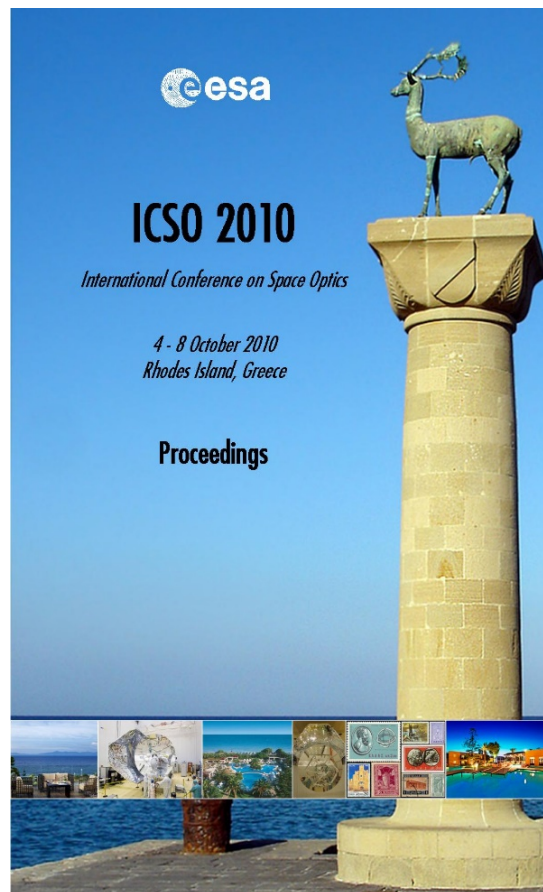# International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas

Electronic speckle pattern interferometry in long wave infrared: a new technique for combining temperature and displacement measurements: application in thermo-mechanical assessment of structures

M. Georges, J-F. Vandenrijt, C. Thizy, Y. Stockman, et al.

ELECTRONIC SPECKLE PATTERN INTERFEROMETRY IN LONG WAVE INFRARED: A NEW TECHNIQUE FOR COMBINING TEMPERATURE AND DISPLACEMENT MEASUREMENTS. APPLICATIONS IN THERMO-MECHANICAL ASSESSMENT OF STRUCTURES

M. Georges[1], J-F. Vandenrijt[1]. C. Thizy[1], Y. Stockman[1], I. Alexeenko[2], G. Pedrini[2], W. Osten[2]

[1]*Centre Spatial de Liège-Université de Liège, Liege Science Park, B-4031 Angleur, Belgium*
[2]*Institut für Technische Optik, Universität Stuttgart,Pfaffenwaldring 9, D-70569 Stuttgart, Germany*

I. INTRODUCTION

Holographic and speckle based techniques are well known for measuring full-field displacements and performing non destructive testing on solid objects [1]. The measurement range and accuracy of these techniques are related to the wavelength of the laser. In visible light they are often not well suited for field applications or for large displacement measurement due to the short wavelength used, which imposes high stability constraints. One way to decrease this sensitivity is to use a longer wavelength. Our purpose is to investigate holography in the Long Wave InfraRed (LWIR) range and more specifically at 10 μm with CO_2 lasers. This provides a typical 20 factor of decrease of the stability requirements; meantime the range of measurement is increased by the same factor.

We present here advanced results obtained within the FANTOM FP7 project. Besides the lower sensitivity to external perturbations, another interesting feature that is put forward in this project is the possibility to develop a sensor which combines displacement by holography/speckle and thermography measurements. Here we take advantage to the fact that the necessary observation device for the holographic signal is a thermographic camera. This has an interest in various applications such as analysis of thermo-mechanical behaviour of structures or non destructive testing, where often displacements and temperature fields need to be observed and correlated one to another. We already presented preliminary results on out-of-plane and in-plane ESPI at 10.6 μm, and also on digital holographic interferometry [2], however without combining thermography. Recently we presented an improved digital holographic interferometry set-up [2], and a study of the scattering problems arising when working at such long wavelengths [3]. In this paper we present for the first time to our knowledge the combination of full-field temperature and displacements, with a single sensor.

