Simple digital speckle pattern interferometer (DSPI) for investigation of art objects

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Technical development and practical evaluation of a simple digital speckle pattern interferometer (DSPI) for the non-invasive, non-contact detection and characterization of early-stage damage of painted objects of art, like fracturing and layer separation, are reported. One of the most important features of the presented measuring system is a possibility to progress stepwise from the simplest version of the instrument based on the digital image correlation (DIC), to more advanced and accurate ones: DSPI for thermally- and sound-induced surface deformation. Analysis of the resonant frequency of a vibrating delaminated paint layer was, for the first time, used to detect the damage progress in polychrome wood and proved to be extremely sensitive and accurate. This method, together with two other presented in the article makes the multilevel analysis of the preservation state of the object's surface possible and provides information on the damage on a desired level of complexity and accuracy.

Keywords: speckle interferometry, non-destructive testing, painted wood, art objects, delamination, fracturing.

1. Introduction

Painted objects and works of art form a significant part of human cultural heritage. The paint layer can perform the practical task of protecting utilitarian objects, or embody spiritual and artistic expressions in panel and canvas paintings, polychrome sculpture and wall paintings that decorate interiors of historic buildings. Whatever their design or purpose, all painted surfaces are complex, layered structures, in which the substrate is coated with glue, priming layers, paints and varnishes. As materials that constitute painted surfaces exhibit differential dimensional responses to variations of ambient conditions, internal stresses can develop which, above certain critical levels, can cause mechanical fracturing: cracks and layer separation at all levels across the structure of the painted surface.

The detection, characterization and tracing of the development of early-stage damage of painted surfaces using non-invasive, preferably non-contact techniques is

an 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 the fracturing and delamination of decorated surfaces at the micro-level well before damage becomes visible. Early detection of damage can help to establish an acceptable range of environmental conditions in the 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. Digital speckle pattern interferometry (DSPI) has proven an especially attractive diagnostic tool for the investigation of artworks as it is a portable, non-contact, full--field holographic technique that offers sub-wavelength sensitivity in displacement measurements. Therefore, it has been used to detect fractures and surface flaws of diverse heritage objects such as panel paintings [1–3], frescoes [4, 5] and mosaics [6] by observing the surface movement produced when the object is subjected to a stressing force. A thorough description of advantages and limitations of the interferometric techniques applied to the analysis of panel paintings since the early 1970s was presented by AMBROSINI [7]. Issues of portability, as well as integration and modifications of the various techniques were discussed in references [8–10].

Recent development of lasers as well as computerized, automatic fringe recording and processing algorithms have provided laser speckle metrology with advantages of very high accuracy and measuring rate in comparison to alternative measuring techniques [11, 12]. Nevertheless, despite its unique characteristics and established diagnosing capacity, DSPI 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 DSPI by conservation practitioners. Commercially available DSPI 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 nor 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 digital 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. The system proposed is, on the one hand, affordable and simple in construction and operation, and, on the other, capable of recording features of multilayer surfaces quantitatively and with a high precision. Furthermore, the system developed is flexible; by a careful choice of experimental setup and analysis algorithm, users can progress stepwise from the simplest to more advanced and accurate versions of the instrument, when their experience and ability to use the system increase.

An optimization 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 DSPI instrument

