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Ph.D. THESIS SUMMARY

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REAL-TIME DIGITAL HOLOGRAPHIC INTERFEROMETRY APPLICATIONS WITH SPATIAL LIGHT MODULATION FOR SURFACES AND PHASE OBJECTS DIAGNOSIS

THESIS COMMITTEE

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Chapter 1

Introduction

Along with technological development, holographic interferometry adapts by using new means of recording and reconstructing waves, as well as by the huge increase in computing speed and information technology. Image acquisition sensors have became digital. Digital holographic acquisition can be correlated with optical reconstruction by using spatial light modulators. These features of these devices combined with various applications and numerical techniques can take holographic investigative techniques to another level. Thus, in addition to the optical characteristics that consecrates them, they also acquired an electronic one. Holography as well as holographic interferometry have therefore become optoelectronic techniques for waves investigation .

1.1 Presentation of the field of the doctoral thesis

With the digitization of sensors and optical recording media, both holography and holographic interferometry are becoming digital. The interference pattern that encodes information about the object in the case of holography and the changes it undergoes in the case of holographic interferometry can be reconstructed numerically and the methods become much more versatile. In digital holography, however, the hologram disappears as a concrete object that reconstructs the light wave through diffraction. This is replaced by a virtual variant that does not actually modulate the light. Optical reconstruction by instantaneous diffraction of the reconstruction wave on the holographic plate has been replaced by numerical processing - a process that consumes time and computational resources. Spatial light modulators practically bring the hologram back into focus as a diffractive optical object.

1.2 Scope of the doctoral thesis

In this paper I tried to achieve a synchronization of the two stages of recording and holographic reconstruction of the waves through an optoelectronic method that involves the reconstruction of the hologram simultaneously with its recording. This optoelectronic method involves the simultaneous operation of two experimental set-ups for holographic acquisition and reconstruction. The interference from the acquisition process is digitally recorded on the sensor of an acquisition camera, and the reconstruction is done simultaneously by optical diffraction of the reconstruction wave on a spatial light modulator. This experimental set-up practically connects the two set-ups and gives the method the possibility of real-time digital holographic investigation of various waves and dynamical phenomena. This installation can be compacted, thus increasing its practicability through the possibility of being transported on-site.

1.3 Content of the doctoral thesis

The seven chapters of the present work are presented as a progressive development of the chosen topic starting with a summary presentation of the scope, purpose and content of the thesis in the Chapter 1. Also, in the first chapter, the experimental basis that we had in the development and support of this project is presented.

Chapter 2 briefly presents the experimental conditions specific to holographic interferometry as well as some theoretical aspects regarding the coherence and interference of light, as the main phenomena present in the present theme of the thesis. Also, because holographic interferometry falls into the category of wave-front recording methods, several other methods from the same category are also described, but the presentations of the methods are accompanied by personally developed examples and experimental applications.

In Chapter 3, holography is described as a method of recording wave-fronts, and all theoretical aspects are also accompanied by experimental examples that have been topics and themes for various scientific articles and presentations. The applicability of the reconstruction of digital holograms by optical diffraction on a spatial light modulator is introduced, as a hard variant of the virtual hologram. Comparative studies of numerical and optical reconstruction of digital holograms are also presented, as well as certain hologram simulation procedures by computer generation.

Chapter 4 presents digital holographic interferometry (DHI) as a method to investigate and compare different light waves as well as to visualize and qualitatively and quantitatively evaluate certain dynamic phenomena that require their real-time connection and investigation. I have insisted a lot on certain comparative aspects between classical and DHI. And in relation to the latter, we emphasized real-time DHI by reconstructing the wave-front with the help of the spatial modulator. In this chapter, the theoretical motivation of the proposed method is presented in detail by comparing it with the classical method. Numerous experimental advantages are highlighted that will later be applied in different applications - advantages brought by the proposed hybrid mounting configuration.

In Chapter 5 I presented practical applications of the experimental set-up for the study of diffuse objects. Conventional interferometry can only be applied to objects with smooth, optical surfaces, whereas in holographic interferometry objects with matte, irregular surfaces can be studied. I have shown that the proposed method can be successfully applied in the study of small displacements of diffuse objects as well as in the detection of structural defects of complex surfaces with applicability in a field highly exploited by optoelectronic investigative techniques - art and heritage. We made real-time determinations on two surfaces painted by different techniques - oil on wood and fresco on plaster - and the results were presented systematically throughout the chapter.

Chapter 6 presents investigations carried out on transparent, phase objects. I have applied the proposed DHI for the real-time visualization of certain phenomena in liquids such as convection, dissolution and diffusion, and an application for the real-time investigation of the evaporation of a water droplet is also presented in order to establish some coordinates for future applications in the study of droplet phenomena. In addition to the experimental application, a theoretical model was also developed, and based on it, a numerical simulation was performed that correlated exactly with the experimental observations, a fact that proved the applicability of the method in this field.

Chapter 7 summarizes the conclusions, the results obtained, presents the original contributions, as well as a list of published works in the type of the thematic course of the thesis. And at the end of the chapter, the further prospects for deepening the physical and optoelectronic applications of DHI as a method for investigating waves are developed.

1.4 Used experimental equipment

In the laboratory of the Spectroscopy and Laser Optics (SOL) collective of the National Institute for the Physics of Lasers, Plasma and Radiation (INFLPR) we used different equipment and optical devices specific to optical interferometry experiments. These were matched with various optoelectronic components to obtain the optimal configurations for various DHI applications. Thus, in addition to usual optical components such as lenses, mirrors, spatial filters, dividing cubes and polarisers, we used laser light sources in continuous mode with He:Ne and YAG:Nd, digital sensors and a spatial modulator in phase with liquid crystals operating through reflection.

Chapter 2

Introduction to the methodology of interference recording of wave-fronts

In this chapter I tried to describe the specificity of the theoretical and experimental methodology of coherent optics as a general field that integrates both holography and holographic interferometry. Theoretical notions and concepts such as interference, coherence and diffraction of light are presented in a synthetic manner, but also the practical particularities present in general interference procedures and experiments.

2.1 Experimental conditions in optical interferometry

Because an interference figure is characterized by a periodic distribution of intensity in the form of fringes of different sizes, aspects and shapes, interference methods assume the fulfilment of certain conditions of stability and resolution for a good correlation of the results with the studied phenomena. In some cases the resolution of the fringes also requires a higher resolution of the recording media of the interference figure [1], [2]. The light sources used in interferometry are also a vast field, they require an adaptation of the wavelength to the specificity of the monitored or recorded objects or phenomena. Because the very phenomenon of interference requires a good definition of the coherence of the wave-fronts and a classification of the types of interference and their correlation with the studied phenomena, both white light sources and light sources of different degrees of coherence are used in interferometry, monochromatic, polarized or not [3], [4], [5].

2.2 Spatial and temporal coherence - types of optical interferometers

Coherence of light used in interferometric investigations is the phenomenon that imposes the most various conditions on the experimental set-up.

Coherence is the most important requirement of interferometry applications in general and holography in particular. It is impossible to obtain the phenomenon of coherence between two beams coming from two distinct sources. Depending on the method by which the interfering waves are obtained (these can be two or more, in the case of multiple interference) interferometers are therefore divided into two major classes - wave front-dividing and amplitude-dividing interferometers

Coherence is also of two types - spatial coherence and temporal coherence and these will be imposed as parameters of the sources used in holographic interferometry in the presented experiments.

2.3 Interferential methods of recording and characterizing wave fronts. Applications

In this section I discussed and exemplified in each case some interference methods for recording and characterizing wave fronts and surfaces. Thus, fringe profiles obtained by numerous interference methods can provide information about the shape of diffuse or transparent objects and the wave fronts reflected or transmitted by them. Among the experimentally proposed interference methods are: speckle interferometry, Murty interferometry, Phase-Shift interferometry, Fizeau interferometry. Also in this section a digital Fourier lambda meter configuration is presented.

Chapter 3

Holography as an interference method for recording wave fronts

In this chapter, all the specific experimental requirements of holography as an interference method are analysed, their applicability in the own laboratory conditions and also a good part of the theoretical cases are exemplified experimentally. Classical holography experiments on analogue recording media such as photosensitive emulsions as well as holography experiments in digital terms with both numerical and optical reconstruction of the wavefront are performed and presented. A comparison between the two recording and reconstruction modes is also presented throughout this section.

