Citation: Deane, S., Avdelidis, N. P., Ibarra-Castanedo, C., Zhang, H., Yazdani Nezhad, H., Williamson, A. A., Mackley, T., Davis, M. J., Maldague, X. & Tsourdos, A. (2019). Application of NDT thermographic imaging of aerospace structures. Infrared Physics & Technology, 97, pp. 456-466. doi: 10.1016/j.infrared.2019.02.002

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Application of NDT Thermographic Imaging of Aerospace Structures

Shakeb Deane, Nicolas P. Avdelidis, Clemente Ibarra-castanedo, Hai Zhang, Hamed Yazdani-nezhad, Alex A. Williamson, Tim Mackley, Maxwell J. Davis, Xavier Maldague, Antonios Tsourdos

PII: S1350-4495(18)30956-3
DOI: https://doi.org/10.1016/j.infrared.2019.02.002
Reference: INFPHY 2858

To appear in: *Infrared Physics & Technology*

Received Date: 25 December 2018
Revised Date: 5 February 2019
Accepted Date: 6 February 2019

Please cite this article as: S. Deane, N.P. Avdelidis, C. Ibarra-castanedo, H. Zhang, H. Yazdani-nezhad, A.A. Williamson, T. Mackley, M.J. Davis, X. Maldague, A. Tsourdos, Application of NDT Thermographic Imaging of Aerospace Structures, *Infrared Physics & Technology* (2019), doi: https://doi.org/10.1016/j.infrared.2019.02.002

Application of NDT Thermographic Imaging of Aerospace Structures

Shakeb DEANE [1*], Nicolas P. AVDELIDIS [1,2], Clemente IBARRA-CASTANEDO [2], Hai ZHANG [2,3], Hamed YAZDANI-NEZHAD [1], Alex A. WILLIAMSON [4], Tim MACKLEY [1], Maxwell J. DAVIS[5], Xavier MALDAGUE[2], Antonios TSOURDOS [1]

[1] School of Aerospace, Transport and Manufacturing, Cranfield University, United Kingdom.
[2] Computer Vision and Systems Laboratory (CVSL), Department of Electrical and Computer Engineering, Laval University, Quebec City, G1V 0A6, Canada.
[3] Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, M5S 3G8, Canada.
[4] Mapair Thermography Ltd, Melbourn, South Cambridgeshire, United Kingdom.
[5] Adhesion Associates Proprietary Limited, Queensland, Australia.

Keywords: active infrared thermography, pulsed thermography, vibrothermography, UAV, composite, kissing bond.

Abstract. This work aims to address the effectiveness and challenges of Non-Destructive Testing (NDT) inspection and improve the detection of defects without causing damage to the material or operator. It focuses on two types of NDT methods; pulsed thermography and vibrothermography. The paper also explores the possibility of performing automated aerial inspection using an unmanned aerial vehicle (UAV) provided with a thermographic imaging system. The concept of active thermography is discussed for inspecting aircraft CFRP panels along with the proposal for performing aerial inspection using the UAV for real time inspection. Static NDT results and the further UAV research indicate that the UAV inspection approach could significantly reduce the inspection time, cost, and workload, whilst potentially increasing the probability of detection.

1.0. Introduction

Active Infrared Thermography is an inspection technique that requires an external source of energy in order to induce a temperature difference between defective and non-defective areas of a specimen under examination. This paper will focus on the optical and mechanical forms of excitation and the proposal of integrating these methods onto an unmanned aerial vehicle. Optical excitation is where an optical device such as a flash or a halogen lamp is used to emit energy. Whereas mechanical excitation will use a sonic or ultra-sonic transducer to excite the specimen by means of mechanical oscillations [1].

To meet the demands of the global economy, companies must turn out the highest quality of products in an efficient manner with minimal manpower and remain profitable [2]. Infrared Thermography (IRT) is predominately being used to detect subsurface defects in a plethora of structural elements and mechanical systems that consist of a wide range of materials [3]. It is one of the newest non-destructive technologies and has proven to provide substantial improvements in performance as well as good cost savings, allowing more frequent maintenance with minimal manpower [4] [5].

Since the successful release of the A380 and Boeing 787 Dreamliner, commercial Aircraft manufacturing has seen a rapid increase in the use of composites materials this demand is putting pressure on companies to develop new inspection solutions [6]. In 1985, around 5 percent of the A310-300 consisted of composite materials, 18 years later and more than half (53%) of the materials used to manufacture the A350XWB consists of composites [7]. Composites offer greater strength characteristics compared to the common structural metallic materials [8]. The materials of an aircraft structure have immense responsibilities, there are required to resist many intense loads repeatedly and be free from damage, delamination, fatigue and corrosion after each cycle. It is estimated that there are more than 120,000 inspectors worldwide and the global NDT industry has an estimated turnover of 5.2 billion, it is an important and growing industry [9]. A cost-efficient NDT method, is needed to keep up with the manufacturing industry and ensure the safety of this complex material [10][5].

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 [11]. IRT is a fast-non-contact method and is well-suited for testing large areas of complex geometry [12]. 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].

1.1. Composites

IRT inspection is well-suited for the inspection of composite materials, which possess low reflectivity and high emissivity, meaning that they absorb and re-emit energy very well. Once the energy is absorbed, the material will retain the energy and release it much slower than traditional metallic materials, such as aluminium, therefore using infrared NDT is very attractive for inspecting composite materials. Composites have some limitations, perhaps the most noteworthy limitation is the poor response to impact loading [13], which can be caused easily by runway debris, a dropped tool or any other impact. It’s been reported that 80% of in-service damages to composites is caused by impact strikes [14]. Composite materials respond differently than metals in terms of impact loading and its ability to dissipate the incident kinetic energy of the projectile [13]. For minor incident energies, metals absorb energy through elastic and plastic deformation, this will usually result in permanent structural deformation however, metals can carry the load and it results in consequences that are less-significant compared to composites. Plastic/Elastic deformation for a composite is very limited as the resultant energy is frequently absorbed in creating large areas of fracture, which will affect the performance of the material due to the reduction in both strength and stiffness [15]. During composite manufacturing, it is possible for the material to be damaged due to the complexity of the manufacturing process [16][5].

Figure 1 shows the composition of a composite material. The figure demonstrates the material properties. Figure 2 presents a delamination within a composite, this is a consequence of misalignments in large aircraft structures.

