Inspection of aerospace materials by pulsed thermography, lock-in thermography and vibrothermography: A comparative study

Clemente Ibarra-Castanedo[1], Marc Genest[2], Stéphane Guibert[1], Jean-Marc Piau[1], Xavier P. V. Maldague and Abdelhakim Bendada[1].

[1]Computer Vision and Systems Laboratory,
Laval University, Quebec City (Quebec) G1K7P4, Canada.
E-mails: {IbarraC, Guibert, JMPiau, MaldaguX, Bendada}@gel.ulaval.ca

[2]Institute for Aerospace Research (IAR), National Research Council Canada (NRC),
1200 Montreal Road, Bldg. M-14, Room 130, Ottawa, ON, Canada, K1A 0R6.
E-mail: Marc.Genest@nrc-cnrc.gc.ca.

ABSTRACT

Inspection of aerospace components has always been a challenge. Infrared thermography has demonstrated to be a useful tool for this matter. In this paper, we offer a comparative study involving three active techniques: pulsed thermography, lock-in thermography and vibrothermography. Some of these techniques have proven to be more effective than others for a specific type of system. We compare the experimental results from these three techniques as applied to two typical aerospace parts: honeycomb structures and Glare. The later is perhaps the most challenging of all as will be pointed out. Some insights are provided regarding the most suitable technique for a number of typical situations.

Keywords: pulsed thermography, lock-in thermography, vibrothermography, aerospace components, honeycomb, cfrp, glare.

1. INTRODUCTION

Infrared thermography has been successfully used as an NDT&E technique in many applications. Contrary to *passive* thermography, in which the objects or features of interest present naturally a thermal contrast with respect to the rest of the scene; the *active* approach requires an external source of energy to induce a temperature difference between defective and non-defective areas in the specimen under examination. A wide variety of energy sources are available and can be divided in *optical*, if the energy is delivered to the surface by means of optical devices such as photographic flashes (for heat pulsed stimulation) or halogen lamps (for periodic heating); or *mechanical*, if the energy is injected into the specimen by means of mechanical oscillations, *e.g.* with a sonic or ultrasonic transducer. Optical excitation stimulates the defects *externally*, *i.e.* the energy is delivered to the surface of the specimen where the light is transformed into heat. Thermal waves propagate by conduction through the specimen until they reach a discontinuity that act as a resistance reflecting the thermal waves back to the surface. Mechanical excitation on the other hand, heats up the defects *internally*, *i.e.* mechanical oscillations injected to the specimen travel in all directions dissipating their energy at the discontinuities in the form of heat, which travels to the surface by conduction.

There are three classical active thermographic techniques based on these two excitation modes: lock-in thermography and pulsed thermography, which are optical techniques applied externally; and vibrothermography, which uses sonic or ultrasonic waves (pulsed or amplitude modulated) to excite surface or internal features. The experimental and theoretical aspects are different for each of these techniques and so are the typical applications. We describe these techniques in the following paragraphs discussing their applicability to aerospace materials.

