Introduction to NDT by Active Infrared Thermography[1]

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Abstract

In this text, a brief review of active infrared thermography for NDT is presented including considerations on radiometry, emissivity, temperature measurement, heat transfer, infrared camera technologies as well as deployment principles of pulsed thermography, step heating, lockin thermography and vibrothermography. Through the presentation, a few applications are discussed as well.

1. Introduction

In recent years, active infrared (IR) thermography has emerged as a widely used method for nondestructive testing. Thermography offers noncontact, wide area detection of subsurface defects, and can be used as an alternative or complement to conventional inspection technologies. In this paper, basic principles of active IR thermography are presented. For examples of applications, references 1-3 are recommended.

1.1 Active and passive thermography

IR thermography can be divided into two approaches, the *passive* approach and the *active* approach. The *passive* approach tests materials and structures which are naturally at different (often higher) temperature than ambient while in the case of the *active* approach, an external stimulus is necessary to induce relevant thermal contrasts.

In many industrial processes temperature is an essential parameter to assess proper operation and passive

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thermography aims at such measurement. Important applications of the *passive approach* are in production, predictive maintenance, medicine, fire forest detection, building thermal efficiency survey programs, road traffic monitoring, agriculture and biology, medicine, detection of gas (by mean of absorbing tracer gas) and in nondestructive testing (NDT). In all these applications, abnormal temperature profiles indicate a potential problem to take care of. Interestingly for some applications, knowledge of the workpiece fabrication and operation combined with proper thermal modelling opens the door to quantitative extraction of information such as for instance the remaining thickness of refractories, etc.

Contrary to the passive approach, in the *active approach*, an external stimulus is required to generate relevant temperature differences not present otherwise. Known characteristics of this external stimulus (example: time t_0 when it is applied) enable quantitative characterization such as for instance the depth of a detected disbond. Depending on the external stimulus, different approaches of active thermography have been developed, such as pulse thermography (PT), step heating (SH), lockin thermography (LT), vibrothermography (VT). These methods will be discussed in the later sections. The active approach finds numerous applications in NDT.

In the text, the focus is on thermography for non-contact deployment through IR measurement. However, thermography can also be deployed following a contact scheme. For instance using arrays of temperature sensors, such as thermocouples or through the use of liquid crystal paints [2, 3].

1.2 Advantages and difficulties of IR thermography

Each NDT technique has its own strengths and weaknesses. In the case of IR thermography, the strengths are as follows [1-3]:

- fast inspection rate (up to a few m^2 at a time);
- no contact (no couplant needed although in some cases a ‘blackpainting’ step is required to perform the inspection so that strictly speaking, a ‘contact’ is thus present in this case, see section 2.1 below);

- security of personnel (since there is no harmful radiation involved, however high power external stimulation - such as powerful flashes - require a shroud, case of pulse thermography, see section 3.1 below);
- results are relatively easy to interpret (you 'see' what you are inspecting) since they are (often) obtained in image format, furthermore images can be processed to extract more information;
- wide span of applications;
- unique inspection tool for some inspection tasks (*e.g.* as in the case of some ceramic coatings hardly inspected by other NDT approaches or in the case of some maintenance surveys).

On the other hand, there are some difficulties specific to IR thermography [1-3]:

- difficulty in obtaining a quick, uniform and highly energetic thermal stimulation over a large surface;
- effects of thermal losses (convective, radiative) which induce spurious contrasts affecting the reliability of the interpretation;
- cost of the equipment;
- capability of detecting only defects resulting in a measurable change of the thermal properties (*e.g.* disbonds and cracks are only detected if they induce interface thermal resistances);
- ability to inspect a limited thickness of material under the surface (thermography is a 'boundary' technique);
- emissivity problems (see next section).

2. Theory

2.1 Radiometry, emissivity and temperature measurement

Radiometry is concerned with the measurement of radiated electromagnetic energy [4]. By respecting some hypotheses and with a proper calibration, it becomes possible to translate radiometric values mea-

sured by the camera into temperature values.

