Userfriendly and Compact Holographic Camera Based on Photorefractive Crystals. Applications in high Accuracy Metrology

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Abstract. We present recent developments achieved in order to make compact and easy to handle a photorefractive holographic camera. The technological interest of photorefractive crystals as holographic recording medium will be shortly recalled. The reported improvement concerns the reduction of the optical head to some basic components (objective lenses, crystal and CCD camera) by use of optical fibers for light transportation. The new compact holographic head can be handled easily and placed in any position rendering this device more flexible and adaptable to any kind of problem. In addition, it offers the main advantage to make easier the interfacing with any kind of laser. Some applications are presented and show the versatility of the instrument as well as the quality of the results.

1 Introduction

A crucial element of Holographic Interferometry (HI) is the photosensitive medium used for the hologram recording. If one generally considers that its principal figures of merit are the energetic sensitivity and the diffraction efficiency, other features such as the self-processing and the erasability/reusability of the medium can appear more important in its practical applicability to HI.

The classical media used for the hologram recording are the silver halides and the thermoplastics. Both have a high sensitivity (so they require few luminous intensity for a fast recording) and generally exhibit high diffraction efficiency (of a few % to tens of %) which is largely comfortable to observe with CCD cameras. Nevertheless, silver halides require chemical processing in a remote location (dark room) and repositioning before the readout step, what limits their use. Thermoplastics require electric charging and heating before recording and cooling down after. They can in principle be reused but a limited number of times due to their deterioration by dusts (rolls can be used to avoid this problem). Nevertheless thermoplastic systems are cumbersome and, despite the in situ processing, the hologram is available after tens of seconds. Also they often show high level of scattering that introduces high noise in interferograms. With both materials, at the readout step, the ratio of the beams (object/reference) has to be changed in order to equalize the intensities of both WF and to maximise the interferogram contrast. This decreases the userfriendliness of these recording media.

The PhotoRefractive Crystals (PRCs) [1] are an interesting alternative to the other ones because they are self-developing in situ and indefinitely reusable. Particularly, the PRCs belonging to the sillenite family, $Bi_{12}SiO_{20}$ (BSO), $Bi_{12}GeO_{20}$ (BGO) and $Bi_{12}TiO_{20}$ (BTO), have been studied for applications in HI because they are among the most photosensitive. Recently, some groups have focussed their works on the development of instruments for applications in industrial or medical fields. Dirksen *et al.* developed a holographic camera that records sequences of double-exposures HI (2EHI) [2, 3]. It is based on a BTO crystal at 514 nm. Each double exposed hologram is readout and the interferogram is processed by the Fourier transform filtering technique [2] or by phase-shifting [3] considering the double-reference technique. Labrunie *et al.* proposed the use of the energy transfer with a special polarization separation technique for obtaining simultaneously two phase-shifted images of the same object displacement [4]. They can so perform quantitative phase measurement of high accuracy based on a single shot. Their holographic camera is breadboarded and has been successfully used in cw at 514 nm and was further used in pulsed illumination with a ruby laser (694 nm) [5]. This is the first use of pulsed illumination with a PRC on an industrial example (turbine blade under vibration).

We present the result of research efforts leading to a compact portable holographic camera based on PRCs. Because the latter are self-developing and reusable, this allowed us to obtain an instrument dedicated to the metrology of scattering objects micro-displacements and that combines the high resolution of HI with the flexibility required for its userfriendly utilization in a wide field of applications. In section 2 we briefly motivate the choice of the HI method, we explain the instrument working principle and, finally, we present the latest prototype of compact holographic camera. In section 3 we show typical results obtained in very different and industrialy relevant applications with this photorefractive camera.

2 Holographic Camera Devices Development

The holographic camera was developed with the following aims. The instrument must be portable, as compact as possible, observe displacements on medium to large objects, easy to use (the fewest manipulations at the level of the optics), the results must be obtained rapidly and easy to interprete (good quality of quantified images and computer-aided pattern evaluation). Also the range of applications covered must be as large as possible and the instrument must be sufficiently versatile in its adaptation to the different kinds of measurements. Following these considerations, a method was first chosen and a thorough study has been carried out to optimize the set-up [6, 7, 8]. It has to be noted that only continuous lasers were considered in this development.