3.1 Theoretical concepts regarding recording and reconstruction of holograms.

The optical information on an object is contained in the light wave originating from it, called as it was said the object wave, namely in the distribution of real amplitude $a_0(\vec{r})$ and phase $\varphi_0(\vec{r})$ of the wave:

$$\mathrm{a} = a_0 e^{i\varphi_0} \tag{3.1}$$

The photographic process of recording the object wave retains only the amplitude information. The photographic plate being a quadratic receiver, its response is proportional to the intensity of the wave, $\left|a_0^2\right|$, and the phase of the object wave is lost when shooting.

The holographic process of the object wave recording retains all the phase and amplitude information contained in the wave. Recording the phase of the object wave is done using a reference wave:

$$\mathrm{r} = r_0 e^{i\varphi_r} \tag{3.2}$$

namely through its interference with the object wave. The two coherent waves form an interference pattern in which the intensity distribution is given by the relation:

$$I(x,y) = |\mathrm{a}+\mathrm{r}|^2 = (\mathrm{a}+\mathrm{r})(\mathrm{a}^*+\mathrm{r}^*) = a_0^2 + r_0^2 + \mathrm{ar}^* + \mathrm{a}^*\mathrm{r} \qquad (3.3)$$

In the process of recording a hologram, the light from each point of the object falls on the entire surface of the hologram, so that each area of the hologram can reconstruct the entire image of the object. This is a very important property of great utility in applications of holography in information encoding.

3. 2 Classification of holograms

Holograms can be classified according to the experimental configuration that leads to obtaining the object and reference wave profiles, as well as according to the mode of registration of the interference figure. Depending on the positioning of the object, implicitly on the geometry of the waves, on the position of the hologram and also depending on the presence of optical elements in the recording configuration, a classification of the types of holograms was presented..

3. 3 Classical holography. Applications

In the Optical Spectroscopy and Lasers (SOL) laboratory of INFLP we recorded and reconstructed a series of holograms on holographic plates, comparing the requirements and methods imposed by this classical recording medium with the digital one. Fig. 3.5 shows the scheme of an experimental Fresnel holography set-up used in classical holographic recordings.

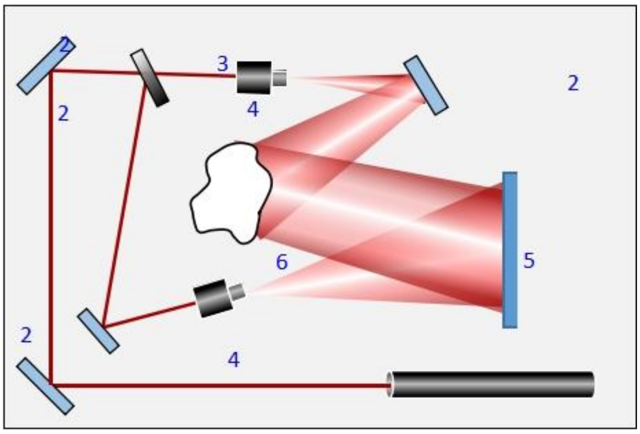

Fig. 3.5 *Scheme of an experimental Fresnel holography set-up used in classic holographic recordings on emulsion plates: He-Ne Laser (λ = 632.8 nm) (1); mirrors (2); variable beam splitter (3); spatial filters (4); holographic plate - hologram (5); the object (6)*

I applied an "off-axis" Fresnel-type holography configuration in which I opted for a plane reference wave to have a higher intensity in the hologram plane and thus to reduce the recording exposure time. In Fig. 3.6 two types of classic holograms recorded on photographic emulsion are presented – Fresnel holograms (1, 2, 3) and an image hologram in which the object is seen from three different angles (4).

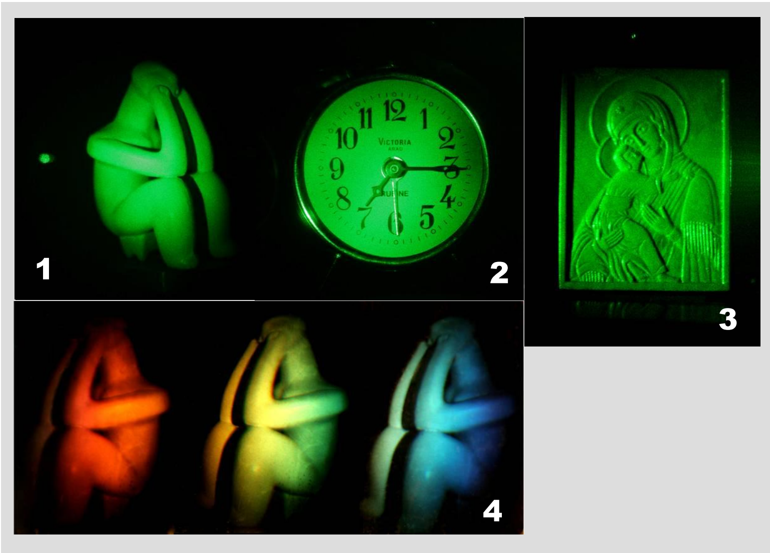

Fig. 3.6 *Photographs of images reconstructed by classical Fresnel holography (1, 2, 3), image type (4, the three images are taken from different angles to observe the entire color spectrum) made on holographic plates in the Optical Spectroscopy and Laser Laboratory of the INFLPR*

Depending on the chemical processing and the way in which the wave diffraction occurs in the hologram plane during reconstruction, holograms are of two types - amplitude holograms and phase holograms. We obtained both types of holograms by applying specific chemical procedures.

3. 4 Digital holography - limitations, advantages and applications.

In digital holography the recording medium is constituted by a digital sensor. When this recording mode is applied, the holograms are saved as simple digital files and can be reconstructed by various computational techniques or with the help of diffractive optical elements (DOE). In the optical reconstruction process or in the computational procedure, the recording set-up must be taken into account, more precisely the characteristics of the two interfering wave-fronts – object and reference. The field is vast and the applications are numerous [6], [7], [8], [9], [10]. The interference figure, once digitally recorded, is processed with digital processing algorithms aiming at the best possible reconstruction of the wave-front corresponding to the object.

Limitations of HD

In contrast to holograms recorded in the classic way on high-resolution photographic emulsions, digitally recorded holograms suffer from certain limitations due to the characteristics of the digital sensors with which the recording is made. Thus, according to equation (3.5), if interference figures, holograms, can be recorded on a holographic plate, with up to 5000 lines/mm, corresponding to fringes of 0.2 μm, in the case of digital sensors where the usual size of the pixels that compose the respective sensor (CCD or CMOS) is on average 5μm, we can end up recording interference figures with up to 70 lines/mm on average.

This limitation that the interference figure suffers directly corresponds to some limitations of the experimental digital hologram recording set-up. Thus, the most important parameter that must be taken into account when recording a digital hologram is the angle that the reference wave makes with the object wave. In order not to exceed the limit resolution of the digital sensor, it cannot be high enough as in the case of classical holograms, where the resolution of the emulsion allowed this.

Advantages of HD

Compared to analogue holography, where the image reconstruction process was quite laborious, presupposing a certain experimental configuration and, prior to that, numerous processes for developing and effectively fixing the photographic emulsion, digital holography has the major advantage that in the reconstruction process all these time-consuming methods are eliminated.

The advantages of digitization in holography will be presented in much greater detail, when we will discuss holographic interferometry and its applicability as a real-time investigation method. In these cases, we propose digital optical reconstruction using a digital spatial modulator, which eliminates computation times and instantly reconstructs the object wave front.

Chapter 4

Real-time DHI as a dynamic method for monitoring and diagnosing phenomena and surfaces

Holographic interferometry is a very effective method in highlighting and monitoring the deformations suffered by a certain wave-front and throughout this chapter the notions of classical holographic interferometry are adapted to the requirements of digital acquisition and optical - diffractive or numerical reconstruction of holographic interferograms. This method involves the interference of waves travelling the same path, but at different times [11].

