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Multiple-aperture speckle method applied to local displacement measurements

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Abstract

The goal of this work is to analyze the measurement capability of the modified speckle photography technique that uses different multiple aperture pupils in a multiple exposure scheme. In particular, the rotation case is considered. A point-wise analysis procedure is utilized to obtain the fringes required to access to the local displacement measurements. The proposed arrangement allows simultaneous displaying in the Fourier plane several fringes system each one associated with different rotations. We experimentally verified that the local displacement measurements can be determined with a high precision and accuracy.

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Keywords: Speckle; Interferometry

1. Introduction

Speckle photography technique allows determining speckle changes by coherent-optical processing of a double exposure specklegram corresponding to the patterns before and after deformation [1–5]. For local displacement analyzing, a point wise or a whole field procedure can be applied to the speckle pattern [6]. In this case, fringes appear at the output plane when an adequate optical Fourier transform and spatial filtering technique are implemented.

The mentioned technique has been implemented both in the diffraction field and in image configurations. In the image configuration case, the shape of the diffraction halo is determined by the aperture function of the recording lens. Although, an optical imaging system with a single aperture pupil is usually employed, some advantage is achieved when using a multiple aperture pupil mask [7–11]. For example, in Ref. [6] the double exposure technique by using for both registers the same multiple aperture pupil was analyzed. It should be mentioned that an increased signal to noise ratio and a better fringes resolution are obtained in the multiple aperture case. It means that diffracted light at the high frequencies in the multiple apertures is higher than in the single aperture case. These methods only allow evaluating a single displacement. Another approach by using the Wigner distribution function allows a simultaneous evaluation of multiple displacements [12,13] and does not need the repeated use of the Fourier transform procedure as in the conventional technique. This method takes advantage of image representation which preserve the space domain information as well the spatial frequency. The application of the WDF to speckle photography requires an optical system to convert

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the 2D speckle existing in a certain position to the 1D speckle by means of a slit as a selection of the inspecting position. This method can display simultaneously the spatial frequency as a function of the spatial position but the procedure introduces degradation in the signal to noise ratio. Based on this concept a new hybrid optical-digital method [14] for local diffuser measurements, which employs a more versatile phase space function that behaves like a multi channel spectrum analyzer, has been proposed. The approach is to perform a sequential scanning of the entire input by a window function. In both methods, the wider the window function is, the better will be the determination of the amount of local deformation to the detriment of the precision of its spatial localization and conversely. It means that the adequate window selection is limited by the uncertainty principle. It is important to emphasize that the signal to noise ratio is improved only if the mean distance between the speckle is controlled to be greater than the magnitude of the local deformation.

In Ref. [15], the use of a different multiple aperture pupil for recording multiple images in speckle photography is theoretically analyzed. This approach consists in selectively combining the spectral components of the speckled images into isolated spots in the Fourier plane. There, by using a different pupil for storing each speckled image, the ensemble-average intensity in the Fourier plane is analytically derived and Young fringes visibility is investigated. The theoretical predictions obtained in that paper become a relevant tool for designing the recording routine and the set of pupils for the experiments to optimize fringe visibilities. In Ref. [16] different non-conventional pupil arrangements for speckle photography in a multiple exposure scheme is presented. Both works are limited to consider uniform in plane displacement.

In the present work, our interest focuses on the metrological tool that the use of different multiple aperture pupils for each exposure in speckle photography represents. In the following, we emphasize the technique measurement capability focusing in the precision and accuracy of the information retrieved. We consider the case of local displacement measurements resulting from in plane rotations. The speckle displacement is measured by using the conventional point-wise analysis procedure, in which a narrow probe laser beam impinges point by point in the specklegram. Straight equal spaced fringes results in each order of the diffraction spectrum associated with the speckle displacement. Note that, to obtain well defined Young fringes, the point-wise procedure requires a sufficiently narrow interrogating beam. In this case approximately constant speckle displacements are of concern. However, it is also necessary to employ an interrogating beam whose diameter is large enough to include various speckle pairs. The conditions to obtain high visibility fringes have been analytically and experimentally studied in detail by several authors [17–20].

It should be pointed out that the adequate selection of different multiple aperture pupils optimize the amount of information stored with a minimum number of exposures. We found in a four exposures scheme a pupil arrangement so that all possible rotations among all diffuser status are obtained. The proposed arrangement not only allows simultaneously depicting several local displacements but a comparison of relative local displacements between non-consecutive speckled images is possible.