2. OPTICAL EXCITATION

The two classical active techniques: pulsed and lock-in thermography, use optical devices as a source of energy, whose deployment is easier than mechanical excitation, as will be discussed in the following section. In pulsed thermography (PT), the specimen surface is submitted to a short heat pulse using a high power source such as photographic flashes; see Figure 1 (left). After the thermal front come into contact with the specimen's surface, a thermal front travels from the surface through the specimen. As time elapses, the surface temperature will decrease *uniformly* for a piece without internal flaws. On the contrary, subsurface discontinuities (*e.g.* porosity, delaminations, disbonds, fiber breakage, inclusions, etc.), can be thought as resistances to heat flow that produce abnormal temperature patterns at the surface that can be detected with an IR camera.
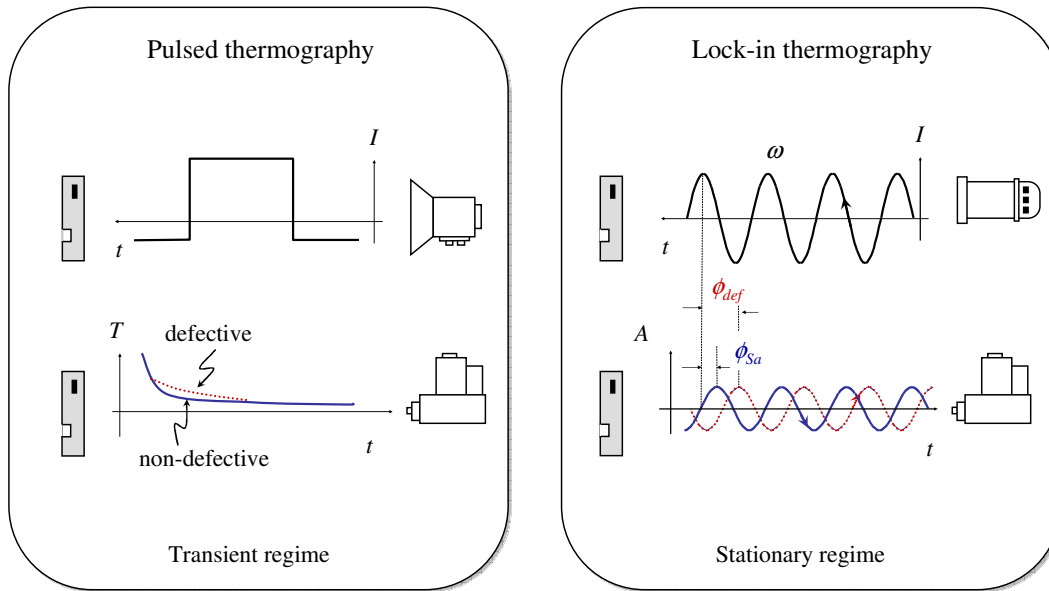
Figure 1. Pulsed thermography (left) and lock-in thermography (right) experimental configurations.

Usually, two photographic flashes are used to heat up the specimen's surface, after what, the thermal changes are recorded with an infrared camera. A synchronization unit is needed to control the time between the launch of the thermal pulse and the recording with the IR camera. Data is stored as a 3D matrix (see Figure 2a) where x and y are the spatial coordinates, and t is the time.
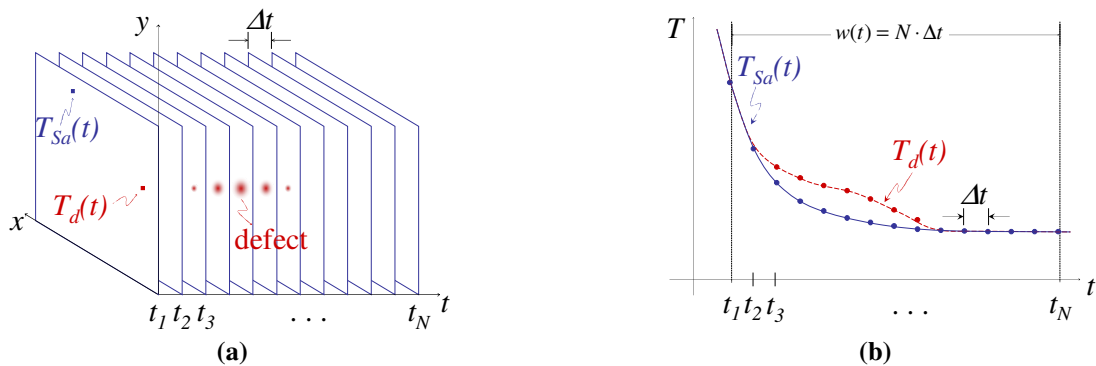
Figure 2. Temperature evolution: (a) data 3D matrix, and (b) temperature profile for a defective (dotted line) and non-defective (continuous line) pixels.

Temperature decreases approximately as $t^{1/2}$ (at least at early times), as predicted by the 1D solution of the Fourier equation for the propagation of heat by conduction in a semi-infinite isotropic solid that has being stimulated with a *Dirac* heat pulse [1]:

$$T(0,t) = T_0 + \frac{Q}{e\sqrt{\pi t}} \tag{1}$$

where $e \equiv (k\rho c_P)^{1/2}$ [m] is the effusivity, which is a thermal property that measures the material ability to exchange heat with its surroundings.

