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Nicolas Budini
Nicolas Balducci
Cecilia Mulone
Andrea C. Monaldi

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Extraction of dynamic speckle activity information from digital holograms

Nicolas Budini,[a,b,*] Nicolas Balducci,[b] Cecilia Mulone,[c] and Andrea C. Monaldi[d]
[a]Universidad Nacional del Litoral, Facultad de Ingeniería Química, Sgo. del Estero 2829, S3000AOM Santa Fe, Argentina
[b]Instituto de Física del Litoral (IFIS Litoral), Güemes 3450, S3000GLN Santa Fe, Argentina
[c]Universidad Tecnológica Nacional, Facultad Regional Paraná, Av. Almafuerte 1033, E3100XAI Paraná, Argentina
[d]Universidad Nacional de Salta, Instituto de Investigaciones en Energía No Convencional, Av. Bolivia 5150, A4408FVY Salta, Argentina

Abstract. In this work we show how dynamic speckle information can be extracted directly from digital holograms. This allows improving the analysis and characterization of dynamic phenomena by combining dynamic speckle with digital holographic interferometry measurements. We have studied the drying process of paint coatings, which is a typical study case in the field of dynamic speckle characterization, since the speckle activity (SA) of drying coatings is known to decay smoothly as a function of time. We recorded both holograms and speckle images during the process. In this way, we could compare the evolution of global SA calculated from speckle images by a standard method with the evolution of speckle correlation extracted directly from the holograms. The results obtained from both methods have shown to be in good agreement. [DOI: 10.1117/1.OE.55.12.121716]

Keywords: dynamic speckle; speckle correlation; digital holographic interferometry; dynamic phenomena; characterization.

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1 Introduction

Speckle patterns are known to possess information about the surface of an illuminated object at a scale below that of the wavelength used.[1,2] If the surface of the object under coherent illumination presents variations over time, a dynamic speckle pattern arises, which allows an analysis of the object in the time domain. The degree of change of the speckle patterns as a function of time is usually called speckle activity (SA), and several methods have been developed to analyze SA both qualitatively and quantitatively.[3] Among them, we can mention the combination of time history speckle pattern[4] and the inertia moment methods,[5] the laser speckle contrast analysis,[6] the generalized differences and the weighted generalized differences methods,[7] the Fujii approach,[8] and correlation-based algorithms.[3,9] In general, these methods provide SA maps with pointwise information along the surface of the sample. Recently, we have also developed a simple algorithm to quantify globally the SA of dynamic speckle patterns, which is based on the calculation of the area fraction presenting variation between consecutive speckle images.[10]

Despite the fact that SA quantification is really simple and straightforward, and also due to the complex relation between speckle patterns and the characteristics of the object under analysis, a clear understanding and a consistent explanation linking the observed dynamics with the underlying physical processes are still lacking.[11] Therefore, the combined implementation of dynamic speckle methods and other characterization techniques can bring some light into the mechanisms giving rise to the observed SA evolution of a particular object or sample under study. Particularly, the combination of dynamic speckle methods and digital holographic interferometry (DHI) is very interesting, since the latter technique allows measuring interferometric variations at the surface of the object under study.

Several works have been devoted to the characterization of dynamic phenomena through implementing dynamic speckle techniques, being the drying process of paints a typical study case in this field that we also adopted for this work. Regarding this particular study case, works found in the literature are based on speckle interferometry[12,13] and dynamic speckle correlation[3,9,14–19] techniques. In a small proportion, other works employed methods based on DHI to analyze the drying process of paints.[20,21] However, the combination of both techniques has not been explored so far.

