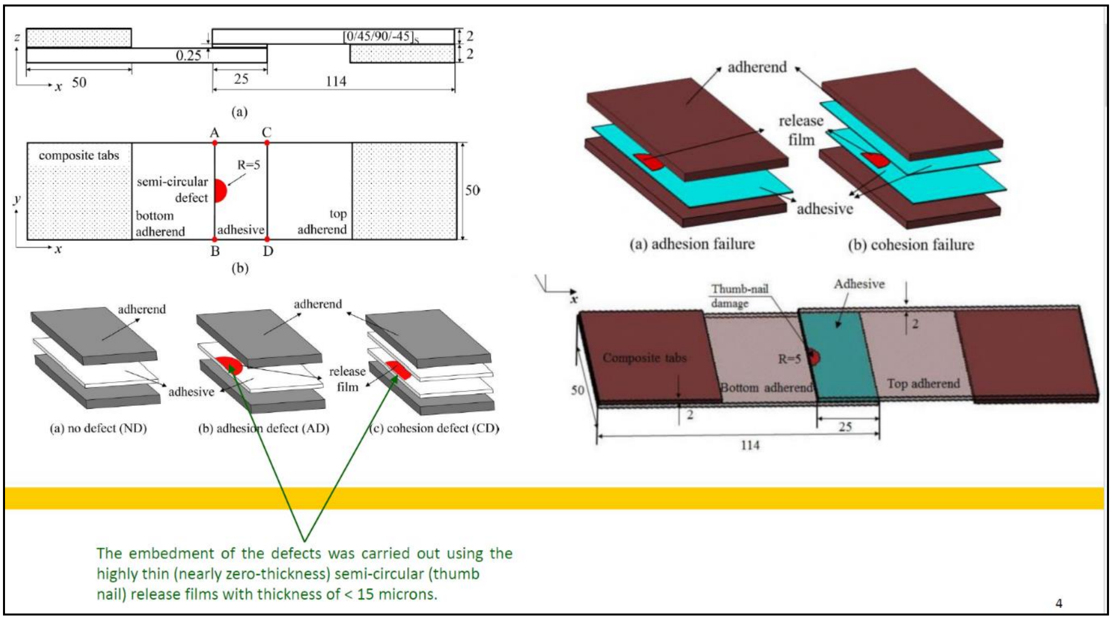



***Figure 10****: Artificial defects release film kissing bond* [17].

### *3.4.* Results & Discussion II

The transducer excited the specimen with a frequency of 20 kHz. The mechanical wave propagates across the surface, if there is a defect on the surface of the object, this mechanical wave will cause friction. The friction has caused heat to be generated around the location of the crack, which can be detected using the IR camera. Not only as this technique discovered a clear kissing bond defect but the results also show an apparently real delamination [5].

***Sample W-DA-F4: Vibrothermography:***

Results clearly show the thumb nail shape in all cases, specimens W-DC-F2 and W-DA-F4, from one side and the other (front and back), after processing by PPT and PCT. Additionally, several indications of real defects seem to be observed. For instance, possible delamination's were found and indicated with red circles [5].