4.1 Double exposure holographic interferometry

Some of the most important advantages of holographic interferometry over optical interferometry are that, on the one hand, it eliminates the condition that the objects under investigation have optical quality surfaces, and on the other hand, the interfering waves do not have to be produced simultaneously. Thus, the advantages of the investigation by holographic interferometry can be extended to the investigation of certain materials, components and systems that were initially outside the scope of classical interferometry due to their surfaces and textures. Also, due to the fact that the interfering waves are not generated simultaneously, it is possible to interferometrically compare different wave-fronts coming either from the same object in different states, or from two objects that we want to compare.

In the case of holographic interferometry with double exposure on the same medium (photosensitive emulsion deposited on glass or digital sensor), two waves originating from an object to be studied corresponding to its two consecutive states are recorded holographically. Any phase difference can be phenomenologically correlated with a displacement or a deformation, phenomena that induce a geometric path difference between the two holographic waves or a change in transparency of the object that induces a change in the refractive index distribution. Both situations lead to the modification of the optical path in the object wave and the generation of interference fringes superimposed on the reconstructed image of the object.

4.2 Real-time DHI with SLM optical wave-front reconstruction. Experimental conditions

DHI involves replacing the conventional sensor (holographic plate) with a digital one (CCD or CMOS digital sensors). Real-time DHI can be analysed as a sequence of differential interferograms resulting from the consecutive subtraction of successive holographic frames from a reference frame, so we are dealing with "a sequence of double exposures" (Fig. 4.1). The reconstruction of the interfering wave fronts is the result given by the diffraction on the resulting matrix of an incident wave (the operation can be done digitally, using a reconstruction software that simulates diffraction, or optically using a spatial light modulator).

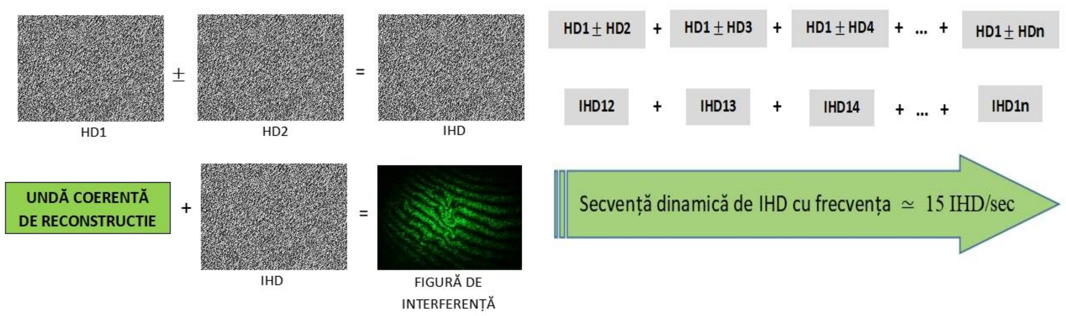

Fig. 4.1 *Schematic representation of digital formation and reconstruction processes in digital holographic interferometry applications.*

Real-time DHI can be analysed as a sequence of differential interferograms resulting from the consecutive subtraction of successive holographic frames from a reference frame.

Chapter 5

Experimental applications of real-time DHI using SLM in the study of diffuse objects

In the sections of the chapter, experimental applications of visualizing the translation of a diffuse object in a direction perpendicular to the viewing direction are presented and also different structural defects of some painted surfaces are studied with applicability in the analysis of works of art. In addition to the experimental methods, a simulation in the case of small displacements is presented and the experimental data are compared with the simulated ones. For these investigations, two experimental set-ups were designed and will be described in the sections of the chapter.

5.1 The study of small displacements

5.1.1 Principle of the method

Waves diffracted by two holograms recorded on the same material that correspond to slightly different states of the same object interfere in turn. The object can undergo small lateral displacements and the holograms corresponding to the object in two different states and numerically composed in an interferogram can generate, through the diffraction of a reconstruction wave, an image of the object itself, over which a network of interference fringes perpendicular to the direction of translation is superimposed. The fringe density depends on the displacement value and we can determine the displacement magnitude from the inter-fringe value.

The fringes obtained by means of optical reconstruction by diffraction were correlated with the lateral translation of the object fixed on a micrometric table allowing control of the displacement. In parallel with the optical reconstruction, we also performed a numerical reconstruction of the same digital interferograms. It can be seen in Fig. 5.5 similarity of interference figures.

5.1.2 Experimental conditions

With the help of the experimental set-up whose configuration is presented in Fig.5.3 I managed to determine and visualize the changes undergone by the surface of a diffuse object, whether it is translation as presented in this section or deformation as will be seen in the next section of this chapter

The experimental set-up is a hybrid composed of a secondary digital holographic acquisition set-up and a reconstruction line that works simultaneously, the whole assembly being able to perform real-time investigations through simultaneous digital acquisitions and reconstructions.

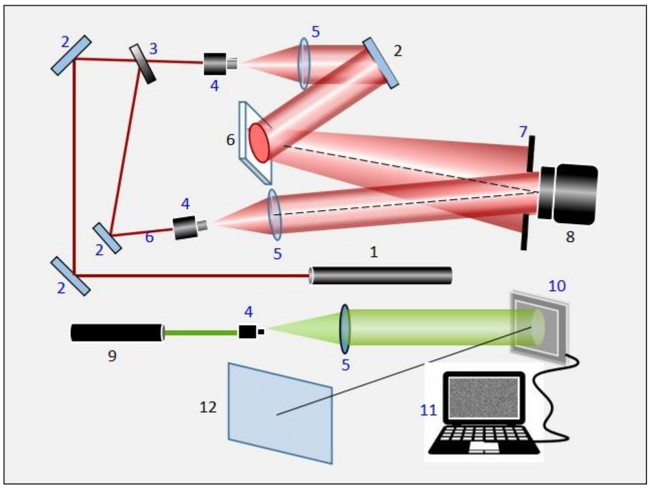

Fig. 5.3 *Schematic of the hybrid real-time holographic acquisition and reconstruction set-up: (1) He-Ne laser; (2) mirrors; (3) variable beam splitter; (4) spatial filters: (5) converging lenses for collimation; (6) diffuse object; (7) diaphragm; (8) CCD digital camera; (9) Yag:Nd laser in continuous mode (532 nm); (10) SLM LCoS HoloEye HEO 1080; (11) laptop; (12) reconstructed image projection screen.*

It should be specified that the spatial modulator completely reconstructs the holographic frames acquired by the camera keeping the same frequency of their display, so we can therefore speak in this first stage of the acquisition and reconstruction of *"holographic films"*.

5.1.3 Experimental results

The digital holographic acquisition was done with a He-Ne laser (λ = 632.8 nm), and the fringe reconstruction was done with a Nd:YAG laser operating in continuous frequency-doubled mode with a wavelength of 532 nm. For a qualitative comparison of the method, the numerical reconstruction of the digitally recorded holograms was also performed. Diffraction on the distribution of pixels of different gray levels associated with the intensity distribution in the sensor plane interference pattern was simulated. Numerical reconstruction was performed in the program Matematica.

In Fig. 5.5 you can see the object illuminated with the reference wave, its holographic reconstruction by diffraction on the SLM and a series of optically and numerically reconstructed holographic interferograms corresponding to the different displacements of the object [12].

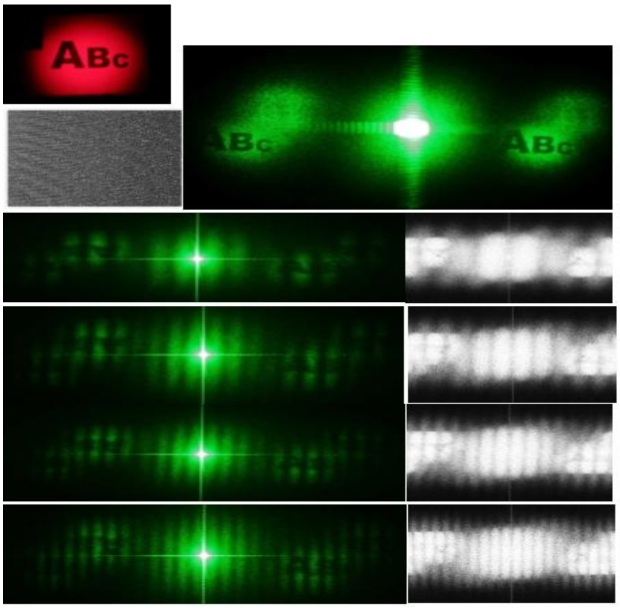

Fig. 5.5 *Real-time sequence of four holographic interferograms corresponding to lateral displacements from a sequence of frames digitally recorded and reconstructed with the HoloEye HEO 1080 spatial phase modulator: a) diffuse object illuminated with coherent wave; b) digitally recorded amplitude hologram c) reconstruction wave diffraction on the SLM displaying the phase hologram; d) sequence of holographic interferograms e) sequence of numerically calculated holographic interferograms*

It can be seen that the focal planes of the respective object of the interference figure are different and selective focusing can be done from the reconstruction montage by changing the position of the focus lens of the reconstruction beam which is modulated by the SLM.

