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IMAGE-BASED STRUCTURAL HEALTH MONITORING OF COMPOSITE STRUCTURES

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Abstract

The paper describes different image-based techniques that can be used for nondestructive inspection of composites. The focus is on four approaches: pulsed thermography, vibrothermography, laser Doppler vibrometry and shearography. All of the considered test techniques offer full field inspection capability and straightforward interpretation of test results. Structural damage can be identified from an image where the presence and the location of damage is readily available. These factors, together with a relatively simple measurement setup and short measurement times, make the considered techniques very attractive for industrial applications. In this study the experiments are performed on laminated composite samples. Both carbon fiber and glass fiber composites are considered. The paper describes the diagnostic procedures and inspection results for the considered measurement techniques.

1 Introduction

Permanent monitoring of structures was firstly introduced in rotating machinery in order to increase the reliability and safety [1]. In recent years however also other industries, including the civil engineering, wind energy and aerospace industries, notice the potential benefits of implementing on-line monitoring within the Structural Health Monitoring (SHM) framework [2-5]. Damage detection and monitoring are especially important in applications where the advanced composite materials are used. One of the factors responsible for that is the susceptibility of composites to impact damage [5]. The damage resulting from a blunt force impact is very hard to identify by visual inspection and causes a serious problem for the integrity and safety of structural components made of composite materials. As an example, in aerospace applications this type of damage typically results from collisions with ground service equipment, bird strike, hail impact or runaway debris during takeoff or landing. A number of different damage detection methods applicable to composite materials have been developed and tested over the years including: visual inspection, passive and active approaches based on ultrasonic signals, liquid penetrant testing, eddy current based methods, radiographic methods, image correlation techniques and thermographic methods [2-5]. In practical engineering applications the successful application of damage detection techniques often depends on the complexity of the experimental setup, the ease of interpretation of the diagnostic data and the need for reference signatures measured in the undamaged state. Measurement techniques considered in this study, i.e. pulsed thermography, vibrothermography, laser Doppler vibrometry and shearography overcome these obstacles. They offer full field measurement capability and damage detection is based on the analysis of the acquired images of the structure. Experimental setup is relatively simple (although some components of these systems are expensive) and they have been tested both in the laboratory and in field conditions.

This paper discusses measurement principles of these techniques and describes application test cases on composite samples.

2 Pulsed thermography

Every object at temperature above 0 K emits infrared radiation. Measurement of this radiation brings valuable information about the object. Measurements can be done by different means but one of the most valuable measurement devices are thermal cameras. Thermal cameras offer non-contact full-field measurements and high frame rate acquisition of thermographic images that can be used for diagnostic purposes. There are two basic configurations of thermographic inspection, namely the passive and active techniques [6,7]. Passive thermography monitors surface temperature of objects in order to identify anomalies in temperature distribution and localize thermal hot spots. Passive techniques are commonly used in applications like civil engineering, rotating machinery or medicine. Active thermography on the other hand assumes that external energy is delivered to an object in order to enhance the diagnostic procedure. The amount of energy, time of exposure and location can be precisely controlled in order to reveal damage features. The thermal energy can be delivered to the test object externally, by means of flash lamps or infrared lamps, or can be generated internally by exciting an object with vibrations or eddy currents.

Pulsed thermography belongs to the family of active thermographic techniques with external excitation. It is schematically presented in Figure 1. The experimental setup consists in: (1) a thermal wave source, which may be a halogen, flash or infrared lamp, (2) an infrared camera, (3) a control unit that allows to synchronize and trigger a measurement and (4) a personal computer with data processing software. If thermal source is located on the same side of a tested component as infrared camera the arrangement is called the reflection mode, if it is located on the opposite side the arrangement is called the transmission mode.

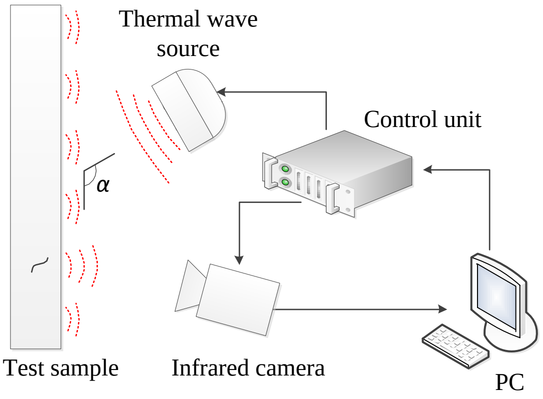

Figure. 1. Experimental arrangement of pulsed thermography

It has been shown in previous studies that pulsed thermography is well suited for damage detection in composite materials [6,8,9,10].

