Modern Methods of NDT for Inspection of Aerospace Structures

G. RIEGERT, K. PFLEIDERER, H. GERHARD, I. SOLODOV, G. BUSSE
Institute for Polymer Testing and Polymer Science (IKP) –Nondestructive Testing– (ZFP),
University of Stuttgart, Stuttgart, Germany

Abstract. Aerospace structures need to be light and safe, an aspect which makes new materials attractive. Therefore maintenance inspection of these light-weight structures is a new and difficult task for non-destructive testing (NDT) which needs methods that are applicable to such high-specific-strength materials. The methods must be robust to be used in an industrial environment and sensitive enough to respond to boundaries and to provide reliable results in a short time. The new methods which fulfil such requirements are based on diverse physical phenomena e.g., heat transport, thermal expansion, air-coupled elastic waves, or non-linear vibrometry responding selectively to defects. The paper presents both the principles of such new NDT methods and their applications to typical aerospace structures.

1. Introduction

Aerospace structures are a compromise between low weight and high safety. Therefore new materials are attractive in terms of weight reduction and fuel economy: The Airbus A 380 has led the way with about 25 percent of the aircraft using composite material, and the Boeing 787 will be have up to 50 percent composites, including the entire fuselage [1]. In smaller modern aircraft the percentage may be even much higher. Maintenance of these light-weight structures is a new challenge for non-destructive testing (NDT) which requires methods that respond with a high probability of detection (POD) to such high-specific-strength materials and their defects. Conventional NDT like x-ray inspection or ultrasound which were optimised for the needs of metal structures cannot satisfy such needs. Some defects go back to the manufacturing process, others are due to in-use damage. Therefore one needs robust methods responding to boundaries and providing reliable results in an industrial environment within short time. The latter requirement means that contacting point-by-point methods are too slow for most large-scale inspections.

2. Modern methods of NDT

The methods developed for aerospace applications are based on heat transport, thermal expansion, air-coupled plate and surface waves as well as non-linear interaction of elastic waves with defects. The principles and methodologies will be briefly described here and the basic applications will be demonstrated. More details could be found in original publications cited through the paper and given in the list of references.
Thermography by itself is not new, it is around since many years, e.g., to find weak points in the thermal insulation of houses. While such “passive thermography” utilises natural temperature patterns, dynamic thermography methods analyse how temperature fields respond to injected heat, where the temporal pattern of heat deposition may be e.g. a pulse, a burst or sinusoidal. There is also some variety in the way how heat is injected. The most convenient way is optical irradiation of the object, where absorption converts electromagnetic energy into heat. If irradiation is pulse-like, all energy is deposited very close to the surface from where it starts spreading out. So it causes initially a high thermal load, especially on non-metals, which are sensitive to temperature anyway. Less thermal load is induced if irradiation is performed in a sinusoidal way, where permanent non-equilibrium results in the generation of a thermal wave. It propagates into the inspected component and is reflected at boundaries back to the surface. There it is superposed to the initial wave so that it affects magnitude and phase of the temperature field, which is recorded by the thermography camera. Without going into the physics of thermal waves and the theory of Lockin thermography [2-5] (this kind of thermography is named after the hardware lockin, a device to determine magnitude and phase of a modulated signal with respect to a reference), it should be mentioned, that thermal waves interact with thermal boundaries and that depth range (defined as the maximum depth where a boundary can be detected) is about the thermal diffusion length:

$$\mu = \sqrt{2\alpha/\omega}$$  \hspace{1cm} (1)

with $\alpha$ = thermal diffusivity and $\omega$ = modulation frequency [6]. If phase is used for imaging instead of amplitude, depth range is almost doubled [7]. A phase image is generated by performing at each pixel a Fourier transformation across the whole stack of images at the modulation frequency. The advantages of Lockin-Thermography with optical excitation (OLT) are

- there is no contact with the object under inspection,
- the full information contained in the whole stack is used in the most efficient way to optimise the signal to noise ratio per injected power density,
- there is no unnecessary heating of the inspected object,
- imaging of a square meter size within several seconds, depending on required depth range,
- robustness due to the use of phase angle,
- perturbations like inhomogeneous heating are suppressed in the phase image.