2.1 Digital image correlation (DIC)

DIC is the simplest interferometric method which can be adopted to the analysis of surface damage [11–14]. The diagram of the optical setup is presented in Fig. 1. The surface investigated is illuminated by a laser beam from a diode-pumped continuous-wave frequency-doubled Nd:Yag laser (Power Technology IQ5C100(532-130) with 100 mW output power) and the scattered light is recorded by digital camera. The BCi4-6600 CMOS Camera produced by C-cam technologies (6.6 MPixels with 3.5×3.5 µm pixel pitch) was used in all experiments together with two different lenses (25 and 75 mm focal lengths) provided by Goyo Optical Inc. A narrow band interferometric filter is placed in front of the camera. This filter blocks all wavelengths different from 532±1 nm, which is the output from the Nd:Yag laser, allowing the instrument to be used in the ambient light. The optical system was built using glass lenses, aluminium mirrors and broad band polarizers provided by Laser Components GmbH. During the measurement, the camera is recording a speckle image – a granular pattern of bright and dark spots – which results from mutual interference of the reflected laser light. When a deformation of the same order as the wavelength of the laser appears on the surface investigated, a change in the speckle pattern occurs. The change can be visualized by digital subtraction of the acquired and stored images. In our case, DIC is used to map local microscopic displacements of the surface induced by variation of the surface temperature. The surface is heated with a flow of warm air for a few seconds. An increase of the surface temperature by approximately 2–3 °C is sufficient for producing high contrast images. Immediately after heating, a speckle pattern on
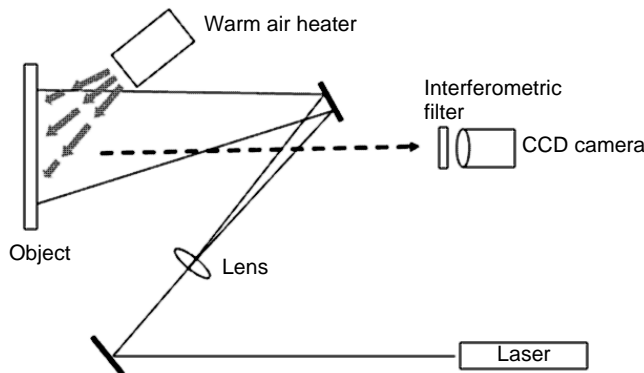

Fig. 1. Experimental setup for digital image correlation.

the surface investigated is recorded as a reference image, then the consecutive images are subtracted arithmetically using the computer and the difference is displayed on the monitor. Local inhomogeneities or structural faults of the surface undergo cooling at different rates, which leads to local out-of-plane displacements visible as bright areas. In this way, features of the painted surface such as delaminated areas of a paint layer or cracks can be detected.

An example of measurement of damage development in a design layer on a wooden support is shown in Fig. 2. The specimens imitating the historic painted wood were prepared in a laboratory following the historic technologies: wooden boards were sized with a solution of rabbit glue in water and coated with six layers of gesso (a mixture of rabbit glue and chalk at a pigment-volume concentration of 92%). The specimens were subjected to cycles of stretching and compressing using a Universal Testing Machine (Inspekt Table with maximum load 10 kN provided by Hegewald & Peschke GmbH), which simulated swelling and shrinkage of wooden boards caused by variations of the ambient relative humidity in the real-world environments. The specimens were taken out after a predetermined number of strain cycles and the state of their surface was monitored. Figure 2**a** shows an initial state of the painted surface whereas Figs. 2**b** and 2**c** show the development of cracks in the gesso layer at two consecutive stages – after 5 000 stretching cycles of the amplitude of 0.25% and after additional 18 000 stretching cycles of the same amplitude, respectively.
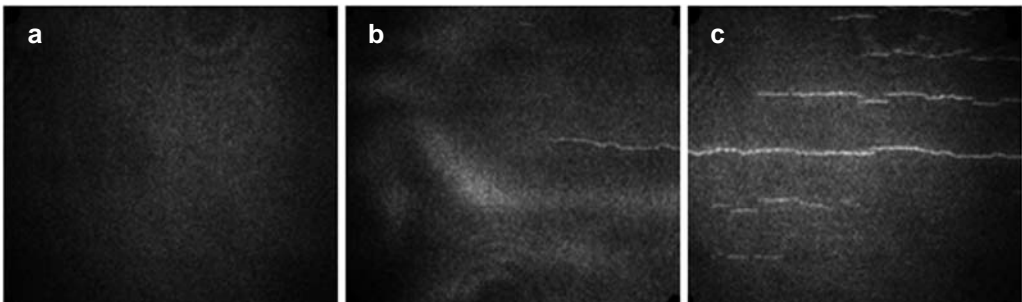

Fig. 2. Microcrack development in the course of damaging cycles of stretching/compressing of a painted wood specimen as visualized by DIC: state before – undamaged design layer (**a**), a single crack formed after 5 000 stretching cycles (**b**), a network of cracks formed after further 18 000 stretching cycles (**c**).

