Contactless Defect Detection Using Optical Methods for Non Destructive Testing

P. HUKE*, O. FOCKE*, C. FALLDORF*, C. von KOPYLOW* and R. B. BERGMANN*

* BIAS Bremer Institut für Angewandte Strahltechnik GmbH, 25359 Bremen, Germany

Abstract. Optical methods are extremely useful for Non Destructive Testing (NDT) due to their ability to measure fast and contactless, to test larger areas or tiny spots in a short time, and to measure on complex shaped parts as well as plane surfaces. In this paper we present laboratory setups for NDT available at BIAS and corresponding results. We present a range of methods suitable for testing of skin-stringer panels, welding seams and carbon fiber reinforced plastics (CFRP) with complex and simple shape and show corresponding results. Defects on or close to the surface can be detected by indirectly comparing a measurement of the undisturbed state of the object and a measurement under a suitable load. The measurements can be realized either by interferometry, speckle shearography or even with reflectometry in case of specular surfaces. Applicable loads vary from heat, static mechanical load, dynamic loads and even laser excited Lamb waves on a surface. Detection of Lamb waves is carried out either one-dimensionally or two-dimensionally with a combination of spatial phase shifting and shearography. Defects hidden in the depths of a body, like pores, inclusions or even debonding can be detected directly by using ultrasound methods. One of the most flexible tools to excite ultrasound waves in a body is a short-pulsed laser. Due to the small excitation area and the independence of the relative angle with respect to the surface it allows for a high accessibility of complex shaped parts. Typically for laser ultrasound, the detection is carried out by vibrometry, interferometry or lock-in technologies always using a laser as detection tool. Finally, we discuss the advancement of NDT towards a quantitative evaluation of the geometry and location of defects.

1. Introduction

Non destructive testing (NDT) is mainly driven by the constant request for quality control of innovative products realized by ever fast evolving production technologies. In the past two decades new materials, e.g. CFRP, new bonding techniques, like adhesive bonding were invented as well as the well-known techniques like welded seams, with different bonding partners were further developed. Their production lines had and always will have a constant demand for detection of flaws and based on this quality control [2]. This includes surface and shape characterization, defect detection on the surface as well as defects hidden in the depths like delaminations in an adhesive layer of a compound. Conventional methods like standard ultrasound or X-ray CT are not always convenient either according to the necessity of contact, the size or the cost of systems. Here we report about two methods under constant development at BIAS as well as their application to industrial demands which arise especially in the aerospace industry. One non-destructive technology, shearography, reveals subsurface defects through comparison of the unloaded and loaded state of the object under investigation [3]. The other, Laser-assisted Ultrasound, is comparable to standard ultrasound with additional advantages [4]. For example it measures remote and contactless, tests parts showing low accessibility and is even capable for two-dimensional NDT of objects [4-7].
3. Shearography

Digital speckle shearography is a well established method to investigate materials. It is mainly used to determine structural imperfections such as inclusions and delaminations hidden under the surface [3, 8, 9]. Up to now, the illumination is laser-based. Investigation areas range from several mm$^2$ up to some m$^2$. The measurement process is relatively short and takes only a few seconds including all steps like loading, data acquisition and evaluation.

3.1 Principle of shearography

Figure 1 shows the principle of digital speckle shearography. The object under investigation, seen on the left side, is illuminated by an expanded laser beam. On the right side the shearing device, a Michelson Interferometer, is shown. One mirror is tilted at an angle $\alpha$ to generate the shear. The other is the reference mirror and can be used for phase shifting. Together with the objective lens this setup produces two laterally shifted images of the same surface on the camera target. The spacing between the two correlated points of the surface is called shear $s = (\Delta u, \Delta v)$. Both of the intensity distributions feature a noisy appearance which is called speckle effect [3]. This statistical effect is based on multiple interferences in the image plane and occurs if coherent light is scattered by rough surfaces. Due to its coherent nature, laser light originating from surface positions $P_1 = (u_1, v_1)$ and $P_2 = (u_2, v_2)$ separated by the shear interferes at the same position on the camera target $P' = (x, y)$.

Figure 1: Principle of digital shearography with a Michelson-interferometer. Schematic setup: For explanation see text.

To obtain information about hidden defects within the object under investigation it is necessary that defects cause a local deformation of the surface if the object is mechanically, thermally or otherwise loaded. The surface deviation caused by the load is in the range of a few microns. After loading a second interferogram is taken. This interferogram is digitally compared with the former taken. One enhancement of digital speckle shearography developed by the BIAS [9-12] is illustrated in figure 2. Figure 2a) shows a photograph of a new setup and figure 2b) the schematic sketch of the setup.