In this work, we show, for the case of the paint drying process, the possibility of extracting or recovering the global dynamic speckle information of the sample contained in a sequence of acquired holograms. This makes it plausible to combine both techniques in a single digital holographic setup without the need of employing a second digital camera for acquisition of speckle images. In this way, the information contained in a sequence of holograms of the sample does not only serve to measure interferometric variations of its surface, but also to determine the SA evolution of the sample. Although in this work we extract the global SA of the sample directly from the correlation of holograms, the implementation of pointwise algorithms for SA determination is also possible. Therefore, the results presented here widen the scope of both dynamic speckle and DHI methods regarding characterization of dynamic phenomena, due to the possibility of correlating SA evolution with interferometric variations.[22,23]

2 Experimental Details

We performed simultaneous measurements of the drying process of a solvent-based paint coating by acquiring holographic images and also dynamic speckle images (with

*Address all correspondence to: Nicolas Budini, E-mail: nicolas.budini@ifis.santafe-conicet.gov.ar

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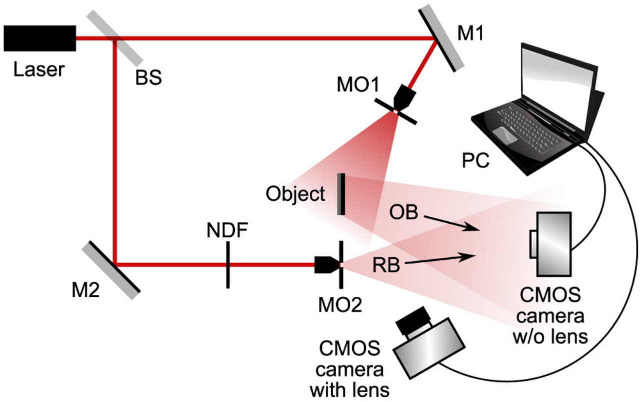

Fig. 1 Simplified diagram of the experimental digital off-axis lensless Fourier holographic arrangement with a second CMOS camera with lens to acquire the sequence of speckle images. Laser: He–Ne; BS: beam splitter; M*i*: mirrors; NDF: neutral density filter; MO*i*: microscope objectives and pinholes; OB: object beam; RB: reference beam; CMOS: digital cameras.

a second digital camera) in order to compare the SA evolution extracted from the holograms with that observed directly from speckle images. The drying process of paint coatings is a typical and predictable study case in the field of dynamic speckle, since the observed SA is known to decay smoothly as a function of time.

We implemented a typical off-axis lensless Fourier digital holographic arrangement with He–Ne laser illumination and a 5 MP CMOS camera (Moticam® 5, 2592×1944 pixels). Also, a 1 MP CMOS camera (Moticam® 1SP, 1284×1024 pixels) with a focusing lens was used for recording speckle images formed right onto the surface of the painted region. A simplified scheme of the experimental setup is shown in Fig. 1.

Two different cases were analyzed, namely: (1) a drying paint droplet deposited onto a horizontal surface, so as to avoid flowing and have a definite shape, and (2) a painted region onto a vertical surface, so as to allow free flowing due to gravity and observe painted regions differing in thickness. Specific details of image acquisition parameters are given as follows for each experiment.

For each studied case, we acquired sequences of holographic and speckle images. All images were treated as 8-bit grayscale maps; holograms were filtered as described as follows to enhance the signal-to-noise ratio of the dynamic speckle information contained in them. The correlation coefficient between successive holograms was calculated and used as a measure of SA. This parameter is inversely proportional to the degree of SA of the analyzed object, i.e., a high-correlation coefficient implies similar images or low SA and vice versa. In turn, speckle images were processed using the algorithm described in the Appendix. Image processing was performed through algorithms implemented in the MATLAB® software.

3 Results and Discussion

3.1 *Drying Droplet onto a Horizontal Surface*

We deposited a small droplet of paint onto a horizontal surface and left it to dry at room temperature. During the drying process, we acquired speckle images every second and holograms every 15 s. Therefore, after a total observation time of 150 min, we acquired 9000 speckle images and 600 holograms.