The experiment shows how DIC can be used to detect early damage of the decorated surfaces. In fact, it provides quantitative information on the number of cracks in the surface layer and their length. Consequently, a precise comparison between preservation states of the object before and after any potentially dangerous event, or just at different points in time, is possible. It should be stressed that damage of the design layer is detected at an early stage long before the object needs any conservation treatment. Therefore, this very simple diagnosing technique can be used in preventive conservation as an early-warning system.

DIC is an attractive technique as it is easy to apply, the interpretation of the results is simple, and a useful visualization of damage is obtained. However, as will be shown below, DIC is less sensitive than the full DSPI in providing more quantitative characteristics of the damage.

2.2. DSPI for thermally-induced surface deformation

An optical setup for DSPI is presented in Fig. 3. The instrument was developed from the DIC system by dividing the laser beam into two beams, called object and reference beams, using a glass plate. The object beam illuminates (as before) the surface investigated while the reference beam passes through magnifying lenses and the ground glass and is merged with the beam reflected from the object using a beam-splitter cube. The object and reference beams superimpose coherently producing an interferogram recorded by a camera.
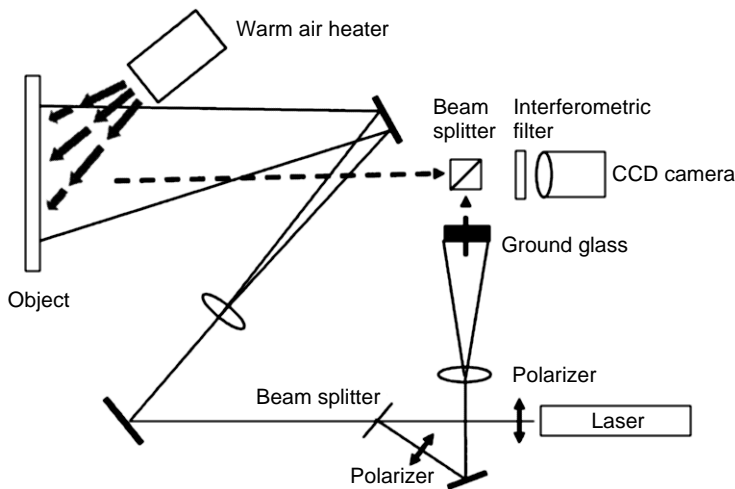

Fig. 3. Experimental setup for DSPI applied for the analysis of thermally-induced surface deformation.

By using a ground glass in the reference beam path the speckled reference beam is obtained but, as is discussed by MOORE [13], information about the surface contained in the interferogram is unchanged in comparison to a DSPI system with a smooth, reference beam. Typically, the DSPI systems combining the object and reference beams require a specific lens system which ensures that the reference beam appears to the detector as if it originated at the centre of the exit pupil of the imaging optical system. Using ground glass in the reference beam path has two advantages at the cost of some reduction of image quality. Firstly, it avoids a complicated and expensive lens 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 lenses – and choosing the intensity of the reference beam by rotating one of the linear polarizers in the reference beam path. Polarizers are used only for adjusting proper ratio between object and reference beams and can be substituted by a neutral density filter, if required.

As in the case of DIC, the recorded interferograms contain information about the surface shape so one can analyse inhomogeneities of the surface by comparing (subtracting) consecutive image during the cooling process.