Important concepts of radiometry for IR thermography are the *blackbody* and the Planck's law. The *blackbody* is the reference for the thermal emission of solids. It is capable of absorbing totally all incident radiations, it re-emits also these radiations uniformly in all directions. For a blackbody in thermal equilibrium, the spectral radiance $N_{\lambda,b}$ is defined by the Planck's law (Fig. 1):

$$N_{\lambda,\,b} = \frac{2hc^2}{\lambda^5\left(1-\exp\frac{hc}{\lambda KT}\right)} \qquad (Wm^{-2}sr^{-1}\mu m^{-1}) \tag{1}$$

where *h* is the Plank's constant (= 6.63 x 10^{-34} Js), *c* is the velocity of light (= 3 x 10^8 [m/s]), *K* is the Boltzmann's constant (= 1.381 x 10^{-23} [J/K]), λ is the wavelength of the emitted radiation [μm] and *T* is the temperature of the blackbody cavity [in Kelvin, K] and subscript b denotes blackbody. For instance, as seen on Fig. 1, the Sun with a surface temperature of about 6000 K has an emission centered in the visible spectrum ([0.4 - 0.8 μm]) while the human body at about 300 K has an emission centered in the long wavelength band ([8 - 12 μm]).

In the case of real objects whose absorbance is limited, only part of the energy will be radiated from the surface. This fraction of the blackbody spectral radiance is given by the property of the surface called the emissivity ε. For these objects the spectral radiance is given by:

$$N_\lambda = \varepsilon N_{\lambda,\,b}(\lambda, T) \qquad (Wm^{-2}sr^{-1}\mu m^{-1}) \tag{2}$$

Generally, emissivity ε has a dependence on λ, T, viewing angle θ and surface condition such as roughness, oxide layers, physical and chemical contamination [chap. 4 in 3]. For most common thermographic IR NDT applications such accuracy is not required and one simply talks about 'emissivity' as the 0 to 1 factor relating the object radiance to the blackbody radiance. A surface having a low emissivity tends to

behave as a mirror (following Kirchoff laws [2-4]). In this case, it is difficult to measure its temperature by a radiative measurement method. Various techniques can be deployed to solve this low or uneven emissivity problem such as the common “blackpainting” method consisting to cover the inspected surface with a high emissivity paint (~ 0.9) which can be later removed if it is water soluble. Blackpainting also increases absorption of light if a radiation heating scheme is selected (section 3). Other techniques are available as well [2, 3, 4].

The fundamental equation of thermography relates the radiance N_{cam} received by the camera to the radiance N_{sur} emitted from the surface under consideration at a given temperature *T*, neglecting the atmosphere contribution. For most NDT applications the atmosphere can be considered transparent to the wavelengths of interest and for small distances (under a few meters), hence:

$$N_{cam} \sim \varepsilon N_{sur} + (1-\varepsilon) N_{env} \tag{3}$$

Where N_{env} is the radiance of the surrounding environment considered as a blackbody. Eq. (3) can be further reduced if emissivity of the surface is high (for instance by covering the surface with a paint of high emissivity as explained above), in this case:

$$N_{cam} \sim N_{sur} \tag{4}$$

and knowledge of the calibration curve of the IR camera linking N_{cam} to T allows determination of the surface temperature. Such calibration curve can be derived experimentally with a commercial blackbody set at different temperatures in front of the IR camera.

Eq. (3) is important to consider in the case of measurements with conditions of significant spurious IR radiations. For instance suppose an experiment is performed on a surface close to a high temperature furnace. In such a case the spurious reflections are likely to superimpose on the self-emission of the surface

of interest. Fortunately, various techniques exist to suppress or take into account such unwanted effects. For instance in a case of stationary spurious reflections, it is possible to acquire an IR image of the scene with the reflections present and another without thanks to some kind of shielding or temporary shut down of the furnace. Subtractions of those two images would yield to the reflection pattern that could then be used to further improve the image sequence recorded in a subsequent thermography experiment.