The object under study cannot be directly observed in the holograms, but the information about its three-dimensional shape and speckle field is contained in them. In Fig. 2(a), we present the time evolution of the correlation coefficient (or speckle correlation) calculated between consecutive raw holograms. For this, we used the `corr2` MATLAB® function, which returns the two-dimensional correlation coefficient between two images treated as matrices. As mentioned previously, this coefficient measures the similarity of the given images (with 1 meaning identical and 0 meaning completely different images). Therefore, a higher correlation coefficient corresponds to a lower degree of SA. This coefficient varied slightly as a function of time due to the dynamic nature of the speckle field reaching the CMOS sensor, after reflecting at the drying droplet. Moreover, obtained values increased to the end of the process, evidencing a diminution of SA. Despite this, the values of the vertical axis in this graph indicate that all holograms were very similar, with correlation coefficients differing by less than 2% around 0.96. In other words, the weak dynamic speckle information (or signal) contained in the holograms is hindered by the intense background contribution of the reference beam (i.e., the signal-to-noise ratio is low). However, this signal could be considerably improved by filtering out the information of the reference beam. For this, we just

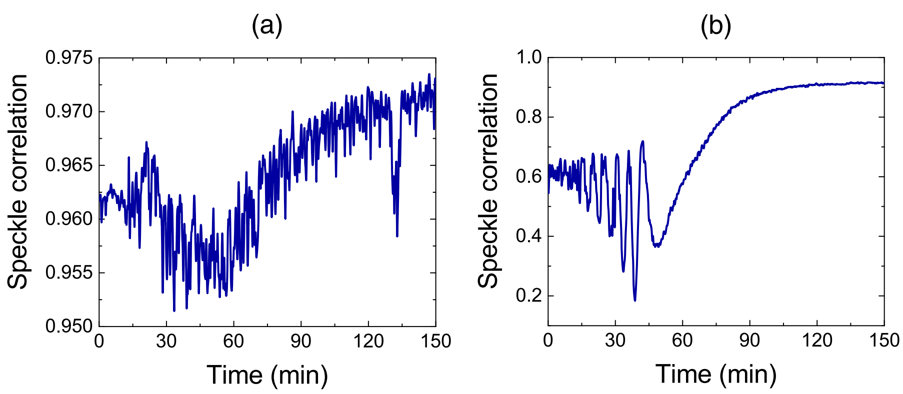

Fig. 2 Time evolution of speckle correlation obtained between consecutive (a) raw and (b) filtered holograms. Improvement of the signal-to-noise ratio is evidenced by both variation of the vertical scale and curve smoothness.

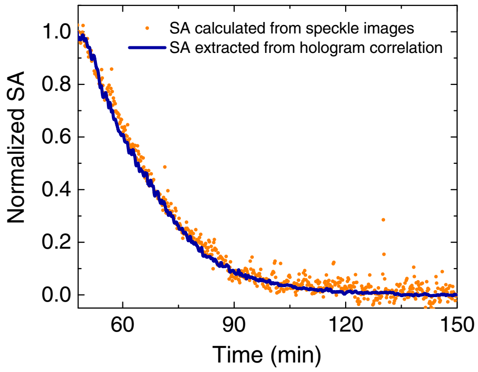

Fig. 3 Comparison between SA calculated from speckle images through the algorithm described in the Appendix (points) and SA extracted from the holograms through calculation of correlation coefficient (solid line). Values of both curves were normalized to the corresponding SA value at the time for which the correlation coefficient started to decay monotonically (i.e., after about 45 min).

selected the region of the frequency domain corresponding to the virtual image, after performing an inverse fast Fourier transform to the hologram, which is equivalent to applying a bandpass filter to the spatial frequencies present in the hologram.[24,25] In this way, we could get rid of the intense and low-frequency signals coming from the reference beam and conserve the frequencies related to the object itself and, simultaneously, to the varying speckle field.

The resulting time evolution of correlation coefficient between filtered holograms is shown in Fig. 2(b). There was a considerable improvement of the dynamic speckle signal (i.e., of the signal-to-noise ratio), which is evidenced by the values of the vertical axis in the graph (ranging now from about 0.4 to 0.9). After 45 min, the curve started to increase monotonically, i.e., SA started to diminish monotonically. This resembles the typical time evolution of SA for a drying paint process. The origin of the oscillations observed during the first 45 min still needs to be clarified and will be the scope of future research. At first sight, they seem to be related with the initial evaporation process of solvents, which might provide interesting information.