II. PRINCIPLE OF ESPI

The speckle effect appears when a rough surface is illuminated by a laser beam. This effect results from the interference of all waves scattered by surface points, having different phases and which add together to give a resultant wave whose intensity varies randomly. The speckle is often seen as a perturbation to be suppressed. However it carries information that can be processed usefully. Speckle interferometry is a technique that takes benefit of this information. In speckle interferometry, two interference fields are compared, each one generated by coherent superposition of the reflected wave field and a reference wave. The two fields to be compared correspond to the object states before and after the deformation.

The most important technique of speckle interferometry is the Electronic Speckle Pattern Interferometry (ESPI) which was invented in early seventies [4]. The object surface is focused onto the sensor where it is superposed to a reference wave, which results in a microscopic interference pattern called specklegram.

The object wave field on the sensor plane (x,y) is given by

$$E_{\text{obj}}(x,y) = \left|E_{\text{obj}}(x,y)\right| e^{i\varphi_{obj}(x,y)} \tag{1}$$

where $E_{\text{obj}}(x,y)$ is the real amplitude and $\varphi_{\text{obj}}(x,y)$ is the random phase due to the surface roughness [1]0. The colinear reference wave field

$$E_{\text{ref}}(x,y) = \left|E_{\text{ref}}(x,y)\right| e^{i\varphi_{ref}(x,y)} \tag{2}$$

is superposed. This reference may be a plane wave, a spherical wave, or an arbitrary one. Only intensities are recorded by the sensor. The so-called specklegram intensity is given by:

$$I(x,y) = \left| E_{\text{obj}}(x,y) + E_{ref}(x,y) \right|^2$$

$$= I_{\text{obj}}(x,y) + I_{ref}(x,y) + 2\sqrt{I_{\text{obj}}(x,y)I_{ref}(x,y)}\cos\psi(x,y) \tag{3}$$

This image is recorded with the phase difference

$$\psi(x,y) = \varphi_{obj}(x,y) - \varphi_{\text{ref}}(x,y) \tag{4}$$

A deformation changes the phase $\varphi_{\text{obj}}(x,y)$ of each point by $\Delta\varphi(x,y)$, so the wave field after deformation is

$$E'_{obj}(x,y) = \left| E_{\text{obj}}(x,y) \right| e^{i\left[\varphi_{\text{obj}}(x,y) + \Delta\varphi(x,y) \right]} \tag{5}$$

Superposition with the colinear reference wave leads to $I'(x,y)$

$$I'(x,y) = I'_{obj}(x,y) + I_{ref}(x,y) + 2\sqrt{I_{\text{obj}}(x,y)I_{ref}(x,y)}\cos\left[\psi(x,y) + \Delta\varphi(x,y) \right] \tag{6}$$

In the digital image processing this second pattern is subtracted point-wisely from the stored $I(x,y)$, where it is assumed that the deformation changes the phase but not the amplitude, meaning $I'_{\text{obj}}(x,y) = I_{\text{obj}}(x,y)$. The resulting difference is

$$(I - I')(x,y) = 2\sqrt{I_{\text{obj}}(x,y)I_{\text{ref}}(x,y)}\sin\left(\psi(x,y) + \frac{\Delta\varphi(x,y)}{2} \right)\sin\left(\frac{\Delta\varphi(x,y)}{2} \right) \tag{7}$$

To display this result in real-time on a monitor, positive intensities are obtained by taking the modulus $|I{-}I'|$. The first sine-term gives the stochastic speckle noise which varies randomly from pixel to pixel. This noise is modulated by the sine of the half phase difference introduced by the deformation. This low frequency modulation of the high frequency speckle noise is recognized as an interference pattern.