In this study, pulsed thermography measurements were performed on a prepared section of wind turbine blade with the dimensions 94×70 cm. Artificial defects were manufactured in the blade by removing the skin of the blade and creating disbonds between the skin and the internal stiffeners. After that the blade has been restored to its initial state using standard production methods. Pulse thermography measurement consists of two stages – heating and cooling. The heating process was performed with use of two high-power 2 kW lamps delivering the energy for 10 seconds, with 40 seconds of cooling phase afterwards. The test system was placed 50 cm from the inspected turbine blade. Because of the small distance to the object, a wide-angle lens has been mounted on infrared camera, which increased its field of view. The resultant thermographic image acquired during the measurement with post-processing applied in ThermoAnalysis software [11] is presented in Figure 2. The defect localizations are marked with rectangular overlays. Areas A1, A2 and A3 present inhomogeneity, which has been initially prepared. Areas A4 and A5 present internal structure defects that have not been prepared during manufacturing process, but have occurred during exploitation of the blade and have not been previously known.

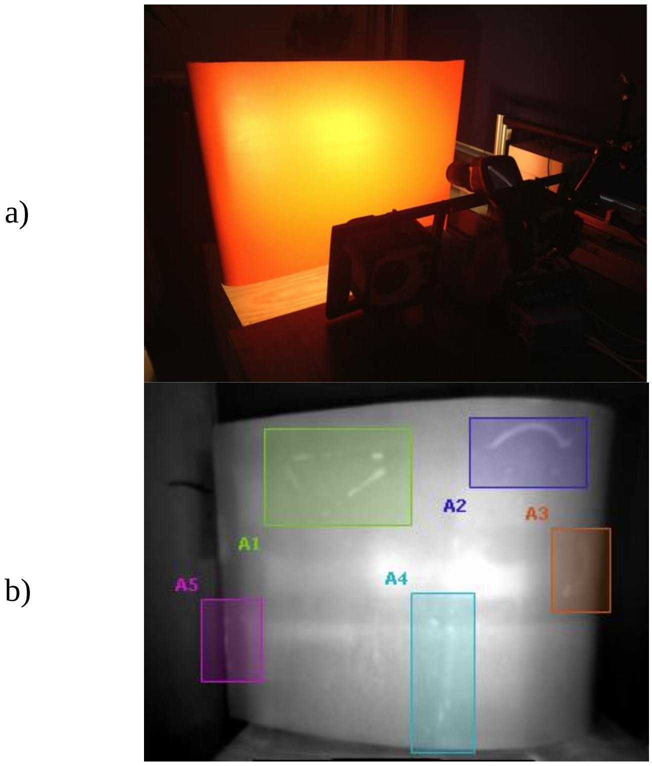

Figure 2 Test rig with pulsed thermography measurement system (a) and test result with highlighted areas containing defects (b).

3 Vibrothermography

Vibrothermography, also referred to as ultrasonic thermography or thermosonics, is an active thermographic approach with internal excitation [12]. It is schematically depicted in Figure 3. The experimental setup consists in: (1) an ultrasonic vibration source, (2) an infrared camera, (3) a control unit that drives the transducer and allows to synchronize and trigger a measurement and (4) a personal computer with data processing software. Ultrasonic vibration source is typically an ultrasonic welding setup that consists in a piezoceramic stack based converter and a waveguide composed of a booster and a sonotrode. Such setup allows for high power, narrowband frequency operation. Vibrothermography is very well suited for materials with intermediate thermal diffusivity values (the ratio of thermal conductivity to mass density and specific heat capacity of a material) as for example carbon fiber reinforced polymer (CFRP) composites [12-14].