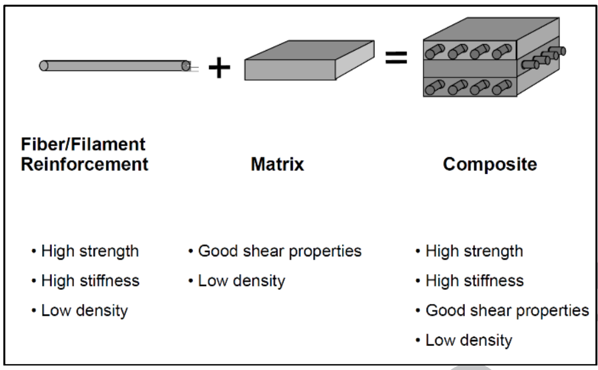


***Figure 1**: The composition of a composite material [8] [5].*

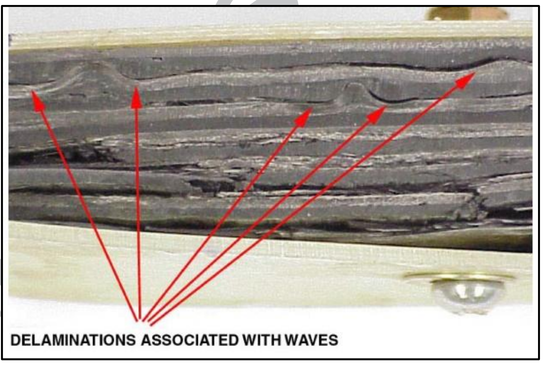


***Figure 2:** An example of a composite delamination, this is the consequence of misalignments in large aircraft structures [17] [5].*

1.2. Demand for NDT inspection on composites

Due to the increased demand of CFRP, it has subsequently caused rapid large-scale manufacturing. For instance, Airbus estimates its Carbon Fiber demand to soar to around 20,000 tons by the year 2020 (see figure 3, right) [7] [5].

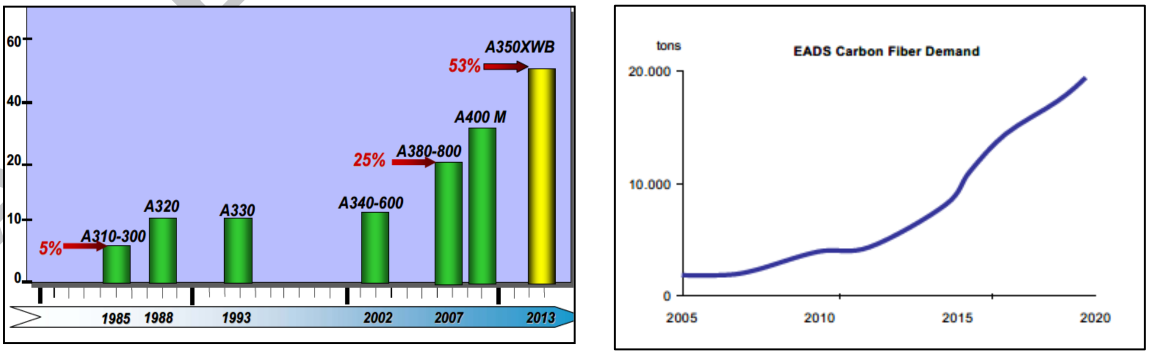


***Figure 3:** The bar chart (left) shows the use of composites in Airbus aircraft since 1985. The line graph (right) represents the demand by tons from 2005 up to 2020 [7] [5].*

The current manufacturing and machining process are novel compared to the manufacturing of traditional metallic structures, in addition, composites have different specific mechanical properties. Consequently, it's proven difficult to control manufacturing defects, due to the complexity of the manufacturing. Composites are layered pieces of laminar with alternating orientation typically 45 or 90°. Composite impact damage can result in damage in many different forms such as matrix cracking, fibre/matric debonding, surface microbuckling, delamination and fibre breakage [15]. Such impacts can cause barely visible impact damage (BVID), this is where the damage will still exist subsurface and extend way beyond the impacted area. This can leave aircraft vulnerable by jeopardising the safety of the structure. The damage zone of a composite is of a more complex nature and can be very difficult to characterise. The complexity of the problem multiplies due to the lack of impact damage testing techniques on a composite material [3]. This calls for an adequate way to search for defects within a composite material [5].

2.0. Experimental procedure I

2.1. Pulsed Thermography (PT)

Pulsed thermography (PT) is a popular and a popular NDT thermal imaging technique that does not require physical contact with the specimen, it is used to evaluate the health of materials and components without interfering with the serviceability [3]. The specimen is subject to pulsed-heating whilst being observed with a thermal camera. The heat will conduct through the material, if there is any present defects either on the surface or sub-surface this will affect the heat diffusion resulting in the thermal camera being able to locate a discontinuity in radiation during the cooling phase [18].

PT can be affected by a range of properties, which need to be considered during post-processing such as reflections from the environment, emissivity variations, non-uniform heating and surface geometry variation [1]. To obtain the most accurate results, it is possible to limit some of the before mentioned effects. For example, applying a washable paint to the specimen will ultimately reduce environmental reflections and increase the emissivity to almost 1 [1]. Note that the surface conditions can affect the PT results due to emissivity variations, this is usually beyond the user's control. For maximum effective results the excitation source needs to be uniform within the inspection area.

2.2. PT Data Acquisition

The experiment and processing took place at the Laval University in Quebec City, Canada. Data acquisition for PT is relatively straight forward, in this case the CFRP (Carbon fibre reinforced polymer) specimen's surface is subject to surface pulse heating using two 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. A synchronisation unit is necessary during this experiment in order to control the time between the initial thermal pulse excitation and the recording. The acquired data is stored as a 3D matrix where t is the time and x and y are the spatial coordinates.
There are two main types of thermography, active and passive as depicted in Figure 4. Passive thermography is an inspection without the use of an external excitation source, its commonly used for inspecting materials that have a temperature naturally different than its surrounding [19]. 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 [19] [5].

2.3. PT Equipment

The CFRP specimens where manufactured and purposely damaged via impact, in the Cranfield composite centre. 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 180°C 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 15 and 20 J of energy. The infrared camera used in this experiment was a FLIR Phoenix, with inSb sensor material, 3-5 mm, 640x512 pixels and allows data acquisition at 50Hz [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 [20].

The surface of the specimens where positioned parallel to the camera lens as depicted in Figure 4. The data was acquired for 40 seconds with a 1.5 millisecond 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].