The intensity of the light in the plane of interferogram is given by:

$$I_{01}(r) = I_o + I_r + 2\sqrt{I_o I_r}\ \cos\left[\varepsilon(x, y)\right] \tag{1}$$

where x and y define the position of a pixel in the plane of the interferogram, I_o and I_r are intensities of the object and reference beams, respectively, ε is a random phase difference between the object and reference beams at point (x, y).
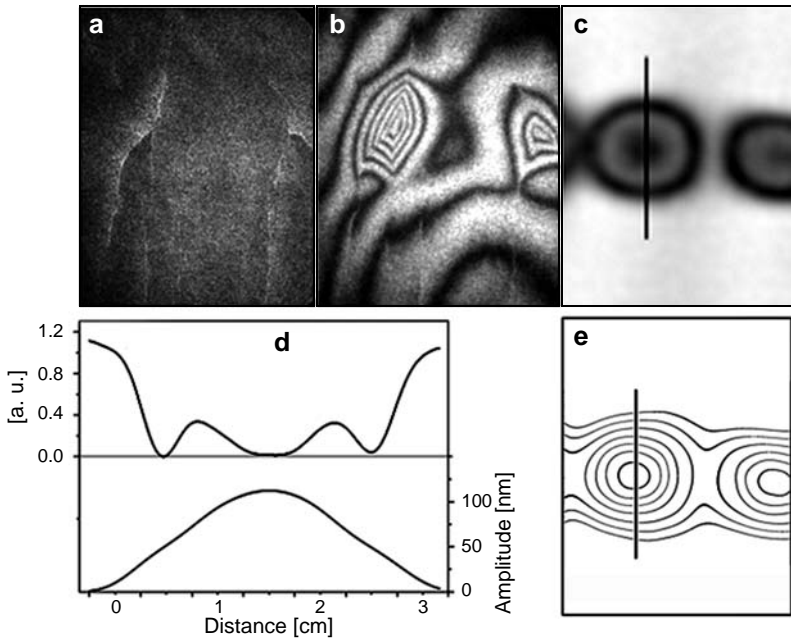

Fig. 4. Tracing damage on the same painted surface with the use of different methods: (**a**) microcracks in the design layer revealed by DIC, (**b**) microcracks and delaminated areas revealed by DSPI analysis of the thermally-induced surface deformation, (**c**) delaminated areas revealed by DSPI analysis of the sound-induced vibration of the surface (3400 Hz), (**d**) analysis of the interferogram along a vertical line shown in (**c**) and (**e**): the top curve represents the measured signal while the bottom curve the distribution of the surface vibration along this line, calculated with the use of Eq. (10), (**e**) spatial distribution of the amplitude of vibration ($\delta z/2$) shown as isolines; the distance between the lines is 15 nm.

The movement of the surface (caused by the cooling process) creates an additional phase $\Delta\varepsilon(x, y)$ in the recorded interferogram:

$$I_{02}(r) = I_i + I_r + 2\sqrt{I_i I_r} \cos\left[\varepsilon(x, y) + \Delta\varepsilon(x, y)\right] \tag{2}$$

Therefore, subtraction of the consecutive interferograms I_{01}–I_{02} leads to the image with dark (for $\Delta\varepsilon = 2n\pi$) and bright (for $\Delta\varepsilon = (2n + 1)\pi$) fringes. Fringes become clustered and distorted around local surface deformations and may be used as a guide to the identification of any heterogeneities in the paint layer. The measuring procedure allows monitoring the formation of fringes in real time, which gives the operator a possibility of selecting and "freezing" a suitable record clearly displaying a feature so that its size and shape are optimally defined. DSPI designed for the analysis of thermally-induced surface deformation is particularly well suited to the analysis of the approximate size and shape of planar features of the paint layer, for example, the delaminated areas, whereas DIC is more effective in revealing cracks of the paint, as illustrated in Figs. 4**a** and 4**b**.

