MOBILE SHEAROGRAPHY FOR NDT OF TECHNICAL AND ARTWORK COMPONENTS

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Abstract

With new carbon fiber technologies and other lightweight constructions in aircraft and automotive manufacturing, adapted examination designs and especially developed testing methods are necessary. Modern optical methods have attracted interest not only for laboratory investigations but also for applications on the factory floor because they can be sensitive, accurate, non-tactile and non-destructive. Shearography as a coherent optical method has been widely accepted as a useful NDT tool. This paper describes a complete mobile shearographic procedure including loading and image processing facilities for structural testing and flaw recognition on aircrafts. The mobile system was successfully tested, e.g. with the up-to-date EADS multi-role combat aircraft Eurofighter. It will be shown that the technology is also suited for the optical investigation on cultural objects and sensitive artworks.

1. Introduction

Shearography is a coherent application of laser based metrology. It is a robust interferometric method to determine locations with maximum stress on various material structures. However, limitations of this technique can be found in the bulky equipment components, the interpretation of the complex shearographic result images and a barely solvable challenge at the work with difficult surfaces like dark absorbing or bright reflecting materials. The great advantage of the developed mobile system is the adjusted balance of all single elements to a complete measurement procedure integrated in a handy body. Only with the arrangement of all involved parameters like loading, laser source, sensor unit and software, it is feasible to get optimal measurement results.

2. Basics of shearography

The method is based on the digital correlation of two speckled wavefronts representing two states of the object under test, loaded and unloaded condition. To every technical surface belongs an own individual speckle field and this fact will applied in all speckle metrology technologies. An optical interferometric technique needs a reference base, a reference wave. A special quality of shearography is that the technique generates the reference wave automatically. By shearing the wavefront scattered from the illuminated object surface, one of both wavefronts serves as the reference for the other [1]. This makes the technique very robust against environmental disturbances.

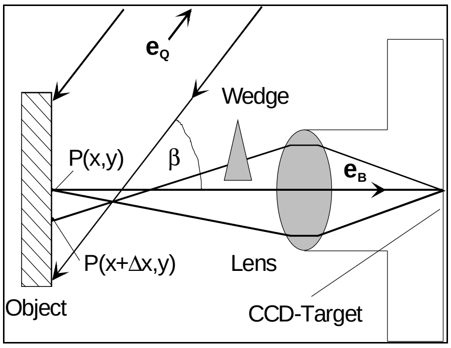


Fig.1: *Shearography basic principle.*

The working principle of shearography is shown in Fig.1. The object is illuminated by a laser and observed by a sensor (CCD target). A shearing element such as a wedge is placed in front of the lens. Consequently the camera sees the usual and a sheared speckle image of the object. These two images interfere on the sensor area and result in another speckle field, which carry the interferometric sensitive object information and can be written as I_1. After loading the object we notice a second speckle field I_2. The difference of these two interferometric object descriptions leads to the shearographic intensity distribution *I(x,y)* and can be written as

$$I(x,y) = I_1(x,y) - I_2(x,y) \tag{1}$$

or with the sheared component *d(x+Dx,y)* as

$$I(x,y) = A(x,y) + B(x,y)\cdot\sin\left[\frac{d(x,y) - d(x+\Delta x,y)}{2}\right] \tag{2}$$

where A(x,y) and B(x,y) may be additive and multiplicative disturbances (electronic noise, modulation V, background intensity I_0, speckle noise).

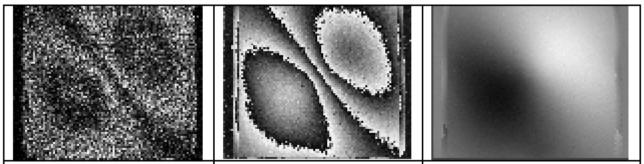


Fig.2a: *Shearogram*	Fig.2b: *Phase-shifting*	Fig.2c: *Demodulation*

Equation (2) leads to a macroscopic fringe pattern and is usually called the shearogram (shown in Fig.2a). After applying a phase-shifting technology the grey values of the shearogram will be transformed into a phase value distribution (Fig.2b). With known algorithms the generated wrapped phase may be transformed into the demodulated or so called unwrapped version (Fig.2c). With all three images nondestructive investigations are possible and will be executed. Interesting point is that these result images represent the mechanical strain of a loaded object. With adequate loading and knowledge about the internal object structure it is possible to detect damages like pores, delaminations, cracks or even faults in bonded composites. Some examples will be shown in the chapters below.