On this background OLT is quite attractive as compared to pulse thermography.

Excitation can also be performed by injection of high power ultrasound, which is converted to heat preferentially in areas with an enhanced mechanical loss angle, which are typical defects. Detection and image analysis are the same as above, so such images display mostly defects and not intact areas with their low loss angle. This defect-selective imaging of ultrasound thermography [8, 9] and ultrasound-lockin-thermography (ULT) [10, 11] enhances the probability of defect detection. The only drawback of this new technique (which keeps being reinvented) is that the input coupling of high power ultrasound requires mechanical contact with the object at a fixed point, but this defect selective “dark field” NDT-technique reveals immediately cracks and loose rivets without mechanical scanning of the ultrasound source, with all the advantages of phase angle images mentioned above. The problems related to standing wave effects and related blind spots may be eliminated by jittering the
frequency of ultrasound excitation [12]. More information about this technique is given elsewhere in this proceedings book [13].

Another kind of remote heat deposition is the combination of thermography and inductive heating which is applicable to conductive materials like metals [14-16] and carbon fibre reinforced polymers (CFRP) [17] (well known for its aerospace relevance). In this case we have the interesting situation that the depth where absorption occurs is about a factor of 30 larger for CFRP than for metals since the skin effect involved in eddy current physics depends on the square root of electrical conductivity, which is by about three orders of magnitude lower for CFRP than for metal. Consequently eddy current at a frequency of about 100 kHz heats mostly the volume of materials with low electrical conductivity and only the surface of metals. Defects within the eddy current penetration depth are differently heated than the intact material around it and contribute directly to the temperature pattern on the surface, a situation which is similar to defect selective imaging with ultrasound lockin thermography. For metal, however, the situation is more like in optically excited lockin thermography. This illustrates that induction heated lockin thermography (ILT) of CFRP or surface defects in metals could be defect selective like ULT and remotely excited like OLT. So it combines the advantages of both methods. Phase images which refer to the low frequency amplitude modulation of eddy current heating have the additional advantage of removing effects caused by an inhomogeneous excitation field.

In all three techniques [18] the modulation frequency affects depth range, therefore depth profiling requires subsequent measurements at various frequencies. To simplify this procedure such measurements can all be performed at once by frequency superposition, e.g., by using a rectangular burst excitation containing a suitable frequency spectrum [19, 20] so that just one stack of thermography images provides phase images with different depth ranges (“thermal tomography”).

2.2 New developments in air-coupled ultrasound

Established ultrasound methods are based on the pulse-echo principle and liquid coupling of the inspected object, while every bat is a living evidence that air coupling of ultrasound is feasible. The basic problem of air ultrasound is impedance mismatch. On the other hand, it has been shown that at certain angles of incidence the efficiency may be enhanced by an order of magnitude due to excitation of plate waves [21]. Completely remote ultrasound methods (focused slanted transmission of air ultrasound) are now sensitive enough to reveal e.g. impact damage. This is of interest for aerospace applications since most structures consist of plate-like components. Meanwhile such remote air-coupled measurements can be performed even in a single ended arrangement [22] which is of practical relevance since many components to be inspected are accessible from only one side. Such methods based on the conversion of air-ultrasound to plate waves and back display local changes of plate wave velocity thus acting as extremely sensitive probes for defects.

2.3 Non-linear vibrometry

Another field where substantial progress has been made is concerned with elastic non-linearity. The relevance for NDT and aerospace applications is the fact that defects are typical weak points which means that their local stress-strain diagram is no longer linear. As an example, a deformation of a crack is not symmetrical with respect to compression-tensile strain and the defect behaves like a mechanical rectifier that produces higher
harmonics of the driving frequency. Therefore a sinusoidal input wave is locally distorted so that the higher harmonics are sensitive indicators for delaminations, loose rivets, and fatigue cracks at a high level of POD [23]. Detection can be performed in a remote way by scanning laser vibrometry while the elastic wave is injected locally at a fixed point very similar to ultrasound thermography described above.