5.2 Applications in the study of structural defects in artworks

5.2.1 Applications of optoelectronic techniques in the conservation and restoration of artworks

Along with the development of various opto-electronic technologies, an application of these technologies in the diagnosis and restoration of artefacts has also been imposed, giving rise to a whole trend in the preservation of objects belonging to an entire historical and cultural heritage by using and adapting new technologies in the specific procedures of this direction . Holographic interferometry is a method that can provide valuable clues about the structure of diffuse surfaces [13]. DHI can be applied in diagnostic and restoration procedures, but also in their authentication and identification methods.

5.2.2 Experimental results in the real-time DHI investigation of structural defects in painted artefacts

In order to apply real-time DHI for the investigation of structural defects for different painted surfaces I used two experimental set-ups. I investigated certain areas of the surface of an icon painted in the oil on wood technique [14]. The identified defects consist of cracks and detachments of the paint layer from the primer substrate and are shown in Fig. 5.7.

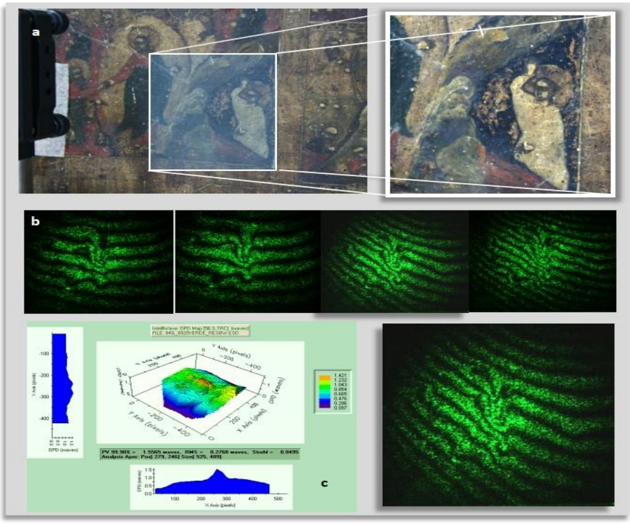

Fig. 5.7 Defect of cracking and detachment of the paint layer from an icon in oil on dry wood. XIX investigated by digital holographic interferometry in real time: a) Image of the studied area; b) sequence of interferograms; c) the distribution of the optical path difference generated by the defect during the investigation.

A second type of experimetal set-up was applied in the study of a surface painted in the fresco technique (Fig. 5.8). I opted for this configuration because most of the time the studied objects are too large to be transported to the laboratory without considerable risks. Also, if the object is too large, a geometry of the components is required to remove the studied object from the assembly.

The proposed holographic interferometry set-up is based on a Michelson interferometer type configuration with amplitude division. This allows the object to be positioned in one arm of the set-up, allowing the reference beam to be propagated to the other arm. In the overlapping area of the two beams I placed the digital camera for the sequential acquisition of the holograms. In addition to the fact that this configuration takes the object practically outside the optical components geometry it also gives the advantage of a small angle between the object wave and the reference wave. This makes the frequency of the fringes on the digital sensor not exceed an optimal value given by the relatively small frequency of the pixels compared to classic plates with emulsions.

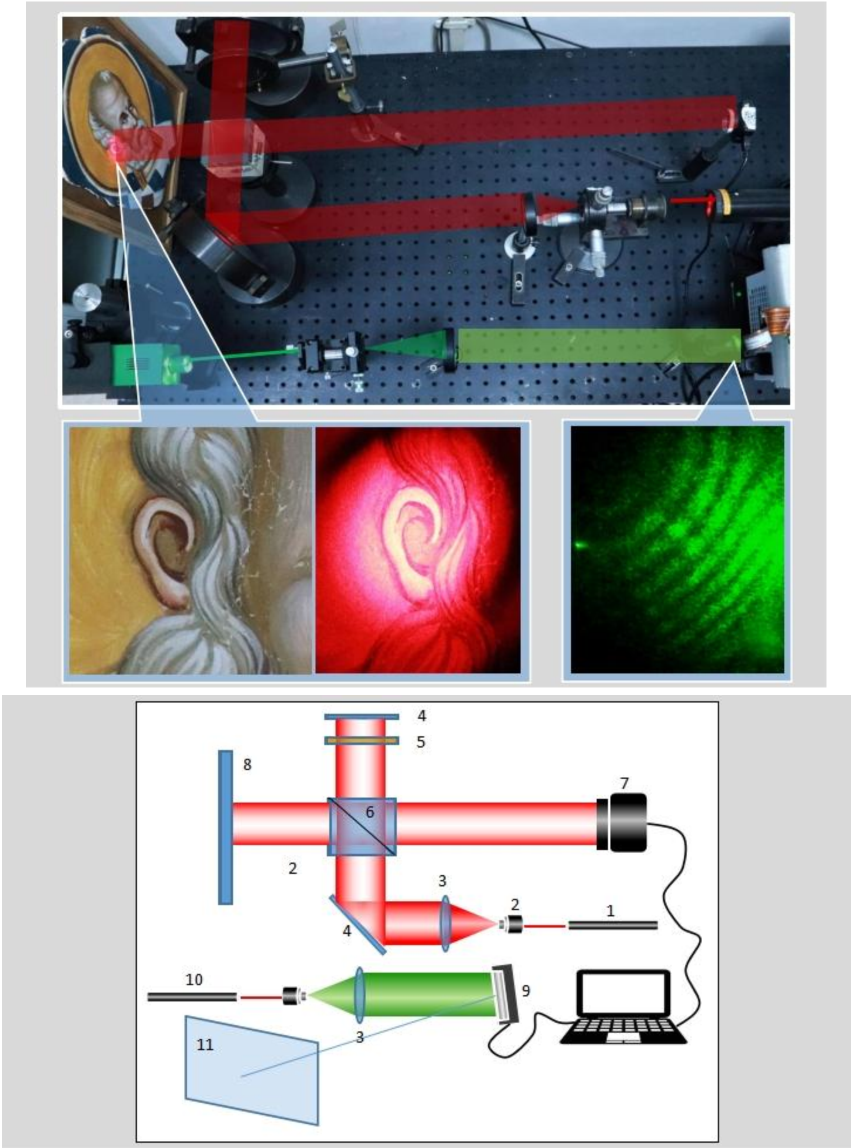

Fig. 5.8 *Laboratory image and scheme of the experimental setup of DHI in Michelson configuration, used in the study of structural defects of a surface painted in the "fresco" technique (1) linearly polarized He-Ne laser; (2) spatial filters; (3) collimating lenses; (4) plane mirrors; (5) polarizer; (6) dividing cube); (7) CCD camera; (8) object; (9) HoloEye HEO 1080 digital spatial phase modulator; (10) YAG:Nd laser in continuous mode 532 nm; (11) interference figure projection screen.*

Fig. 5.9 shows three areas of the fresco studied in detail over which small temperature changes were induced to generate interference fringes.