PT is probably the most extensively investigated approach because of its easiness of deployment, even though raw PT data is difficult to handle and analyze. There are a great variety of processing techniques that have being developed to enhance the subtle IR signatures [2], [3], [4], [5]. Pulsed phase thermography (PPT) [2] is particularly interesting since it allow retrieving phase and amplitude data from a PT experience through the discrete Fourier transform (DFT).PPT was originally proposed for PT data, although it can be applied to any type of signal, including LT and VT as will be discussed below. Thermographic signal reconstruction (TSR) [5], is another very useful PT processing technique, which considerably reduce the amount of data to be handled, de-noising the signal and allowing the algebraic manipulation of data.

In lock-in thermography (LT) [6], also known as *modulated thermography* [7], the specimen's surface is periodically illuminated by one or several modulated heating sources, *e.g.* halogen lamps, to inject thermal waves into the specimen. The periodic wave propagates by radiation through the air until it attains the specimen surface where heat is produced and propagates through the material. Internal defects act as barrier for heat propagation, which produces changes in amplitude and phase of the response signal at the surface. The thermal response is recorded at the same time using an infrared camera capable of monitoring the whole (or a large part of the) surface (typically in a 320x256 or 640x512 pixel matrix configuration). Sinusoidal waves are commonly used, although other periodic waveforms are possible. Using sinusoids as input has the advantage that the frequency and shape of the response are preserved; only the amplitude and phase delay of the wave may change (*i.e.* sinusoidal fidelity).

Figure 1 (right) depicts an LT experiment. One lamp is shown although it is possible to use several lamps mounted on a frame to reduce the non-uniform heating and/or to increase the amount of energy delivered to the surface. The lamps send periodic waves (*e.g.* sinusoids) at a given modulation frequency ω, for at least one cycle, ideally until a steady state is achieved. This depends on the specimen's thermal properties and the defect depth, as described by the thermal diffusion length, which determines the rate of decay of the thermal wave as it penetrates through the material and is defined by [8]:

$$\mu \equiv \sqrt{\frac{2 \cdot \alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi \cdot f}} \tag{2}$$

where $\alpha = k/\rho c_P$ [m^2/s] is the thermal diffusivity of the material being inspected, k [W/mK] its thermal conductivity, ρ [kg/m^3] its density and c_P [J/kgK] its specific heat at constant pressure, $\omega = 2\pi f$ [rad/s] is the modulation frequency, f [Hz] is the frequency.

In practice however, only a few cycles are needed to adequately retrieve phase and amplitude data, much before attaining steady state conditions.

Contrary to PT for which a great variety of processing techniques are available, only a few signal processing techniques are commonly used for LT data. A four point methodology for sinusoidal stimulation is frequently cited [6], [9] as a means to retrieve amplitude and phase. The 4-point method is fast but it is valid only for sinusoidal stimulation and is affected by noise. The signal can be de-noised in part by averaging of several points instead of a single one and/or by increasing the number of cycles. Another possibility is to fit the experimental data using least squares regression [10] and to use this synthetic data to calculate the amplitude and the phase. These two alternatives though contribute to slow down the calculations. Alternatively, as for the case of PT, the DFT can be used to extract amplitude and phase information from LT data. The DFT can be use with *any* waveform (even transient signals as in pulsed phase thermography and burst phase vibrothermography, see below) and has the advantage of de-noising the signal.

3. MECHANICAL EXCITATION

Vibrothermography (VT), also known as *ultrasound thermography* [11] or *thermosonics* [12], makes use of mechanical waves to directly stimulate defects without heating the surface as in optical methods (*e.g* LT and PT). In VT, ultrasonic waves travel freely through a homogeneous material, whereas an internal defect produces a complex combination of absorption, scattering and dispersion of the waves, whose principal manifestation will be in the form of heat. Heat then travels by conduction to the surface where an IR camera can capture the defect signature. Hence, VT is very useful for the detection of cracks and delaminations. Unlike electromagnetic waves, mechanical elastic waves do not propagate in a vacuum; on the contrary, they require a medium to travel. They travel faster in solids and liquids than through the air. The common approach in VT is to use a coupling media such as a piece of fabric, water-based gels or aluminum, between the transducer and the specimen to reduce losses.