3. The mobile shearography system

3.1 Hardware

An appropriate testing approach must meet nondestructive evaluation and inspection in an industrial environment and must be also mobile, flexible and easy to handle. The developed shearographic system fulfils these demands. It is a comprehensive testing device for the inspection of aircraft structures. But it is also possible to apply it at other structures and materials as well as in automobile or in other manufacturing works. Fig.3 gives a first impression.

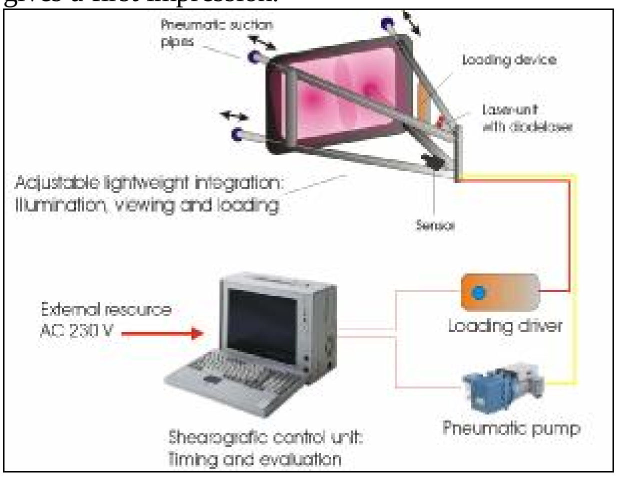


Fig.3: *Mobile shearography system.*

The system contains a portable cabinet (also called head-box) with mounted laser, sensor and loading components. In many testing situations the system has to have contact with the object under test. Therefore the necessary pneumatic pressure will be generated and controlled internal with a pneumatic pump driver. A portable computer contains both control and evaluation unit. Important consideration is that the only external resource is a conventional AC 230V (16A) power supply.

An easy handling of the hardware tools means integration and a miniaturized assembly of the equipment. A good example is visualized with Fig.4. An especially developed diode laser delivers the optical power output of nearly 2 Watt. The dimension of this important hardware tool is only 20x20x40mm.

Fig.4: *Diode laser system.*

The influence of the laser illumination is fundamental in the shearographic technique [2,3]. The evaluation of the measurement result depends direct proportional to the quality of the illumination. The investigation of large scaled components leads to a careful preparation of both the used light system and the elements of the beam expansion system.

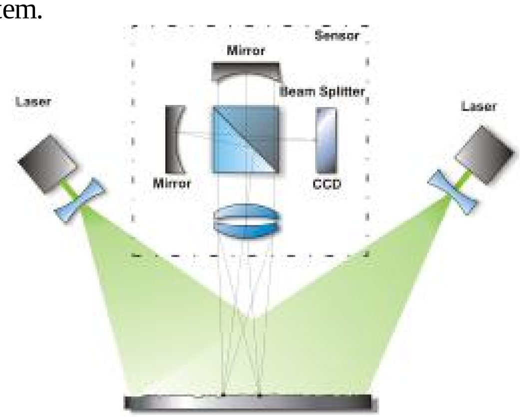


Fig.5: *Shearographic senor with laser illumination.*

The shearographic sensor is also an integrated lightweight construction (Fig.5). It contains the optical elements, shearing and phase-shifting units mounted at mirrors and additionally the CCD camera. The measurement concept based on Twyman-Green interferometry.

An adequate loading of the object under test is of great importance for the success of a NDT-experiment. The objective of loading is the generation of surface displacement gradients in the region where flaws should be detected. The response of the object on an applied loading depends on several factors: the material, the size and location of the fault, the stiffness of the construction and the kind of loading. However, the only free parameter is the loading itself. Consequently, the type and the amount should be selected carefully. Most recipes that can be given in this case are the result of empirical investigations using especially prepared specimen. Following three types of loading have proved to be useful for certain cases:

- thermal loading caused by an adjusted illumination with an infrared lamp or by an intensive thermal flash,
- mechanical loading caused e.g. by a change of the pressure in the test environment and
- vibrational loading caused by a shaker.