2.4 Dynamic interferometry methods

Conventional interferometry methods are based on the comparison of two states, e.g., component with and without deformation which is caused by thermal or mechanical load. The difference is displayed by lines of equal deformation. In that case the presence of a defect is revealed by the influence that it has on the deformation field. As also the intact component deforms under load, the influence of the defect may be difficult to detect. The idea is to remove the background by exciting the defect selectively.

As a defect is usually an area with an enhanced loss angle, it warms up selectively during ultrasound excitation. Instead of monitoring the resulting local temperature rise (or its phase) like in ultrasound thermography, one can monitor the thermal bump on top of it caused by local defect heating. The difference as compared to conventional interferometry is the detection of the defect itself and not its effect on overall deformation [24].

Another possibility to enhance POD is load modulation since the reaction of the defect area has a different phase lag than the intact area. Therefore in a phase angle image derived from a sequence of interferometric images taken during periodical deformation (induced e.g., by modulated illumination) the defect area stands out clearly on the constant background of intact structure. This analysis is similar to Lockin thermography methods (and described in the same patent [18]), and of course these concepts are applicable to all kinds of interferometry. Examples are presented only for the out-of-plane component of electronic speckle pattern interferometry (ESPI) [25].

2.5 Defect selective imaging

The reader may have realised that some methods respond selectively to defects if the defect itself has specific properties. An example is fluorescence spectroscopy, or fluorescence of dyes for detection of open cracks, but in the cases mentioned above the response relates to loss angle heating detected by its thermal effects causing thermal emission or thermal expansion. Or the selective response may relate to a non-linear response function. Such methods ignore any intact structure since it does not give rise to defect-specific effects. The relevance with respect to applications is the enhancement of POD.

3. Examples for inspection of aerospace structures

Typical examples are now presented that were obtained on aerospace components using NDT methods described above.

3.1 Detection of loose rivets

There are still metal aircraft around which need to be inspected with respect to loose rivets, cracks, corrosion, and fatigue. An example is Fig. 1 where a panel made for demonstration purposes is imaged using lockin thermography with access only to the outer surface. With optical excitation the whole hidden structure is imaged regardless of the riveting quality. With ultrasound generation, however, loose rivets cause heating by friction, so they appear selectively as bright areas.
3.2 GFRP: Quality of bonding

Glass fibre reinforced plastics (GFRP) is used for smaller aircraft. For locally spherical shapes several layers are put next to each other with a small overlap. Fig. 2 shows an aircraft (Grob G 115) and the result of OLT applied to its nose section [27]. The optical surface appearance is ignored, the overlap of the CFRP material stands out clearly (Fig. 2).
3.3 Inspection of CFRP structures

Carbon fibre reinforced plastics (CFRP) has the highest specific strength. As stringers are used to enhance stiffness along specific directions, detection of local disbond is vital. In the following examples a disbond had to be detected under the 3 mm thick outer skin in a section cut out from a CFRP landing flap. The results are compared for various methods. With Ultrasound-ESPI the line pattern indicates a small bump thereby revealing the defect underneath (Fig. 3).

![Schematical drawing of landing flap front side](image1)

**Figure 3.** Result of ultrasound activated ESPI on landing flap with stringer rupture [28].

The phase image of ultrasound activated lockin-thermography with mono-frequent excitation (20 kHz) shows a confusing pattern of many equidistant lines, which is a typical indicator for standing waves (Fig. 4, top). With frequency modulation, the standing waves are suppressed and the defect stands out clearly (Fig. 4, bottom).

![Result of ultrasound ESPI](image2)

**Figure 4.** Results of ultrasound activated thermography on landing flap with stringer rupture. Phase images at 0.05 Hz [29].

The same section has been inspected with eddy current lockin-thermography. The phase angle image obtained at a carrier frequency of 100 kHz and 0.01 Hz modulation frequency (to which phase of thermal wave refers) displays also the subsurface defect together with fibre orientation of the skin due to the electrical conductivity of the carbon fibres (Fig. 5).
The same landing-flap was also inspected with non-linear vibrometry. This defect selective method uses the same 20 kHz excitation source as ultrasound activated lockin-thermography and an additional source of 3.25 kHz. The non-linear behaviour of damaged areas - in this case the broken stringer - causes a mixed frequency of 23.25 kHz. The result is an image where the amplitude at this frequency is displayed in red colour and superposed with a photo of the image surface (Fig. 6).