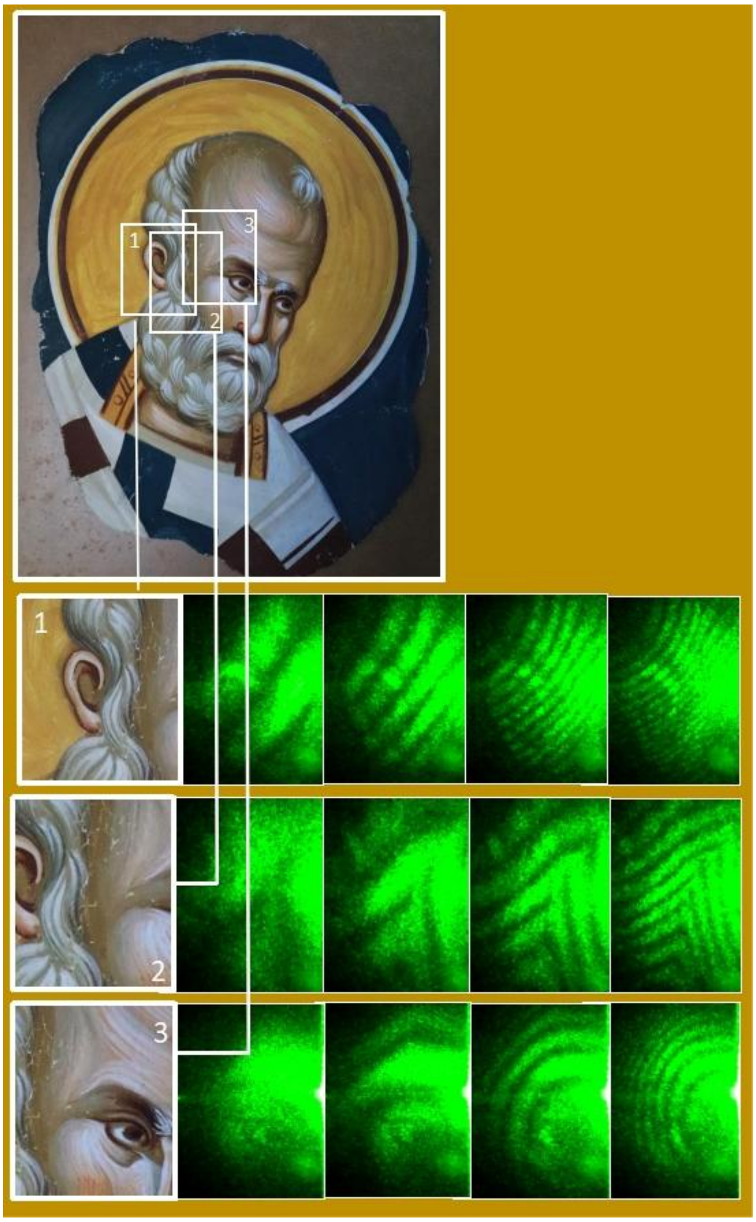

Fig. 5.9 *Profiles of interference fringes in a series of real-time DHI sequences applied to areas of an icon in the fresco technique.*

This method can be successfully used in this type of applications with the main limitation being the relatively small area that can be investigated in a single sequence of holographic interferograms (diameter ~ 7 cm). This is caused both by the power developed by the coherent source used, by its spatial coherence, but also by the boundary conditions of the fringes spatial frequency in the hologram imposed by the pixel frequency of the digital sensor.

Chapter 6

Experimental applications of real-time DHI in the study of phase objects

A very important category of objects included in the study of holographic interferometry are phase objects, transparent to the radiation used, but which modify the optical path of the light from a beam through the variations of the refractive indices induced compared to a coherent beam with the same geometric path. Certain chemical reactions, liquid diffusion, dissolution, crystallization, heat conduction, dissolution or turbulence are phenomena that lead to variations in the refractive index in the volume of objects. Refractive index variations generate optical path differences that can be the object of investigation of DHI [15], [16], [17].

6.1 Real-time visualization of turbulence and dissolution in liquids.

In order to demonstrate the applicability of the proposed real-time holographic interferometry method for this type of investigation, I used an experimental set-up similar to the one presented in section 5.1.2, with the difference that the diffuse object was replaced by a matte white screen with a very small grainy surface , and the transparent object studied, in our case a liquid, was placed in a quartz tub positioned in front of the diffuse screen (Fig. 6.2). The geometric path is the same in the two arms of the holographic arrangement, the difference in optical path and implicitly the interference figure being generated by variations in the refractive index within the volume of the liquid positioned in the object arm. In the present case, convection and diffusion were visualized in real time [18].

Convection was observed in real time with the formation of eddy currents in the liquid volume when a saturated solution of NaCl or 70% ethanol was dropped into water.

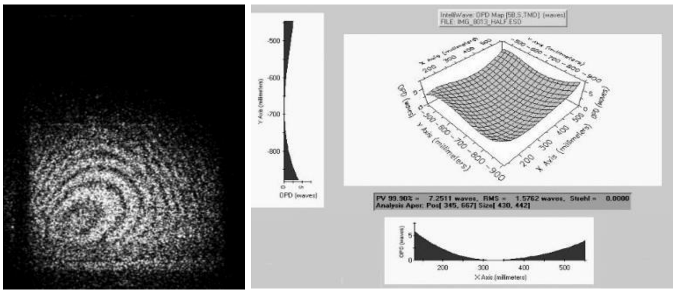

Fig. 6.2 *Interference fringes generated by the optical path difference induced by the presence of water in a quartz cuvette, the first holographic frame acquired being that of the empty cuvette (a); a distribution of optical path difference illustrated by fringes (b).*

Fig. 6.3 shows a series of four images reconstructed at an interval of one second from a series of holographic interferograms acquired during convection. The process could be observed in real time with a frequency of 22 interferograms per second.

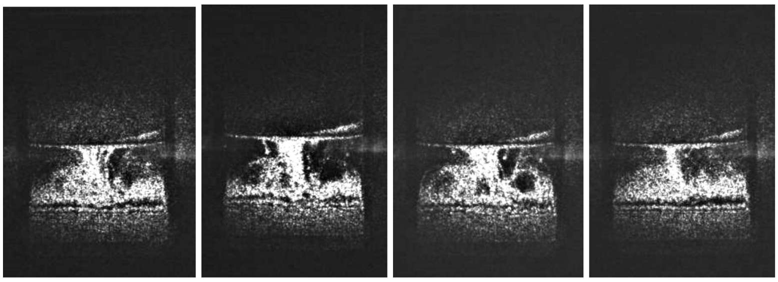

Fig. 6.3 *Sequence of 4 images reconstructed at one second intervals of the convection process observed in real time by DHI*

Fig. 6.4 shows a sequence of four images in which, in addition to convection, the dissolution process of a saturated solution of NaCl or 70% ethanol in water can be seen.

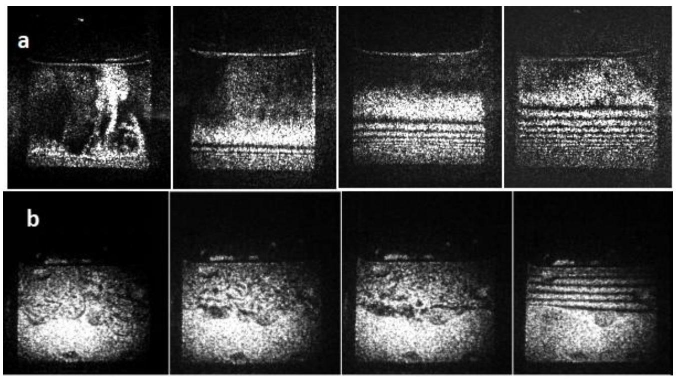

Fig. 6.4 *The sequence of 4 images reconstructed from interferograms recorded in real time (22 fps) in which a dissolution process of two liquids is presented: a) saturated saline solution in water (in the first image you can see the convection generated by a drop of saturated solution of NaCl in water); b) ethanol in water*

The last three images are acquired at different intervals and it can be seen that the linear density of the fringes differs on the one hand from frame to frame, but also with depth. For the last frame in Fig. 6.4.a a map of the optical path difference of the refractive index variation as well as an intensity distribution according to depth is drawn (Fig. 6.5).

