Simple Electronic Speckle Pattern Interferometer (ESPI) for the investigation of wooden art objects

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Abstract
The development of a simple electronic speckle pattern interferometer (ESPI) for the non-invasive, non-contact detection and characterization of early-stage damage of painted surfaces, like fracturing and layer separation, is reported. The ESPI system developed relies on the analysis of sound-induced vibration of the investigated surfaces. A simplified optical system as well as special algorithms for the analysis of interferograms were developed for the purpose of gaining precise information on the different indicators of the destruction process: the characteristic resonance frequency for the damaged area, its size and the spatial distribution of the vibration amplitude. The technique was applied to trace damage in specimens of painted wood subjected to damaging cycles of dimensional change.

1. INTRODUCTION
The detection, characterization and tracing of the development of early-stage damage of painted surfaces using non-invasive (non-sampling, non-contact) techniques is a very important task for conservation science, as works of art are usually both fragile and extremely valuable. In particular, preventive conservation in museums and historic sites needs scientific tools capable of detecting cracks, delaminated areas, the fracturing of decorated surfaces at the micro-level well before damage becomes visible. They can serve as ‘early warning’ systems and help to establish an acceptable range of environmental conditions in the micro-environment of art objects on display, while in storage or during transportation.

The past ten years have seen much interest in the application of deformation/strain measurement techniques for the inspection and monitoring of works of art, covering point-strain measurements using resistance-strain gauges and fibre-optic sensors, as well as full-field optical measurement approaches such as holography, electronic speckle pattern interferometry, photoelastic stress analysis and photogrammetry. Dulieu-Barton et al. reviewed the relevance of each technique from a conservation perspective through accounts of usage on a wide range of artworks, including panel paintings, statues, wall-paintings and mosaics [1]. An earlier review by Ambrosini and Paleotti [2] critically discussed the developments in the use of holography and related techniques in the cultural heritage field since the first application of holographic interferometry to diagnose paintings in 1974 [3, 4].

Electronic speckle pattern interferometry (ESPI) has proven an especially attractive optical-based non-contact tool for the investigation of artworks made of diverse materials [5-9]. The technique is very accurate, being capable of mapping out-of-plane displacements to a fraction of a micrometer. It also has the capability to detect fractures, micro-cracks and surface flaws. However, despite its unique characteristics and established diagnosing capacity, ESPI has not yet been applied on a wider scale in day-to-day museum and conservation practice. There are several reasons that prevent the use of ESPI by conservation practitioners. Commercially available ESPI systems are expensive and require trained researchers to carry out the measurements and interpret the results. In particular, defect identification and the analysis of defect development is not simple or unambiguous, as it requires relating the registered deformation of the object’s surface to the change of its mechanical characteristics.
The principal aim of this study was to design, build and implement a simple and inexpensive electronic speckle pattern interferometer which could be used as a standard diagnostic tool in museums and field work, capable of making measurements at the micro-level scale. An optimisation of the apparatus, measuring protocols and analysis algorithms is proposed based on inexpensive and high-quality optical components available on the market and also the sufficient computing capacity of portable computers.

2. FEATURES OF THE ESPI INSTRUMENT

The diagram of the optical setup of the instrument is presented in Fig.1. A laser beam from a continuous-work diode-pumped Nd:Yag laser (100 mW) is divided into two beams, called object and reference beams, using a glass plate. The object beam illuminates the investigated surface while the reference beam passes through the ground glass and is merged with the beam reflected from the investigated object using a beamsplitter cube. The object and reference beams superimpose coherently producing an interferogram recorded by a BCi4-6600 CCD camera. The interference of light is possible only when the difference between the optical paths of the object and reference beams does not exceed the coherent length of the light source. In the developed system, a laser light source with the coherence length of 30 meters (the distance at which interference of the laser light is possible) is used, which exceeds all dimensional scales involved in the measurement. The parameters of the CCD camera - 6.6 MPixels with 3.5 x 3.5 pixel pitch - together with the long coherence length of the laser also make possible measurements for large-scale objects like wall-paintings or other architectural surfaces. An important feature of the camera is its ability to increase the frame-recording rate with the simultaneous reduction of spatial resolution. This feature makes it possible to trace processes in small areas at a reduced resolution and high frame-recording rate, or trace long-term changes for large-scale objects at a high resolution and slow frame–recording rate. It should be stressed at this point that both the light source (laser) and the detector (CCD camera) are crucial for the measuring system to perform well, but the system can be made less expensive by the careful selection of their operational parameters.