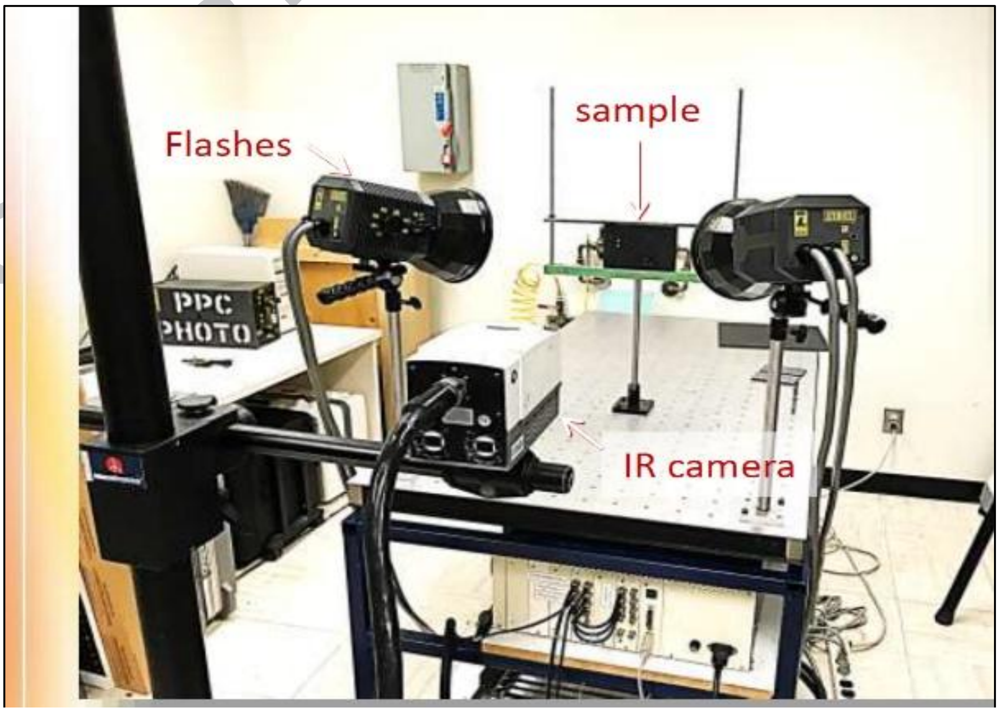


Figure 4: Images showing the PT testing equipment and the experimental set up [5].

3.0. Results & Discussion I

3.1. Experiment

The figures below (Figures 5-11) 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].

3.2. Processed Results

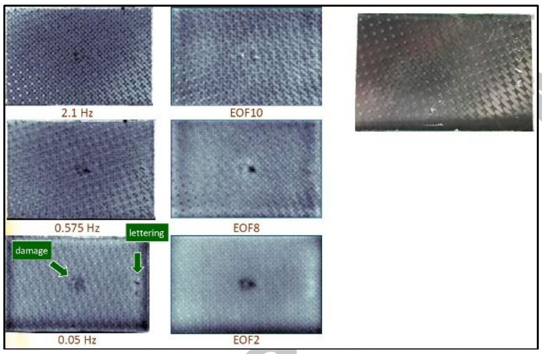


Figure 5: Sample A4 (15 J woven), front face (impacted side), PPT and PCT. *The damage is barely visible in the original image of the composite (Far right image), the white marks are lettering from labelling the specimen. The 0.05Hz PPT image, shows clear subsurface damage [5].*

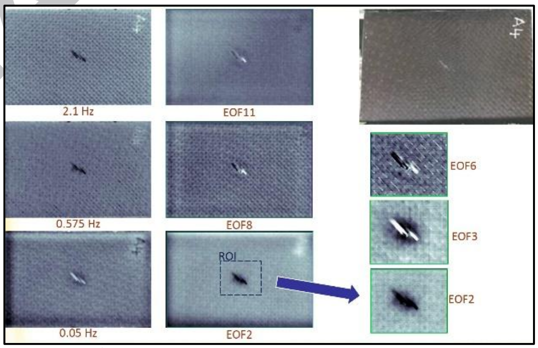


Figure 6: Sample A4 (15 J), Reflection rear face PPT and PCT. *The rear surface is cracked, this is interesting because this side is significantly more damaged than the impacted side. This is a prime example of barely visible impact damage [5].*

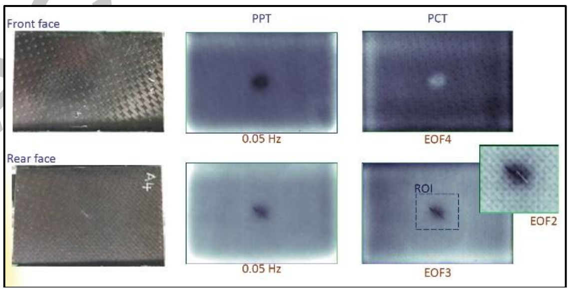


Figure 7: Sample A4 (15 J). *Transmission is where the one side of the composite is excited, and the other side is observed by the camera and captures the data [5].*

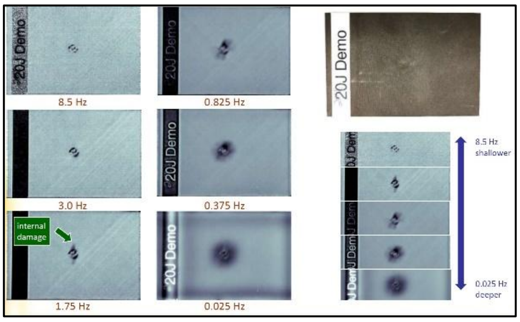


Figure 8: Sample 20 J Demo, Reflection front face, PPT. *The damage is visible on the front face, how, it's clear that the damage is much worse subsurface and spreads further than the impacted area [5].*

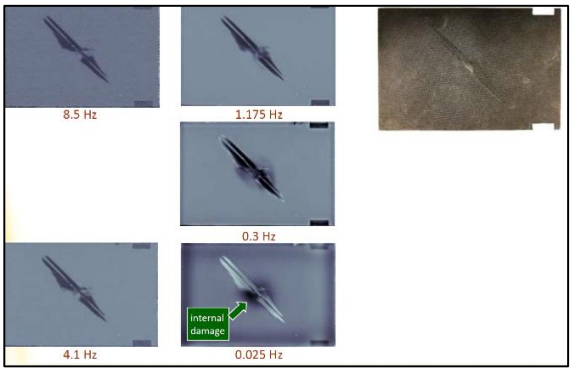


Figure 9: Sample 20 J Demo, Reflection rear face*. PPT. The rear face has some substantial damage. The PPT locates the surrounding internal damage [5].*

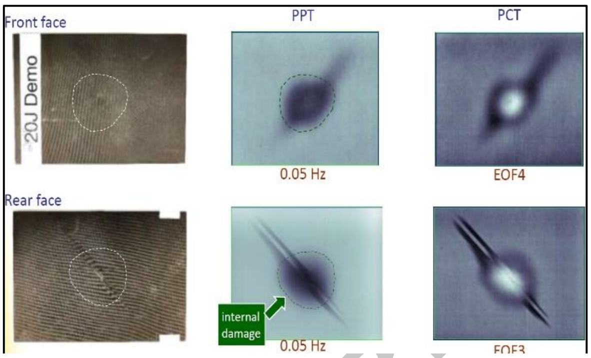


Figure 10: Sample 20 J Demo, Reflection front face, Transmission. *The test has adequately located the internal damage [5].*