The purpose of our work is to verify that the proposed modified version of the speckle photography technique allows simultaneously determining multiple local displacements with high accuracy comparable with the conventional technique. Experimental results that confirm the metrological capability of the technique are presented.

2. Technique description and results discussion

Experimental arrangement is schematized in Fig. 1. In the recording step (see Fig. 1a), a random diffuser, located

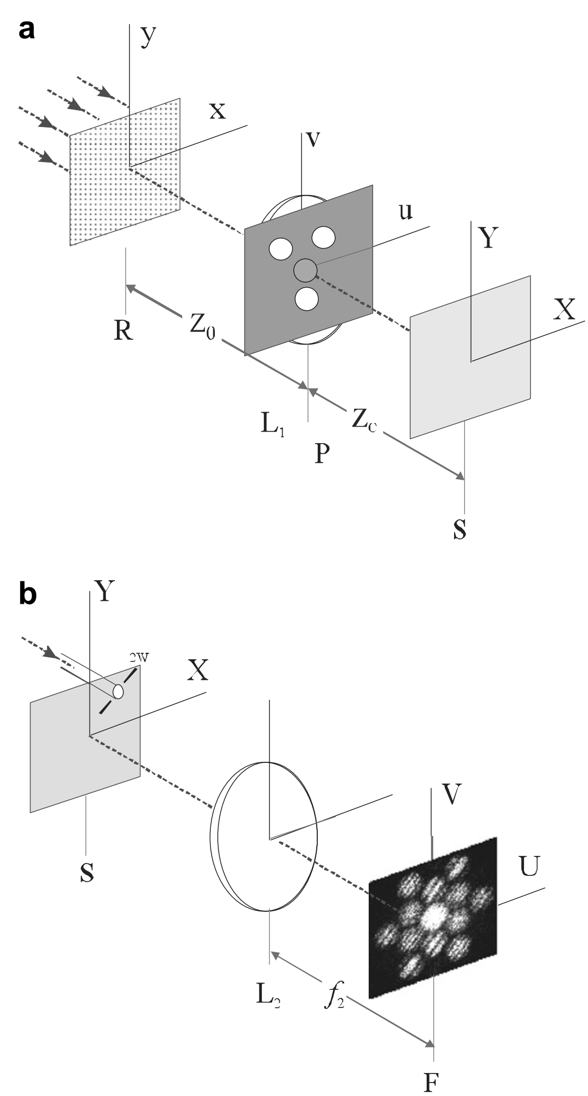

Fig. 1. Experimental arrangement, (a) recording step (R: random diffuser; L_1: lens (focal length f_1); P: pupil mask; S: specklegram) and (b) analysis step (S: specklegram, L_2: lens (focal length f_2); F: Fourier plane).

at the input plane $x - y$, is illuminated by a collimated He–Ne laser beam ($\lambda = 633$ nm) and imaged onto a high-resolution holographic film (Agfa-Gevaert 8E75) located at the $X - Y$ plane. The distances from the diffuser R to the lens L_1 and from L_1 to the camera are set to Z_0 and Z_C, respectively. A pupil mask $\mathbf{P}^k(u,v)$ with multiple apertures is located immediately in front of the imaging lens L_1 in the $u - v$ plane. Then a speckled image of the input diffuser is produced through each aperture. The resulting speckle patterns at the $X - Y$ plane are fringe modulated due to the interference of speckle distributions produced by each aperture pair. The frequency and orientation of each fringe system depends on the separation and orientation of each apertures pair that constitute the pupil.

Our proposal implies to change the pupil of the optical system between exposures in a multiple exposure scheme. As mentioned above, each pupil mask consists of several apertures, and the function $a(u,v)$ defines the aperture shape. The input complex amplitude and the pupil associated with the kth exposure are represented as $A^k(x,y)$ and $\mathbf{P}^k(u,v)$, respectively. It is assumed that, for any pair of pupils $\mathbf{P}^k(u,v)$ and $\mathbf{P}^l(u,v)$, some of their apertures coincide exactly and the remaining apertures do not overlap at all. Let the functions $a_n^k(u,v)$ and $a_m^l(u,v)$ represent two apertures belonging to the pupils $\mathbf{P}^k(u,v)$ and $\mathbf{P}^l(u,v)$ associated with the kth and lth exposure, respectively, where $n = 1,2,3$ and $m = 1,2,3$. They are named common apertures if $a_n^k(u,v)a_m^l(u,v) \equiv 1$ and non-common apertures if $a_n^k(u,v)a_m^l(u,v) \equiv 0$.