Thermally-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 (their size, shape and mechanical properties), it is crucial to know the exact values of the dimensional response of damaged areas to a particular driving force. This information may be obtained using most advanced of the three interferometric systems presented in this article. An experimental setup for DSPI designed for the analysis of sound-induced surface deformation is not much more expensive to build or difficult to use but requires application of a sophisticated analysis algorithm and thus should be treated as an option for the most advanced users.

2.3. DSPI for sound-induced surface deformation

2.3.1. Measuring procedure

A scheme and a photograph of the most advanced DSPI based on the analysis of sound--induced vibration of the surface investigated are presented in Fig. 5. There are two changes in comparison to the system presented in Fig. 3. The heater is replaced by a loudspeaker which emits sound waves inducing vibration of detached fragments of the paint layer, and a phase shifter is placed in the object beam path. During the measurement, the phase shifter is used for recording images with a well-defined phase retardation between the object and reference beams which is used for the phase unwrapping algorithm described below (see the next paragraph). For the setup presented, a liquid crystal (LC) ARCoptix phase shifter was selected. The optical retardation of the LC phase shifter can be electrically tuned with 10 nm precision by a simple laboratory power supply, or a function generator.
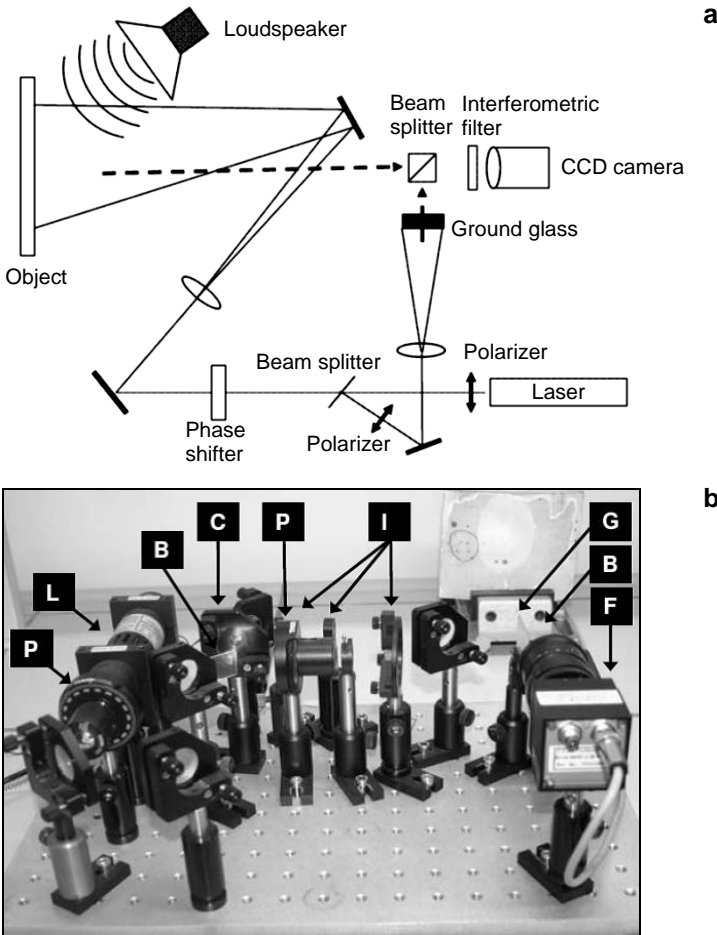
Fig. 5. Experimental setup for DSPI applied for the analysis of sound-induced surface deformation: a scheme (**a**) and a photograph (**b**). L – laser, P – polarizers, C – phase shifter, G – ground glass, B – beam splitters, F – CCD camera, l – lens.