Figure 3 shows the comparison between normalized SA values calculated from speckle images (points), acquired with the second digital camera of the experimental setup, and SA information extracted from the correlation coefficient between holograms (solid line), as mentioned previously.

Each point in this plot corresponds to the SA value calculated from 10 consecutive speckle images. Since speckle images were acquired every second, the total elapsed time between two consecutive points is 10 s, as is detailed in Appendix. To allow for comparisons between both evolution curves, we have transformed the values of the curve in Fig. 2(b) to get a decaying trend and we have also normalized them. For normalization, to the range between 0 (lowest SA) and 1 (highest SA), we chose 1 as the SA value of each curve at the time for which the curve of Fig. 2(b) started to increase monotonically (or, correspondingly, SA started to decay monotonically). This time corresponded to about 45 min. As seen in Fig. 3, both curves have shown a very good agreement. As a remarkable fact, and mainly due to the image filtering process, the curve extracted from digital holograms presented a considerably lower dispersion than that obtained from speckle images.

3.2 *Painted Region onto a Vertical Surface*

We proceed now to show the results obtained from our second experiment, consisting of determining the SA evolution of a painted region onto a vertical surface. The paint was applied to the surface by using a plane rectangular stamp. As mentioned before, the vertical surface allowed paint to flow due to gravity but it is worth noting that, once applied, flowing took only a few seconds until paint reached a fixed shape and started drying. This was confirmed by analyzing the reconstructed images of the drying paint from holograms. Therefore, the period of time during which flowing of paint could contribute to the observed speckle correlation or SA values can be neglected if compared with the 2-h total observation period of time. Speckle and hologram images were acquired at different rates in this experiment, namely every 5 and 60 s, respectively, during the drying process.

Figures 4(a) and 4(b) show the evolution of speckle correlation coefficients obtained from raw holograms [Fig. 4(a)] and filtered holograms [Fig. 4(b)]. The correlation coefficient varied in a similar way as in the previous case. A low signal-to-noise ratio was again observed in the raw holograms, as evidenced by the values in the vertical axis scale. After high-pass filtering the holographic images, to reduce the contribution of the reference beam signal, the information

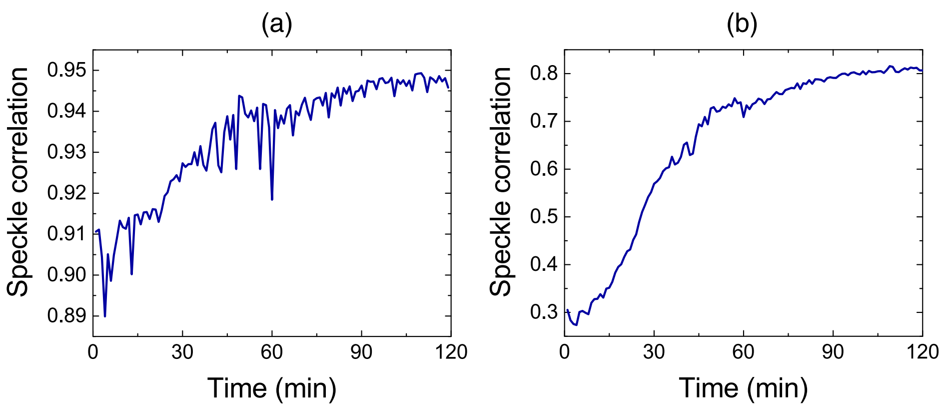

Fig. 4 (a) Time evolution of speckle correlation between consecutive raw holograms and (b) time evolution of speckle correlation after filtering the holographic images.