Here we report about thermal loading.

One way to transport thermal load into a material is the application of infrared radiation sources. The absorption peak of most plastics, such as CFRP (carbon fiber reinforced plastics), is in the infrared region. In our test equipment we use high power infrared radiator bars just as they are used in automobile manufacturing to dry the varnish. The power load can be adjusted by the portable computer.

To have high mobility the thermal loading system is mechanically combined with the shearographic sensor and the light source in one single cabinet [4-6]. Fig.6 shows the construction. It is a lightweight design with a high safety level in handling and operation. Inside the head-box the position of the laser sources and the shearographic sensor can be simply adjusted over three angles. The complete head-box can be connected with pneumatic pressure very safe with the object under test.

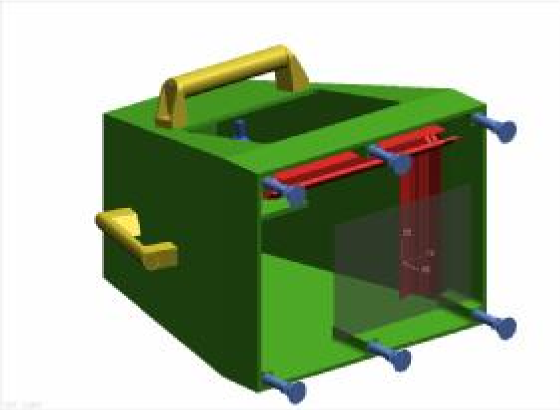


Fig.6: *Portable shearographic cabinet (head-box).*

3.2 Software

The software of the shearographic system is based on the shell of the BIAS Fringe Processor™ the so-called *Fringe Processor Shell* [7]. It is a Microsoft Windows XP™ based software system that requires the same hardware basis as Windows itself. No special hardware is necessary, the complete processing is performed by the general purpose processor of the PC. The *Shell* and its programming interface based on a hierarchy of C^{++} classes representing the used image types including some integer formats, a floating point and a complex format.

The user interface of the shearographic software is built up quiet effective and very easy to use with push-button operations. It is a very fast single-monitor system and works with either conventional hardware components like normal frame-grabbers, standard PC graphic cards, CCIR-format CCD-cameras or with IEEE-CMOS. A main feature of the shearographic software is to handle with several different windows. In this way it is possible to grab in the shearographic process and to observe the results while the live-mode under the same condition is still running and visualized on the screen. If a frame-grabbing situation is enabled the Fringe Processor *Shell* calculates automatically the phase-shifting image and its unwrapped-frame (demodulation) and shows them on the same screen (Fig.7). While the shearographic live-mode is running it is also possible for the operator to communicate with external hardware, such as the loading system, with sliders and push-buttons on the *Shell* main window. So it is practicable to vary the pressure in the vacuum-chamber loading system while watching the response of the measuring system simultaneously.

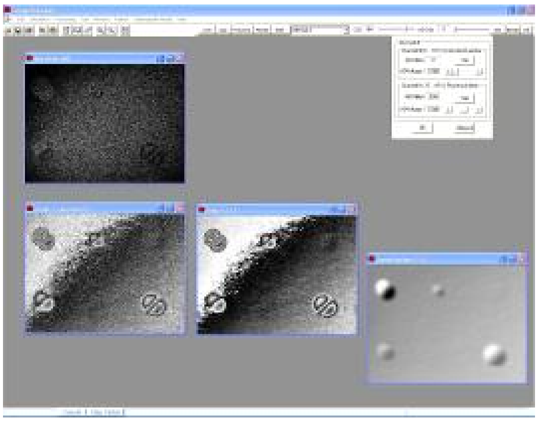


Fig.7: *Fringe Processor main frame in the shearographic operation mode.*

4. Results

4.1. Testing of technical objects

The following examples should visualize some results of our work by testing airplanes or airplane components. The shearographic investigations were made in cooperation with Airbus Germany (NDT-Group Bremen) and EADS Military Aircrafts (Material Testing Facility Manching, Germany).

