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2D and 3D non-destructive evaluation of a wooden panel painting using shearography and terahertz imaging

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ABSTRACT

Structural diagnostics information about artwork is commonly obtained by adapting and applying non-destructive testing techniques from engineering. Shearography is a technique well known for type inspection, and for structural analysis in automotive, aerospace and industrial applications. In art conservation, a limited number of shearography sensors are in use at museums and research institutes throughout the world for detecting surface and sub-surface defects. Terahertz imaging is a new and rapidly developing non-destructive testing technique that has so far found application mainly for security. The aim of this study is to measure a complex object, a wooden panel painting using both techniques and to determine the capability of a combined sensor for cultural heritage applications.

1. Introduction

Art is one of the products of cultural heritage; hence its preservation is necessary for the continuation of the historical evolution of the human species. In order for artefacts to be preserved, art conservators need to constantly record the condition of objects and, if necessary, to apply methods and materials which stabilize their condition without affecting the integrity of the object. Therefore, a thorough understanding of the exact preservation condition is necessary. This can be achieved mainly by structural diagnosis techniques, which can offer unique information concerning structural evolving defects which are quite often not observed by other techniques. Structural diagnostics techniques can lead to the identification of specific areas in need for immediate treatment and can also guide the conservator to the choice of proper methods and materials.

Structural diagnostics [1] is one of the main fields in lasers in the conservation of artwork [2,3]. A number of optical and related techniques are employed for the non-invasive, non-destructive investigation of panel paintings. Speckle interferometry [4], shearography [5] and holography [6] provide interferometric resolution displacement data on the object under loading. Optical coherence tomography [7] is able to measure the thickness of paint and other semi-transparent layers at tens of micrometer resolution. The X-ray radiography [8] gives a non-invasive measurement of the internal structure of art objects and X-ray spectroscopy [9] is among the most popular and has the ability to detect under-drawings, cracks, knots, nails and damage produced by wood-boring insects, it cannot, however, detect detachments, inborn and evolving defects. Up to now, terahertz (THz) radiation has only been applied in a limited way to spectroscopic applications in art conservation, including ink pigments [10,11], investigation of under-drawings [12,13] and the analysis of paint pigments [14,15].

Terahertz radiation (0.1–10 THz, $\lambda = 3000$–$30\,\mu m$) exhibits properties which make it interesting for quality control and inspection. For example paper, canvas and dry wood have a medium absorption coefficient in this frequency range, which gives a good contrast in imaging applications [16]. Using fs-lasers it is possible to generate and detect, not only continuous wave (cw), but also single cycle ultra-short THz-pulses covering more than one order of magnitude in the frequency range [17]. Due to the possibility of coherent detection of the complete electromagnetic field, the intensity can be recorded time-resolved, which makes it possible to determine the amplitude and time delay of measured pulses directly. Thus, it is possible to get structural 3D information of a sample under investigation.

Shearography [18], also known as speckle shearing interferometry, is a speckle interferometry technique usually used for non-destructive testing and strain measurement. Shearography is a double-exposure technique. Interferograms recorded before and after object deformation are processed to give unwrapped phase

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maps. After unwrapping the phase discontinuities a map of the displacement gradient field is obtained.

The focus of this paper is to use terahertz imaging as a structural diagnostics tool to gain 3D information about a wooden panel painting sample. The sample is of realistic construction, as described in Section 4, to allow the investigation of measurement techniques in a controlled way on a test sample with similar characteristics to a real artwork.

The terahertz imaging results are compared with the shearography surface and sub-surface non-destructive results. The results are then merged to provide detailed information about the structural state of the object. The final step is the comparison of results from the art conservation point of view, comparing them with the detailed drawings, photos and notes prepared during the sample construction.

2. Shearography

Shearography [18,19] is a full-field speckle interferometry technique sensitive to displacement gradient. In shearography the reference is scattered light from the object surface, displaced in the interferometer to form a double image. This interferometer is therefore common path and as such is relatively insensitive, for an interferometric sensor, to environmental disturbances, such as rigid body motion.

To perform a measurement the object is illuminated by the expanded beam from a laser. The light scattered by the optically rough surface of the object forms a speckle pattern which is imaged through a shearing interferometer. This generates an interferogram, which can be recorded by a camera. Shearography is a double-exposure technique. Interferograms are recorded either before and after loading, or at two points in the loading cycle, and are correlated using a computer. Fig. 1 shows a typical experimental layout.