High stiffness at low weight is obtained by bonding CFRP-sheets to both sides of a honeycomb plate. Here NDT has the task to find disbonded areas. A model sample was produced where triangular PTFE-foils were embedded between CFRP layers and a honeycomb plate and afterwards removed. The left PTFE-foil in the sample could not be removed any more. On top of the simulated delaminations three different thicknesses of CFRP-laminate were added in order to simulate various different depths of delamination (Fig. 7, left).

The simulated delaminations can be imaged with OLT (Fig. 7, bottom). The different phases (grey coded) indicate different depths of the three triangles. The PTFE-foil which could not be removed can be seen on the left triangle in the phase image as the PTFE produces a phase angle which is coded by black colour.

Also single ended air-coupled ultrasound in the focused slanted reflection mode (FSRM) mode (schematical setup in Fig. 8, left) shows the simulated delaminations (Fig. 7, top).
Results with air-coupled ultrasound with single side access (top) and optical lockin-thermography (bottom) showed that the triangles of the delaminations could also be detected at the rear side of the sandwich (Fig. 8), probably because the inhomogeneous thickness of the upper laminate caused a pressure inhomogeneity on the lower laminate on the rear side of the structure. This result shows how sensitive these NDT methods respond on deviations of quality relevant parameters.

It should be mentioned that dynamic thermography can be applied also for imaging of whole parts of an airplane in short time [27]. A recent example is a modern CFRP-airplane, where the painted fuselage was inspected in the area of the emergency exit using Optical-Lockin-Thermography. Both amplitude and phase are evaluated (Fig. 9). The amplitude image (Fig. 9, left) is influenced by inhomogeneous heating, while the phase image shows the hidden structure, the inhomogeneities of illumination are suppressed (Fig. 9, right).
3.4 Integrated sensors/Smart structures

Smart structures consist typically of a laminate with built-in piezoceramics either to induce deformations or to detect them ("integrated sensor"). In fact the same piezo can do both, which is of interest for applications. As such structures depend on good bonding, NDT is applied to locate disbonded areas. Examples of inspections were described previously, where such actuators were used to monitor impact damage [32] or acted as built-in transmitters of elastic waves to perform ULT and overtone imaging [33, 34]. Besides these methods also eddy current induced thermography can be used for smart structure inspections, since the actuator and its electrodes differ electrically from their environment. As an example, a smart structure was inspected with Induction-Lockin-Thermography (Fig. 10). The smart structure consists of a CFRP-plate with four embedded piezoelectric actuators. On one of them a disbond was simulated by a circular sheet of PTFE.

The two images were obtained with eddy current activated lockin-thermography at the same carrier frequency (50 kHz) but at different modulation frequencies (1.5 and 0.5 Hz) (Fig. 10, left and right, respectively). The change of phase contrast of the actuator structure is consistent with theory [7], but only at the lower frequency of 0.5 Hz the simulated bonding defect is visible. At 1.5 Hz the structural integrity of the piezo can be inspected.
4. Conclusions

Modern aerospace components consist of new materials which are a challenge for modern NDT. In response to these requirements new NDT methods have been developed that display typical defects in a short time, part of them in a completely remote way or selectively. The optimum choice depends on the material and on the defect to be detected. In terms of maximum POD, the defect selective methods (based on non-linear vibrometry, ultrasound activated thermography, interferometry, or inductive lockin-thermography) seem to be promising, while for structural inspection OLT seems to be a flexible tool.

Acknowledgement

The authors are grateful to the German Research Foundation (DFG) for financial support in the project BU 624/23 “Wirbelstrom Phasenthermografie”. They also thank GROB Aerospace/Mindelheim-Mattsies, Dornier/Friedrichshafen, Airbus/Bremen, and last not least Institut für Flugzeugbau (IFB) of Stuttgart University for kindly providing samples.

References


[28] H. Gerhard, G. Busse, Deformation-measurement with speckle-interferometry by ultrasound excitation, 8th ECNDT Barcelona, CD-Rom, 2002