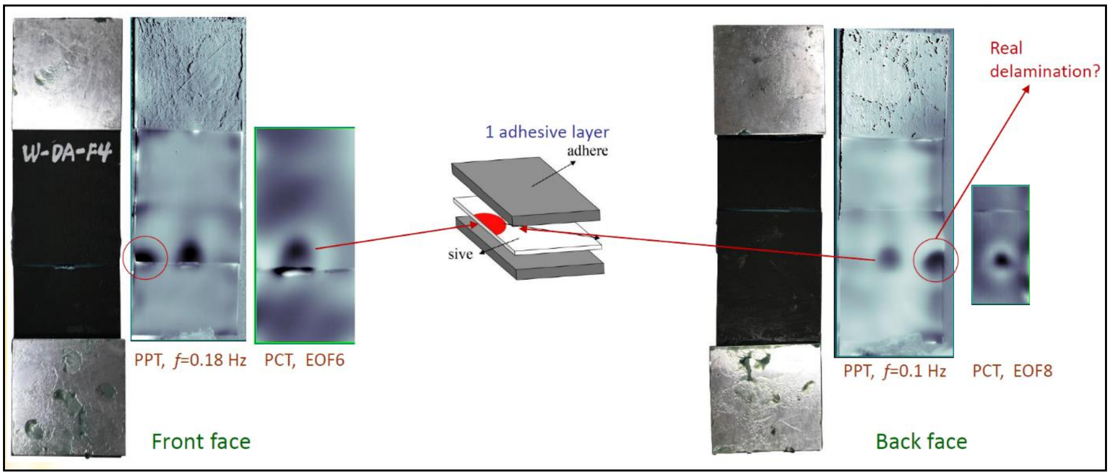



***Figure 11:*** *The processed results from the vibrothermographic inspection on sample W-DA-F4* [5].

## Sample W-DC-F2: Vibrothermography:

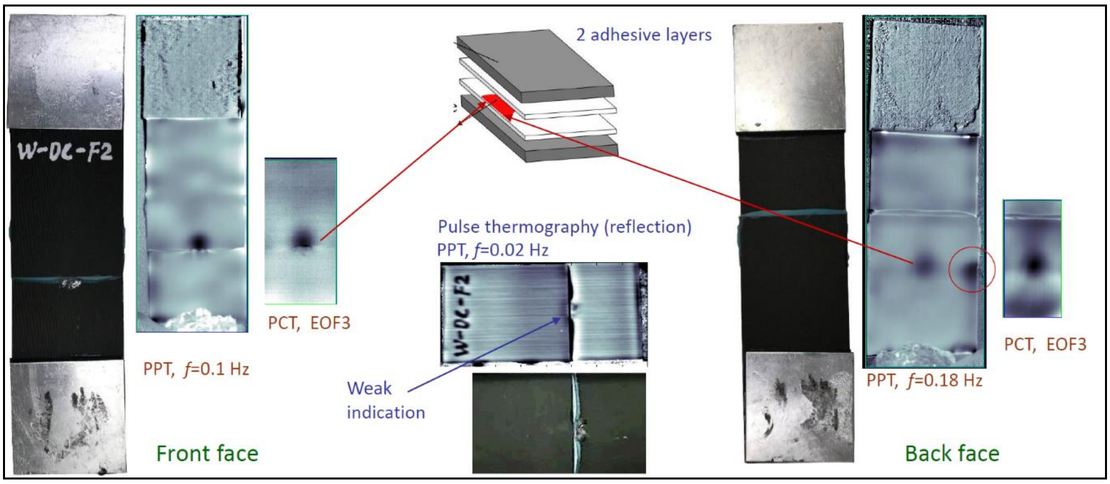



***Figure 12: T****he processed results from the vibrothermographic inspection on sample W-DC-F2* [5].

There was no kissing bond defect detected in specimen N-D-F4P (as expected) however, delamination-like defects were identified. The vibrothermography results in the two previous samples are promising for the detection of kissing bond defects. Further testing using alternative NDT techniques or destructive testing could be used in the future to validate the nature of these indications.

### Sample N-D-F4P: Vibrothermography:

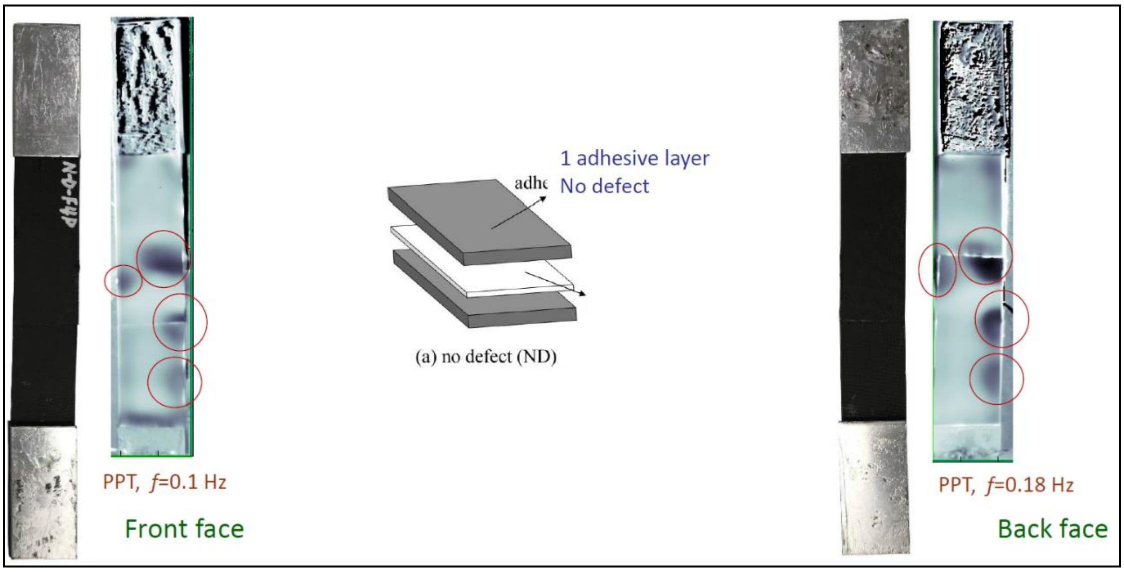



***Figure 13:*** *The postprocessed results from the vibrothermographic inspection on sample N-D-F4P* [5].

## 4.0. Proposed UAV

The NDT results show the effectiveness of this inspection method, the possibility of combining this method with a UAV could be an amazing technological advancement in the NDT industry. Following on from this testing, a DJI M210 equipped with an RGB and thermal camera will be used to inspect a composite wing.

DJI M210 system;

- Weight: 3.84 kg approx.
- Max payload: 2.3 kg (with 2 batteries)
- Thermal camera;
  - 640 x 512 pixels (same pixels as the FLIR Phoenix IR)
  - Weight: 0.27kg
  - Lens: 13mm [18].