Fig. 1. Experimental setup for ESPI

The simplification of the design and operation of the system without compromising its sensitivity was achieved by simplifying the optical system, in particular by reducing the optics that form the reference beam. A ground glass was used in the reference beam path before the imaging optics [10]. As a result, the reference beam is a speckle beam but the performance of the system is unchanged from that with a
smooth reference beam with the exception that the irradiance of the reference beam contains a position dependent phase. This fact must be taken into consideration when choosing a proper algorithm for the analysis of the interferograms. The adopted solution has two advantages. Firstly, it avoids a complicated and expensive optical system for the reference beam. Secondly, the reference beam does not need to be realigned when the distance from the object, or size of the analyzed area, is changed, which is very convenient for an operator. Realigning the instrument, while recording data, is very simple, as it is carried out by focusing imaging optics - using a commercial camera lens - and choosing the intensity of the reference beam by rotating one of the linear polarizators in the reference beam path.

Sound- or thermal-induced deformation of the object’s surfaces can be recorded and analyzed to provide information about the preservation state of the surface as well as the development of damage. However, to obtain quantitative information about damaged areas, it is crucial to know the exact values of the dimensional response of damaged areas to stimulation. Since the interpretation of recorded interferometric patterns is difficult and even ambiguous, a method for the determination of absolute values of phase at every point is needed. This is achieved by using a liquid crystal ARCoptix phase shifter with 10nm adjustment precision for recording several images with well-defined phase shifts between the object and reference beams. These images are used for phase unwrapping, and provide straightforward deformation data.

The last element of the optical system is a narrow band interferometric filter placed right before the CCD matrix. The filter is chosen to block all wavelengths different from 532 ± 1nm which is the output wavelength from the Nd:Yag laser used in the instrument. Therefore, any ambient light is blocked and the interferometer can be used for the investigation of objects illuminated by sunlight or artificial light.

The ESPI method proposed in this study has been based on the analysis of sound-induced vibration of the investigated surface. A signal with controlled frequency and amplitude is generated by a National Instrument NI PCI 6221 computer card, and further transformed by a Monacor Img Stage Line STA-302 amplifier. To generate a sound wave, a Monacor MPT – 177 loudspeaker with a frequency range from 3.5 to 20 kHz is utilized. The sound wave can induce vibrations of delaminated parts of a decorative layer when the generated wave is close enough to the resonant frequency. When the time of measurement is much longer than the vibration period, the intensity of light in the plane of the interferogram can be represented as a two-dimensional fringe pattern [11] and provides information on the amplitude of the object vibration. However the information is still relative because the intensity of light as well as its initial random phase in plane of interferogram are unknown. One may assume that the intensity of light is constant during the time of the measurement so its value is irrelevant for the final result of the analysis, but the map of the initial phase values is a key piece of information which must be found for an unambiguous analysis of the deformation of the surface.