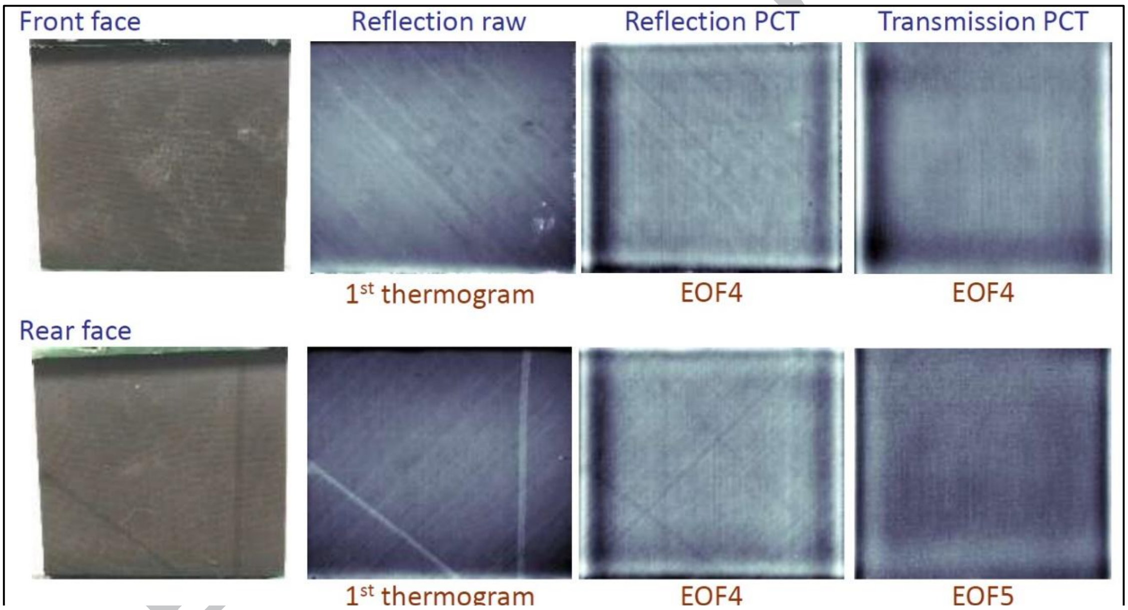


Figure 11: Sample No Name, Reflection front, back, transmission PCT. *Undamaged composite sample, which was manufactured the exact same way as the 20J sample, the different NDT test prove that this sample is damage-free [5].*

4.0. Experimental Procedure II

4.1. Vibrothermography (VT)

Vibrothermography (VT) in scientific literature is also referred to as; ultrasonic infrared thermography, acoustic thermography, thermosonics, sonic IR, elastic-wave-activated thermography, thermal vibration method or vibroIR [21]. VT is an alternative NDT method that uses vibration and/or ultrasonic excitation to evaluate the structural health of the specimen. There has been a significant increase of research into this NDT method since the accessibility of more affordable thermal sensors, however the available literature shows there is still an area for improvement in the industrial use of this technique due to concerns over the reproducibility and reliability of measurements [21]. 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 [21]. More specifically, the exact amount of heat that is expected to dissipate on certain defects is usually assumed. Despite this, it is certain that generated heat depends on frequency and position of the excitation source [21]. Vibrothermography is becoming a popular technique to detect cracks in metallic structures and several types of damages in composite materials.

Sonic waves vibrate between 20 Hz and 20 kHz, which is audible for humans. However, the range for ultrasonic waves, which is beyond humans' audible capabilities, is between 20 kHz and 1 MHz, 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, and travel faster through solids and liquids as opposed to air [1]. 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 [1]. On the contrary, there are currently ultrasonic non-contact inspection methods being investigated in many areas, this is more appealing due to the reduced risk of damage.

The traditional VT inspection works by placing a transducer in contact with the specimen assisted by a coupling media as before mentioned (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 [22].

4.2. VT Data Acquisition

There are two main analogues that can be considered when gathering data. The two techniques are lock-in and burst VT. Note the frequency can be modulated in addition to the amplitude. When acquiring data, the wobbulation procedure is often used, this procedure seeks to cover a range of different frequencies in a single experiment, the purpose is for the user to predict the right frequency for the specific application as each application is different and requires tailored inspections [22]. The amount of damage detection is proportional to the amount of excitation, too much power (higher frequency) will be costly and will risk damage to the specimen. Therefore, using the minimum amount of power required to acquire satisfactory results is becoming a major interest for researchers [24].

The transducer is made of a stack of pie piezoelectric elements and concentrated in a titanium horn that acts like a hammer [22]. The specimen must be firmly restraint without damage, the immobilized specimen seeks to avoid cantilever effects, clapping, and sliding of the transducer [22]. 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 [22]. 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. Crack detection is extremely sensitive to whether the specimen is fixed or free, in figure 12 the results from the constrained specimen proved the most accurate [23].

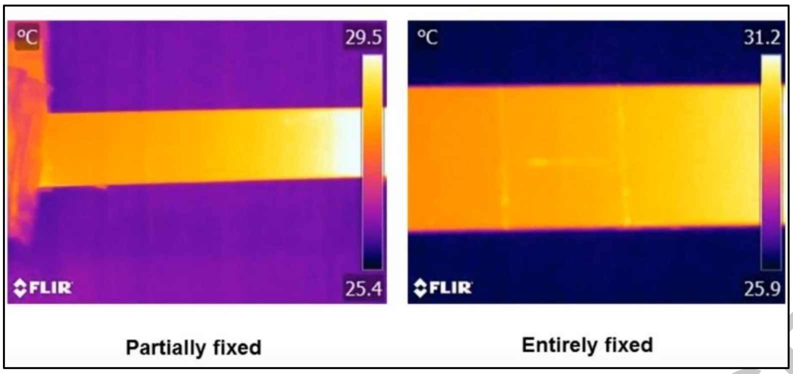


***Figure 12**: The mechanical wave can be more easily converted into heat when the specimen is entirely fixed* [24].

The temperature of the cracks will usually increase slowly when the excitation is injected into the specimen, as a result the thermal waves travel by conduction to the surface, which can then be detected by the IR camera. 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.

4.3. 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 [23]. The IR camera used to capture the data, is the same as used in the PT experiment explained in 2.1. The transducer used is a 20 kHz ultrasound generator (BRANSON 2000), as seen in Figure 13.