An in-plane rotation of the input diffuser between exposures is produced. Afterwards, in order to measure these rotations, a point-wise analysis is done. In the analysis procedure, the specklegram is illuminated by a narrow laser beam, which impinges in a limited region of the specklegram (see Fig. 1b). The analysis beam direction is perpendicular to the $X - Y$ plane. The limited transmitted light is Fourier transformed by means of a lens L_2 of focal length f_2 and the intensity distribution is observed at the $U - V$ plane.

Let us now study the consequences of changing the multiple apertures pupil between exposures. The field amplitude in the Fourier plane $G(U,V)$ can be expressed as the overlapping of the Fourier transformed waves $G^k(U,V)$, $k = 1, 2, \ldots N$, each one representing the complex amplitude associated with an individual exposure:

$$G(U,V) = \sum_{k=1}^{N} G^k(U,V) \tag{1}$$

In this equation $G^k(U,V)$ is given by:

$$G^k(U,V) = \{S^k \otimes (S^k)^*\}(U,V) \tag{2}$$

where $\otimes$ means complex auto-correlation and $S^k(\chi,\varsigma)$ is defined as:

$$S^k(\chi,\varsigma) = P^k\left(-\chi \cdot \frac{Z_C}{f_1}, -\varsigma \cdot \frac{Z_C}{f_1}\right) \cdot T^k\left(-\chi \cdot \frac{M}{f_1}, -\varsigma \cdot \frac{M}{f_1}\right) \tag{3}$$

and

$$T^k\left(-\chi \cdot \frac{M}{f_1}, -\varsigma \cdot \frac{M}{f_1}\right) = \int A^k(x,y) \cdot \exp\left(\mathrm{i}\frac{2\pi}{\lambda}\frac{M}{f_1}(\chi \cdot x + \varsigma \cdot y)\right)\mathrm{d}x\,\mathrm{d}y \tag{4}$$

According to Eqs. (1)–(3), the pupil limits the spectral content of the encoded image that contributes to the amplitude field in the Fourier plane. It can be inferred that the spectral content of each image is gathered into the diffraction spots associated with the respective pupil. Meanwhile, the overlapping of the two spectra occurs exclusively in the spots where both diffraction patterns coincide. In the $U - V$ Fourier plane the spectral components of the input $A^k(x,y)$ are concentrated in the regions where $\left\{\mathbf{P}^k\left(-\chi \cdot \frac{Z_C}{f_1}, -\varsigma \cdot \frac{Z_C}{f_1}\right) \otimes \mathbf{P}^k\left(-\chi \cdot \frac{Z_C}{f_1}, -\varsigma \cdot \frac{Z_C}{f_1}\right)\right\}(U,V) \neq 0$, and the components of $A^l(x,y)$ are located exclusively where $\left\{\mathbf{P}^l\left(-\chi \cdot \frac{Z_C}{f_1}, -\varsigma \cdot \frac{Z_C}{f_1}\right) \otimes \mathbf{P}^l\left(-\chi \cdot \frac{Z_C}{f_1}, -\varsigma \cdot \frac{Z_C}{f_1}\right)\right\}(U,V) \neq 0$.

As introduced in Eq. (1), the whole spectral content consists of the spectral overlapping of all recorded speckled images. The spectra of a pair of images can be selectively overlapped in the UV plane in accordance with the aperture arrangements. This is the key point in the multiple speckle displacement storage.

To experimentally verify the proposal, we implement an in plane rotation of the diffuser between exposures. Then, by rotating the diffuser an angle $\theta \ll 1$, the magnitude of the diffuser displacement $|\vec{a}|$ at a distance r from the axis is $|\vec{a}| = r\theta$. Similarly, in the specklegram plane the speckle relative displacement magnitude at a distance R from the axis is $|\vec{A}| = \frac{Z_C}{Z_0}|\vec{a}| = \frac{Z_C}{Z_0}r\theta = R\theta$. Consequently, to address a point-wise analysis of the specklegram, a sufficiently narrow interrogating beam is utilized to have approximately constant speckle displacements. However, it is necessary to employ an interrogating beam that at least includes various speckles pairs in order to form interferometric fringes in the Fourier plane. By following this approach, well defined Young fringes for local in plane displacements are obtained by using single or multiple aperture pupils, in which a double exposure scheme with the same pupil for both exposures is employed [8,20]. Also, the conditions to obtain high visibility fringes have been analytically and experimentally studied in detail by several authors [17].

