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Inspection of aircraft structural components using lockin-thermography

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Abstract

Lockin thermography with its capability to monitor modulated heat flow in larger areas (several m^2) within a few minutes is applied to the inspection of aircraft. Using up to 6 lamps each with a power of 1 kW, we could inspect subsurface structures (e.g. stringers) and subsurface defects (e.g. impact, delaminations) from a distance of several meters. The method is well suited to monitor the structural integrity of aging aircraft in the near-surface area. By using ultrasonic excitation instead of radiation one can display selectively hidden defects that are characterised by a local enhancement of mechanical loss angle (e.g. cracks).

1. Introduction

Modulated heat transport can be described in terms of a heavily damped wave where both real and imaginary part of the complex wave number are given by the inverse of the thermal diffusion length μ

$$\mu = \sqrt{2k / \omega \rho c} \qquad (1)$$

Here k denotes thermal conductivity, ρ the density, and c the specific heat. While these are properties of the material, the angular frequency ω of heat transport modulation is chosen by the experimentalist. The importance of μ is that it determines the maximum depth from where subsurface structures may affect the oscillating temperature on the surface into which heat is injected periodically [1-3]. So the depth range for the detection of subsurface features can be selected via the frequency. For metals, μ is about 1 mm at 10 Hz, while for most polymers this diffusion length is obtained at 0.01 Hz or less. Thermal waves at such low frequencies are suited for remote inspection of layers or layered material, e.g. laminates.

The technical reason for the use of fibre reinforced materials in aerospace application is their high specific strength which is the quantity of interest for all materials undergoing accelerations while their own weight acts on them, as for aircrafts and space vehicle structures. As structural integrity is essential for safe operation, there is considerable interest in methods allowing to reveal areas of damage or other kinds of defects in laminates.

2. Lockin-Thermography

The use of thermal waves for the remote nondestructive inspection of laminates has been more of academic interest as long as raster images had to be taken using a point-by-point photothermal technique [4, 5] where at every pixel one had to spend many seconds at the low modulation frequencies. For a 250 x 150 pixel image and a modulation frequency the time for one serial scan would be more than a month. Therefore one is interested to reduce this time by exciting the thermal wave on the sample surface everywhere simultaneously and to monitor

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amplitude and phase of the oscillating temperature field everywhere within only a few modulation cycles. This multiplex photothermal detection is possible using lockin-thermography [6-8] where one reconstructs the temporal behaviour of temperature at each pixel in the image. This is achieved by a suitable synchronisation of modulated illumination (at such low frequencies possible with high power lamps) and camera frequency (figure 1) in such a way that finally all thermographic images are compressed into four raw images (S_1 to S_4) distributed equidistantly along one modulation cycle. From them one obtains the phase image φ (showing the local delay of modulated heat transport) according to [8]

$$\varphi = \arctan \frac{S_3 - S_1}{S_4 - S_2} \quad . \qquad (2).$$

This equation shows that

- only modulated thermal emission contributes to the image and that
- non-uniform intensity distribution,
- optical surface structure, and
- non-uniform infrared emission coefficient

cancel at each pixel due to the ratio in the equation.

Therefore such a phase image is quite insensitive to all kinds of perturbations, it shows essentially the thermal features from the surface down to a depth of about 1.8 times the thermal diffusion length μ [1-3].

3. Results

Aircraft structural components have typical sizes that make homogeneous illumination difficult.That is why conventional thermography is not a very helpful tool of NDT for these applications. To give an example, figure 2a shows the thermography image of a small airplane wing (Extra 300) while figure 2b shows the phase image of lockin-thermography. Obviously the non-uniform illumination affects only the noise in the phase image. The subsurface features in this carbon-fibre reinforced plastics (CFRP) wing are clearly revealed. Structural integrity can be confirmed by such an inspection. Subsurface features could also be imaged on an airplane (Grob 115) made of glass fibre reinforced plastics (GFRP). Figure 3a shows the airplane (together with the experimental setup) while figure 3b is the phase image of the nose section. One sees the areas of increased thickness due to overlapping material, and the three bright spots indicate positions where the cables for the landing light are attached underneath the surface.