The first advancement is a 4f-configuration with the lenses $L_1$ and $L_2$. The second is the replacement of the shearing device by a spatial light modulator (SLM) enabling a compact and rugged sensor system. For the functionality the incident light has to be linearly polarised. After passing the $\lambda/2$ plate, the circular polarized light will interact with the SLM. The SLM is a reflective panel based on nematic cells with birefringent properties and allows for manipulation of the lateral phase of one polarization directions. Accordingly the incident light beam splits up into two beams, the ordinary beam (figure 2b straight line) and
the extraordinary beam (figure 2b dashed line). The angular displacement caused by the SLM generates the shear which is detected by the CCD camera.

![Figure 2: Digital speckle shearography system. a) Photograph of the sensor developed by BIAS and VEW GmbH; b) Sketch of the principle using a SLM. Object, λ/2 - λ/2 plate, L1 and L2 - lenses, A – analyser.](image)

One of the major benefits compared to other interferometric techniques is that the digital speckle shearography setup has a rather low demand at the stability. This is because of the small difference in the relative path length. Another convenience of the Digital Speckle Shearography is that no reference beam is needed; this fact makes the optical setup quite simple [3].

### 3.2 Application: CFRP defect detection

Even though expert knowledge is necessary to analyse the measured data the sensor can be directly applied to industrial parts, see figure 3.

![Figure 3: Application of the speckle shearography to a complex sheet metal part. The measured area is overlaid on the surface of the part. The defect is encircled in red.](image)

Another drawback is that the required power of the laser is in the range of watts for illumination of larger objects. The related safety issues are crucial for industrial applications. On the other hand, the coherence requirements for shearography, especially in the set-up with a SLM developed by BIAS and VEW are low: The coherence length may be in the range of micrometres since both light paths differ only by the height difference of the two sheared and superposed points. Taking this into account, white light shearograms using a mercury lamp, showing low spatial coherence, have been developed in the BIAS [10]. The group of Gert von Bally recorded digital holograms for microscopy by means of high brightness LEDs [13, 14].
4. Laser Ultrasound

In a wide range of applications quality control includes NDT using ultrasound. Single transducer and as a follow-up phased-array techniques has been developed over decades. This technology combines high resolution with a large depth of measurement and is easy to use [2, 6]. It is standardized and certificated as a standard test method for CFRP-parts in aeronautic production engineering. However, it needs a coupling medium, parts with poor accessibility due to complex shape or high temperature remain a challenge. Lately, air-guided ultrasound has been brought to market and finds its application. However, the applicability is limited due to the great loss in signal transfer.

Laser assisted generation of ultrasound signals on the other hand is contactless and is therefore able to operate in extreme environments like the production of hot tubes [2]. The generated ultrasound waves can be divided in two categories: the bulk and the surface acoustic waves (SAW). For thinner bodies also Lamb waves may be excited. Lamb waves are full body waves, where the plate as a whole oscillates [15]. Accordingly, these waves can be measured as surface waves on the rear and the front of the plate. The surfaces can oscillate in phase or out of phase producing a compression in the bulk, showing that these waves are a combination of both categories.

Scattering of acoustic waves and therefore the detection limit for solitary defects is directly related to the wavelength $\lambda_{\text{sound}}$. However, the wavelength not always constitutes a lower limit for the resolution. A broad spectrum may result in a distinct waveform which allows for phase-sensitive measurement. A high density of small defects like pores or nests of pores would produce significant scattering [18].

4.1 Principle of generation

Ultrasound waves can be excited using a short-pulsed laser. Other than standard ultrasound commonly all waves (bulk and SAWs) are excited depending of the amount of energy deposited in the material. The amplitude of the different waves depends on the laser energy and the absorption behaviour of the material either producing a thermoelastic stress zone suitable for NDT see figure 5 or an ablation of the material. In the latter case the central bulk wave is strongly excited whilst the shear waves are suppressed.