Fig.8: *Shearographic head-box applied on an aircraft wing.*

With Fig.8 and 9 the application of the mobile shearographic equipment in a real maintenance environment is shown. In Fig.8 an aircraft wing will be investigated under thermal loading and in Fig.9 the aluminium body of the aircraft. The red cabinet contains the compact driver hardware. Inside this cabinet the power and the pneumatic supply for all components is situated. Beside the operator the shearographic head-box is in working condition. The bright light shining from the wings surface comes from the thermal infrared loading. In Fig.9 we can notice the actual live image from the running shearographic measurement.

Fig.9: *Shearographic head-box applied on an aircraft fuselage.*

The first here presented test sample is an aluminum honeycomb structure from the aircraft body (Fig.9). It is a metal-metal bonded aluminum type with pocket damages through the honeycomb structure. The size of the smallest fault is 10x10mm. The successful shearographic measurement result is shown in Fig.11. All damages are clearly visible. Besides, an unknown damage is located in the result pattern, also to be seen in the radiographic comparison as the white marked area (Fig.10).

Fig.10: *X-ray result image.*

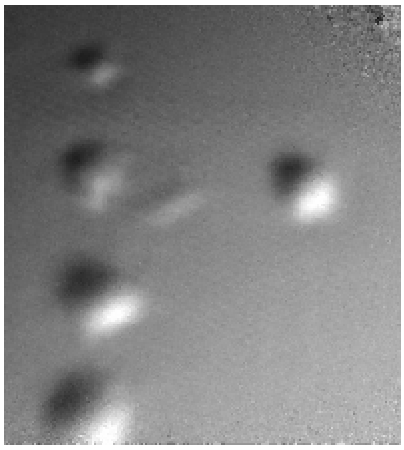


Fig.11: *Shearographic result image.*

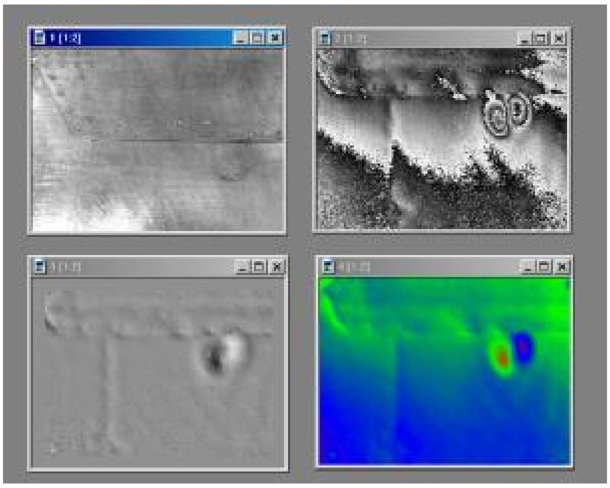


Fig.12: *Shearographic result images*

The next sample is also from the same aluminum sandwich type like in Fig.8. With Fig.12 we can see the object surface, the shearographic phase image, the unwrapped result image and the same with a colored look-up table. The clearly visible defect may be caused by an impact because the aircraft was in a heavy hailstone storm before it came to the maintenance facility.