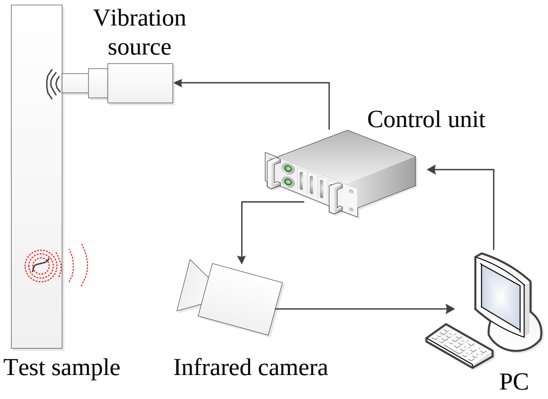

Figure. 3. Experimental arrangement of vibrothermography.

To demonstrate the effectiveness of the method, experimental testing was performed on a layered composite plate made of carbon epoxy prepreg system. The overall dimensions of the plate were 488x588x1.2 mm. The laminate was composed of 4 plies with [0,45,-45,0] ply stacking sequence. The plate has been damaged in a with low velocity impact event which resulted in matrix and fiber cracking in the vicinity of impact location.

The measurement was performed with the commercial vibrothermographic test system from *MONIT SHM* company [15]. Ultrasonic excitation at 35 kHz was delivered to the structure for 3 seconds at 20% maximum output power of the amplifier. The data was acquired and post processed using the *ThermoAnalysis* software package [11]. Thermal image processing in case of vibrothermography is less demanding than in case of other active thermographic approaches, because the heat source in vibrothermography is the damage itself. The energy of mechanical vibrations is selectively dissipated into heat at material discontinuities. For this reason, as a first step approach it is sufficient to just subtract the background temperature distribution on the sample, before the beginning of the test in order to observe only the portion of heat generated during the test.

Figure 4a presents the thermal image acquired before applying ultrasonic excitation. The initial temperature distribution on the sample was subtracted from the image therefore only the camera detector noise can be seen in the image. Figure 4b presents the thermal image acquired 3 seconds after applying ultrasonic excitation. The damaged area can be clearly identified as a bright spot in the image.

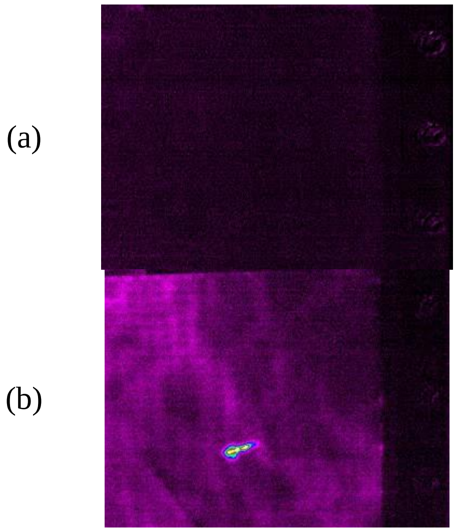

Figure. 4. Experimental arrangement of vibrothermography.

4 Laser Doppler vibrometry (LDV)

Laser Doppler vibrometry (LDV) is a noncontact measurement technique for measuring velocity of moving surfaces [16]. To determine the velocity of a moving/vibrating object, the Doppler frequency shift is measured at a known wavelength. This is done in the LDV by analyzing the optical interference of two coherent light beams. The beams are generated from one laser source (typically a helium neon laser) and sent through a beam splitter to produce the measurement beam, that is directed towards the moving surface, and the reference beam. Interferometer is used to analyze the frequency shift between the two beams and the velocity of the target surface is calculated. The measurement is noncontact and can be employed in situations that cannot be handled by other techniques as for example on very hot surfaces. In addition this measurement technique adds no mass loading on a structure, which is very advantageous for measuring vibration of small objects, membranes or thin plates. It has been shown that LDV measurements can be effectively applied to structural damage detection [17,18].

Experiments with LDV imaging were performed using the experimental setup shown schematically in Figure 5.

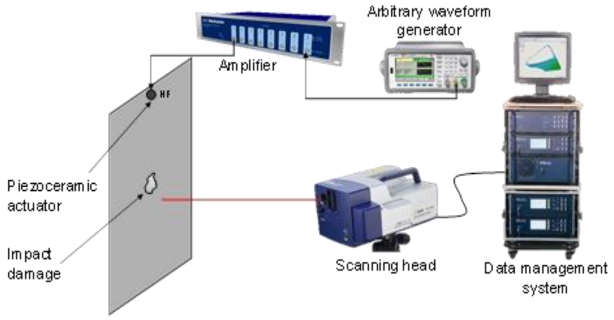

Figure. 5. Experimental arrangement of scanning laser Doppler vibrometer (LDV) measurements.