In order to obtain quantitative measurement of the phase difference can be achieved using the phase stepping technique. This technique consists in applying phase shifts to one of the arm of the interferometer. Therefore n acquisitions of the object at its initial state and n others when deformed are recorded.

$$I_n(x,y) = I_{\text{obj}}(x,y) + I_{ref}(x,y) + 2\sqrt{I_{\text{obj}}(x,y)I_{\text{ref}}(x,y)}\cos\left[\psi(x,y)\Phi_{Rn} \right] \tag{8}$$

$$I'_n(x,y) = I_{\text{obj}}(x,y) + I_{ref}(x,y) + 2\sqrt{I_{\text{obj}}(x,y)I_{\text{ref}}(x,y)}\cos\left[\psi(x,y) + \Delta\varphi(x,y) + \Phi_{Rn} \right] \tag{9}$$

where Φ_{Rn} represents the phase shift applied at the nth acquisition. This phase shift can by arbitrarily chosen. However the most often used values are $\Phi_{R1} = 0°$, $\Phi_{R2} = 90°$, $\Phi_{R3} = 180°$ and $\Phi_{R4} = 270°$. Solving those equations leads us to the phase values by the relationships

$$\varphi_1 = \arctan\left(\frac{I_4 - I_2}{I_1 - I_3} \right) \qquad \varphi_2 = \arctan\left(\frac{I'_4 - I'_2}{I'_1 - I'_3} \right) \tag{10}$$

Whe can now compute the phase difference

$$\Delta\varphi_{\text{computed}} = \varphi_2 - \varphi_1 \tag{11}$$

The latter can be related to the displacement of all object points through the so-called sensitivity vector [1] which depends on the laser wavelength and geometrical parameters of the set-up.

II. DESCRIPTION OF ESPI SET UP IN THE LWIR RANGE.

The set-up is a classical ESPI one (Fig1), except that all components and equipments are working in the range of 10 µm. The laser is a CO_2 emitting up to 8 Watts from VM-TIM company. The camera is a VarioCAM hr from Jenoptik LOS, with a 640x480 uncooled microbolometer array. It is equipped with a 50 mm focal length objective lens, made of Germanium. Other lenses are made of ZnSe glasses. A beam combiner is used to recombine the object beam (in red) and the reference beam (in green) at the level of the sensor. The ESPI technique is the same as is applied in visible, with the possibility of phase-shifting for quantification of phase.
The important feature of LWIR holographic/speckle interferometry is that the thermal background is present in the specklegrams, as DC component. Therefore it is easy to recover it solely by various kinds of processes, or simply by fast shuttering of the laser beam in order to capture it alone, a very short instant before capturing the specklegram with the laser. This simple procedure is valid for slowly varying thermal phenomena, what is assumed here.
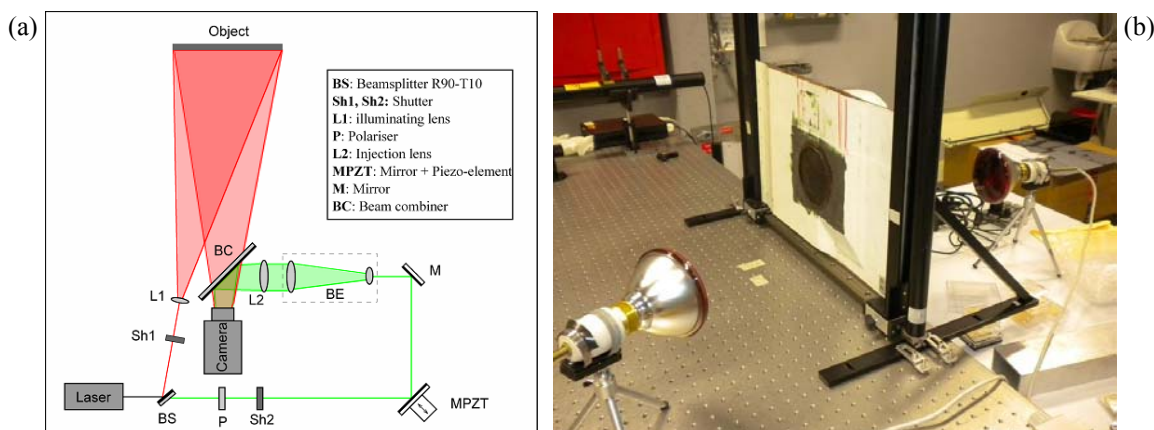

BS: Beamsplitter R90-T10
Sh1, Sh2: Shutter
L1: illuminating lens
P: Polariser
L2: Injection lens
MPZT: Mirror + Piezo-element
M: Mirror
BC: Beam combiner