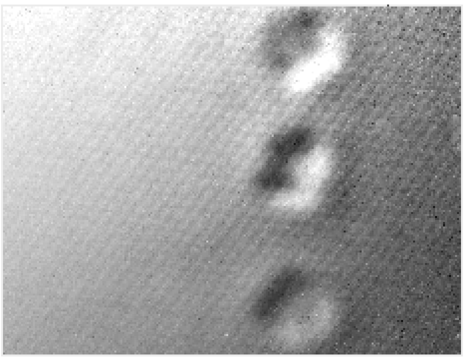


Fig.13: *Water in a honeycomb sandwich structure.*

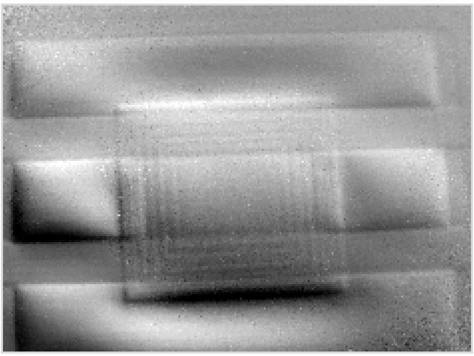


Fig.14: *Repaired monolithic stringer structure.*

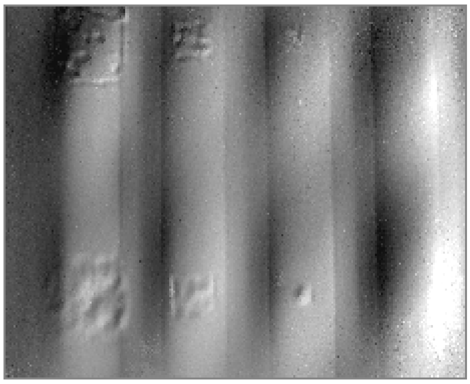


Fig.15: *Skin damages.*

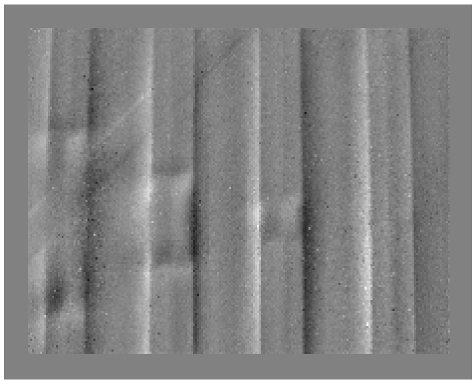


Fig.16: *Stringer debondings.*

The inspected material in all next presented results is CFRP. With Fig.13 we see a honeycomb sandwich structure which is introduced e.g. in the rudder. The inspected damage is water in the honeycomb core. In Fig.14 we notice a repaired monolithic stringer structure. The skin over the stringer was damaged by an impact. This record was made after the repair. The single CFRP-layers are clearly visible. The next results show monolithic stringer structures with different sorts of damages. In Fig.15 we notice delaminations of the skin with different extensions. The sizes range from 10mm to 50mm. In Fig.16 we have stringer debondings. The detected faults in the frame range from 50mm to 200mm.

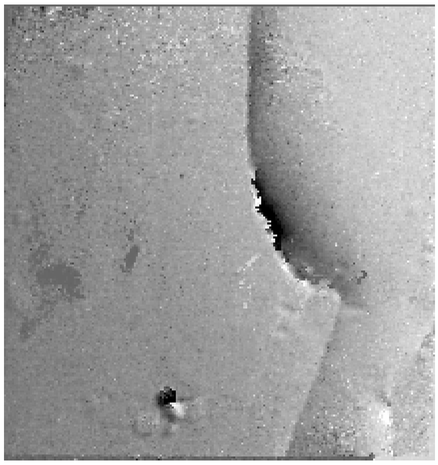
4.2. Testing of cultural objects

Many laboratory experiments have shown that holographic non-destructive testing is a powerful tool for the evaluation of artwork with respect to structural flaws, damaging and environmental influences. Recognition of sub-surface flaws, identification of individual sensitivity to handling and testing the effect of external climatic or other changes is of prime importance for precious artwork maintenance worldwide. Even when the most advance technology is implemented in museum preservation policies, such as x-ray facility to reveal structural interventions, gas-chromatography for pigment analysis, stereoscopic high-magnification microscopes, multi-spectral cameras etc., the provided information is point-estimated and the knowledge for the object remains segmented. Therefore in conservation communities worldwide there is a lack of an integrated method providing a detailed topographic map of flaws and defected regions while enables for the assessment of the best handling of single items and sensitivity to environmental and climatic changes. Digital speckle shearography and related optical techniques incorporate an integrated tool providing all the necessary structural information about the object of interest.

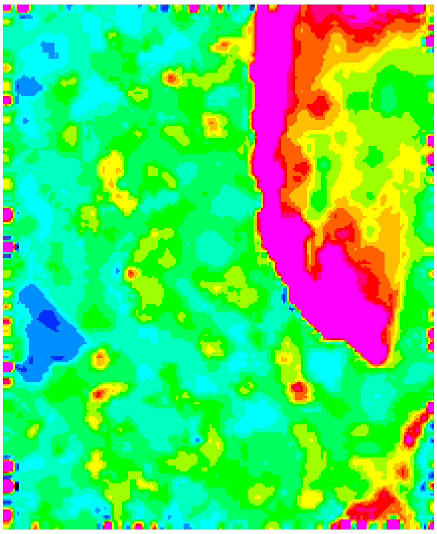
The shearographic system, developed by BIAS, was tested on historical Greek icons of the Velimezis collection in a joint action of the Benaki Museum Athens, Greece, the University of Ancona, Italy, (responsible for SLDV, Scanning Laser-Doppler-Vibrometry) and the F.O.R.T.H/IESL Heraklion, Greece, (responsible for holographic interferometry) [8].