DATA ANALYSIS

In general, there are two types of phase-unwrapping procedures: temporal and spatial [12]. In the presented system, the first type of procedure is applied. In order to simplify the calibration of the instrument and the measuring procedure, a version of the normalized max-min phase shift scanning routine proposed by Vikhagen [13] was utilized. The process of fringe identification in the obtained interferogram is semiautomatic. A preliminary identification of fringes is done manually but the procedure of the assignment of particular pixels on the image to consecutive minima and maxima of the Bessel function is automatic – based on an iterative algorithm.
An exemplary analysis of the damaged specimen of painted wood is presented in Fig. 2. Gesso was composed of rabbit-skin glue and ground chalk; the ratio of the inert solid to glue expressed as the pigment-volume concentration (PVC) was 92%. The PVC value was practically selected by a participating restorer as being that which has been commonly used in the restoration of panel paintings. Six coatings of gesso were laid and the thickness of dried gesso layer was approximately 1 mm. A crack and a loss in the decorative layer are visible in the upper part of the specimen (Part (a) of the figure). A series of measurements were performed at increasing frequency of the sound enforcing vibration of the surface, which enabled the detection of the delamination on the right side of the vertical crack. Furthermore, the measurements revealed the existence of two mechanically independent delaminated areas divided by another, horizontal crack visible on the photograph. For the best visualisation of the complexity of the damaged area, a sound frequency of 3400Hz was chosen to induce vibration of the surface. This frequency is intermediate between the resonant frequencies of the two delaminated areas, thus allowing the vibration of both areas to be simultaneously observed. The difference in response to sound vibration for both areas is clearly visible in Fig. 2b and a further analysis of the interferometric fringes gives precise information about the spatial distribution of the vibration amplitude for the investigated area. The results are presented as a 2D map of isolevels drawn every 40nm (Fig. 2c) and a 3D map (Fig. 2d).

**MONITORING THE EXPANSION OF DAMAGE**

An exemplary result is shown in Fig. 3. The measurement was performed on a wooden board coated with a gesso layer. In the central part of the specimen, a circular area of delaminated gesso about 1 cm in diameter was introduced. To record differences in the state of preservation of the object during the damage development process, two measurements were made. The first, the reference measurement, was made before the application of any external forces on the object while the second was performed after the object had been subjected to damaging cycles of stretching and compressing. Temperature and relative humidity in the laboratory were kept constant during the measurements to eliminate their influence on the surface shape. The amplitude of the stretching/compressing cycles was increased until...
some additional damage was detectable. An interferogram for the damaged specimen obtained by the thermally induced ESPI is shown in Fig. 3a: three microcracks are visible on the surface of the decorative layer. Sound-induced ESPI measurements conducted prior to and after damaging cycles and the respective interferograms reveal the vibrating delaminated areas, and are shown in Figs. 3b1 and b2 (the respective resonant frequencies were 11.5 and 11.8 kHz). The comparison of the two images allows the shape and size of the delaminated areas to be determined. A detailed calculation gives a 6% increase of the delaminated area as a result of the damaging process. The spatial distribution of vibration presented in Figs. 3c1 and 3c2 also differs for both cases, but the difference is not very pronounced. On the other hand, an easily detectable change appears in the resonant frequencies of the delaminated areas (Fig. 3d). The resonant frequency shift of about 300 Hz reflects a change in the mechanical properties of the defect with a high sensitivity, and can serve as a quantitative measure of the development of the damage.

Fig. 3. Different indicators of the development of damage recorded using sound-induced ESPI. See text for explanation.

In conclusion, it can be stated that rough changes of size and shape of the delaminated area can be followed relatively easily by recording the vibrating areas after each consecutive damaging event (the analysis is fast and direct). Though the distribution of the vibration amplitude changes when the delaminated area increases, the parameter is difficult to measure since it depends on the relative position of the loudspeaker and the investigated surface. The resonant frequency of delamination is the most sensitive parameter determined by the developed system. Moreover, it is independent of the relative position of the camera, the loudspeaker and the object, or the amplitude of the sound.

CONCLUSIONS

A simple ESPI system, capable of measuring sub-micrometer, out-of-plane surface deformations and thus able to detect early-stage development of damage in decorated surfaces of works of art, was developed. By an appropriate design of the instrument and selection of the measuring protocols and analysis algorithms, it was possible to significantly reduce the costs, to make the device simple without losing its sensitivity, and to meet the requirements of practical use in the cultural heritage field also by non-research personnel with backgrounds in conservation or heritage management. The results presented have demonstrated that the relatively simple system developed is adequate in terms of accuracy and repeatability for any practical requirements of the conservation field. The multilevel analysis of the data proved capable of providing information on a desired level of complexity and accuracy.

The speckle interferometer described is still a laboratory device. However, the results presented establish firm foundations for the development of a fully portable instrument which can be taken to museums and historic buildings and can operate on site.
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