The measurement consists in analysing a sound-induced vibration of the surface investigated. A signal with controlled frequency and amplitude is generated by a National Instrument NI PCI 6221 multi-function data acquisition module, 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 design layer when the generated wave is close enough to the resonant frequency. Generally, for an object vibrating with frequency ω, the intensity of light in the plane of the interferogram is given by:

$$I(x, y) \ = \ I_o + I_r + 2\sqrt{I_o I_r} \ \cos\left[\varepsilon(x, y) + \Delta\varepsilon(x, y, \omega)\right] \tag{3}$$

The symbols used in Eq. (3) have the same meaning as in Eq. (1). But in case of the induced vibration of the surface, an additional phase shift $\Delta\varepsilon$ resulting from the vibration of the object appears as an argument of the cos function. For the object beam perpendicular to the illuminated surface:

$$\Delta\varepsilon(x, y, \omega) \;=\; \frac{4\pi\delta z(x, y)}{\lambda}\cos(\omega t) \tag{4}$$

where λ is a wavelength of the laser light and δz is an out-of-plane displacement of the surface. Note that $\Delta\varepsilon = 0$ for a still object.

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 time integral of Eq. (3). As a result [15]:

$$I(x, y) \;=\; I_o + I_r + 2\sqrt{I_o I_r}\,\cos\!\Big[\varepsilon(x, y)\Big]J_0\!\Big(\frac{4\pi}{\lambda}\delta z(x, y)\Big) \tag{5}$$

where J_0 represents the zero-order Bessel function of the first kind and δz is twice the vibration amplitude.

The final image is obtained by the subtraction of interferograms for the still and vibrating object and is given, within a constant, by [13]:

$$I(x, y) \;=\; 2\sqrt{I_o I_r}\,\cos\!\Big[\varepsilon(x, y)\Big]\Big[1 - J_0\!\Big(\frac{4\pi}{\lambda}\delta z(x, y)\Big)\Big] \tag{6}$$

Equation (6) provides information on the amplitude of the object vibration, but the information is still relative because the intensity of light as well as the initial random phase $\varepsilon(x, y)$ are unknown.

It is assumed that the intensity of light is constant during the time of the measurement and that its value is irrelevant for the final result of the analysis, but the map of the initial phase values $\varepsilon(x, y)$ is a key piece of information which must be found for an unambiguous determination of the surface deformation.

2.3.2. Phase unwrapping

From the various types of phase-unwrapping algorithms [16], a version of the normalized max–min scanning routine proposed by VIKHAGEN [17] was utilized in the system presented. This method for the analysis of the object vibrations is based on phase shifting between interfering laser beams and processing the obtained images. The algorithm consists in recording a set of interferograms with a controlled phase retardation between the object and reference beams for both still and vibrating surfaces. Changing the phase retardation in consecutive measurements for a vibrating object influences the initial phase value, therefore for the surface vibrating with a chosen

frequency, the subtraction of the measurements with a different phase shift (Eq. (5)) gives:

$$I(x, y) \;=\; 2\sqrt{I_o I_r}\left\{\cos\Big[\varepsilon_1(x, y)\Big] - \cos\Big[\varepsilon_2(x, y)\Big]\right\} J_0\Big(\frac{4\pi}{\lambda}\delta z(x, y)\Big) \qquad (7)$$

where ε_1 and ε_2 correspond to two different initial phase shifts between the object and reference beams.

The procedure consists in eliminating the expression in the curly brackets. By measuring the intensity of light for the consecutive measurements (with an increasing phase shift) for each pixel of the interferogram, it is possible to find values of the phase shift when the intensity of light is maximal and minimal. The maximum value of light intensity at point (x, y), according to Eq. (5), corresponds to $\varepsilon = 0$, while the minimum value to $\varepsilon = \pi$. For the (x, y) pixel of the image, when $\varepsilon_1 = \pi$ and $\varepsilon_2 = 0$ Eq. (7) gives:

$$I(x, y) \;=\; 2\sqrt{I_o I_r}\; J_0\Big(\frac{4\pi}{\lambda}\delta z(x, y)\Big) \qquad (8)$$

whereas the same measuring procedure utilized for the still object gives:

$$I_{\text{ref}}(x, y) \;=\; 2\sqrt{I_o I_r} \qquad (9)$$

Finally, dividing the first image (Eq. (8)) by the second image (Eq. (9)) on a pixel by pixel basis, a map of vibration amplitude can be found in the unambiguous way:

$$\frac{I(x, y)}{I_{\text{ref}}(x, y)} \;=\; J_0\Big(\frac{4\pi}{\lambda}\delta z(x, y)\Big) \qquad (10)$$