Fig1. (a) Scheme of LWIR ESPI setup, (b) view of helicopter composite structure with heating lamps

III. APPLICATIONS IN THERMO-MECHANICAL ASSESSMENT OF STRUCTURES.

CSL was and still is implied in various ESA or non ESA projects dealing with thermomechanical assessment of composite materials and structures, for comparison with Finite Element Models [5][6]. In all these projects it is asked to measure the mechanical behaviour or the expansion of samples or structures of complex shapes and which undergo thermal stresses. Obviously the temperature needs to be known with accuracy on these objects at both instants of hologram/specklegram capture and later of the interferogram acquisition for deformation measurement. Usually thermocouples are glued in some specific locations but they provide partial information. Another possibility that was envisaged is to use a thermographic camera in parallel. The interest of our technique is that both information are obtained at the same time and on every pixel, improving the correlation of both.
The examples shown here were obtained with the above described set-up and in the case of composite aeronautical structures. Figure 2 presents interferograms obtained after substraction of phases calculated from a set of phase-shifted specklegrams. They correspond to various thermal loads of a helicopter composite structure (Figure 1(b)). Figure 3 shows the combination of deformation and temperature fields.
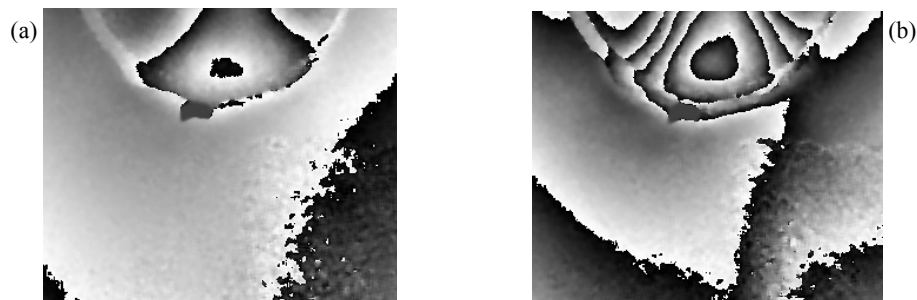
(a)

(b)

Fig2. Interferograms obtained with thermal infrared ESPI after heating of the helicopter composite structure
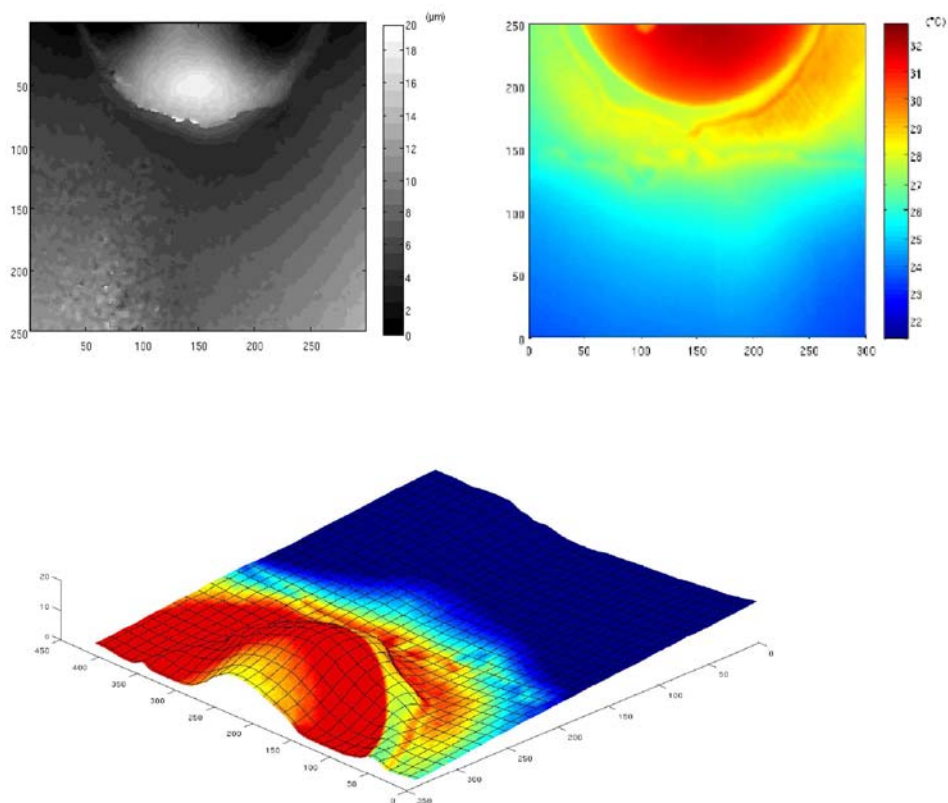
Fig3. (Upper Left) Unwrapped phase image, (Upper Right) temperature field, (Bottom) superimposition of displacement and temperature fields.