There are basically two configurations for VT that can be sought as analog to optical methods described above. The first one is *burst* vibrothermography (Figure 3, left), which is analog to PT; and the second technique is *lock-in* (Figure 3, right) vibrothermography (or amplitude modulated VT), analog to the LT approach. It is also possible to modulate the frequency either in lock-in or burst VT [13]. This procedure is sometimes called *wobbulation*. The idea is to cover a range of ultrasonic frequencies, instead of only one, since it is not always possible to predict the right frequency for a particular application. Ultrasonic wobbulation can be compared to a heat pulse, which is composed of thermal waves at many frequencies. Wobbulation is useful as well to prevent the appearance of *standing waves*, which are produced when working at the natural harmonics resonance frequency of the material. In practice however, it is sometimes preferable to repeat the acquisition at a different frequency since the commercial transducers commonly used are not suitable for frequency modulations
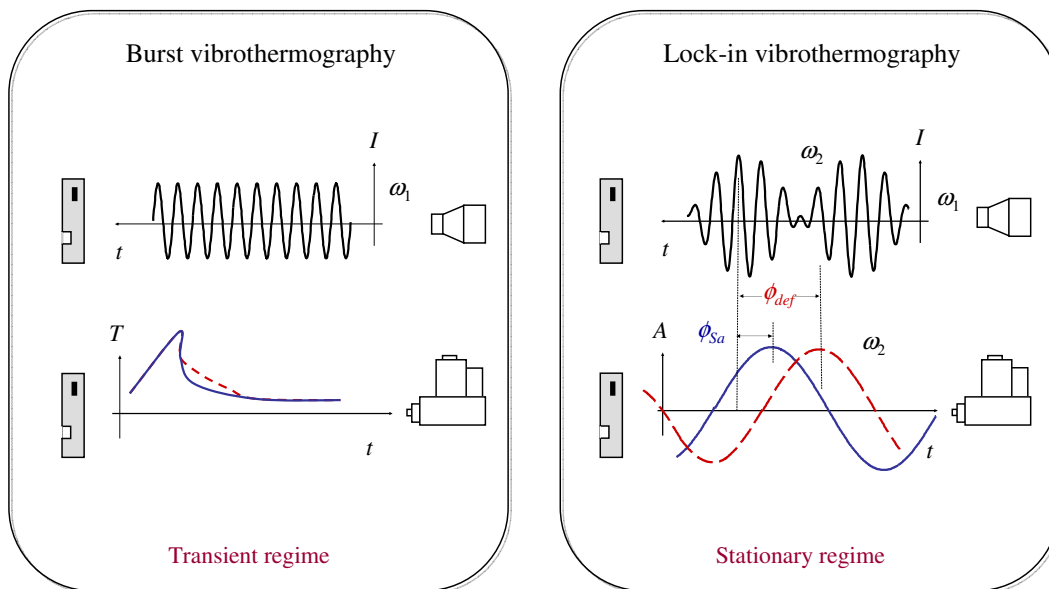

Figure 3. Burst vibrothermography (left) and lock-in vibrothermography (right) experimental configurations.

The ultrasound wave is produced by a transducer made of a stack of piezo elements and concentrated in a titanium horn that acts like a hammer. Hence, the part being inspected should be firmly immobilized (but without damaging) to avoid cantilever effects, clapping and sliding of the transducer. The transducer horn must be pressed against the sample as well to improve the coupling transmission of the ultrasound into the specimen. Insertion of a material between the transducer and the sample is strongly recommended not only as a coupling medium, but also to avoid damage of the sample and correct misalignment. A bad coupling implies a poor ultrasound transmission but more seriously it creates unwanted heat in the vicinity of the ultrasound injection point. After the elastic waves are injected to the specimen, they travel through the material and dissipate their energy mostly at the defects so heat is locally released. The thermal waves then travel by conduction to the surface, where they can be detected with an IR camera.

When compared to optical/external techniques, the thermal wave travels half the distance in a VT experiment since heat propagation is performed from the defect to the surface, whereas for optical techniques heat travels from the surface to the defects and back to the surface. Hence, VT is very fast, even faster than PT. A typical experiment last from a fraction of a second to several seconds. However, there area variety of experimental aspects that must be addressed at every experiment [14], [15]. For instance, the pressure applied between the horn and the specimen, the contact area between the horn and the specimen and the duration of the stimulation have a great impact on the thermal response. The longer the transducer operates at the surface; the most heat is released at the contact surface, increasing the probability of damaging the area.