In conventional approaches, a single pupil is employed in a double exposure routine for recording. Then, when locally interrogating the specklegram, cosine square fringes pattern modulating the speckled diffraction halo associated with the pupil is observed. The orientation and period of this pattern depends on the local displacement corresponding to the locus the interrogating beam impinges. In our approach, a different pupil is employed for each exposure. Then, in the analysis step, a set of the different diffraction halos are simultaneously displayed in the Fourier plane. Moreover, by judiciously selecting the set of pupils, the halos can be selectively overlapped to obtain elementary Young fringes patterns in the loci where only two diffraction halos coincide.

To select the set of pupils some criteria are needed. Let us assume that for each pair of pupils $\mathbf{P}^k$ and $\mathbf{P}^l$ in the recording scheme, it holds that one pair of apertures in one pupil coincides exactly with one pair of apertures in the other pupil; meanwhile the remaining apertures do not overlap at all. As a consequence, when comparing the speckled images of the diffuser corresponding to any pair of pupils, a similar system of fringes modulating speckles can be found because of the pair of apertures the two pupils have in common. Indeed, when interrogating the specklegram, these elementary fringe systems associated with a given pair of common apertures in the respective pupils generate the same pair of diffracted spots in the Fourier plane. Then, the loci of one spots pair of the diffracted pattern of $\mathbf{P}^k$ coincide with the loci of one spots pair of the pattern corresponding to $\mathbf{P}^l$. In those spots the spectra of both the kth and lth image are overlapped. Moreover, it is possible to selectively isolate the relevant information of all possible pairs of images that were recorded. As a consequence, elementary Young fringes comparing the kth and lth images can be formed in those spots where the respective diffraction halos overlap. In the following, we assume that each diffraction halo consists of several pairs of diffraction spots and that for any pair of diffraction halos there is only one pair of diffraction spots that coincide.

Let us discuss the Young fringes characteristics in one of these spots. In Ref. [20], as in our case, in each exposure the diffuser is illuminated by a Gaussian profile beam whose waist is $2W_0$. The specklegram is stored in a linear medium. For analyzing the specklegram a narrow beam of gaussian profile of waist $2W$ is employed. Under these conditions, the average intensity distribution in the Fourier plane for a generic spot is given by;

$$\langle I(U,V)\rangle = t_1 W^2 \exp\left(\frac{-(U^2+V^2)}{r_0^2}\right) + \kappa r_s^2 \times \exp\left(\frac{-(U^2+V^2)}{W_0^2}\right) \cdot \left[1+\exp\left(\frac{-(A_X^2+A_Y^2)}{W^2}\right)\cos\left(\frac{2\pi(UA_X+VA_Y)}{\lambda f_2}\right)\right] \tag{5}$$

where the parameter t_1 depends on the constants of the recording medium and the average intensity in the specklegram plane; the parameter κ is a constant; the vector $\vec{A} = (A_X, A_Y)$ represents the approximately uniform local speckle displacement between exposures at the point (X, Y) in the specklegram; r_s and r_0 represent the average speckle radius on the specklegram and on the Fourier plane, respectively; $W_0 = f_1\lambda/\pi r_s$ and $W = f_2\lambda/\pi r_0$ are the half waist of the gaussian beams illuminating the diffuser and interrogating the specklegram, respectively. In Eq. (5), the first term represents the zero order diffracted light and the second term represents the spatially oscillating variation of the Young fringes, whose period is $\Lambda = \lambda f_2/\sqrt{(A_X^2+A_Y^2)}$. As the zero order term and the diffracted orders are not overlapped, the Young fringes visibility out of the zero order can be defined exclusively in terms of the spatially oscillating intensity of the fringes as follows:

$$V = \frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}} = \exp\left(-\frac{(A_X^2+A_Y^2)}{W^2}\right) = \exp\left(-\left(\frac{\pi}{2N}\right)^2\right) \tag{6}$$