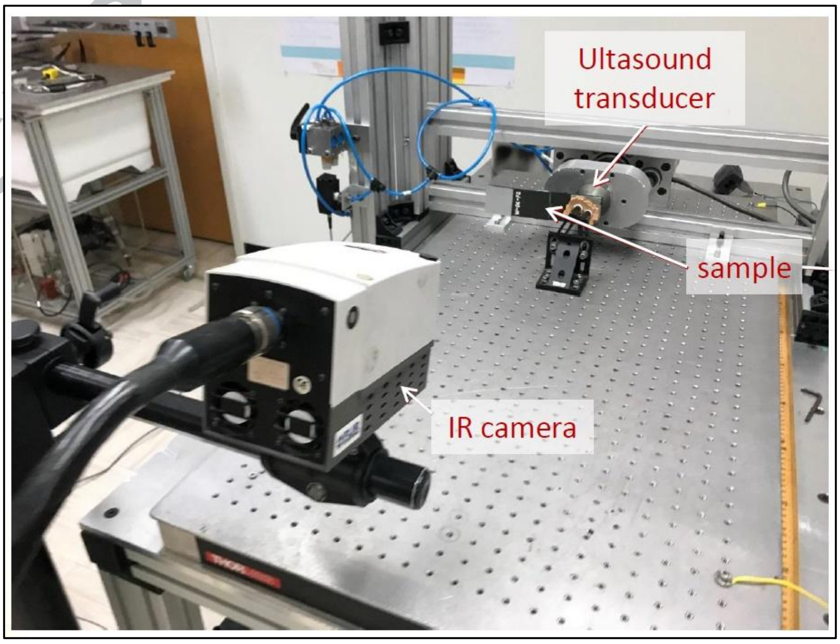
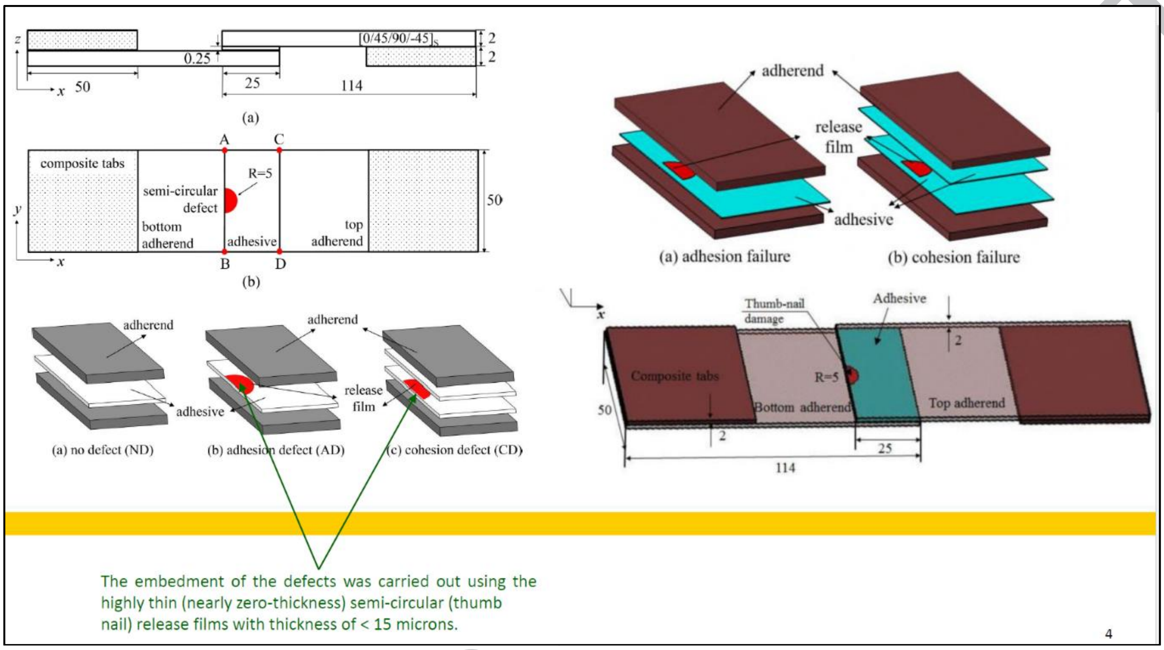


***Figure 13:** Image displaying the VT testing equipment and the experimental set up.*

The experiment will consist of inspecting three different specimens, to search for defects but more specifically concentrating on kissing bond defects. 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.



The embedment of the defects was carried out using the highly thin (nearly zero-thickness) semi-circular (thumb nail) release films with thickness of < 15 microns.

Figure 14*: Artificial defects release film kissing bond* [25].

The three inspected specimens are all composite material with artificial defects as shown in Figure 14.

- **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 a 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.

5.0. Results & Discussion II

5.1. Experiment

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.

5.2. Processed Results

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.

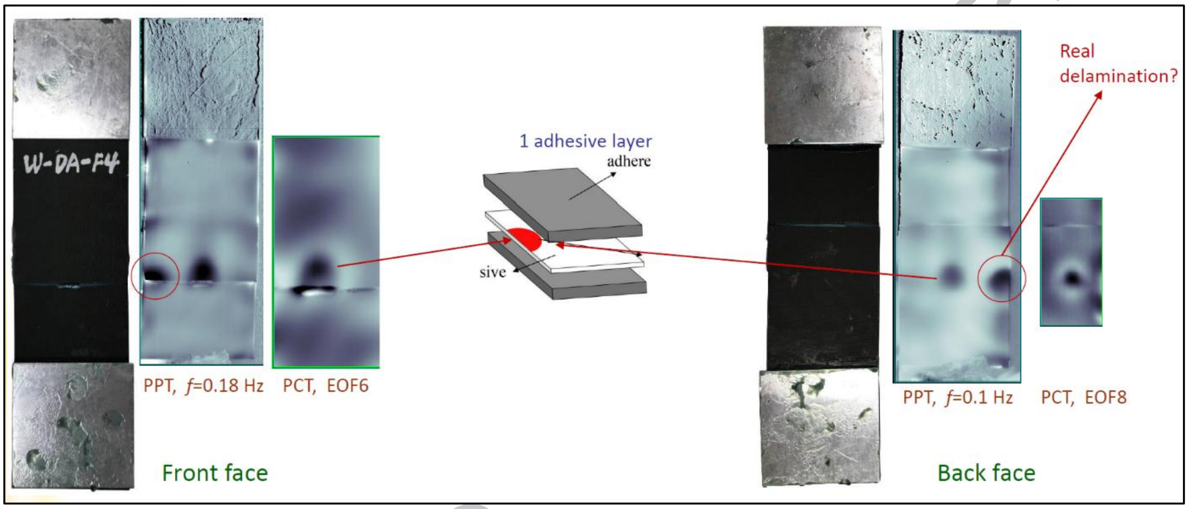


Figure 15: *Image showing the processed results from the vibrothermographic inspection on sample W-DA-F4*