2.1.1 On IR cameras

Currently, Focal Plane Arrays (FPA) are the norm. They are based on two types of detector arrays: Photonic Cooled Detectors (PCD) and uncooled micro-bolometers [2, 3, 5]. For PCD FPAs, the principle consists in directly measuring the excitation generated by incident photons. Heating of the sensitive surface is unnecessary. Photonic excitation is measured by a change of electrical conductivity (ex: photoconductor detectors) or by measuring a generated voltage (ex: photovoltaic also called photoelectric). These IR cameras have the following features:

• contain a matrix of IR detectors (ex: 320H x 240V, 640H x 512V);

• rugged since the technology is solid state (with low count of bad pixels);

• low noise (ex: 20 mK to allow detection of surface temperature difference of 0.1 °C);

• high frame rate can be achieved with subframes sampled in the kHz (e.g. FPA camera model SBF125 - photovoltaic indium antimonide - InSb - detector - has a 1 kHz maximum frame rate in a 128 x 128 subwindow and 400 Hz at full 320 x 256 matrix resolution [6]);

• adjustable integration time;

• high linearity;

• synchronization of acquisition;

• direct digital links (12-14 bits);

• required cooling, down to cryogenic temperatures (~ 77 K), for instance with liquid nitrogen poured into a Dewar flask or using a Stirling close cycle cooler [1-3];

• high cost;

• output signal is uncalibrated unless a blackbody is introduced in the field of view.

Because of their low cost, cameras based on uncooled micro-bolometer FPAs are becoming increasingly popular for NDT (and other applications as well). The principle consists of having the FPA surface grooved to make up a mosaic of thermal masses [2, 3, 7]. These masses of a few micron size are heated by the impinging IR radiation so that one of their property, say the electrical conductivity, changes. Measurement of these changes lead to the IR measurement. These cameras have the following features:

• do not require cryogenic cooling, however a thermo-electric stabilization is performed internally;

• contain a matrix of IR thermal detectors (ex: 320H x 240V, 320H x 256V);

• wide spectral response tunable on demand (with an interference filter placed in front of the array);

• good price (as compared to PCDs) so that micro-bolometer FPAs are leading the market;

• highly portable (ex: battery operated, image storage on PC-MCIA cards);

• ultra-compact products are now available opening new applications (ex: products from Indigo company with size 1.35"W x 1.45"H x 1.90"D, weight less than 120 g (without lens), 160H x 120V pixels);

• due to the requirement of heating the thermal masses, the response time is relatively slow, in the order of a few ms (still allowing compatibility with TV standards of 50-60 Hz).;

• average overall performance (if compared to PCDs).

When selecting an IR detection system, an important aspect is the selection of the operating wavelength band. For common applications, the useful portion of the IR spectrum lies in the 0.8 to 20 μm. Among the important criteria for band selection are operating distance, indoor-outdoor operation, temperature and

emissivity of the bodies of interest. As Planck's law stipulates (eq. 1), high temperature bodies emit more in the short wavelengths; consequently long wavelengths will be of more interest to observe near room temperature objects. Emitted radiation from ordinary objects at ambient temperature (300 K) peaks in this long wavelength range. Long wavelengths are also preferred for outdoor operation for which signals are less affected by radiation from the Sun. For operating distances restricted to a few meters, in the absence of fog or water droplets, the atmosphere absorption has little effect (for IR thermographic NDT) [3-4].

Although no specific rule can be formulated, generally the most useful bands (for IR thermographic NDT) are 3 to 5 μm (called ‘short waves’ or SW) and 8 to 12 μm (called ‘long waves’ or LW) since these match the atmospheric transmission bands. It is interesting to add that generally speaking, for temperature comprised in the [-10 °C to + 130 °C] interval, measurements can be done without much difference in both band (3-5 μm and 8-12 μm), with however a slight preference for 3-5 μm devices [1-4].

2.2 Heat transfer considerations

A short discussion is presented here, further information on the three heat transfer modes (conduction, convection, radiation) can be found in heat transfer books such as [8].