The specimen chosen for experimental testing was a rectangular composite plate of the size 120×420×2mm. The laminate was composed of 12 plies with $[0_3/90_3]$s stacking sequence. The plate was made of a carbon epoxy prepreg system. Damage was introduced in the composite plate using a drop-weight impact testing tower instrumented with a hemispherical indenter. During testing, the composite specimen was simply supported on a steel plate with a rectangular opening and subjected to two impacts at two adjacent locations close to the main symmetry axis of the plate. The distance between the impact points was approximately 12 mm and the impacts on the two locations had energies of 6 J and 3.9 J, respectively.

For LDV measurements the plate was suspended using elastic cords to simulate free-free boundary conditions. The excitation was applied by a surface-bonded *Noliac CMAP* stack actuator driven by the *EC Systems PAQG* signal amplifier. A *Polytec PSV-400* scanning laser vibrometer was used for non-contact measurements of vibration responses at 2345 points on a 35×67 measurement grid. Excitation signal was a wave packet of 8 cycles 100 kHz wave in a Hanning window.

Figure 6 shows the root mean square (RMS) value of the out of plane vibration velocity measurement in the area of damage. As can be seen the damage can be clearly identified as the areas with increased RMS values of vibration velocities. Four regions of increased amplitude can be identified corresponding to the locations of internal delaminations that resulted from the impact test.

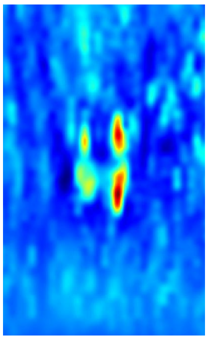

Figure. 6. Result of the laser Doppler vibrometer (LDV) measurements. Damaged areas of the laminate are visible as bright spots on the image.

4 Shearography

Shearography is the common name for the digital speckle pattern shearing interferometry (DSPSI) [16]. It is a full-field nondestructive testing technique that can be used to screen the structural components for surface irregularities and internal defects. The structure being studied is illuminated by a coherent laser light and a stochastic interference pattern is created on its surface. The image of the test object is sheared to create two superimposed images and a digital camera is used to record the resulting shearogram. The speckle pattern changes when the object is deformed, typically due to mechanical or thermal load. The two speckle patterns (in the unloaded and loaded states) interfere to produce a fringe pattern that provides information on the first derivative of surface deformations. Shearography with thermal excitation is a noncontact measurement technique with a relatively simple hardware setup.

In the present study the *Steinbichler ISIS 1100* system was used [19]. The system uses thermal excitation and consists of a sensor with attached heating lamps mounted to a tripod. The sensor has a central shearing optics unit combined with a phase shifter and an attached illumination segment with symmetrically arranged laser diodes. On either side of the laser diode segment, powerful heating lamps have been added to allow for homogeneous thermal loading of the object under investigation. The value of 5 mm horizontal shear was used.

Measurements were performed on the same composite specimen that was previously used for LDV experiments. Results of the shearography inspection are shown in Figure 7. As can be seen the shearogram acquired on the plate under thermal loading clearly reveals the presence and location of the internal damage.

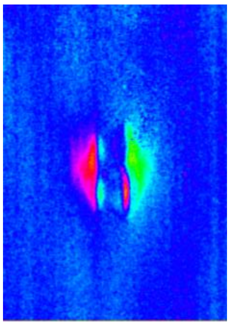

Figure. 7. Result of the shearography test on the test specimen. Bright areas on the image indicate the location of damage.

5 Summary and conclusions

The paper presented the application of four different image-based damage detection approaches to composite structures. The methods that have been considered include pulsed thermography, vibrothermography, laser Doppler vibrometry and shearography. It has been shown on different test cases that all of the discussed techniques can be effectively applied to identify damage in composite structures. Moreover the methods have the advantage of delivering the result in form of an image where the presence and the location of damage is readily available, also for a moderately qualified technician. These factors, together with a relatively simple measurement setup and short measurement times, make the considered techniques very attractive for industrial applications.

Acknowledgments

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