Importantly, the procedure presented does not really require precise calibration of the phase shifter. However, it is necessary to ensure that the measurements are made in a phase range not smaller than 2π whereas the phase shift step can be chosen as a compromise between the speed of the measurement and accuracy in the determination of the vibration amplitude value [17].

2.3.3. Image analysis

The determination of the spatial distribution of vibration amplitude is just equivalent to solving Eq. (8). However at this stage of analysis, it is important to discuss the problem of a limited fringe visibility in a recorded interferogram. Firstly, the difference in intensity between the consecutive minima and maxima decreases for the J_0 function when the argument of the function increases. The first maximum of the J_0 function is 30% of the zero-order maximum and decreases for the subsequent maxima. As a result, a quantitative analysis of the deformation is possible only for vibrations of relatively low amplitudes – in practice not bigger than a few micrometers for the applied light

source. Another limitation in the interferogram analysis is a speckle noise which limits spatial resolution of the fringes.

Graphical filtering of the images is useful for improving the contrast and reducing the granular structure of the recorded interferograms. The results presented were obtained by implementing median filtering and two-dimensional backward Fourier transformation into the image-processing algorithm. The process of fringe identification in the interferograms obtained is only semiautomatic. A preliminary identification of fringes is done manually (in particular, the definition of the zero-order maximum of the J_0 function in the image is critical) but the procedure of assigning particular pixels on the image to the area between consecutive minima and maxima of the Bessel function is automatic – based on an iterative algorithm developed by the authors.

In the first step, the whole interferogram is divided into separated areas in which no discontinuity in the fringes is observed. Typically, lines separating these areas correspond to cracks in the design layer. In these areas, the approximate curves following shapes of the consecutive fringes are drawn manually on the registered interferogram. A set of points (pixels) is selected on the curves at equal distances, usually corresponding to around 5 pixels. An interactive algorithm which localizes maxima (minima) of light intensity, is started at these points. During the calculations, the light intensities in neighbouring pixels are compared and the position of a pixel with the highest (lowest) values is found. The procedure terminates when no neighbouring pixels with higher (lower) intensity can be found. These local maxima (minima) are connected by straight lines which finally define real positions of the fringes.

In the next step of the analysis, the amplitude of the surface vibration is calculated. For each pixel located between the well-defined fringes, the relationship between the light intensity and the vibration amplitude is determined by the modulus of Eq. (10), where the minimum and maximum values of the light intensity correspond to the closest points belonging to the surrounding fringes. Because this procedure is local, it helps to avoid a problem with non-uniform light intensity over the whole interferogram.

Finally, the amplitude of vibration for each pixel of the registered image is calculated. Results are presented in the form of a two-dimensional map of the surface vibration amplitude.

The outcome of applying DSPI for the analysis of sound-induced vibration of the surface in order to provide a mechanical characterization of the defects is illustrated in Fig. 4**c** for the same area of paint for which the cooling process was analyzed earlier using DIC and DSPI. The measuring procedure consists in scanning sound frequencies during the consecutive measurements to find the resonant frequencies for all delaminated areas. When the resonant frequency is established, a phase-stepping measurement is conducted and the consecutive analysis described in the previous section results in the determination of the surface vibration amplitude (Figs. 4**d** and 4**e**). The method applied provides precise information on the characteristic frequency of the delaminated area, its size and the spatial distribution of the vibration amplitude.

3. Monitoring the expansion of damage

The usefulness of the DSPI system in tracing the development of damage consists in its ability to determine simultaneously the three different indicators of the destruction process described above: the characteristic frequency of the delaminated area, its size and the spatial distribution of the vibration amplitude.