The “inverse problem” refers to the ability to determine if a given “hot spot” witnesses an abnormality and to further quantitatively characterize its properties. To perform such a task, it is often convenient to start with the “direct problem” which consists of “predicting” the thermal behavior of the surface under consideration. Two approaches are possible for the direct problem: establish an analytical solution or rely on an heat transfer model. The first is often restricted to simple cases: flat, semi-infinite surfaces of isotropic properties. The second is of practical interest for the more complex cases and can be for instance deployed by finite differences. For such purposes, dedicated program packages are available from various vendors (a simple program is provided in [2]).

For the direct problem, the first step in finite difference modelling generally consists of representing the

workpiece under study by a mesh of elementary volumes of material. The basic idea is then to compute at each time step the temperature for all the nodes taking into account the thermal properties of the material and the thermal exchanges between the nodes themselves and the external world.

Even if comparisons with experimental data are not straightforward (for instance due to some unaccounted factors such variability of material thermal properties), such modelling brings useful information about the general thermal behavior of the sample. It is useful to establish the limits of the effectiveness of IR thermography, sets inspection parameters (such as the type of the thermal stimulation to use if any). It also permits to consider different defect geometries, to determine their detectability and the expected optimum time window of observation for best subsurface defect visibility without the expense of making and testing the corresponding specimens.

3. On thermal stimulation in the active approach

Various modes of thermal stimulation are of interest for practical active IR thermographic NDT. Pulse thermography, step heating, lockin thermography and vibrothermography will be briefly discussed now.

3.1 Pulse thermography (PT)

Pulse thermography (PT) [1-3] is one of the most popular thermal stimulation method in IR thermography. One reason for this popularity is the quickness of the inspection relying on a thermal stimulation pulse, with duration going from a few ms for high thermal conductivity material inspection (such as metal parts) to a few seconds for low thermal conductivity specimens (such as plastics, graphite epoxy components). Such quick thermal stimulation allows direct deployment on the plant floor with convenient heating sources. Moreover, the brief heating prevents damage to the component (heating is generally limited to a few degrees above the initial component temperature).

Basically, PT consists of briefly heating the specimen and then recording its temperature decay curve. Qualitatively, the phenomenon is as follows. The temperature of the material first rises during the pulse.

After the pulse, it then decays because the energy - the thermal front - propagates by diffusion under the surface. Later, the presence of a subsurface defect (example: a disbonding) reduces the diffusion rate so that when observing the surface temperature, such a subsurface defect appears as an area of higher temperature with respect to the surrounding sound area. In fact in such a case the reduced diffusion rate caused by the subsurface defect presence translates into “heat accumulation” and hence higher surface temperature just over the defect. Moreover, such phenomenon occurs in time so that, deeper defects are observed later and with a reduced “diluted” or “spread” thermal contrast. An interesting relationship relates (in a first approximation) the observation time *t* as a function of the square of the subsurface defect depth *z* [2, 3]:

$$t \sim z^2 / \alpha \tag{5}$$

where α is the thermal diffusivity of the material. A widely used rule of thumb says that *the radius of the smallest detectable defect should be at least one to two times larger than its depth under the surface*

That rule of thumb is a useful guideline for basic PT in homogeneous isotropic materials [2, 3]. However, better results may be possible through the use of advanced signal processing methods [9,10].

Various configurations are possible (Fig.2):

(a) Point inspection: heating with a laser or a focused light beam; advantages: repeatable heating, uniformity; drawback: the necessity to move the inspection head to fully inspect a surface slows down the inspection process.

(b) Line inspection: heating using line lamps, heated wire, scanning laser, line of air jets (cool or hot); advantages: fast inspection rate (up to 1 m^2/s) and good uniformity thanks to the lateral motion; drawback: only part of the temperature history curve is available due to the lateral motion of the specimen and the fixed distance between thermal stimulation and temperature signal pick-up. Projec-

tion of a series of line heating strips is also used to detect surface cracks (on concrete for instance [3]).