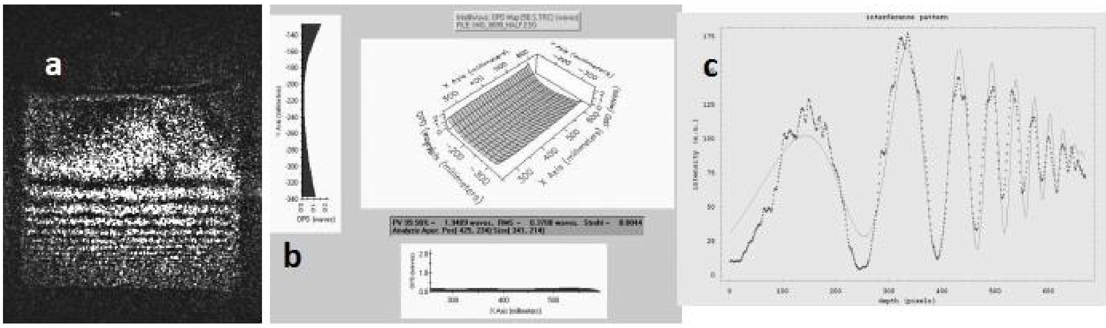

Fig. 6.5 *Reconstruction of a holographic interferogram generated by a quartz vat filled with water in which NaCl was dissolved. (a); Refractive index distribution correlated with OPD distribution generated with IntelliWave (b); Intensity distribution as a function of depth (c).*

The density of the fringes corresponds to the variation of the refractive index which is also correlated with the variation of the density with depth. The image is recorded during the dissolution process after 1450 s. The interfringe variation corresponds to a refractive index gradient correlated with the exponential variation of density with depth.

6.2 Monitoring the water droplet evaporation

Water droplets are widely used in technological and biological applications and their behaviour under certain conditions is studied by various methods [19].
Because it is almost impossible to optically investigate the changes in shape and refractive index inside a drop by using a plane wave, I proposed in one of the scientific works that fell within the theme of this thesis the use of a divergent wave as an interferometric investigation tool [20]. Even if the use of divergent beams in interferometry applications is not a new practice, the innovation and originality consists in the configuration of the experimental set-up. The investigation and characterization of a water drop using the Mach-Zehnder interferometer did not give the expected results according to Logofătu and all. [21].

The real-time holographic interferometry set-up (Fig. 6.7) is composed, like the other configuration presented, of a holographic acquisition component on a digital sensor and another holographic reconstruction component using a spatial phase modulator.

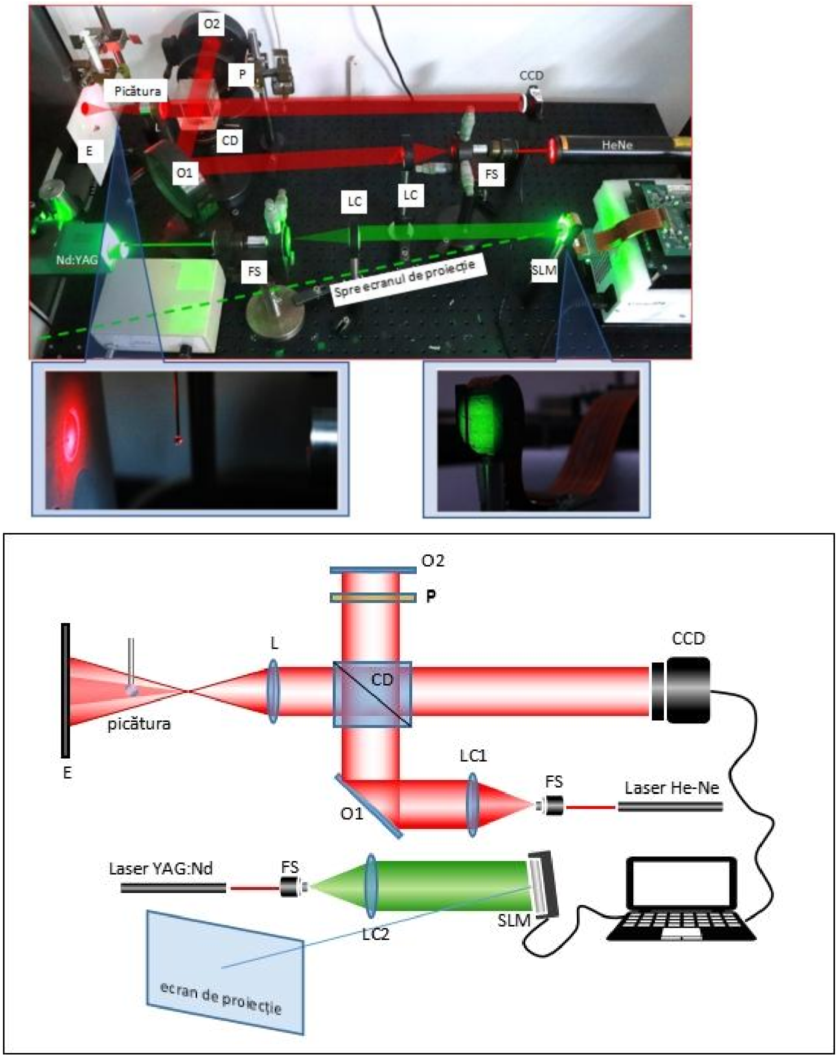

Fig. 6.7 *Real-time DHI setup for monitoring the evaporation of the water droplet in suspension: polarized He-Ne laser (633 nm); frequency-doubled Nd:YAG laser (532 nm); FS - spatial filter; LC1, LC2 - collimating lenses; O1, O2 - plane mirrors; P - polarizer (used as an attenuator); CD - dividing cube; E - matte white screen.*

The lens and the droplet as transparent refractive media have different roles in the montage depending on the direction of the light rays passing through them. When the beam passes from the spatial filter to the matte screen, the lens transforms the collimated beam into a divergent one. In the second pass from the screen to the spatial filter, the droplet, which is very small, has almost no effect on the complex wave front reflected by the screen, and the lens L in this case has the role of forming the image of the screen carrying the projection of the drop . In parallel with the experimental data, a theoretical simulation of the water droplet evaporation was also performed, and some dynamic sequences of the interferograms were also calculated to be compared with the experimental data (Fig. 6.8). In the simulations, the variation speed of the interfringe was adjusted with the one obtained experimentally and based on this correlation we could obtain an evaporation speed of $v = 0.14\ l/m^2s$.

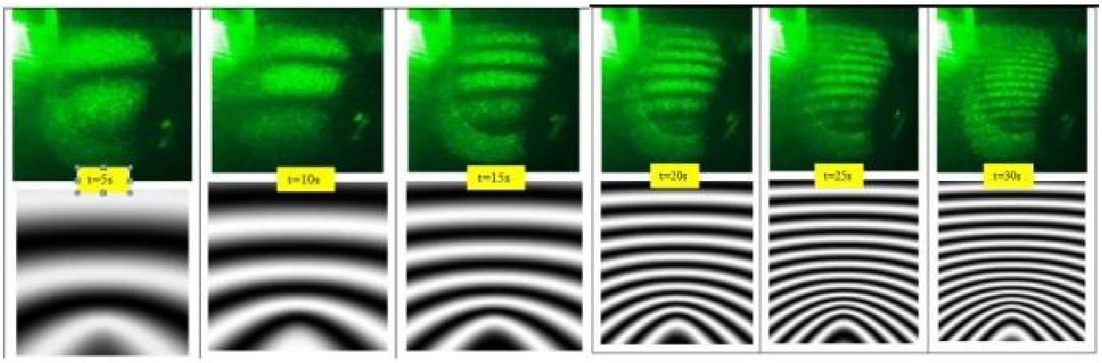

Fig. 6.8 *– Two sequences of six reconstructed images selected from the dynamic interferograms characterizing the evaporation of the water drop, experimentally (green light) and in numerical simulation (black and white).*

In addition to the study of the evaporation of the water droplet in suspension, we also developed a holographic interferometry set-up that allows the study of the evaporation of the water droplet from a surface (Fig. 6.9). Due to evaporation, its curvature changes and this induces changes in the shape of the object wave-front which are seen in the dynamic figure of the interference fringes which are Heidinger type.