The method used is the Real Time HI (RTHI) associated with the crystal configuration exhibiting anisotropy of diffraction (here, "real time" is used in the holographic common sense : record of one hologram and subsequent readout with deformed object, in opposition to 2EHI, where 2 subsequent holograms are recorded and furtherly readout together in a third step). The choice of the RTHI technique is justified by the fact that it is *a priori* open to more applications than other techniques (2EHI and Time average (TAHI)). Indeed, static, dynamic and vibratory displacements can be examined in RTHI. 2EHI can be used also in all cases but is more complicated in the case of the dynamic (continuously evolving) displacements because sequences of double exposed holograms must be related one to another, what necessitates multiplexing procedures. Also, phase quantification techniques are more complicated to introduce with 2EHI. TAHI is only applicable with vibrating objects so, basically it is too much limited. Also, phase quantification technique are generally addressed to sinusoidal fringe patterns, what is not the case in TAHI (Bessel fringe profiles). The choice of the crystal orientation is justified by the fact that anisotropy of diffraction allows to optimize easily the interferograms contrast. In this configuration, once the necessary polarizers are correctly orientated, there is no further adjustment needed, what copes with the "ease of use" condition. As this behavior is optimum when no electric field is applied to the crystal we work in diffusion mode. Moreover, in this case, the diffraction efficiency is maximised at large angles between reference and object beams. This allows to use short focal lengths optics close to the crystal without being disturbed by the reference beam. As a consequence, large objects placed close to the holographic head can be observed. Also, short focal lengths render the optical system very compact, what is also an major practical advantage. As the reading process during interferogram visualization erase the recorded hologram shutter control and rapid image acquisition by computer are provided.

Figure 1 shows a picture of the compact and portable photorefractive holographic optical head that has been developed (25 cm length and 8 cm diameter, weight 1 kg). The laser head is included in a mobile rack and the light is conducted by an optical fiber up to the optical head. In addition to the fiber light injection device, the latter contains also acousto-optic modulator before the injection device (for stroboscopic applications) and, of course, all necessary electronics for the instrument control (e.g. piezoelectric translator, shutter and CCD camera power supplies, computer). For applications on small objects, one can use small OEM YAG lasers (a few tens of milliwatts) directly attached to the camera itself (no fiber). Also the reference beam forming elements are strongly reduced by considering either a fine optical design including exotic optical elements. As example, observation of a 60 x 40 cm^2 object need a distance of 1 meter and a laser power of 500 mW (λ = 514 or 532 nm) for a response time (hologram at rest recording) of a few seconds. However the optical system can accommodate other object size by simple adjustment. Moreover the response time is directly related to the reference beam intensity and consequently can be adapted to specific need. The phase quantification can be performed either by Temporal

Phase Shifting technique (TPS) of Fourier transform with spatial carrier technique (FT). Typical accuracy is between $\lambda/40$ and $\lambda/25$ depending on the number of fringes.

Fig. 1. Compact and portable holographic camera PHC-1

3 Applications

The first example presented is the detection of damages and defects in CFRP structures (here used in the aeronautical industry). The following results were obtained in the framework of the project EUCLID-CEPA3-RTP3.1. Field of view is about 55 x 45 cm^2. The procedure consists in first recording the hologram of the sample at the rest, afterwards it is heated a few seconds by IR lamp. The heating is then switched off and the object is under thermal relaxation. After a certain time (tens of seconds), the object is in a sufficiently stable deformation status and the hologram can be readout. A typical observed interferogram is shown in figure 2(a) and the TPS can be applied, to obtain the modulo 2π phase map (figure 2(b)). The high spatial resolution of the system allows us to obtain this interferogram image without any filtering process. The defects and damages (size below 1 cm of diameter) are clearly visible as local variations of the global residual deformation. Post-processing, such as the differentiation of the unwraped phase map, give final image that can be easily threshold for automatic detection. The corresponding result of figure 2 is shown in figure 3(a). Figures 3(b) is an other example.