While these two examples were obtained on small airplanes having only one or two seats, we investigated how well one can use lockin-thermography to inspect larger objects: the fuselage of a large helicopter and of a commuter plane (Do 328). The thermography image (figure. 4a) gives an impression of the inspected helicopter area. One sees the effect of non-uniform illumination of the CFRP skin laminate and some indication of subsurface features which stand out much more clearly in the phase image of the same area (Figure 4b). This fuselage had been provided with various kinds of damage (honeycomb structure partly filled with water, impact damage) which appear as spots on the background of known structure. In this case illumination was performed with 6 lamps (each 1000 W) operated at a modulation frequency of 0.015 Hz. Figure 5a shows the drawing of the tail core of Do 328 while figure 5b is the phase image confirming the integrity of structure: all stringers are well attached to the skin. If such a structure is exposed to excessive load the result might be stringer disbonding. Such an example is displayed in figure 6 where the horizontal bright lines in the center indicate the stringers while the interruption of these lines shows areas of disbonding. This is an example where loss of structural integrity could be detected from the inspection of the intact outer skin laminate. Duration of measurement was about 4 minutes for all examples. This time should be of interest for routine inspection. No surface treatment was required. Therefore we could even inspect the

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horizontal stabilizer of the Do 328 though it was 3 m above us. In these examples the defects could be detected by comparing the observed structure pattern with the expected pattern. This comparison requires good knowledge about normal aircraft features and small deviations from them. Though various kinds of image processing could be helpful in this case, it would be highly desirable to distinguish defects from intact areas in a way like dark-field-microscopy displays only certain kinds of structures.

First attempts to develop such a technique have been performed recently [9]. The basic idea is that defects have a special mechanical behaviour by which they may reveal themselves under certain conditions: their increased hysteresis effect results in selective heating under periodical load. Figure 7 shows an aluminum component of an aircraft. In this case the lamp was replaced by an ultrasound source whose amplitude was modulated at the low thermal wave frequency which was again synchronised to the lockin-analysis of the camera. The component under inspection suffered from corrosion on the rear surface. This area appears as a bright spot in the lower left edge of figure 7. The reason is that the corroded part has a higher loss angle resulting in modulated heat generation when the sample is exposed to ultrasonic excitation. The other features of the component (e.g. thickness variation) are suppressed by this principle of selective modulated defect heating. So this technique might be suited for fast and reliable detection of hidden corrosion, delamination, and impact.

4. Conclusion

Lockin-thermography allows for remote imaging of thermal features using low frequency thermal waves. During the short imaging time (typically 4 minutes) one can monitor the structure integrity of large components with a size up to several m^2. As this inspection does not require any modification of the inspected component, it is well suited for fast inspection e.g. of aerospace structures where one is interested to detect areas of disbond, hidden corrosion, or impact.

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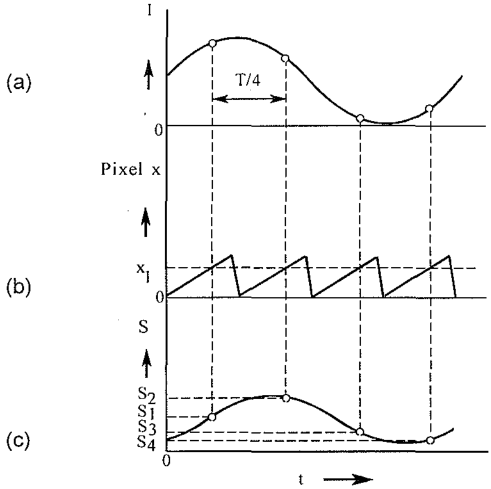
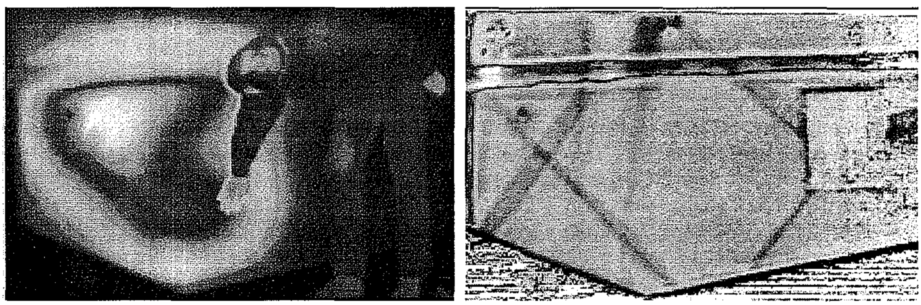
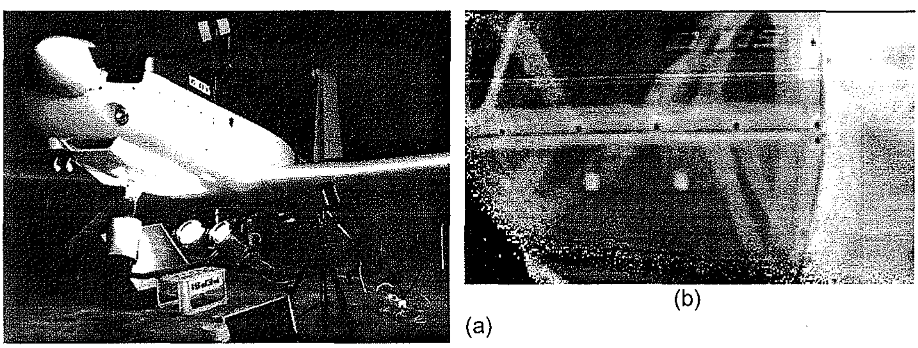