The component of displacement gradient measured is determined by the shear direction and by the object illumination and viewing directions. Direction and magnitude adjustments of the shearing interferometer control the displacement gradient component measured and the measurement sensitivity. The most common configuration is sensitive to one of the out-of-plane displacement gradients, as given by Eq. (1)

$$\Delta\phi_{(x,y)} = \frac{4\pi}{\lambda}\frac{\delta w}{\delta x_{(x,y)}}\,dx, \text{ or } \Delta\phi_{(x,y)} = \frac{4\pi}{\lambda}\frac{\delta w}{\delta y_{(x,y)}}\,dy \tag{1}$$

where $\Delta\phi$ is the phase change in the interferometer, λ the optical wavelength, $\delta w/\delta x$ the out-of-plane displacement differentiated in the horizontal direction, $\delta w/\delta y$ the out-of-plane displacement differentiated in the vertical direction, and dx and dy are the horizontal and vertical shear magnitudes, respectively.

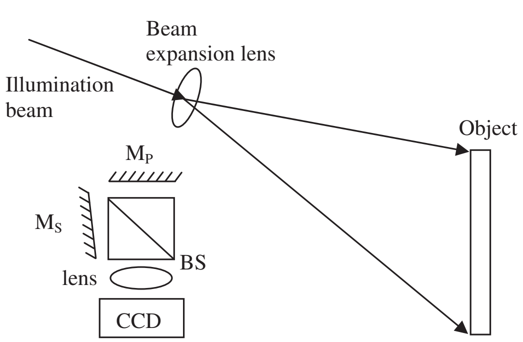

Fig. 1. Shows a typical shearography experimental layout. The illumination beam is expanded by a lens to illuminate the surface of the object. Light scattered by the object to the interferometer is optically mixed and is imaged onto the camera chip, CCD, by a lens. The interferometer components are beam splitter, BS, phase-shifting mirror, M_P, and shearing mirror, M_S.

The simplest form of phase correlation is subtraction. More commonly phase-shifting is used to recover the phase without ambiguity in the phase direction in the form of a wrapped phase map [20]. Phase unwrapping [21] is an optional final step to remove the phase discontinuities at fringe boundaries. The unwrapped phase map generated by this process can be scaled by referring to Eq. (1), to obtain the displacement gradient field.

3. Terahertz imaging

One method for the generation and coherent detection of ultra-short THz-pulses for imaging is based on femtosecond laser pulses [17], see Fig. 2. These fs-pulses are split into a pump beam and a gate beam. The pump beam polarization is turned by a half-wave plate ($\lambda/2$) to achieve a maximum absorption at the THz-emitter and the pump beam is chopped for phase sensitive amplification of the signal. For THz generation, the pulses are focussed onto a surface emitter (p-doped InAs) to emit single cycle THz-pulses. The outward radiated THz-pulses are collimated by an off-axis parabolic mirror and focussed by a lens into the sample. A second lens and a second off-axis parabolic mirror focus the THz-pulses into the electro-optic detection crystal.

The linear polarized gate beam is delayed by a mechanical translation stage and is also focussed into the detection crystal for probing the THz-pulse. Inside the electro-optic crystal, the linear electro-optic effect (Pockel's-effect) rotates the gate beam polarization proportionally to the electric field of the THz-pulse. This polarization in turn is converted to an intensity change by a quarter-wave plate ($\lambda/4$), which turns the linear gate pulse polarization into circular polarization. A polarization-dependent beam splitter (e.g. a Wollaston prism) separates both polarization components. The intensity change between the arms is measured by a balanced detector and is approximately proportional to the electrical field of the THz-pulse. Because of the gate pulse being an order of magnitude shorter than the THz-pulse, only a part of the THz-pulse is measured. By moving the optical delay line, the time delay between the two pulses is changed and the THz-pulse can be sampled time-resolved as shown in Fig. 3(a). A more detailed study on the electro-optic detection of ultra-short THz-pulses can be found in [22,23].

For THz-imaging the object is placed on a motorized x/y stage to move it in the focal plane. The measured THz-pulses are analyzed with respect to amplitude and time delay as shown in Fig. 3(b).

4. Sample construction

The structural diagnosis of panel paintings is a procedure which investigates complex systems of materials and defects that in many cases are not visible to the naked eye. To develop structural diagnostic techniques, artificial samples that satisfactory simulate original objects are required. For the application of these methods to panel paintings, one artificially made sample was constructed (Fig. 4). The protocol of construction was based on the traditional techniques described by the famous art masters of the time, such as Dionysios ek Fourna and Cennino Cennini [24]. Additionally, the study of the most typical defects found on panel paintings led to the selection of the ones chosen for the construction of the model sample (Table 1).