Fig. 15. DJI M210 with thermal camera [19]

The radiometric camera uses a set of techniques to measure electromagnetic radiation, including visible light, this means that the acquired data can be extensively analysed after the survey in order to visualise and understand the data such as the temperature variations, which ultimately lead to accurate NDT results [19] [5]. UAV dynamic inspection has the potential to provide a complete portrait of the aircraft structure much faster than static inspections. For a UAV inspection an external excitation source will be employed to excite the surface. When inspecting something of this significance, the best results need to be obtained. Therefore, finding the most suitable excitation source is critical. vibrothermography may not be the most suitable due to the complexity of the setup and the minor possibility of damage to the subject. On the contrary, there are several alternative excitation sources more practical for UAV applications. For instance, halogen lamps (heating the surface for longer), Heat Blankets or a Laser [5].

### 4.1. Performing an NDT inspection

Once results are obtained, they will be analysed to see how effective the UAV NDT method is. The next step is to use the autonomous system for real life applications. For example, inspect a full-size passenger aircraft wing before and after its assembly to the fuselage during manufacturing. A UAV carrying an IR camera can provide much more mobility and allow for inspections that would usually be difficult and time consuming when using the traditional inspection techniques. There are, several challenges that need to be taken into consideration for using a UAV for NDT [5].

The goal is to inspect full size composite aircraft and composite panels straight from the manufacturing line, to verify their worthiness and quality assurance, this however does come with some limitations. Indoor UAV inspection limits the availability of GPS, inevitably will result in an unstable flight and affect the data. Therefore, it’s possible to set up a localisation scheme by distributing some ultrasonic sensors around a specific geographic area, the UAV will communicate with these sensors to understand its location, which will ultimately result in stabilisation [5].

Once the flight is ready – due to the size of aircraft parts, the subject will need to be segregated into separate regions of interest, and separated images will be taken and then stitched together as a mosaic image, this segregation will ensure the subject is excited uniformly. Once the data is acquired, it will then need to be processed to improve results, the benefit of an indoor inspection is that you have full control of the scene, meaning that you can take into consideration the following properties during post-processing without any external factors affecting the data [5];

- Thermal Properties: conductivity, diffusivity, effusivity, specific heat.
- Spectral Properties: emissivity, absorption, reflection, transmission.
- Material’s properties-characteristics: density, porosity, thickness, geometry [13] [5].

These properties allow the user to understand the data more accurately. For instance; when a material presents voids or pores in its structure, then its thermal conductivity and density decreases, its thermal diffusivity is altered and so the conduction of heat transfer within the material is affected. For instance, materials with low-effusivity values will present higher temperatures. With this and all other factors taken into consideration, a better damage assessment can be done [13] [5].

## 5.0. Conclusion

The purpose of this paper is to present various results from active thermography on composite materials (locating different types of defects within the materials) and integrate the proposed developed methodology into a UAV thermographic inspection system. This study contributes to reducing the time and cost of NDT composite inspections. The research shows the effectiveness of two different excitation sources used for NDT inspection. The raw data that is acquired often contains noise caused by the environment such as, the reflections, the emissivity variations of the specimen or if the excitation was non-uniform, it is important to take this into consideration and to employ specific algorithms for image processing in order to produce accurate results. Signal processing techniques, such as PPT and PCT, allow to improve defect contrast and hence, visualise the extent of the damage and the surrounding areas. When acquiring data, the value of each pixel will represent the temperature at a specific point. The temperature profile of the point corresponding to the healthy area is different from that of the point corresponding to the defective area. Using further digital image processing it is possible to enhance the images to reveal the location and geometry of the defects [4]. These methods can potentially become beneficial to the aerospace industry and possibly integrated onto a UAV. There are results from a UAV NDT test which was used for a civil application, the results indicated an excess of noise from the UAV, since this flight was performed without the use of GPS, this affected the results and the noise was due to the stabilisation problem. It is necessary to perform pixel by pixel treatment in addition to the standard average signal study [11]. To do this, the IR camera needs to be as static as possible, GPS or other localisation techniques can be used to compensate for any stability problems. The data acquired has shown that different techniques are better suited for different defects. Pulsed thermography can accurately locate delamination’s. Delamination is where the material fails due to the layers separating which result in significant loss of mechanical toughness. In the future, a UAV inspection will be performed, and the fidelity and performance of the image processing algorithms will be further evaluated. An excitation source that is small, light and produces enough energy to penetrate the material, can possibly be equipped on the UAV soon, this will offer an all in one inspection product and minimise time as there will be no need to set up an external excitation source. To quantify these parameters, the excitation source that is planned to be equipped is approximately 200 * 254 * 254 mm, the mass is 1.5 kg and consist of four 100w LEDs. Several active thermography tests on a sample composite wing will determine how effective this excitation source is before it is equipped onto the UAV. There are multiple excitation sources on the market that offer a sufficient weight to energy ratio [5].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