The following figures show another example of aeronautical composite structure undergoing a thermal stress and which undergo a deformation
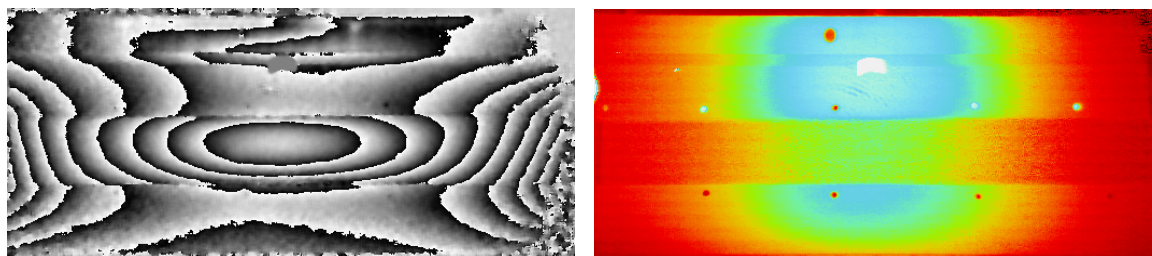
Fig4. (Left) Phase interferogram of composite structure deformation, (right) temperature field

III. CONCLUSION

The ESPI technique applied at 10 µm with CO_2 laser and microbolometer arrays allow simultaneous recording of full-field holographic deformation and temperature information. The interest of this combination is that a single sensor is used instead of 2 separate. Moreover both type of data are obtained on the same pixel at a the same instant, which is an obvious advantage for correlating both.

We show that this technique can be used appropriately in thermomechanical assessment of aeronautical structures but they can be applied in space applications as well.

REFERENCES

[1] T. Kreis, "Holographic Interferometry – Principles and Methods", Vol. 1, Akademie Verlag, 1996.

[2] J-F. Vandenrijt and M. Georges, "Electronic Speckle Pattern Interferometry and Digital Holographic Interferometry with Microbolometers Arrays at 10.6 microns", *Applied Optics*, in press.

[3] I. Alexeenko, J-F. Vandenrijt, M. Georges, G. Pedrini, C. Thizy, and W. Osten, "Digital Holographic Interferometry by Using Long Infrared Radiation (CO2 Laser)", 7th BSSM International Conference *on Advances in Experimental Mechanics*, Liverpool, September 2010.

[4] J. N. Butters and J. A. Leendertz, "Holographic and video techniques applied to engineering measurement", J. Meas. Control, 4:349–354, (1971)

[5] C. Thizy, Ph. Lemaire, M. Georges, P. Rochus, J-P. Colette, R. John, K. Seifart, H. Bergander, and G. Coe, "Comparison between finite element calculations and holographic interferometry measurements, of the thermo-mechanical behaviour of satellite structures in composite materials", Trends in Optics and Photonics Series, Vol 99 on *Photorefractive Effects, Materials and Devices,* G. Zhang, D. Kip, D. Nolte, J. Xu, eds., p.700-706 (2005)

[6] C. Thizy, C. Barbier, P. Barzin, Is. Tychon, S. Roose, Y. Stockman, M. Georges, "Dynamic holographic interferometry for dilatation measurements in vacuum-thermal conditions", Proc. SPIE Vol 7398 on *Optical Measurement Systems for Industrial Inspection VI*, Paper 73891P, Munich, June 12-14 (2009)