a) *Icon*

b) *Shearogram made with thermal load*



c) *Demodulated phase map*



d) *Result obtained with SLDV*

e) *Overlay of results obtained with shearography and SLDV*

f) *Overlay of d) with the icon*

Fig. 17: *Inspection of an icon using shearography and scanning laser Doppler vibrometry.*

The primary carrier of an icon is a special wooden panel. Usually, the panel will be selected from the wood of the pine, cedar or the cypress tree. Only seasoned wood will be taken and the surface has to be prepared according to old Byzantinic traditions. In spite of a very careful prepared surface of the panel, it can't be prevent that cracks or delaminations of the paint or the gold leaf applications appear during the centuries. Due to these circumstances, it will be searched for new non-destructive technologies to evaluate the condition of these valuable artworks.

Exemplary, the following images show some results of the test series at the Benaki Museum. In Fig.17a we see a photo of the icon. Nearly in the middle of the sample from the top to the end of the gloriole we notice a crack at the painting. The amazing result of the shearographic measurement is not to certify this visible crack. But only the shearographic results to another part of the crack not visible under the painting (Fig.17b and 17c). Below with Fig.17d-f we can compare the results from the SLDV investigations (with kind permission of Enrico Esposito from University Ancona (Italy)).

Fig.18: *Photo of the icon and shearographic result images.*

Fig.19: *Sandstone sculpture illuminated with Nd:YAG laser light. Red marked the measuring area.*

With Fig.18 we see another icon with typical delaminations. The semicircle in the upper part of the frames is not a damage but belongs to the gloriole.

The last example shows investigations on sandstone sculptures. Fig.19 shows a sample under test. The laser illumination was produced by a Nd:YAG laser system. The thermal load brought only a 4°C difference temperature in the structure. Red drawn is the measuring area. A result can be seen with Fig.20. Clearly visible is a delaminated area of the sandstone surface.

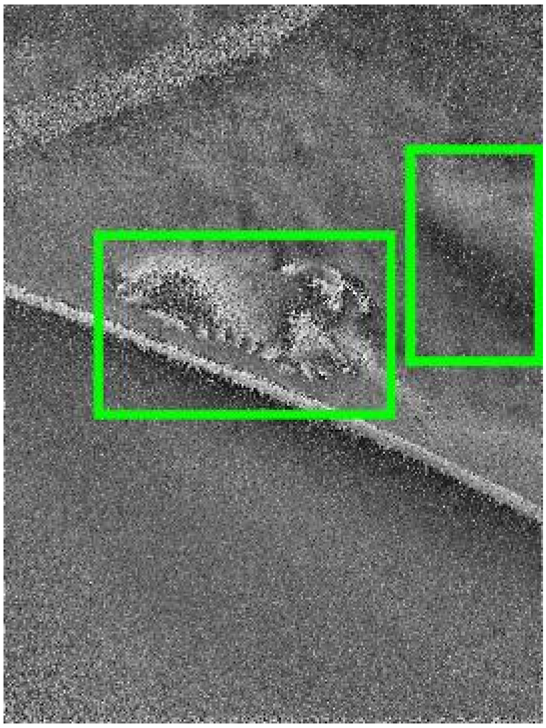


Fig.20: *Delaminated surface crust of the sandstone sculpture.*

5. Conclusion

A comprehensive shearographic testing device for the inspection of aircraft structures is achieved. The presented measurement concept is tested successfully on different aircraft materials and structures as soon as lightweight monolithic construction components, thin laminates and honeycomb-structures. The system is also suitable for sensitive cultural objects.

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Germany (Manching) for the constructive cooperation during the system tests at the maintenance facility in Manching [12]. Thanks also to R. Klattenhoff (BIAS, Germany) for his experimental work with the sandstone sculptures.

6. References

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