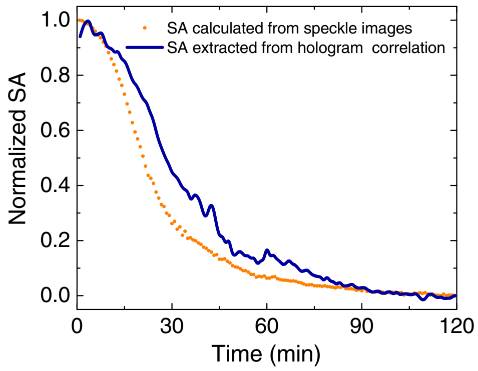

Fig. 5 Comparison between SA calculated from speckle images through the algorithm described in the Appendix (points) and SA extracted from the holograms through calculation of correlation coefficient (solid line). Curves were normalized to their highest SA value.

related to the variation of the speckle field resulted considerably improved. The evolution of correlation coefficient, which increased as a function of time, was also consistent with a diminution of SA. We recall that as hologram images become more similar, the correlation coefficient between them gets higher and the degree of SA diminishes.

The comparison between normalized SA values calculated from speckle images (points) and from hologram correlation (solid line) is shown in Fig. 5. In this case, speckle images were processed in groups of $N = 10$ to calculate a single global SA point of the curve, as detailed in the Appendix. Thus, with $\tau = 5$ s, each SA value is an average of 10 consecutive speckle images over a temporal extension $\Delta\tau = 50$ s. In turn, the SA curve extracted from hologram correlation (solid line) is an interpolation of points separated by 60-s time intervals.

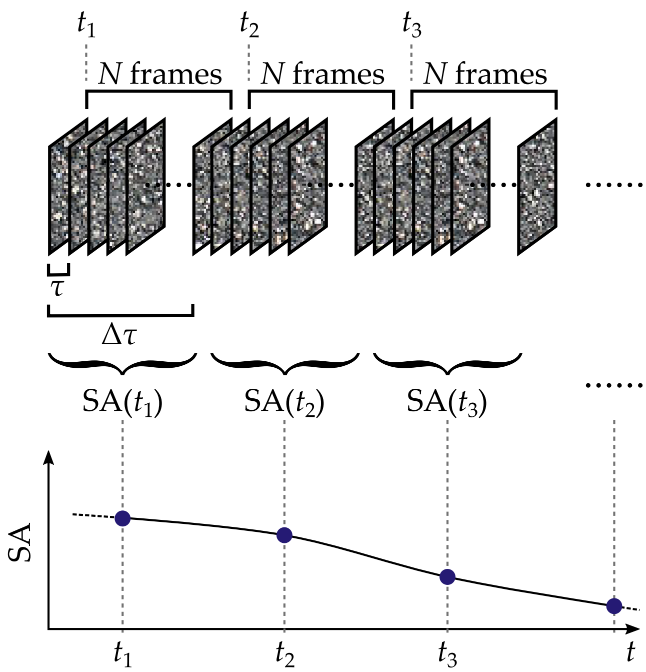

Fig. 6 Schematic illustration of the speckle image acquisition process. Images or frames are acquired with a time interval τ between them and arranged in groups of N frames from which a single global SA value is obtained. Therefore, each SA value represents an average activity along an elapsed time $\Delta\tau = (N - 1)\tau$.

In this experiment, the agreement of both curves is not as good as in the previous case. However, the comparison is acceptable by taking into account that the elapsed time between acquired images was considerably higher than that for the drying droplet, i.e., holograms were acquired each 60 s instead of 15 s and speckle images were acquired each 5 s instead of 1 s. Therefore, it is reasonable to expect a smoother curve obtained from speckle images, since we are averaging images over a longer time period. In counterpart, correlation between holograms is prone to be lost for increasing time between them, since it is strongly affected by vibrations, thermal fluctuations, influence of spurious reflections, and so on. In other words, the correlation between holograms acquired further in time is more affected by experimental noise than between holograms acquired nearer in time. From this, we conclude that a worst agreement between obtained curves in this second experiment is not surprising but raises up the relevance of choosing an adequate sampling rate for determining correlation between holograms.