(c) Surface inspection: heating using lamps, flash lamps, scanning laser; advantages: the complete analysis of the phenomenon is possible since the whole temperature history curve is recorded; drawback: concerns about non-uniformity of the heating (lamps, flashes, heat gun, laser, microwave [2, 3]).

If the temperature of the part to inspect is already higher than ambient temperature, it can be of interest to make use of a cold thermal source such as a line of air jets (or water jets; sudden contact with ice, snow, etc. [2-3]). In fact, a thermal front propagates the same way whether being hot or cold: what is important is the temperature differential between the thermal source and the specimen. An advantage of a cold thermal source is that it does not induce spurious thermal reflections into the IR camera as in the case of a hot thermal source (as discussed in section 2.1). The main limitations of cold stimulation sources are related to practical considerations as for instance it is generally easier and more efficient, to heat rather then to cool a part.

In case of microwave heating, direct internal heating of the part is achieved and since travel time is reduced from subsurface defect to surface with respect to surface to subsurface defect to surface in case of surface heating, defects are delineated better with less thermal contrast “spreading” [2, 3].

Possible observation methods are as follow (Fig. 3):

(a) in reflection: the thermal source and detector are located on the same side of the inspected component,

(b) in transmission, the heating source and the detector are located one on each side of the component to inspect.

Generally, the reflection approach is used for detection of defects located close to the heated surface while the transmission approach allows to detect defect close to the rear surface (due to the spreading

effect of the energy propagating within the specimen). Obviously, if the rear surface is not accessible, the transmission approach is not possible. Finally, in the transmission approach, the defect depth can not be estimated due to the same travel distance whatever is the defect depth (the transit time of the thermal front through the total material thickness is the same).

Nowadays, fully integrated systems combining acquisition head and heating unit are commercially available, such as for instance the one shown on Fig. 4-a. Such systems are convenient on the plant floor since deployment is fast. For laboratory experiments table-top apparatus are preferred because various configurations can be tested, Fig. 4-b. In both cases, image processing allows improved visibility of subsurface defects, extended depth range and quantification of thermal properties (e.g.: depth). References [2, 3] present in details many of the recent popular image processing techniques. Among them: Neural Networks (NN), Pulsed Phase Thermography (PPT) or Synthetic Data (SD). Interestingly, combinations of processing techniques are also possible as shown on Fig. 5. PPT consists to observe images in the frequency rather than in the time domain, in particular phase images related to travel time are interesting since they are less affected by unwanted effects such as non-uniform heating (section 3.3.2 below). SD fits the raw data with a polynomial (of fourth order) for significant denoising and data reduction [10], Fig. 6. Simple thermal contrast processing is also common, Fig. 5 and 6. For instance speaking about reflections in section 2.1, acquisition of image “zero” before pulse heating and subtraction of all subsequently acquired images with this image will suppress efficiently static reflections. More complex thermal contrast definitions are also available [2, 3].

3.2 Step heating (SH)

Contrary to the previous thermal stimulation scheme, for which the temperature decay is of interest, here the increase of surface temperature is monitored during the application of a stepped heating pulse (a “long pulse”). The sample is continuously heated, at low power. Variations of surface temperature with time are related to specimen features as in pulse thermography. This technique of step heating (SH) is

sometimes referred to as time-resolved infrared radiometry or TRIR. The time-resolved part means the temperature is monitored as it evolves during and after the heating process.

SH finds various applications such as for coating thickness evaluation (including multilayered coatings, ceramics), integrity of the coating-substrate bond determination or evaluation of composite structures, characterization of airframe hidden corrosion among others. More details about this technique can be found in [12, 13].

In a typical set-up for SH experiments, an Argon laser is used to point-heat or line-heat (Fig. 2) the specimen and is time-gated using an acousto-optic modulator allowing a variety of pulse lengths. If the specimen is opaque at the Argon wavelength (= 0.514 μm) then surface heating is obtained. Dedicated electronics allow synchronization of the laser heating with respect to IR camera frame rate (notice that the IR camera operates here in the line mode). Three types of measurement are possible: • temperature line scan at a specific time after heating, • collection of temperature line scans as function of time (showing the temperature development in time over a location of the specimen) and • reconstructed image at a specific time (reconstruction proceeds on a line by line basis with the specimen mounted on a positioning stage moved step by step). One of the main advantages of TRIR is the temporal resolution which is faster than in full-field imaging since only one image line is acquired per thermal event (instead of recording a complete image for each thermal event). Such observation of quick thermal events enables inspection of thin coatings as explained below. A corresponding disadvantage is that the line must be scanned over the sample, thus increasing the time to analyze a given surface completely.