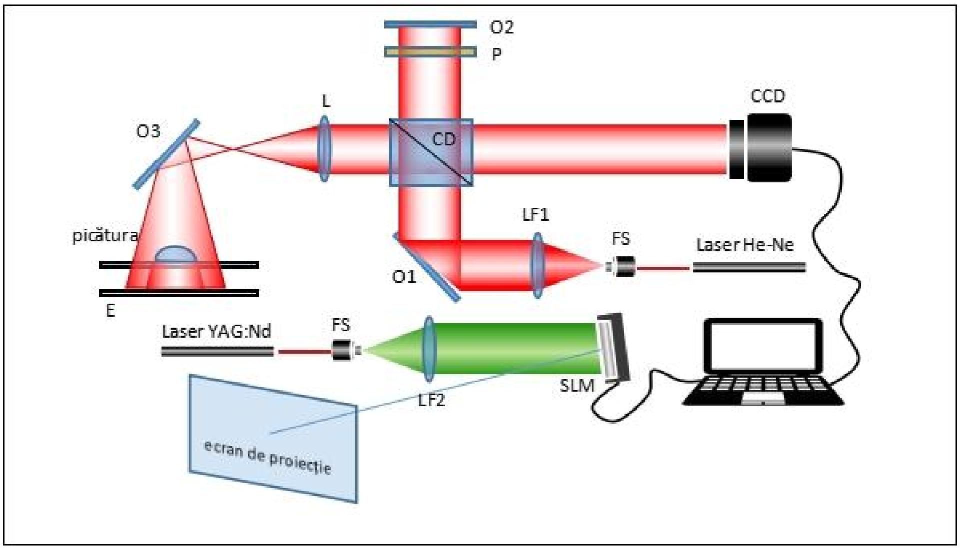

Fig. 6.9 *Schematic of the real-time DHI experimental set-up for monitoring the evaporation of a water drop from a horizontal surface: polarized He-Ne laser (633 nm); frequency-doubled Nd:YAG laser (532 nm); FS - spatial filter; L, LC1, LC2 - collimating lenses; O1, O2, O3 - plane mirrors; P - polarizer (used as an attenuator); CD - dividing cube; E - matte white screen.*

To compare the results obtained by DHI with spatial light modulation, we evaluated the evaporation rate of the dropler and with the help of the Ambios Xi-100 white light interferometer. In Fig. 6.11 selected snapshots from the sequences of dynamic interferograms obtained by the two methods are presented.

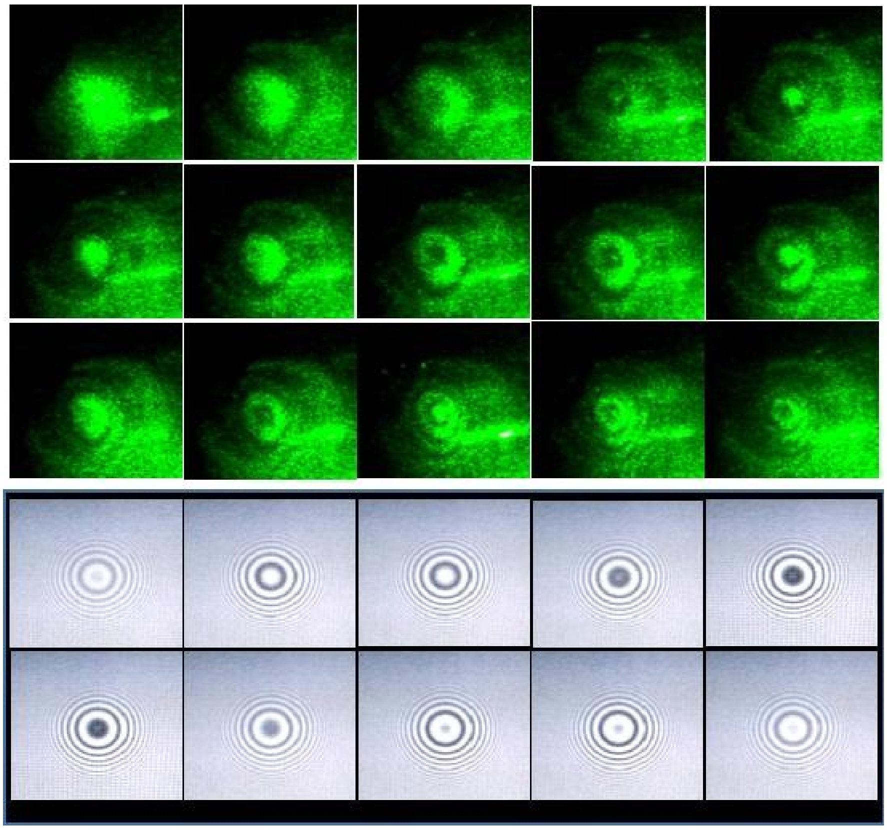

Fig. 6.11 *Successive frames from a dynamic sequence of interferograms obtained by real-time holographic interferometry (green light) and white light interferometry generated by the evaporation of a water droplet from a horizontal surface.*

The research on this behaviour of the droplet on surfaces will be deepened, in order to understand the "coffee stain effect" from the perspective of fluid dynamics, the way of investigation by using DHI and its application in different fields.

Chapter 7

Conclusions

The calculation techniques, the reconstruction algorithms developed in digital holography are resource and time consuming and most of the times the applications require a correlation with the dynamics of the studied phenomena. Numerical reconstruction of holograms has certain limitations in real-time phenomena investigation applications due to the computational time. Optoelectronic technologies must be found in holography because they can be the link between the recording on the digital medium that generates a virtual file, a digital hologram as a matrix distribution of pixels of different intensities and the reconstruction of the object that can be instantaneous, physical through concrete diffractive optical methods , directly on the SLM device which becomes the "hard" version of the virtual hologram. This coupling of the two stages was successfully achieved during the experiments that were carried out during the thesis.

7.1 Results

In this thesis, all methods of recording and diagnosing wave fronts, other than holography or interferometry, were accompanied by experimental examples carried out personally or in which I took part within the *Optical Spectroscopy and Lasers* team within the INFLPR. Any method of investigation that was presented theoretically was therefore accompanied by an experimental part carried out personally.

- I designed and applied digital holography set-ups and experiments with digital acquisition and numerical and optical-digital reconstruction using SLM. I compared the parameters and results obtained in digital and numerical reconstruction experiments.
- I managed to correlate the digital holographic recording process using a CCD camera with the reconstruction process by instantaneous optical diffraction on SLM and I obtain a hybrid DHI set-up that performs real-time investigations on various transparent (phase) or diffuse objects .
- I managed to prove the functionality and usefulness of this montage in various investigations like

- ➢ real-time monitoring of the movements of an object in a plane perpendicular to the viewing direction
- ➢ real-time monitoring of various phenomena such as dissolution, diffusion, turbulence in liquids, evaporation rate of water droplets.

- I demonstrated that it is possible to interferometrically investigate the behavior of water droplets by using a divergent beam that interferes with a reference one and that produces fringes that can be holographically reconstructed and visualized in real time.
- I have identified structural defects in diffuse objects through real-time DHI investigations of surfaces. Surfaces of icons in oil and fresco were studied, the method can also be applied to art objects made of stone, ceramic, wood, metal, etc. Structural defects were visible through fringe discontinuities generated by structural discontinuities present in the surfaces.
- I proposed a compact montage scheme consisting of a digital holographic acquisition sub-mount and an optical-diffractive reconstruction sub-mount using SLM. Digital interferograms obtained by consecutively subtracting holograms from a hologram corresponding to a wavefront reference state are displayed simultaneously on the computer monitor and implicitly on the SLM which behaves as a second, in-phase monitor.

7.2 Original contributions

In this paper I tried to apply and adapt the classical methods of holography and holographic interferometry to different applications using computational techniques, and optoelectronic devices that transformed the classical methods into digital methods. Although we used classic montages, consecrated by holography in the same classic manner, in some applications they were adapted according to the optoelectronic components used and the numerical or optical method of reconstruction taking into account the digital character of the method. We have also developed numerical methods for generating holograms and simulating optical reconstruction phenomena such as Fresnel, Fraunhoffer or Fourier diffraction. Although in holography recording and reconstruction are two distinct phases of the process, I tried in the phase work to correlate these stages and apply them simultaneously in order to give the method applicability in real-time investigations while preserving the digital aspect of the method that connects it to the IT facilities, but also the classic dimension of the method that preserves its dynamic character and eliminates numerical processing time.

So, it can be said that the element of originality of this thesis is *the contribution made to the development of a compact opto-electronic device that can perform real-time holographic or digital holographic interferometry investigations on various phenomena or objects of interest*.