Although raw thermograms present sometimes good enough contrast to detect defects, some processing is required most of the time. As for the case of LT and PT, the DFT can used and amplitude and phase images are recovered.

Some comparative results from these three techniques on typical aerospace components are presented in the next section.

4. COMPARATIVE RESULTS

Sandwiched structures composed by a honeycomb core between two multi-layer CFRP facesheets are very common on aerospace parts. This kind of structure is normally affected by anomalies such as delaminations (between plies in the facesheet or between the inner facesheet and the core) and core crushing. Possible causes for a delamination is material contamination, *e.g.* dirt, solvents, moisture, oils, etc., either during manufacture

A sandwiched panel, shown in Figure 4 (specimen HONEYCOMB1108), was inspected by the tree active techniques described above. The panel consists of an aluminum honeycomb core of 1.6 cm between two 10-ply CFRP. The specimen is divided in three zones as depicted in Figure 4.
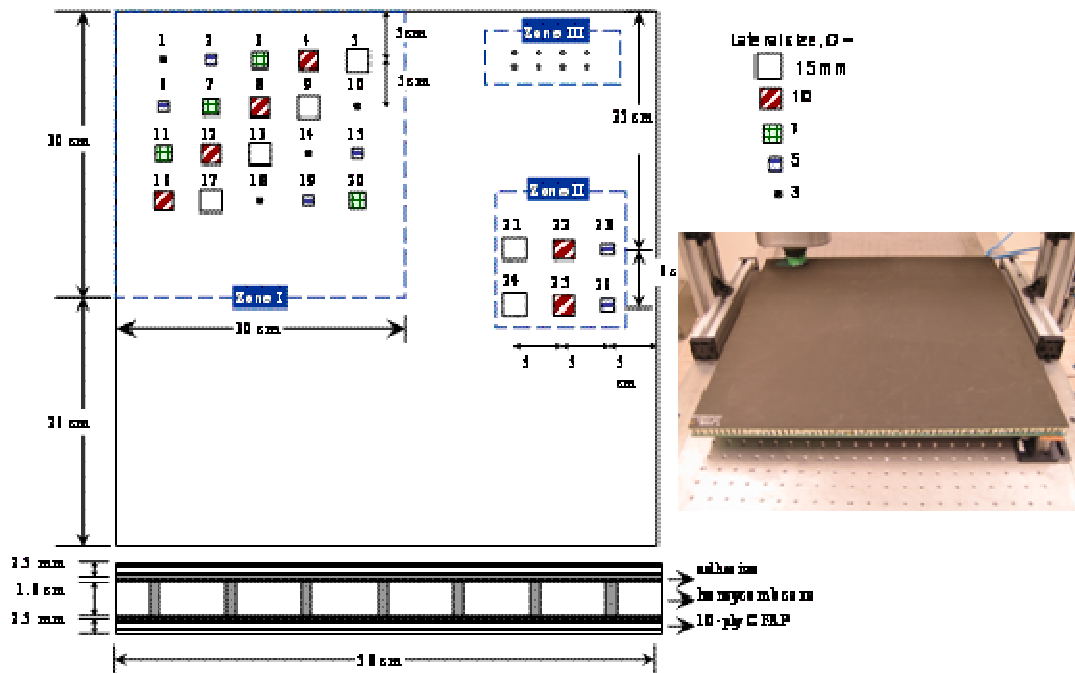

Figure 4. Geometry and defect distribution of specimen HONEYCOMB1108.

In Zone I, twenty (20) Teflon® inserts of different dimensions and thicknesses are placed between CFRP plies at different locations and depths as specified in Table 1 to simulate delaminations between plies. In Zone II, six Teflon® inserts of different dimensions were inserted between the adhesive and the core (top row) and between the facesheet and the adhesive (bottom row), simulating delaminations at those locations. In Zone III, eight cells were filled with water to

simulate water ingress to the core. Water was injected to the cells through small wholes perforated in the opposite face of the panel to avoid damaging the panel side facing the camera (in which the thermal excitation was performed by the optical techniques).