The 2nd example concerns quantitative measurement displacement of thermal deformation in order to evaluate a finite element model (FEM) and correlate it to

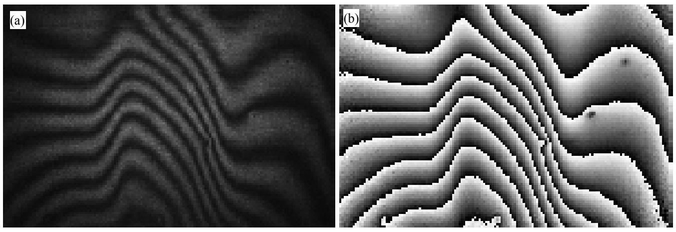

Fig. 2. Default detection in CRFP. (a) Interferogram, (b) phase image

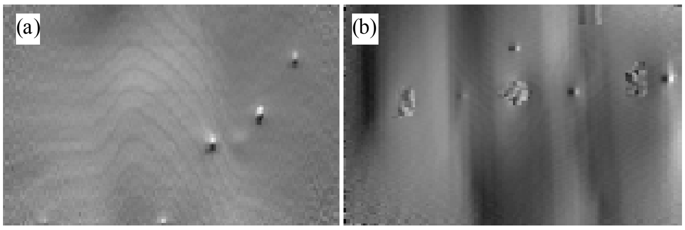

Fig. 3. Defects detection in aeronautical composite structures. Results after differentiation of phase image

the temperature distribution. The sample is here a honeycomb (core and skin both in aluminium). One of the goals of these measurements is also to determine the influence of the presence of inserts. The thermal stimulation is applied by a sheet electric resistance strapped on the back side of the panel which is clamped on the table by thermally insulated holder. Fig. 4 shows 2 examples of typical interferograms acquired after thermal stabilisation (≈ 1 hour after hologram recording of the object at rest). Typical temperature increases are around 3 to 4 °C from ambient. The heater is centred on the honeycomb (25 x 25 cm^2) and the observed area is about 15 x 19 cm^2 (located 7 cm above the holder). A strong but local perturbation is clearly induced by the insert (fig. 4(b)) in comparison with the case without inserts (fig. 4(a)). This example proves clearly that in spite of the erasability of the recorded hologram during the read-out process, it could be well conserved during long time when the crystal is not illuminated by reference beam.

In the following work the purpose is the measurement of carbon fiber hollow rods coefficient of thermal expansion (CTE). The CTE of such samples was calculated by their designer and we had to measure it experimentally, in order to confirm their model. The modelled value of the CTE allows to determine the couple of the samples length and the temperature step parameters, in order to stay in the measurement range of HI. In practice, a length of a few centimeters and a temperature elevation of a few °C were used. The sample (fig. 5(a), 1 cm^2 section) stands on a base plate. The object-ensemble (incl. base and thermal shroud) is placed inside a vacuum chamber in order to insure a homogeneous temperature increase. An hologram is recorded at a given temperature of the sample.

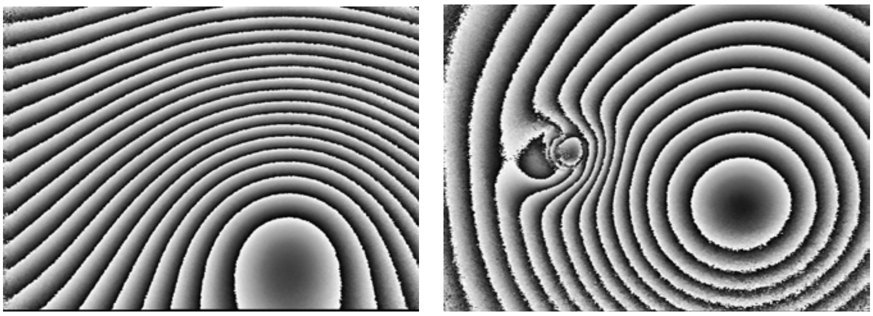

Fig. 4. Honeycomb structure without (a) and with inserts (b). Thermal stress

The sample is heated via the base plate and the thermal shroud surrounding it. After temperature stabilization, the phase difference between the base and the sample is measured by the holographic camera and one deduces the sample elongation. The relative error on measurement is estimated to be about 10%, the main inaccuracy coming from the temperature step knowledge. The proposed technique has been certified with an aluminium sample for which the CTE is known with accuracy.