Sample W-DC-F2: Vibrothermography:

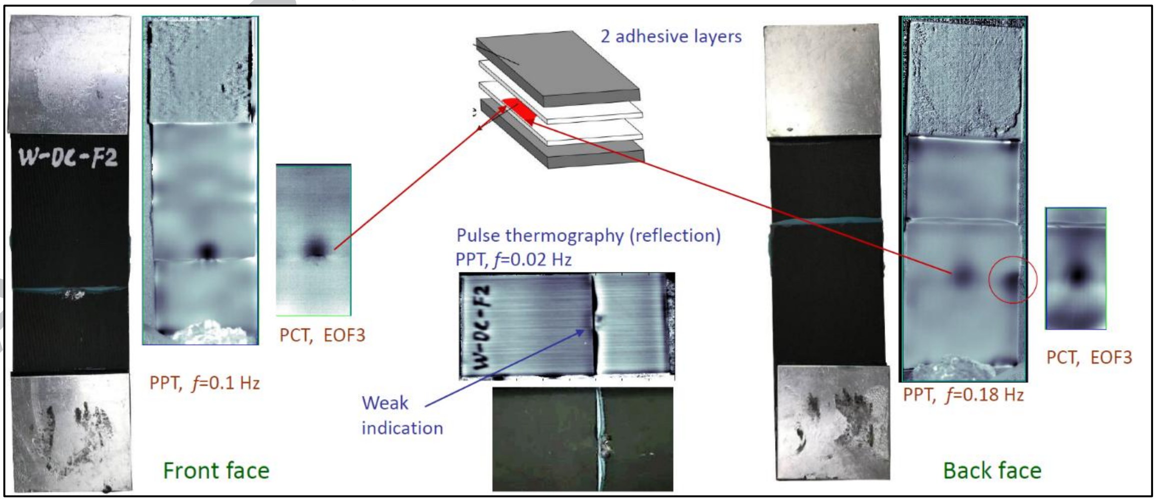


Figure 16: *Image showing the processed results from the vibrothermographic inspection on sample W-DC-F2*

There was no kissing bond defect detected in specimen N-D-F4P (as expected) however, delamination-like defects were identified. 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:

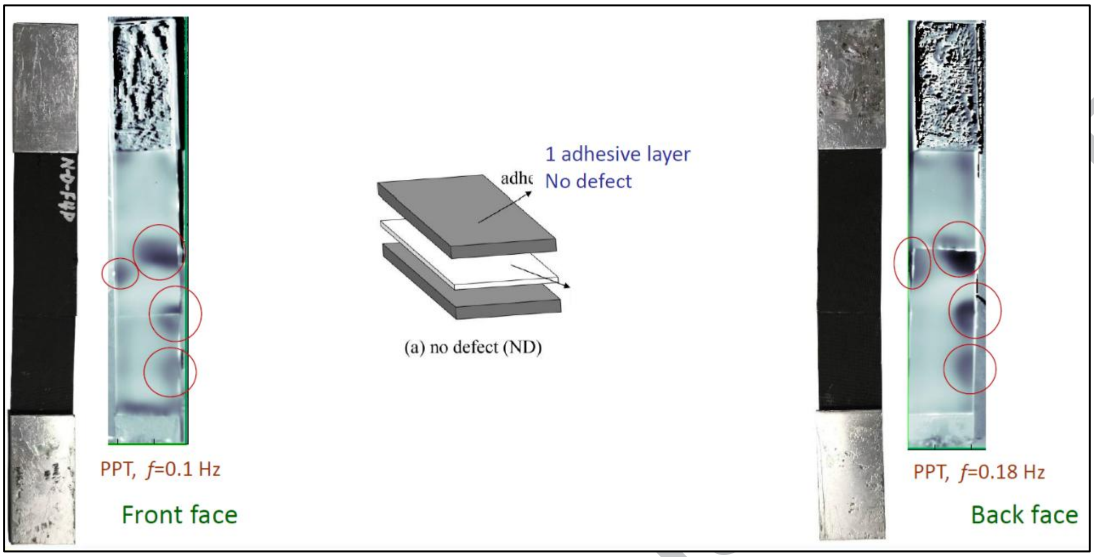


Figure 17: *Image showing the postprocessed results from the vibrothermographic inspection on sample N-D-F4P.*

For instance, additional tests using long-pulse thermography in transmission mode could possibly detect such kind of defects. However, this test would require access to both sides of the specimen, which is not always possible in industry e.g. an aircraft wing panel after assembly.

Figures 18 and 19 show some examples of previous IR NDT inspections of similar specimens [26]. Figure 18 is a pulsed thermographic inspection; the defects are located however they are not easily visible in this case.

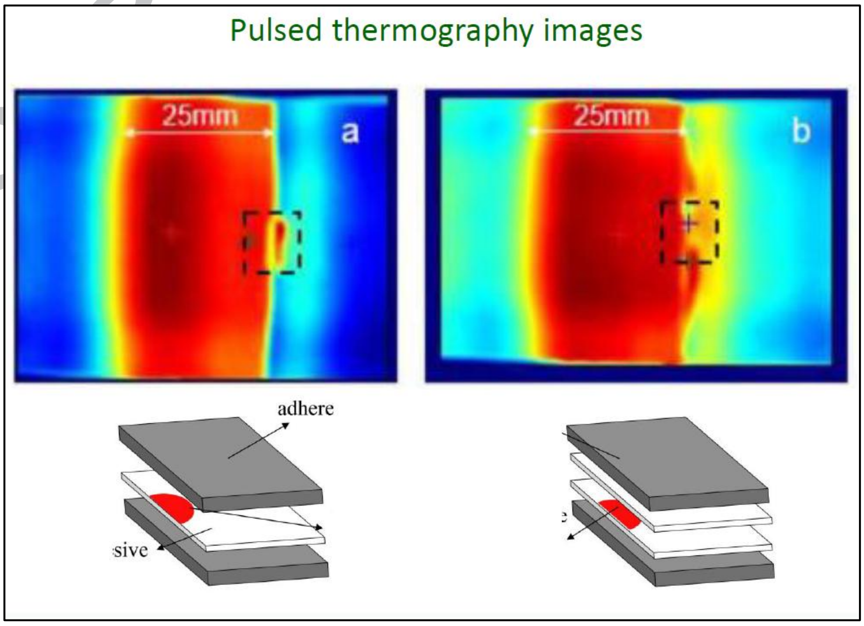


Figure 18: *Past pulsed thermographic inspection from similar specimens as used in the before mentioned VT inspection* [25].