Table 1. Defect distribution

Defect number	Thickness, t [mm]	Lateral size, D [mm]	Between plies	Depth, z [mm]
1	0.16	3	1 and 2	0.25
2	0.16	5	2 and 3	0.5
3	0.16	7	3 and 4	0.75
4	0.16	10	4 and 5	1
5	0.16	15	5 and 6	1.25
6	0.16	5	6 and 7	1.5
7	0.16	7	7 and 8	1.75
8	0.16	10	8 and 9	2
9	0.16	15	9 and 10	2.25
10	0.16	3	9 and 10	2.25
11	0.33	7	1 and 2	0.25
12	0.33	10	2 and 3	0.5
13	0.33	15	3 and 4	0.75
14	0.33	3	4 and 5	1
15	0.33	5	5 and 6	1.25
16	0.33	10	6 and 7	1.5
17	0.33	15	7 and 8	1.75
18	0.33	3	8 and 9	2
19	0.33	5	9 and 10	2.25
20	0.33	7	9 and 10	2.25
21	0.16	15	adhesive and core	2.5
22	0.16	7	adhesive and core	2.5
23	0.16	3	adhesive and core	2.5
24	0.16	15	face sheet and adhesive	2.5
25	0.16	7	face sheet and adhesive	2.5
26	0.16	3	face sheet and adhesive	2.5

Zone I was inspected by PT and data processed using the PPT algorithm. It is possible to detect almost all of the defects from two phasegrams (Figure 5a and b). Inspection of Zone I by LT, allow to detect almost all defects from a single phasegram (Figure 5c). Although PPT phasegrams show better contrast for some inserts (defects 1 to 5 and 11 to 17), the LT phasegram provide a better overall detection, being able to detect all defects from a single phasegram. On the other hand, the VT result (Figure 5d) only shows some of the thicker inserts ($t = 0.33$ mm, two bottom lines of defects in Zone I). Apparently, the thicker inserts dissipated the mechanical energy more effectively than the thinner inserts ($t = 0.16$ mm, two top lines of defects in Zone I), hence the heat conduction from the thinner inserts is practically undetectable.

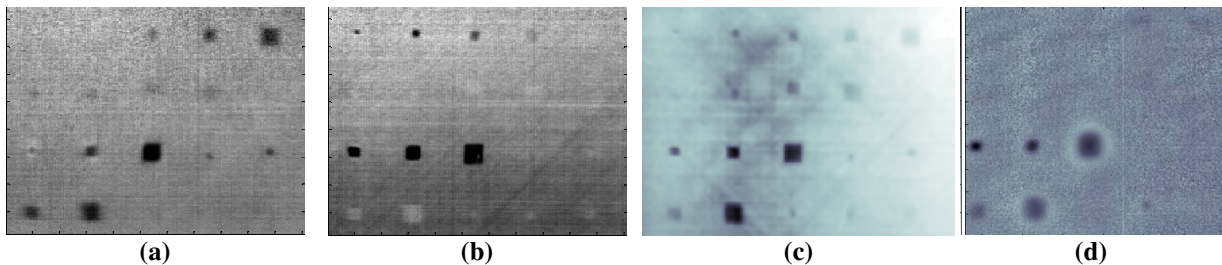(a)   (b)   (c)   (d)

Figure 5. HONEYCOM1108, Zone I: PPT phase at $f =$ (a) 0.082 and (b) 0.74 Hz, (c) LT phase at $f = 0.001$ Hz, and (d) VT result.

Figure 6 presents the results for Zone II, where the inserts have a thickness of $t = 0.16$ mm, see Table 1. Only a slight sign of the presence of the inserts can be seen from the PT result (processed by PPT), see Figure 6a. The fiber structure is visible however, contributing to hide the defect signature. On the contrary, the VT result clearly shows four of the inserts (the largest ones). This highlights the advantage of mechanical/internal excitation over optical/external excitation for the inspection of deep delaminations.
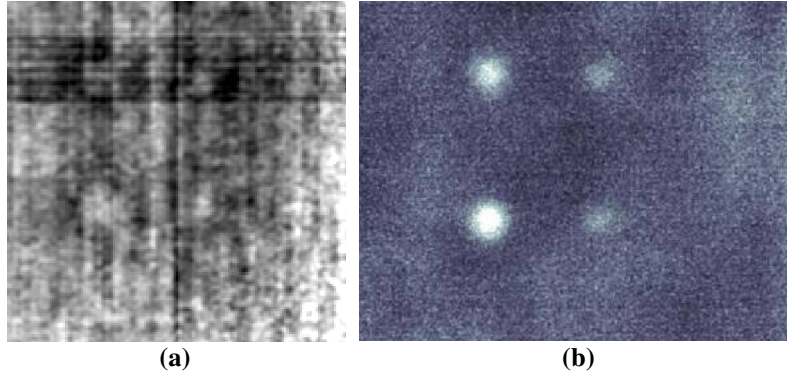