As an illustration of SH, Fig. 7 shows the effect of coating thickness on specimen temperature rise [12, 11] for a series of three zirconia coatings of different thicknesses. On the figure, temperature is plotted versus square root of time since this linearizes the result for the semi-infinite response. All the curves of Fig. 7 exhibit the same linear behavior at early times but at later times each curve begins to drop below

the semi-infinite case at a characteristic time t_c set by the coating thickness L:

$$t_c \sim \frac{0.36L^2}{\alpha} \quad (6)$$

When time is getting larger than t_c, the thermal front reaches the substrates (of higher thermal conductivity than the coating for the example) and the rate of temperature increase reduces. Knowing the thermal diffusivity, and after measuring t_c, it is possible to compute the coating thickness L. In the case of a thermally-insulated substrate, instead of a drop as shown, the rate of temperature increase would augment (the curves would depart above the semi-infinite case).

3.3 Lockin thermography (LT)

3.3.1 Lockin thermography with a modulated heating

Lockin thermography (or LT) is based on thermal waves generated inside the specimen under study by submitting it to a periodic (sinusoidal) thermal stimulation ([14]). In the case of a sinusoidal temperature stimulation of a specimen, highly attenuated and dispersive waves are found inside the material (in a near surface region). These waves are known as “thermal waves.” This is not a new concept since these thermal waves were first investigated by Fourier and Angström back in the XIX century.

Of interest, is that these waves can be generated and detected remotely, for instance by periodically depositing heat on the specimen surface with a lamp. This is called *photo-thermal lockin thermography.* The lockin terminology refer to the necessity to monitor the exact time dependence between the output signal and the reference input signal *(i.e.* the oscillating - also called modulated - heating). The resulting oscillating temperature field (following the oscillating thermal stimulation) in the stationary regime (that is after the transient regime) is remotely recorded through its thermal IR emission. A proper experimental apparatus allows to observe the amplitude and phase of the resulting thermal wave on the specimen.

The thermal images obtained from such apparatus are different than thermographic images described pre-

viously (for instance in the *Pulse Thermography* section) by many aspects since both phase and amplitude images are available. In basic PT, *thermographic images* are obtained. These images correspond to a mapping of the emitted thermal IR power while phase images are related to the propagation time and the amplitude images are related to the thermal diffusivity [14, 2, 3]. For many NDT applications, a strong point of LT is the phase image which is relatively independent of local optical and thermal surface features [14].

The depth range of amplitude image is roughly given by thermal diffusion length μ expressed by [14]:

$$\mu = \sqrt{2k/\omega\rho c} \tag{7}$$

with thermal conductivity *k*, mass density ρ, specific heat *c* and modulation frequency ω. In the case of phase images, it has been reported that depth range is about twice as large [14]. In eq.(7), it is seen μ is related to the inverse of ω, this means a low modulation frequency will probe deeper (as in ultrasonics).

LT concepts can be deployed (Fig. 2) in a point-scanned laser fashion but also on a full-field basis by illuminating the whole sample periodically with a lamp (to generate the thermal wave) while the signal pick-up is performed by an IR camera and associated equipment (Fig. 8). In fact, the relaxed heating constraints associated with the phase image enables the inspection of large surfaces, up to several square meters, provided the spatial resolution of the IR camera is high enough [14]. Interestingly, it is relatively easy to deposit the modulated heating over a surface using lamps. Commercial products exists for such purpose such as those from companies [15, 16]. As an illustration of LT, Fig 9 shows phase images obtained at various frequencies on a graphite epoxy plate which was submitted to an impact damage.