Figure 19 is an ultrasound testing inspection. The defects are successfully located and are more visible than the PT results in figure 18. The size of the defect can also be measured during processing, the defect present has a radius of 5mm. The vibrothermography results are promising for the detection of kissing bond defects.

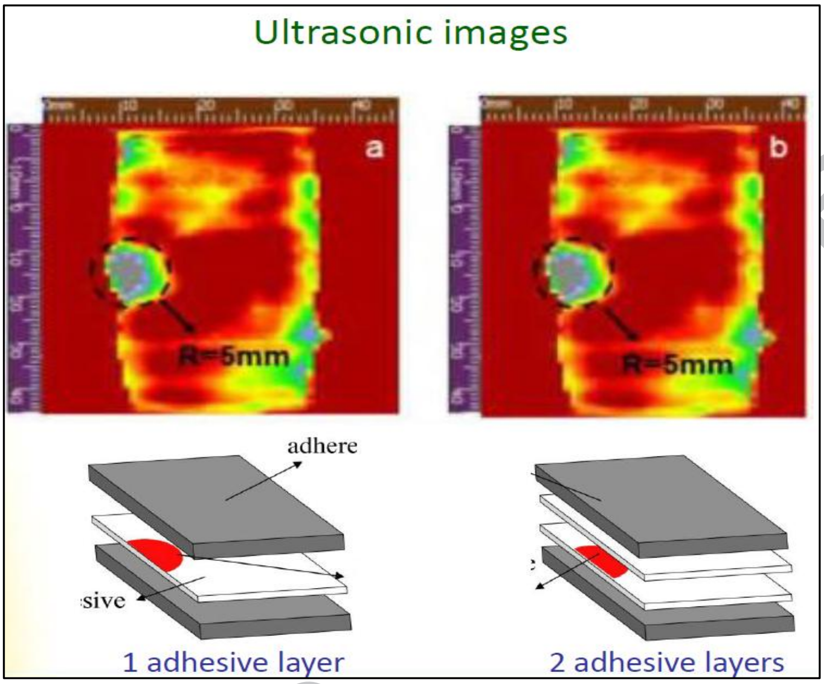


Figure 19: *Past ultrasonic thermographic inspection from similar specimens as used in the before mentioned VT inspection* [25].

5.3. Proposed UAV

Although a cooling camera was used in the beforementioned NDT tests, this type of camera will not be feasible for a UAV thermographic inspection. Cooling cameras usually require cryogenic cooling, which is an excess of weight. The equipment that will be used in future UAV NDT testing is a DJI M210, which carries an RGB and thermal camera. The weight of the UAV is approximately 3.84kg with a maximum payload of 2.3kg with 2 batteries [26]. The thermal camera weighs 0.27kg and is 640 x 512 pixels, which is the exact same number of pixels as the FLIR Phoenix IR camera that was used [26]. It has a 13 mm lens and is radiometric, therefore it 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 [27] [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. 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.

Along with the liquid penetrant NDT method as mentioned in the introduction, a UAV thermographic inspection was tested for civil engineering applications (see Figure 20B). The UAV is equipped with a FLIR A320, this IR camera is connected to a computer via a cable, one is a power cable and the other provides real time radiometric thermal images, which will reveal heat patterns and thermal anomalies [12]. Transient thermography with flash and step heating where the methods used in this inspection. An inspection took place and gathered data on different distances between the camera and the samples (2, and 6 metres). Along with the UAV equipped with the IR camera, there was a fixed IR camera, therefore two sets of data could be acquired and compared. A thermally uniform area of a sample is delimited, and the IR cameras captured the data [12] [5].

FIGURE 20 A*: DJI M210 equipped with thermal camera* [27]. ***FIGURE 20 B:*** *UAV equipped with thermal camera* [12]. ***FIGURE 20 C****: Comparison of front face temperature responses to flash heating in the case of a large uniform irradiation with a fixed camera and a stabilized camera with UAV at two distances (2 m and 6 m)* [12] [5].

5.4. Performing an NDT inspection

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. The autonomous system is to be tested in real life application on a full-size passenger aircraft wing before its assembly to the fuselage. In theory, it is the same method as the beforementioned experiments, the only difference is the camera will be moving. 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 however, several challenges that need to be taken into consideration for using a UAV for NDT. The future plan is to inspect full size composite aircraft and also composite panels straight from the manufacturing line, to verify their worthiness and quality assurance. There are some limitations for this proposed idea. Due to the fact the inspection is inside it could provide problems for the UAVs GPS system, which will result in an unstable flight and affect the data as before-seen. There are a few ways to combat this issue, one of them is 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. 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, when post processing, many properties need to be considered [5];

- Thermal Properties: conductivity, diffusivity, effusivity, specific heat

- Spectral Properties: emissivity, absorption, reflection, transmission
- Material's properties-characteristics: density, porosity, thickness, geometry [19] [5].

With these properties understood, data process can be performed, 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 all this information taken into consideration, a better damage assessment can be done [19] [5].

6.0. Conclusion

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 [3]. These methods can potentially become beneficial to the aerospace industry and possibly integrated onto a UAV. The results from the UAV inspection indicate 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 [12]. 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*254mm, the mass is 1.5kg 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].

Acknowledgements:

This research was part supported by the British Engineering and Physics Sciences Research Council.

References

1. C. Ibarra-Castanedo, J.M. Piau, S. Guilbert, N.P. Avdelidis. M. Genest, A. Bendada. X.P.V. Maldague. 2009. "Comparative Study of Active Thermography Techniques for the Nondestructive." Research in Nondestructive Evaluation 1–31. doi: 10.1080/09349840802366617.

2. Bin Industrial Training. 2014. What is Thermography (thermal imaging). Bin Industrial Training. 25 November. Accessed 12 13, 2018. doi:https://www.youtube.com/watch?v=4xulzkBOFKI&t=3s.

3. A. P. Chrysafi, N. Athanasopoulos, N. J. Siakavellas. 2017. "Damage detection on composite materials with active thermography and digital image processing." International journal of thermal sciences 242-253.

4. T. Ullmann, T. Schmidt, S. Hofmann, R. Jemmali. 2010. "In-line Quality Assurance for the Manufacturing of Carbon Fiber Reinforced Aircraft Structures." 2nd International Symposium on NDT in Aerospace.