Fig. 1. Principle of lock-in thermography: light intensity (a), camera scan (b), and reconstructed thermal wave signal S at pixel x_1 (c).



(a) (b)

Fig.2. (a) Thermography image of an airplane wing (Extra 300) and (b) phase image at 0.03 Hz



(b)

(a)

Fig. 3. (a) Optical image of an airplane (Grob 115) and experiment setup and (b) phase image of the nose section

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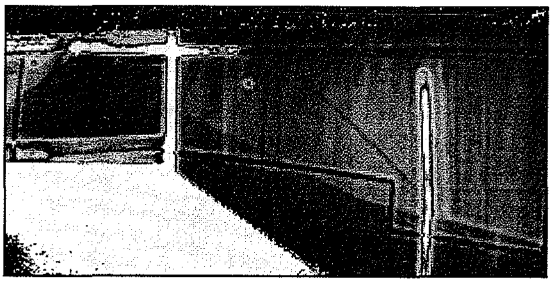
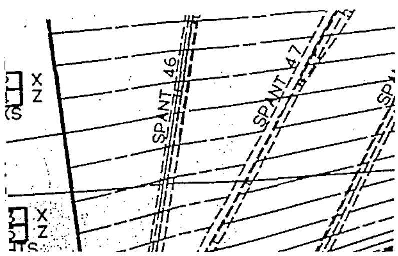
(a)



(b)

Fig. 4. Thermography image (a) of helicopter fuselage shows nonuniform heating while phase image (b) reveals internal structures and damages

(a)



(b)

Fig. 5. Drawing of the tail cone of Do 328 (a) and the corresponding phase image (b) showing the integrity of the stringers

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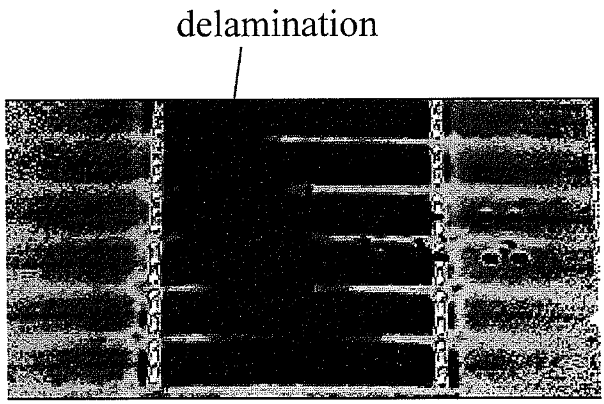

Fig. 6. Phase image of an airplane structure with rear surface stringers (horizontal bright lines in the center). Disbonding areas indicated by the interruption of bright lines.

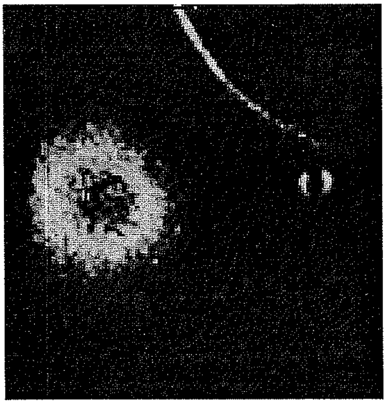

Fig. 7. Ultrasonic lockin thermography of an aluminium airplane component. Hidden corrosion revealed by its increased loss angle.