For the data reduction, we have chosen to apply a method based on a carrier fringe pattern. Such pattern can be generated by translating the illuminating objective between the hologram recording and the interferogram acquisition. When no temperature step is applied, only the carrier pattern is visible (figure 5(a)). The section of the hollow rod is visible on the left and a reference zone of the base plate is visible on its right. It has to be noted that the object upper surface is about 6 cm higher than the reference surface.

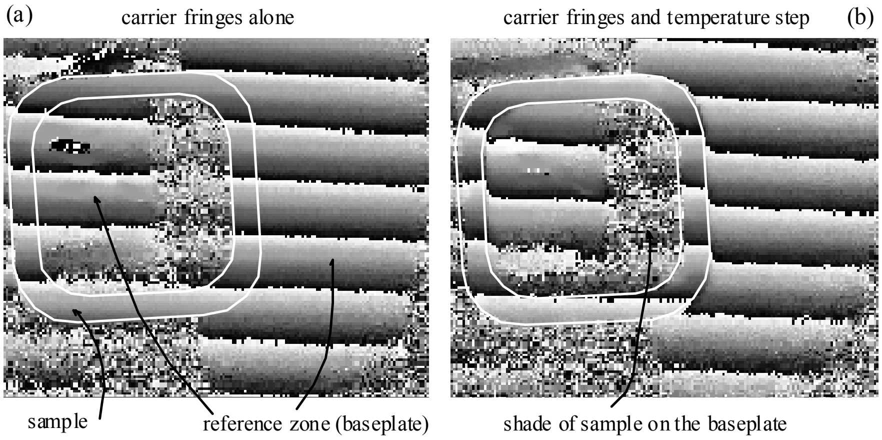

Fig. 5. Interferograms used to deduce the CTE of the sample. (a) Preliminary interferogram with a carrier fringe pattern alone, (b) interferogram obtained after temperature elevation and carrier fringes addition

If a temperature step is applied, the phase difference between the object and the reference zone is seen as a shift between the fringe pattern on both zones. Figure 5(b) shows an interferogram corresponding to a 1°C temperature step. By measuring this shift, we deduce the displacement and the CTE.

A quite different and interesting type of application is the FingerPrints (FP) detection by HI. Indeed, classical methods of FP detection sometimes fail when the substrate is ill-conditioned (badly adapted texture, color, shape,...). In order to overpass this problem, we proposed to use HI in the following way. A hologram of the object with the FP is taken first. Afterwards the FP is either removed or enhanced. The hologram is then readout. The resulting phase difference in interferograms (ideally π) shows FP pattern. Tests concerning the removal and enhancement of FP was carried out in order to see which methods gives the best results. It was found that enhancement of FP by cyanoacrylate selective vapor deposition was the choice method, because it allows to adjust the phase difference by controlling the deposition time. Figure 6 shows an example of FP visualization.

Fig. 6. Detection of fingerprint

6 Conclusion and Future Prospects

We have presented the achievement of a holographic camera using photorefractive crystal as dynamic recording medium. This development is based on an extended breadboards and configurations study that involves the original optical concept of PRC use in holographic camera as well as the metrological certification of the device [7]. Now a flexible and adaptable instrument based on an optical compact head linked by optical fiber to its laser power units is available and opened to a large applications range.

At the present time this camera has already been used in a large panel of applications. Most of them are industrial inspection or R&D study cases. High quality results are obtained and, as well important, the system was found to be very easy to handle and userfriendly. As a prove, most of the applications were performed by non-specialists in optics that used the holographic camera as a metrological tool. This is mainly due to the photorefractive crystal used for dynamic and repetitive holographic recording, to the simplicity and to the high degree of instrument control automation.

The present works are centered on several aspects. First the use of pulsed illuminations for dealing with perturbed environments and vibration measurements. Second metrological and interpretation aspects are deeply studied, i.e. complete 3D displacement measurements with multiple illumination or multiple camera systems. A further important step is to consider semiconductor photorefractive materials instead of the sillenite because they are more sensitive than the latter and they have a spectral sensitivity compatible with smaller laser sources (e.g. laser diodes), allowing then smaller devices.

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