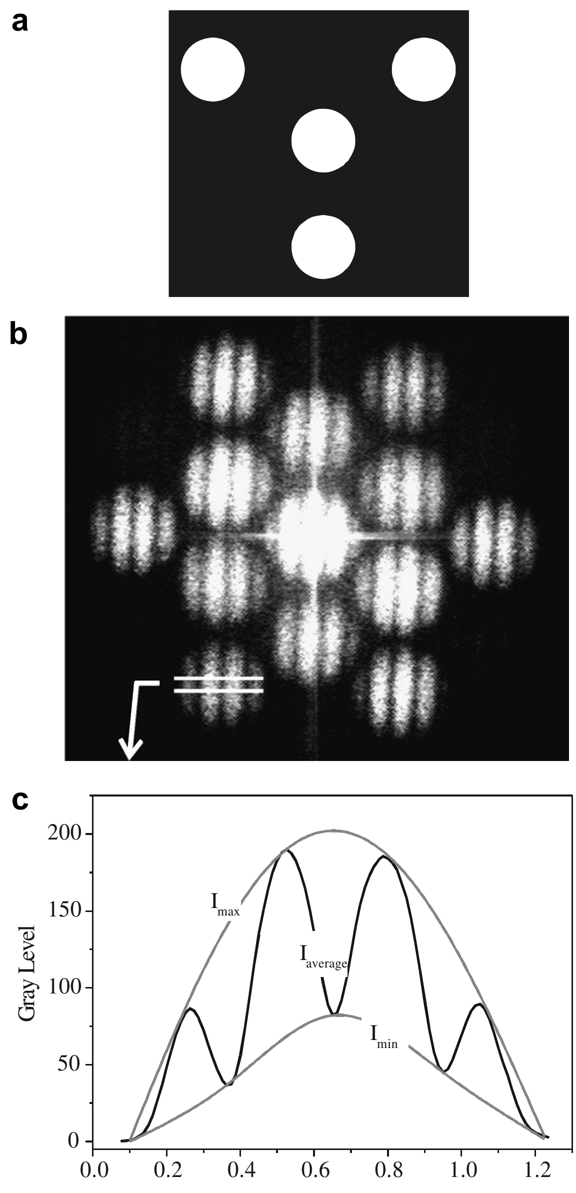

Fig. 2. (a) Scheme of a multiple aperture pupil; (b) diffraction halo of the double exposure specklegram corresponding to the pupil schematized in (a); (c) average intensity profile corresponding to the indicated diffracted order.

where I_{max} and I_{min} are the maximum and the minimum intensity values of the Young fringes envelopes (see Fig. 2), being $N = \Lambda/2r_0$ the average number of speckles in one period of the Young fringes. This result shows that if N diminishes, then the fringe visibility decreases. Also, the visibility decreases as the speckle displacement increases, when the read-out beam radius remains constant.

To illustrate the previous discussion, let us first consider the simplest case, which corresponds to a double exposed specklegram obtained by using the same multiple apertures pupil in both exposures. As an example, in Fig. 2 a four apertures pupil and the respective diffraction halo modulated by Young fringes are presented. Also the intensity profile for one diffraction spot is included. As expected, the profile presents the same behavior as described in Ref. [20]. Note that each spot replicates essentially the same Young fringe system [6]. Then, the use of the same pupil in both exposures implies that all spots contain the same speckle displacement information.

To demonstrate our proposal, we select different multiple aperture pupil in a multiple exposure scheme. Each pupil has three apertures (see Figs. 3–5). In-plane rotations of the input diffuser around the optical axis are produced. Fig. 3 corresponds to a double exposure specklegram. To carry on the experiment, the diffuser was in-plane rotated an angle $\theta_{12} = 0.16°$ between exposures. The pupils P^1 and P^2 employed in each exposure and the corresponding diffraction halos are depicted. When analyzing the specklegram by means of an interrogating beam which impinges on a given point outside the optical axis, fringes corresponding to local displacements appear at the common loci of the respective diffraction halos. In Fig. 4, a third exposure by using the pupil P^3 is introduced. The rotation between the second and third exposure is $\theta_{23} = 0.12°$. By comparing the diffraction halos corresponding to the pupils, it is observed that there are common and non-common diffraction spots associated with common and non-common aperture pairs belonging to the pupils,