(a)　　　　　　　　　　　　　　　**(b)**

Figure 6. HONEYCOMB1108, Zone II: (a) PPT phase at $f = 0.041$ Hz, and (b) VT result.

Finally, water ingress in Zone III was successfully detected by PT and LT, but not by VT. Figure 7 shows a phasegram obtained by PPT from PT data. Similar results (not shown) were observed by LT inspection. In this case, water detection in the core by VT is difficult, given the very high transmission loss through the aluminum honeycomb core.
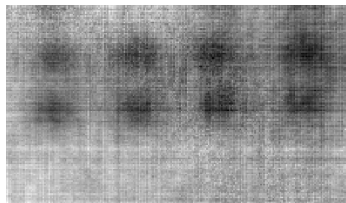

Figure 7. HONEYCOMB1108, Zone III: synthetic PPT phase at $f = 0.07$ Hz.

Glass-reinforced fiber metal laminate or Glare is another aerospace structure whose popularity is growing rapidly. Glare is composed of several layers of aluminum or other metal interlaced with very thin layers of glass-fiber and bonded together with epoxy.

A Glare specimen was tested by PT and VT. It consisted of three multi-layer glass-fiber structures in between four aluminum layers as shown in Figure 8a. Inserts of different material and sizes were embedded between the second and the third ply as indicated in the figure. All defects can be seen by PT (Figure 8b) with data processed by TSR [5] (first time derivative), and most of them can be detected by VT (Figure 8c). However, is more difficult to differentiate between materials from the VT results than by PT. Aluminum inserts in particular have a distinctive signature with inverted sign as can be seen.
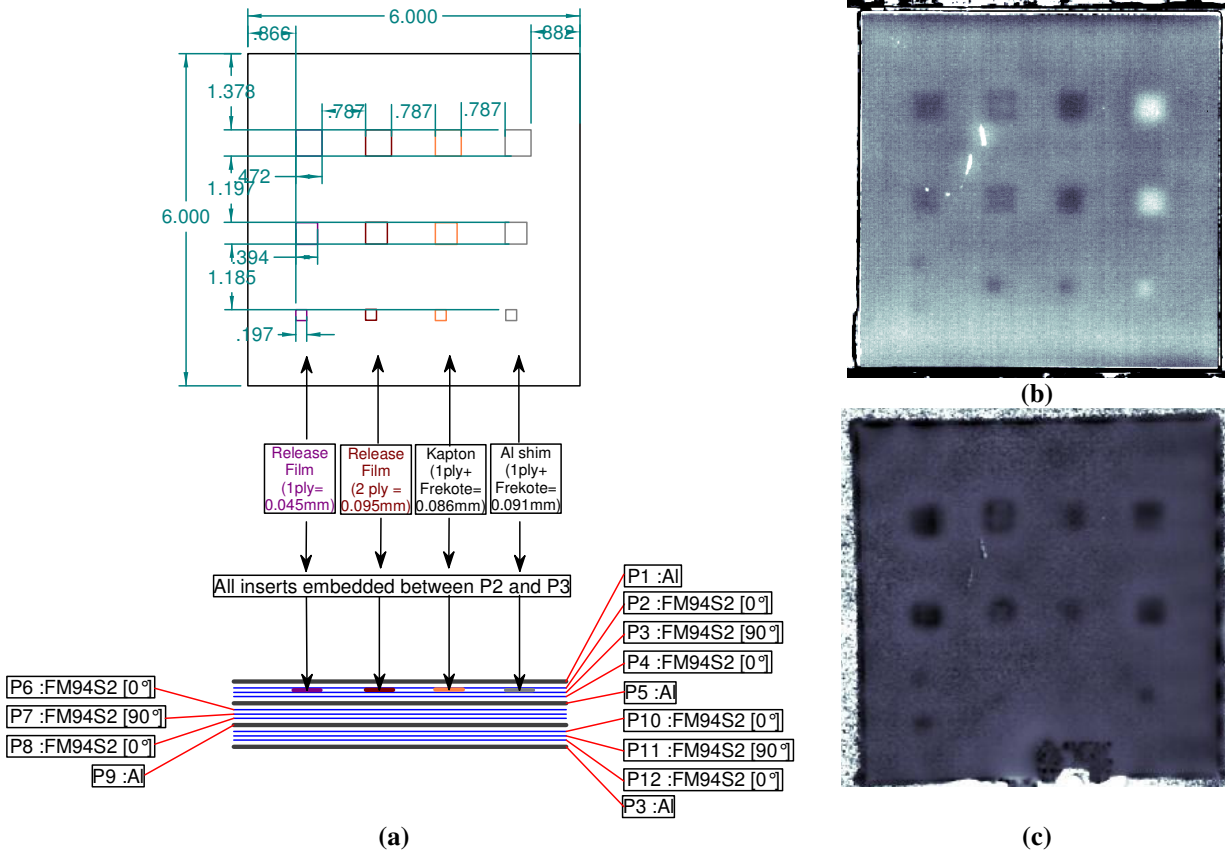
Figure 8. Glare specimen: (a) geometry and defect distribution (b) first derivative at *t*= 0.6 s, and (c) VT.