It is important to notice that if the modulation frequency ω is not selected correctly, it is possible to miss a defect or another experiment has to take place at a different modulation frequency ω. For instance, on Fig. 9 four different experiments at four different modulation frequencies were required to delineate the defect extent. For such a reason it is a good practice to always start at the lowest possible ω value.

More recently [17], it was shown that a suitable thermal stimulation can also be obtained using an ultrasonic transducer (shaker) attached to the specimen (conversely, the specimen can be partly immerged into an ultrasonic bath). In this case, the high frequency ultrasonic signal (typ. 40 kHz) is modulated with a low frequency signal. This low frequency modulation creates a thermal wave of desired wavelength as in conventional LT while the high frequency acts as a carrier delivering heating energy right inside the specimen. This technique is also known to as the ‘loss angle lockin thermography’ and it is reported to detect deeper and smaller defects while the selective heating allows a better discrimination among detected defects [17]. Typical applications are for detection of corrosion, vertical cracks and delaminations.

3.3.2 Pulsed Phase Thermography

Pulsed phase thermography (or PPT) is a processing technique which combines somehow advantages of both PT and LT. In PPT deployment [2, 3], the specimen is pulse-heated as in PT and the mix of frequencies of the thermal waves launched into the specimen is unscrambled by performing the Fourier transform of the temperature decay on a pixel by pixel basis thus enabling computation of phase images as in LT. The process is as follow, for each pixel (i, j), the temporal decay f(x) is extracted from the image sequence (where x is the index in the image sequence). Next, from f(x), the discrete Fourier transform $F(u)$ is computed (u being the frequency variable). Finally, from the real $R(u)$ and imaginary $I(u)$ components of $F(u)$, the phase is computed [18].

In PPT as in LT, it is possible to explore the various frequencies u. However, differences exist since analysis in PPT is performed in the transient mode while in LT the signal is recorded in the stationary mode. This means for instance the quality of images will be higher in LT due to the summation process involved in the computations.

On the other hand, a single pulsed experiment is needed in PPT while LT sometimes requires more as said before. Previous Fig. 5 shows an illustration of PPT.

3.4 Vibrothermography (VT)

Vibrothermography [3, 19, 20] is an active IR thermography technique where, under the effect of mechanical vibrations induced externally to the structure at a few fixed frequencies (based on the availability of commercial equipment), heat is released by friction precisely at defect locations (such as cracks and delaminations). In such experiments, direct conversion from mechanical to thermal energy occurs and flaws are excited at specific mechanical resonances: *local subplates formed from delamination presence resonate independently of the rest of the structure at particular frequencies* [20]). Consequently, by changing (increasing or decreasing) the mechanical excitation frequency, local thermal gradients may appear or disappear. However, in current practice, fixed frequency excitation is commonly used, largely as a matter of convenience and commercial availability.

Finite element modelling applying three dimensional equations of linear elasticity permits evaluation of local energy concentration for components submitted to mechanical loading. For instance such study reveals that thermal patterns corresponding to two simulated delaminations (10 x 7 mm and 7 x 7 mm) embedded in the specimen appear *only* with mechanical excitation between 13.5 and 15.0 KHz (specimen: 28 x 13 cm graphite epoxy beam with plies 90/0/90 attached to a piezoelectric shaker from one side [20], Fig. 10).

Vibrothermography most significant advantages are: detection of flaws hardly visible by other IR thermography schemes (such as for instance closed cracks in gears) and inspection of large structural areas *in situ.* On the other hand, the required mechanical loading may be difficult to achieve.

4. Conclusion

In this text a blend of fundamental and practical concepts of NDT by IR thermography was presented. Interestingly, IR thermography has not yet reached its ‘stationary regime’ and further advances should be seen in the future both at the data collection and at the data processing stages. For instance less expensive

uncooled micro-bolometer FPAs coupled to advanced image processing techniques should spur new applications.

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Figure captions

Fig. 1 **Plots of the Plancks' law** showing locus of visible, short and long IR spectral bands.