An examplary analysis is shown in Fig. 6. 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 done. The initial, reference measurement, was done before the application of any external forces to 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 analysis of the surface cooling process by DSPI is shown in Fig. 6a: three new microcracks (indicated by arrows and the consecutive numbers) are visible on the surface of the design layer. Measurements of sound-induced surface vibration
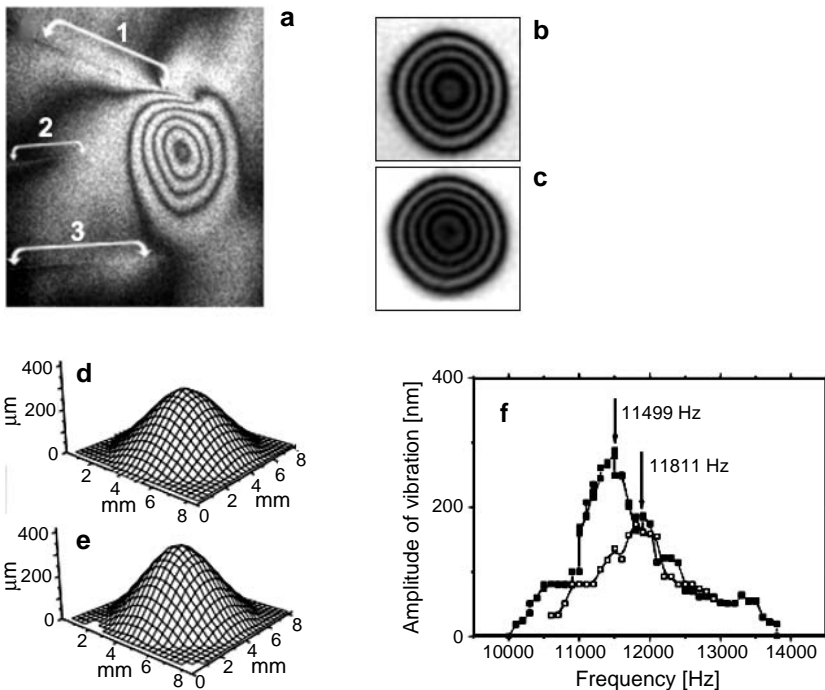

Fig. 6. Various indicators of the development of damage recorded using DSPI. See the text for explanation.

conducted prior to and after the damaging cycles, and the respective interferograms revealing the vibrating delaminated areas, are shown in Figs. 6**b** and 6**c** (the respective resonant frequencies were 11.5 and 11.2 kHz). The inspection of the two images allows comparing the size of the delaminated areas. 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. 6**d** and 6**e** also differs for the two cases, but the difference is not very pronounced. On the other hand, an easily detectable difference appears in the resonant frequencies of the delaminated areas (Fig. 6**f**). The resonant frequency shift of about 300 Hz reflects a change in the mechanical properties of the defect which is highly sensitive, and can serve as a quantitative measure of the development of the damage.

In conclusion, it can be stated that approximate changes in 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 a relative position of the loudspeaker and the surface investigated. The resonant frequency of delamination is the most sensitive parameter determined by the system developed. Moreover, it is independent of either the relative position of the camera, the loudspeaker and the object or the amplitude of the sound.

4. Discussion

A simple DSPI 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 and evaluated.

The system described is flexible: one can start from a simple digital image correlation (DIC) optical system and progress stepwise into a full DSPI using heat or sound to induce surface deformation. Each version of the instrument is capable of providing different information: DIC is particularly useful in tracing the fracture development, the DSPI analysis of thermally-induced surface deformation can reveal the planar features of the paint layer, whereas the most advanced DSPI system for recording sound-induced vibration can provide precise information on the characteristic frequency of the delaminated area, its size and the spatial distribution of the vibration amplitude.

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