5. CONCLUSIONS

The three main active thermography techniques can be used in the NDT assessment of aerospace materials. Pulsed thermography is fast (from a few seconds for high conductivity materials to a few minutes for low conductivity materials) and easy to deploy. There are numerous processing techniques available. Thermal based techniques are affected by non-uniform heating, emissivity variations, environmental reflections and surface geometry. These problems however, are dramatically reduced using advanced processing algorithms, *e.g.* PPT and TSR. For instance PPT allows the recovering of amplitude and phase data as in LT with the advantage that, since a heat pulse can be seen as a set of several periodic thermal waves launched at once, several data points (amplitude or phase) can be extracted from a single experiment.

Lock-in thermography allows having a better control of the energy that is to be deposited on a surface. Given that LT requires to perform an experiment for each and every inspected depth and there is a stabilization time before reaching a permanent regime, inspection by lock-in thermography is in general slower than other approaches such as pulsed thermography. A complete LT experiment is carried out by inspecting the specimen at several frequencies, covering a wide range from low to high frequencies, and then a fitting function can be used to complete the amplitude or phase profiles for each point (*i.e.* each pixel). Nevertheless, there exists a direct relationship between depth and the inspection frequency that allows depth estimations to be performed from amplitude or phase data without further processing. Furthermore, the energy required to perform an LT experiment is generally less than in other active techniques, which might be interesting if a low power source is to be used or if special care has to be given to the inspected part.

The vibrothermography approach is relatively new on the active thermography scene. It had showed however to be very attractive for the inspection of some types of defects. For instance, it is possible to detect deeper delaminations by VT than with optical means. This is because of the way heat is generated and transformed into heat. In VT, the thermal

waves only have to travel half the distance (from the defect to the surface) than with optical methods in reflection mode (from the surface to the defect and back to the surface). Nevertheless, VT is still lacking of quantitative studies, and very often optimal inspection parameters must be found experimentally. In either lock-in or burst configuration, VT is extremely fast, although it is necessary to relocate the transducer (and to immobilize the specimen again) to cover a large area for inspection. Hence, VT is more suitable for relatively small objects. It is the most appropriate technique to inspect some types of defects, *e.g.* micro cracks. On the contrary, it does not perform very well in some other cases in which application of optical techniques are straightforward, *e.g.* water detection. But probably the most inconvenient aspect of VT is the need of a coupling media between the sample and the transducer, and the need of holding the specimen. On the other hand, there is only minimal heating of the inspected specimen since energy is usually dissipated mostly at the defective areas, although there is some localized heating at the coupling and clamping points.

In summary, a group of active techniques is available for a wide variety of applications. The selection of the most adequate approach depends on the particular application and the available experimental and expertise resources.

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