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Original article

Combining digital speckle pattern interferometry with shearography in a new instrument to characterize surface delamination in museum artefacts

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ABSTRACT

Digital speckle-shearing-pattern interferometry (DSSPI) combined with digital speckle pattern interferometry (DSPI) were used to document the state of preservation of 8th to 14th century wall paintings of Christian Nubia. The original plasters of the paintings were multilayer inhomogeneous structures cracked in some parts. They were removed from the cathedral in Faras, Sudan, between 1961 and 1964 as part of efforts to rescue archaeological works threatened by flooding and are now held in the collection of the National Museum in Warsaw. Delaminated areas in surfaces of the paintings were detected by inducing surface vibrations with a sonic wave of varying frequency emitted from a loudspeaker. DSPI allowed the size of the areas and vibration resonant frequencies to be characterized, whereas DSSPI was successful in obtaining the spatial distribution of the vibration amplitude with sub-micrometre accuracy as a function of the sound frequency used. The procedure provided precise, detailed and reproducible information on the character of each damaged area in spite of the considerable size of the paintings and the unstable out-of-lab conditions of a conservation studio in which the measurements were carried out. The obtained results will be used as a reference for future surveys of the paintings in order to trace the possible development of surface detachments, even at an incipient stage, which cannot be easily detected by the naked eye or manual inspection.

1. Research aims

The principal aim of this study was to develop a digital speckle-shearing-pattern interferometer capable of detecting and documenting the surface damage of art objects at the micro-level in the real-world display conditions of a gallery or a storage area. Emphasis was placed on the optimisation of the measuring protocol and applying fully automated data analysis not utilized so far for shearography measurements. The developed system, combining digital speckle pattern interferometry (DSPI) and digital speckle-shearing-pattern interferometry (DSSPI), was used to analyse the state of preservation of wall paintings from the Faras collection at the National Museum in Warsaw. The results allowed optimum display conditions for the paintings to be established.

2. Introduction

Repeated condition surveys, aimed at developing an optimum strategy for the storage and exhibition of art objects, are important operations of museums and conservation studios. In order to effectively protect vulnerable works of art, non-destructive, highly sensitive and quantitative methods are needed to detect and document damage at the incipient stage. Early damage detection is especially important in case of slowly progressing, environmentally-induced surface deterioration, as such detection allows preventive action to be undertaken long before the structural integrity of an object is at risk. Monitoring methods, when sensitive and accurate enough, can serve as 'early warning' systems, helping to detect harmful impacts, vibrations or climate fluctuations in the environment of art objects on exhibition, while in storage or during transportation.

The above requirements are suitably met by speckle interferometric methods which are well-established and widely used for measuring sub-micrometre displacement components, strain, deformation, and the vibration of diffusively scattering surfaces.

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The interferometric techniques provide high-speed and real-time measurements and are, therefore, especially attractive for the analysis of surface integrity of art objects. Speckle interferometry has, so far, been particularly successful in detecting fractures and surface flaws in various heritage objects as panel [1–3] canvas [4,5] and mural [6–8] paintings, as well as mosaics [9] by observing surface movement produced when an object is subjected to stress. Reviews of early and recent applications of interferometric techniques in the analysis of artworks can be found in Refs. [10,11].

Despite the indisputable advantages of speckle interferometry when compared to standard methods of condition surveys (such us macrophotography or tapping method), two serious problems pose a considerable barrier to the method's application in diagnosing surfaces on a wider scale in practice. The first difficulty is the quantitative and, at the same time, automatic interpretation of speckle interferograms, whilst the second is achieving a high level of precision during the condition surveys performed outside the laboratory – in a gallery or a conservation studio.

The problem of the automatic interpretation of the measurements is of principal importance. To meet the expectations of conservators and curators working with art objects, any method of surface analysis must not only be sensitive, but must provide an unequivocal interpretation of features represented by local clusters of fringes on the recorded interferometric images. This is possible only when the interpretation process is fully automated. To fulfil this requirement, a fully automated algorithm was used in this study for recording and analysing vibrating objects using DSSPI. The algorithm has been already successfully tested for DSPI, utilizing continuous-wave laser light, both in the laboratory [12] and in a conservation studio [13].