In general, both speckle and hologram images should be acquired at a relatively high rate. However, holographic images are stored in quite big image files and image processing time will then increase in linear proportion to the amount of acquired images. In this context, there is a compromise between time resolution to get a better correlation between images, computing time, and storage capabilities. From the aforementioned results, it is evident that the acquisition parameters used in the case of the droplet were enough to obtain a good agreement between the evolution of SA and that of speckle correlation between holograms. However, this will strongly depend on each particular case of study.

4 Conclusion

In conclusion, the results presented in this work evidence that the global dynamic speckle information of the object under study is readily available in the raw holograms and can be extracted without the need of numerically reconstructing the holograms. Despite the fact that the speckle information in the raw holograms has a low signal-to-noise ratio, it can be considerably enhanced by simple filtering processes. This information can be correlated with good agreement to the degree of SA in the object under study. Moreover, the reconstruction of holograms and their subsequent comparison yield even more information about the evolution of morphology of the object or surface under analysis. Although we extracted the global SA information directly from the correlation of holograms, pointwise algorithms for SA mapping are also applicable, as mentioned before. Therefore, the combination of dynamic speckle and DHI methods in a single technique (DHI in this case) opens a new spectrum of possibilities to characterize dynamic phenomena, which has been so far unexplored. In this context, this work aims to contribute to the field of nondestructive optical techniques for characterization of dynamic phenomena.

Appendix: Determination of SA from Speckle Images

In the context of this work, global SA was analyzed through a simple method that counts the average fraction of pixels whose intensity $I(i, j)$ changes as a function of time in more than certain amount, r, called speckle noise. The details of this method are described elsewhere,[10] and here we limit to show its basic equation, which reads

$$\mathrm{SA} = \frac{1}{m \times n} \sum_{k=1}^{N-1} \frac{1}{N-1} \sum_{i=1}^{m} \sum_{j=1}^{n} \Theta[|I_{k+1}(i,j) - I_k(i,j)| - r], \tag{1}$$

where N is the number of images from which a single SA value should be determined, I_k is the k'th image, m and n are the image sizes, and $\Theta(x)$ is the well-known Heaviside function. Therefore, each SA value calculated through Eq. (1) corresponds to an average activity over N images, which were captured during a total temporal extension $\Delta\tau = (N-1)\tau$, where τ is the time interval between each image acquisition. In Fig. 6, we show a schematic illustration of the global SA calculation process by means of this method.

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Nicolas Budini received his BS and PhD degrees in physics in 2007 and 2012, respectively. He is an assistant professor in the Physics Department at National University of Litoral, Santa Fe, Argentina. He is also a fellow researcher at the Group of Semiconductor Physics of the Litoral Institute of Physics, Santa Fe, Argentina. His current research interests include optical metrology, digital holography, holographic interferometry, digital holographic microscopy, semiconductors, and photovoltaic devices.

Nicolas Balducci is an assistant professor at the Electromechanical Department of the National Technical University in Argentina. He received his BEng in 2009 with specialization in metrology and automation. He is currently an MSc student in physics at the National University of Litoral, Santa Fe, Argentina and develops research activities at the Litoral Institute of Physics, Santa Fe, Argentina. His current research interests include optical metrology and characterization of materials by means of holographic techniques.

Cecilia Mulone is an electronics engineering student at the National Technical University, Argentina, where she has worked as intern at the Applied Physics Group since 2011. She is currently doing an internship at SeeReal Technologies GmbH and working on her diploma thesis in the chair for large area based surface micro/nanostructuring at TU-Dresden, Germany. Her current research interests include optical metrology, digital holography, holographic interferometry, digital holographic microscopy, nanoimprint lithography, and direct laser interference patterning.

Andrea C. Monaldi is an assistant professor in the Physics Department of the exact sciences faculty, National University of Salta, Argentina. She received BSc and PhD degrees in physics in 2009 and 2015, respectively. She is also a fellow researcher of the Group of Laser Optics at the National University of Salta, Argentina. Her current research interests include optics, digital holographic microscopy, biological physics, and optical characterization of microorganisms.