![Figure 4](image-url): Non-destructive excitation of different ultrasound waves in a medium. a) A thermo-elastic stress zone is generated in the upper region of the material. The energy is carried away via lattice vibrations. b) Propagation vectors for different ultrasound waves: $C_R$ (Rayleigh waves) and $C_K$ (skimming wave) are SAWs. The bulk waves are $C_S$ (Shear wave), $C_L$ (Longitudinal wave). The wave denoted $C_{L\rightarrow S}, S\rightarrow L$ is a wave that exhibits mode conversion due to reflection at the next boundary layer and the central body wave.
4.4 Principle of detecting laser-excited surface acoustic waves (SAW)

Laser-excited SAW’s show a wide spectrum depending on the pulsewidth and the energy of the exciting laser. They were used excitation of acoustic phonons in crystal lattices using femtosecond-lasers [19]. Due to the high frequency and therefore the short wavelength the waves can be used to detect very small defects like cracks in the lattice structure or larger defects like delaminations on or close to the surface of the specimen [7]. On thinner parts these waves can interfere with bulk waves to Lamb waves showing other characteristics. Additionally, the propagation of the waves depends on the material constants and its inherent structure and is often highly nonlinear, showing dispersion, polarisation and damping [22]. Hence, the choice of the detection point(s) influences the measurement.

![Figure 5: Principles of detection methods used at BIAS. a) Pointwise detection using a vibrometer, b) Two-dimensional measurement using digital speckle shearography.](image)

The easiest way to detect SAWs with frequencies up to 1GHz is to use an off-the-shelf vibrometer, see fig 5a. Another possibility is to use a lockin technique [19]. A drawback is that the point wise measurement induces movement of the specimen or the measuring beams which is not convenient for NDT of larger objects.

In order to detect the SAWs two dimensionally interferometry [21], holography [20] or digital speckle shearography, see fig 5b, can be used. All these methods avail the measurement of one or more wave fields to reach the necessary resolution of a few nm or less.

4.5 Application: Measurement of defects with Lamb waves

Basically Lamb waves can be used to measure a wide range of defects in the volume of a given object or compound. Especially bonding with adhesives is interesting for the automotive and aerospace industry. Normally, testing of these bondings is carried out destructively using loading tests or non-destructively with standard ultrasound. The standard ultrasound is not able to detect every defect and the measurement is time consuming for larger surfaces. In the MultiMat (multifunctional materials and technologies) cluster a larger project is concerned with the process chain of adhesive bonding. One of the topics included is the NDT of the bondings. Therefore, one of our partners produce bonded CFRP-plates where defects are included. The measurements were carried out according to the principle shown in Fig. 6a with a measuring distance \(d=40\text{mm}\). Figure 6a shows the result of 120 successive measurements.

The echo sequence is disturbed where defects in form of small Teflon films (5mm x 7 mm …10 mm x 10 mm) were introduced in the adhesive layer. Consistent with Huygen’s principle the defects act as point sources for new waves that interfere with the original wave. This effect can be detected as interferences.
Even though the pointwise measurement with a vibrometer shows a higher resolution it is time consuming. Two dimensional acquisition of propagating waves enable the detection of larger surface defects and often reveals further characteristics of the material under investigation. Figure 7 shows propagating Lamb waves at 30µs, 60µs and 120µs after excitation. The excitation point is close to the delamination and accordingly diffraction took place in an earlier stage. The defect can be seen even after the Lamb wave has passed.

4.6 Application: Measurement of prestressed CFRP-parts

During manufacturing of CFRP-parts local stresses develop due to the mismatch in material properties (order thermal coefficients) between the fibres and the matrix. Fatigue or additional stress after insertion may cause failure which can not be predicted unless the pre-stress is known. Conventional techniques like X-ray CT, well developed for conventional materials, are not applicable for CFRP. This has motivated to use SAW’s for the measurement of prestressed plates. The SAW’s were excited with a piezoelectric crystal or a laser, see figure 8.
Figure 8: Experimental setup for the visualization of laser generated lamb waves. For the generation of the surface acoustic waves either a piezo with amplifier and frequency generator (a) or a Nd:YAG Laser (b) is used. The object is attached on a four-point-bending-test-rig. A load cell is used for calibration.

Figure 9: Measured Lamb waves under different loads. The loads are be applied using the four-point-bending-rig.

Application of different loads influences the propagation velocity of the Lamb waves perpendicular as well as parallel to the residual stresses, see figure 9). However, the determination of local stresses has to be carried out two-dimensionally. Therefore measurements with the shearographic detection method, see figure 6b), were carried out but show, up to now, too much noise.

5. Conclusions

In this publication we present two different non-destructive techniques that are applied to industrial needs. The applicability of the flaw-detection system based on digital shearography to industrial products is shown. Further development focuses at automation to avoid the necessity of an expert and LED illumination to get rid of laser safety issues.

Further on, laser-assisted generation and detection of ultrasound signals are shown. This method features a range of NDT like impulse-echo mode or detection of SAW’s. We showed the successful inspection of adhesive bonding as well as the influence of prestress in CFRP-parts on the propagation of Lamb waves. Further development focuses at the two-dimensional measurement of local stresses.

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References