5. S. Deane, N. Avdelidis, C. Ibarra Castanedo, H. Zhang, H. Yazdani Nezhad, A. A. Williamson, X.P.V. Maldague, A Tsourdos. 2018. "Autonomous systems imaging of aerospace structures." 10th International Symposium on NDT in Aerospace. Dresden: DGZfp. doi:https://www.researchgate.net/publication/329558466_Autonomous_Systems_Imaging_of_Aerospace_Structures.

6. J. Pora. Airbus. 2001. "Composite materials in the Airbus A380 - from history to future." 13th international conference on composite materials. Beijing: INTERNATIONAL COMMITTEE ON COMPOSITE MATERIALS. paper-1695. doi:http://www.iccm-central.org/Proceedings/ICCM13proceedings/SITE/PAPERS/paper-1695.pdf.

7. G. Hellard. 2016. "Composites in Airbus, A Long Story of Innovations and Experiences." Edited by Dr Roland Thévenin. Global Investor Forum. Airbus. doi:http://docshare.tips/gif2008-workshop-composites-hellard_58259e7eb6d87f6b018b4575.html.

8. M. Mrazova. 2013. "Advanced composite materials of the future in aerospace industry." Incas Bulletin 5 (3): 139-150.

9. Materials KTN, R. Young, K. Newton, T. Dunhill, C. Huggins. 2014. A landscape for the future of NDT in the UK economy. Brochure , Materials KTN, Knowledge Transfer Networks, Materials KTN, NPL Product Verification Programme, Materials Knowledge Transfer Network. Accessed December 13, 2018. doi:http://www.bindt.org/downloads/Materials-KTN-Future-of-NDT-in-UK-economy.pdf.

10. N.V. Nayak. 2014. “Composite Materials in Aerospace Applications.” International Journal of Scientific and Research Publications Volume 4 (Issue 9): ISSN 2250-3153. Accessed December 12, 2018. doi:https://pdfs.semanticscholar.org/3a73/9ca726a88cf833ba89708a4944c46457e42d.pdf.

11. K. Malandrakis, A. Savvaris, J. A. G. Domingo, N. Avdelidis, P. Tsilivis, F. Plumacker, L. Z. Fragonara, A. Tsourdos. 2018. “Inspection of Aircraft Wing Panels Using Unmanned Aerial Vehicles.” 2018 IEEE MetroAeroSpace. Rome.

12. L.E. Mavromatidis, J.L Dauvergne, R. Saleri, J.C Batsale. N.D. “First experiments for the diagnosis and thermophysical sampling using impulse IR thermography from Unmanned Aerial Vehicle (UAV).” doi:http://dx.doi.org/10.21611/qirt.2014.213

13. W. J. Cantwell, J. Morton. 1991. “The impact resistance of composite materials — a review.” Composites 347-362. doi:https://doi.org/10.1016/0010-4361(91)90549-V

14. Y. Zhao, J. Mehnen, W. Xu, M. Alrashed, S. Abineri, R. Roy. 2015. “Degradation Assessment of Industrial Composites Using Thermography.” Procedia CIRP 147-152. doi:https://doi.org/10.1016/j.procir.2015.07.045.

15. N. Razali, M.T.H. Sultan, F. Mustapha, N. Yidris, M.R. Ishak. 2014. “Impact Damage on Composite Structures – A Review.” The International Journal Of Engineering And Science 08-20.

16. J.E.King. 1989. “Failure in composite materials.” Metals and materials Bury St Edmunds Volume 5 (Issue 12): 720-726. doi:https://www.scopus.com/record/display.uri?eid=2-s2.0-0024923342&origin=inward&txGid=8ae9d8890817115ae04936fb5108292a.

17. D. S. Cairns. 2009. “Composite Materials for Aircraft Structures.” Montana State University. Accessed September 09, 2018. doi:http://www.montana.edu/dcairns/documents/composites/MSUComposites2009.pdf.

18. M.Genest, M.Martinez, N.Mrad, G.Renaud, A.Fahr. 2009. “Pulsed thermography for non-destructive evaluation and damage growth monitoring of bonded repairs.” Composite Structures Volume 88 (Issue 1): 112-120. doi:https://doi.org/10.1016/j.compstruct.2008.02.010.

19. N.P. Avdelidis, D.P. Almond, A. Dobbinson, B. C. Hawtin, C. Ibarra-Castanedo, X.P.V. Maldague. 2004. “Aircraft composites assessment by means of transient thermal NDT.” Progress in Aerospace Sciences 40 (3): 143-162.

20. FLIR Systems Inc. 2016. What's the difference between cooled & uncooled thermal detectors? Edited by FLIR Systems Inc. FLIR Systems Inc. 02 08. Accessed 12 13, 2018. doi:https://www.youtube.com/watch?v=PYHjAdf8bU0.

21. M. Szwedo, L. Pieczonka, T. Uhl. 2013. “Application of Vibrothermography in Nondestructive Testing of Structures.” 6th European Workshop on Structural Health Monitoring. Krakow: DGZfp.

22. C. Ibarra-Castanedo, J.R. Tarpani, X.P.V. Maldague. 2013. “Non-destructive testing with thermography.” European Journal of Physics s91-s109.

23. L. Ambrozinski, B. Piwakowski, T. Stepinski, L. Pieczonka, T. Uhl. 2014. “Pitch-Catch Air-Coupled Ultrasonic Technique for Detection of Barely Visible Impact Damagesin Composite Laminates.” EWSHM- 7th European Workshop on Structural Health Monitoring. Nantes: Le Cam, Vincent and Mevel, Laurent and Schoefs, Franck. hal-01022043.

24. Smart materials and structures lab. 2015. Youtube. 19th October. Accessed November 27th, 2018. Available at: https://www.youtube.com/watch?v=f-fYmrQtNsI.

25. H. Yazdani Nezhad, D. Stratakis, D. Ayre, S. Addepalli, Y. Zhao. 2018. “Mechanical performance of composite bonded joints in the presence of localised process-induced zero-thickness defects.” Procedia Manufacturing 16:91-98. doi:https://doi.org/10.1016/j.promfg.2018.10.175.

26. DJI Official. 2019. MATRICE 200 SERIES SPECS. [online] Accessed February 04 2019 Available at: https://www.dji.com/uk/matrice-200-series/info.

27. A.A. Williamson. 2018. Mapair, Frequently Asked Questions. Accessed September 09, 2018. Available at: https://www.mapair.co.uk/faqs.

Application of NDT thermographic imaging of aerospace structures

Highlights:

- Active thermography is effective in locating defects in aerospace composite
- Advantages and limitations of pulsed thermography and vibrothermography
- NDT inspection of the challenging kissing bond defect
- UAV thermographic system is a promising approach for inspecting large structures
- Increase demand of composites, calls for adequate time/cost-efficient inspection