However, the measurements performed out of the laboratory showed that typical environmental noise caused by vibrations of the measuring system with respect to the analysed surface resulted in instability of the observed interferometric fringes. As a result, measurements in a conservation studio or a gallery had to be repeated many times for the same analysed area to obtain quantitative information about the state of preservation of the surface using the automatic algorithm. The larger the environmental noise one had to deal with, the more difficult the measurements. To mitigate the problem of insufficient mechanical stability whilst carrying out measurements in gallery conditions, a Michelson-type digital speckle-shearing-pattern interferometer (from here on, shearing interferometer) with a fully automated algorithm for recording and analysing data was developed. Shearing interferometry is much less sensitive to external vibration and noise as analysed in Section 3 below. However, as the shearing interferometer records two partially overlapping images, data interpretation may be difficult when damaged areas are small but numerous, or, conversely, larger than the image recorded. To avoid these problems, the shearing interferometer was combined with a digital speckle pattern interferometer within one measuring device during the measuring campaign reported in this paper. With a combined use of DSPI and DSSPI, it was possible to perform a high precision analysis of surface flaws of selected wall paintings from the Faras collection in a fully automatic way despite the relatively poor stabilisation of the device in the conservation studio.

3. Digital speckle-shearing-pattern interferometry

Speckle interferometry consists of analysing speckles – a stochastic interference pattern produced whenever a rough surface is illuminated by a coherent laser light. In both DSPI and DSSPI, results are obtained by analysing the interference of speckle light with reference light. To create this interference pattern in a shearing interferometer, unlike in digital speckle pattern interferometer, only a single object beam with two interfering speckle patterns coming from neighbouring points of the analysed surface is used [14,15]. This makes the method much more insensitive to external vibration and noise, since movement of the object and the measuring system changes both the object and reference beams in the same way. Therefore, the phase difference between the object and the reference beam is significantly more stable compared to the DSPI. This feature is essential in measurements performed outside the laboratory.

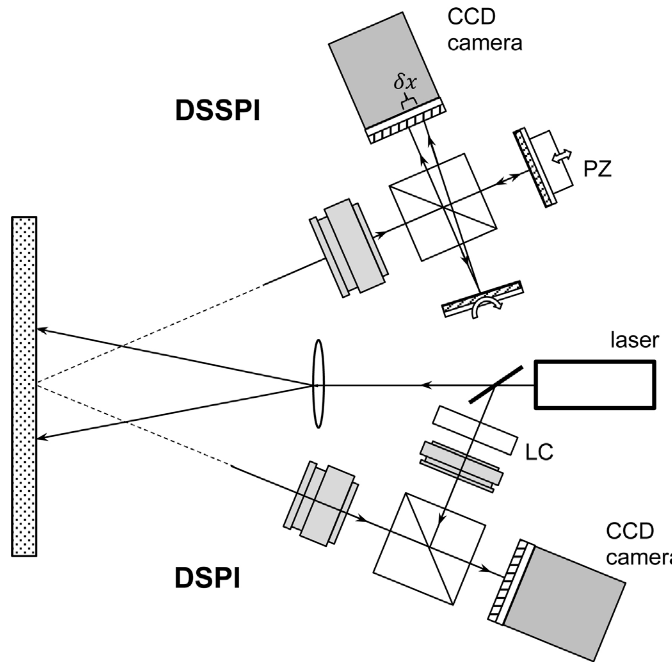

Fig. 1. Layout of the experimental setup used for the analysis of sound-induced surface vibrations. PZ: mirror on a piezoelectric crystal; LC: liquid crystal phase retarder; δ represents a lateral shift between the interfering speckle patterns in the Michelson-type digital speckle-shearing interferometer which is introduced by tilting an adjustable mirror.

The formation of a double image in the Michelson-type shearing interferometer built by the authors is schematically presented in the upper part of Fig. 1. The object is illuminated by laser light, and the reflected light is focused on a CCD array of a camera. The small tilt of an adjustable mirror introduces a shift between the two speckle patterns in the image plane. As a result, any pixel in the CCD array receives light from two points of the object surface. The two sheared speckle patterns combine coherently to create the resulting speckle pattern, which is analysed.

The surface of an object deforms non-uniformly under an external load when the quality of a material differs in neighbouring areas. If an image captured after the deformation is subtracted from the reference image captured before the deformation, the resulting distribution of brightness allows the deformation of the surface to be visualized. The method of analysis depends on the magnitude of the lateral shift δx between the interfering speckle patterns adjusted by the tilting mirror located in front of the camera. For small values of δx, partial derivatives of the out-of-plane and in-plane displacements of the deformed object can be analysed in order to detect surface flaws. Successful applications of DSSPI to measure gradients of displacement under thermal load for cultural heritage objects were already demonstrated [16,17]. It should be stressed, however, that this method is very effective in detecting rather than characterizing damage.

When δx is larger than the size of the image of the damaged area, it is possible to analyse the deformation of the damaged area in respect to the deformation of the undamaged part of the surface.

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