For this purpose, I made several experimental setups that finally led to a proposal for a compact opto-electronic DHI setup in real time. During the thesis I tried to demonstrate the functionality of this compact montage through various investigations:

- lateral displacements of diffuse objects were monitored in real time through digital acquisition of holograms in video mode correlated with their simultaneous reconstruction through an optical-digital method using a digital spatial modulator.
- I used the proposed experimental configuration in real-time monitoring of refractive gradients in transparent objects. For this purpose, I visualized in real time through digital holographic interferometry different phenomena that take place in transparent liquids (dissolution, dissolution, turbulence, convection). The experimental data were numerically processed and important information was extracted regarding the operating parameters of the assembly as well as data regarding the investigated phenomena.
- different experimental set-ups were developed and also they were successfully used in the investigation of structural defects of diffuse objects. For this purpose, I investigated various structural defects of the surfaces of some icons painted in oil and fresco techniques. One of the advantages of the proposed assembly is that, due to the fact that it is compact, it can be transported and used in-situ, a very useful facility in the case of this time of investigations.

The originality of the proposed assembly consists precisely in the elimination of some constraints typical of holographic investigations consisting in the high stability of the experimental configuration, a very good mechanical isolation of the optical components, numerical processing for reconstruction that consumes time and digital resources. The experimental conditions are simplified when using a spatial modulator in tandem with a digital acquisition sensor coupled through a numerical application that can couple the recorded holograms into a holographic interferogram. The main advantages of the proposed device are:

Mobility: It can be easily transported for on-site applications. It is compact, all the optical and electronic components being fixed on a metal plate. The acquisition is performed digitally and the optical reconstruction is made by using SLM, therefore the recording times are very short, a fact that further isolates the method from mechanical influences.

Considerable elimination of the need for mechanical isolation: unlike classical holography, where recording is done on conventional media and exposure times are long (of the order of tens of seconds) compared to the fineness of the details that are recorded (interference fringes of the order of tens of nm), a fact that requires a good mechanical isolation of the experimental assembly. If the recording is done digitally, the sensor allows a very good control of the exposure parameters (exposure time, gain, gamma, frame rate, etc.) that can successfully compensate the experimental conditions (brightness, mechanical noise, etc.)

The possibility of real-time adaptation of the experimental parameters: unlike classical holography methods in which the exposure conditions and the experimental configuration can be adapted and modified after recording, in the present case, because the reconstruction is done simultaneously with the recording, all the experimental parameters (exposure time, alignment, etc.) can be adjusted and adapted to the recording conditions and to the parameters that characterize the object during the experiment itself.

The possibility of connecting to the experiment, in real time. The recording and reconstruction method being completely digitized, it can be done with the help of optoelectronic devices that can connect in real time through networks and the Internet. Thus, observers from different locations can take part in the same investigation, each one being able to adapt experimental parameters according to their own preferences.

It is therefore observed that the proposed method combines the advantages of digitization in the holographic recording of waves and the advantages of instantaneous reconstruction by diffraction in the process of reconstruction of wave fronts.

7.3 Original papers

1. F. Garoi, **A. Sima**, D. Apostol, V. Damian, P. C. Logofătu, V. Nascov, Iuliana Iordache, Ludmila Serghei, Mihaela Bojan, *"SNR improvement of digital speckle pattern interferograms"*, Proc SPIE 6606-12, Advanced Laser Technologies 2006, Dan C. Dumitras; Maria Dinescu; Vitally I. Konov, Editors, 25 April 2007
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3. V. Damian, P. C. Logofatu, D. Apostol, L. Vekas, D. Bica, A. Damian, F. Garoi, I. Iordache, **A. Sima**, M. Bojan, *"Magnetic liquid surface behavior to external stimulus"* ROMOPTO 2006, Proc SPIE 6785 23, V.I. Vlad eds., (Bucharest, Romania, 2006) 1 August 2007
4. D. Apostol, **A. Sima**, P. C. Logofatu, F. Garoi, V. Nascov ,V. Damian, Iuliana Iordache, *"Fourier transform digital holography"* ROMOPTO 2006: Eighth Conference on Optics, Valentin I. Vlad, Editors, Proc SPIE 6785 678522 Date: 1 August 2007
5. D. Apostol, **A. Sima**, P. C. Logofatu, F. Garoi, V. Damian, V. Nascov, Iuliana Iordache, *"Static Fourier transform lambdameter"* ROMOPTO 2006: Eighth Conference on Optics, Valentin I. Vlad, Editors, Proc SPIE 6785 678521, 1 August 2007
6. Damian, V; Bojan, M; **Sima**, A, et al., *"White light interferometry for vertical artifact calibration"*, Conference on Industrial Laser Applications (INDLAS 2007), Date: MAY 23-25, 2007, Bran, Romania, Proc SPIE 7007 0J (2008)

7. Petre Catalin Logofatu, **Adrian Sima**, Dan Apostol, Invited Paper *"Diffraction experiments with the spatial light modulator: the boundary between physical and digital optics,"* ATOM-N 2008, Constanta, SPIE Proceedings [7297- 03] (2009)
8. B. Ionita, M. Rosu, D. Apostol, **A. Sima**, V. Damian, I. Cristea, *"IntelliWave™ Interferometric analysis software in laser interferometry laboratory,"* ATOM-N 2008, Constanta, SPIE Proceedings [7297-18] (2009)
9. **A. SIMA, P. SCHIOPU, P. C. LOGOFATU, *„Real-time digital holographic interferometry set-up for phase gradient in dynamic phase objects using spatial light modulator"* ATOM-N Constanta, Proc. of SPIE Vol. 10010, 100100R (2016)**
10. **A. SIMA, P. SCHIOPU, P. C. LOGOFATU, *„Real-time digital holographic interf erometric measurement of diffusive objects displacements using spatial light modul ator"* Electronics, Computers and Artificial Intelligence (ECAI), 2017 9th Intern ational Conference, IEEE, december 2017**
11. **A. SIMA, P. SCHIOPU, M. VLADESCU, F. GAROI, V. DAMIAN, B. M. GAVR ILOAIA, *„Real - time spatial light modulated digital holographic interferometry ap plied in art structural diagnosis"* , FABULOUS 2017 CONFERENCE, BUCHAR EST, ROMANIA, OCTOBER 12 - 14, 2017**
12. Petre Cătălin Logofătu, John Robert McNeil, **Adrian Sima**, Bogdan Ioniţă, Florin Garoi, Dan Apostol*, "The characterization of gratings using the optical scatterometer,"* Romanian Journal of Physics 55(3-4), 376-385 (2010)
13. P. C. Logofatu, F. Garoi, **A. Sima**, B. Ionita, D. Apostol, *"Classical holography experiments in digital terms,"* Journal of Optoelectronics and Advanced Materials, 12(1) 85-93 (2010)
14. **A. SIMA, P. C. LOGOFĂTU, M. L. PASCU, I. NICOLAE, *"Monitoring droplet evaporation via real-time digital holographic interferometry using a phase only spatial light modulator",* ROMANIAN REPORTS IN PHYSICS 74, 402 (2022)**
15. **Cristian Damian, Adrian Sima, Tiberius Vasile, and Daniela Coltuc. *Microscanning in hadamard spectroscopy.* Applied Optics, 56(18):5211, jun 2017.**

7.4 Future work

I want to optimize the software for producing digital interferograms by introducing in the reconstruction algorithm from the sequentially recorded holograms an option that moves the +1 diffraction order corresponding to the reconstructed object compared to the 0 order. At this moment the movement is done from the configuration of the experimental assembly. In the future, an in-line holography setup can be kept with greater ease of realization and better diffraction efficiency upon reconstruction, and the +1-order reconstructed object can be moved by numerical algorithms that I plan to introduce in hologram subtraction software.

I also want to apply for a patent to make a compact real-time DHI montage with SLM reconstruction that can be transported and used in in-situ applications

I also intend to apply the experimental setups proposed by DHI in new investigations on the behavior of micro droplets of water and other liquids when interacting with coherent radiation in order to obtain active liquid laser media, the behavior of water droplets loaded with different pollutants. I also want to expand the applicability of the method in various investigations of the surfaces of works of art or archaeological objects, in restoration procedures I give non-destructive diagnostics.

Even if holography and holographic interferometry are established as classic interferometric methods of investigating and diagnosing wavefronts, by digitizing the recording and light modulation media I want to deepen and keep these two methods connected to the current technology present and developed in different optoelectronic devices. All the advantages of digital technology will keep these methods extremely versatile in numerous applications and their use will largely respond to new challenges drawn by new research directions.

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