Fig. 2 **Various configurations for infrared thermography inspection**: (a) by point, (b) by line, (c) by surface. 1: sample, 2: subsurface defect, 3: thermal stimulation source, 4: infrared camera with signal processing and recording unit, 5: heated area, 6: observation area.

Fig. 3 **Observation methods:** (a) in reflection, (b) in transmission. 1: sample, 2: subsurface defect, 3: thermal stimulation source, 4: infrared camera with signal processing and recording unit, 5: surface temperature profile, 6: observation area.

Fig. 4 **Pulse thermography**: experimental set up. (a) For plant floor deployment, integrated heads with shroud, flashes, IR camera are practical (image courtesy of [11]). (b) Table-top equipment common for laboratory experiments showing two high power flashes each delivering 6.4 kJ - 15 ms pulses and with a PCD FPA.

Fig. 5 **Pulse Thermography:** Thermographic inspection of an aircraft aluminum component. Pulsed Phase Thermography (PPT) coupled to neural network (NN) thermogram processing for depth estimation of corrosion. In this case a three-layer NN was used. The uncorroded profile indicated corresponds to the case of a non defective component. Heating was performed in reflection using high power flash lamps (total of 12.8 kJ of electric energy, pulse duration was 15 ms). Thermal inspection proceeded from the front - undamaged - side of the component.

Fig. 6 **Pulse Thermography**: Synthetic Data Processing. Image of coefficient a_1 of the polynomial along with profiles across defect centers as indicated. Graphite epoxy plate with two embedded defects 3 (top) and 2 (bottom) mm below front surface. For reference, the maximum thermal contrast image is provided. Heating was performed in reflection using high

power infrared lamps (total of 6.4 kW of electric power, pulse duration was set to 8 s).

Fig. 7 **Step Heating**: Normalized experimental surface temperature as function of $\sqrt{t}$ for a series of zirconia coatings of different thickness for a 1 s step heating pulse. Heating was performed in reflection using laser beam as explained in the text. Reproduced with permission from [12].

Fig. 8 **Lockin Thermography**: Experimental set-up for full-field deployment. 1: sample, 2: subsurface defect, 3: thermal stimulation source, 4: infrared camera, 5: heated area, 6: observation area, 7: signal processing and recording unit.

Fig. 9 **Lockin Thermography**: Thermographic inspection of a graphite epoxy component with an impact damage. LT phase images at various frequencies correspond to different depth range. The typical “butterfly” shape of such an impact defect is visible. Changing orientation is related to the various orientations of damaged plies. Heating was performed in reflection using an high power infrared lamp (total of 1 kW of electric power, frequency as indicated). Images courtesy of IKP - University Stuttgart (Germany).

Fig. 10 **Vibrothermography**: (a) finite element discretization of damaged 90/0/90 graphite epoxy beam, (b) normalized energy along center of delamination nodes as function of frequency (in kHz) and (c) thermogram at 13.5 KHz, showing heat generated by the excited flaw. Stimulation: see text. Reproduced with permission from [20], fig 8, 9, 10).

1. Introduction. Infrared (IR) thermography is a nondestructive testing (NDT) technique, i.e. an inspection method for the examination of a part, material or system without impairing its future usefulness [1]. When compared with other classical NDT techniques such as C-Scan ultrasonics or X-Rays, data acquisition by infrared thermography is safe, nonintrusive and noncontact, allowing the detection of relatively shallow subsurface defects (a. few millimeters in depth) under large surfaces (typically 30x30 cm2 at once, although inspection of larger surfaces is possible) and in a fast manner (fro...Â Infrared thermography. Active. Optical/external excitation. Introduction Infrared thermography (IR/T) as a condition monitoring technique is used to remotely gather thermal information for monitoring the condition of virtually all of the electrical components on an entire system and from generation to end user. How can we say all of the electrical components? Because all electrical components, when operating under regular conditions, have a normal operating thermal signature which is typical of the specific component being inspected. Infrared thermography presents this normal signature or baseline to us. Once the baseline is established, Infrared therm...