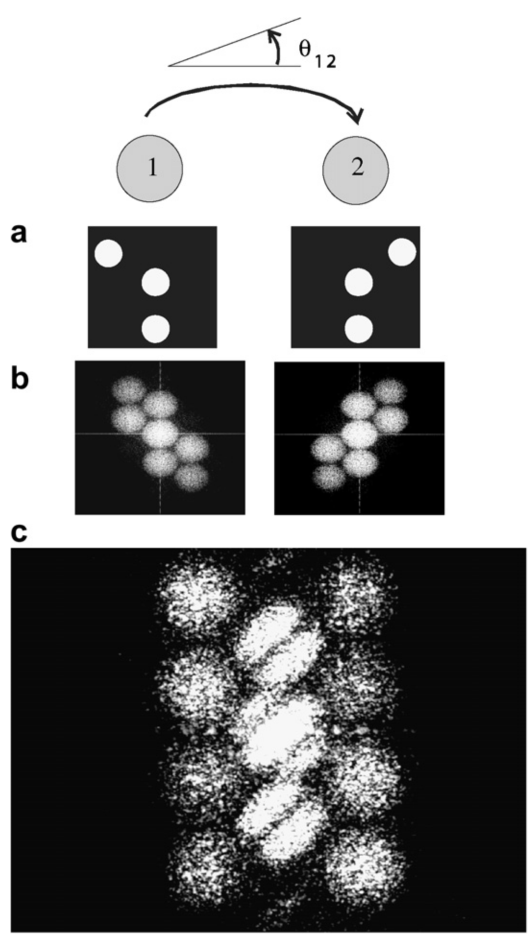

Fig. 3. (a) Schemes of the multiple aperture pupils employed in each exposure. The pupils are indicated by (**1**) and (**2**); (b) diffraction pattern corresponding to each pupil (c) diffraction pattern corresponding to a double exposure specklegram by in-plane rotating the diffuser an angle θ_{12} between exposures.

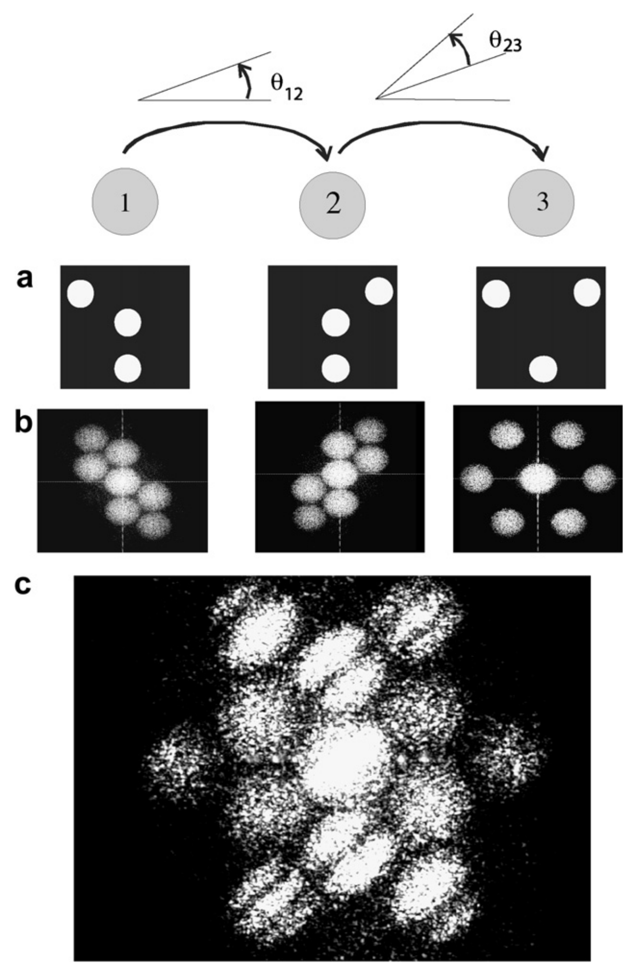

Fig. 4. (a) Schemes of the multiple aperture pupils employed in each exposure. The pupils are indicated by (**1**), (**2**) and (**3**); (b) Diffraction pattern corresponding to each pupil (c) diffraction pattern of the triple exposure specklegram by in-plane rotating the diffuser an angle θ_{12} and θ_{23} between exposures, respectively.

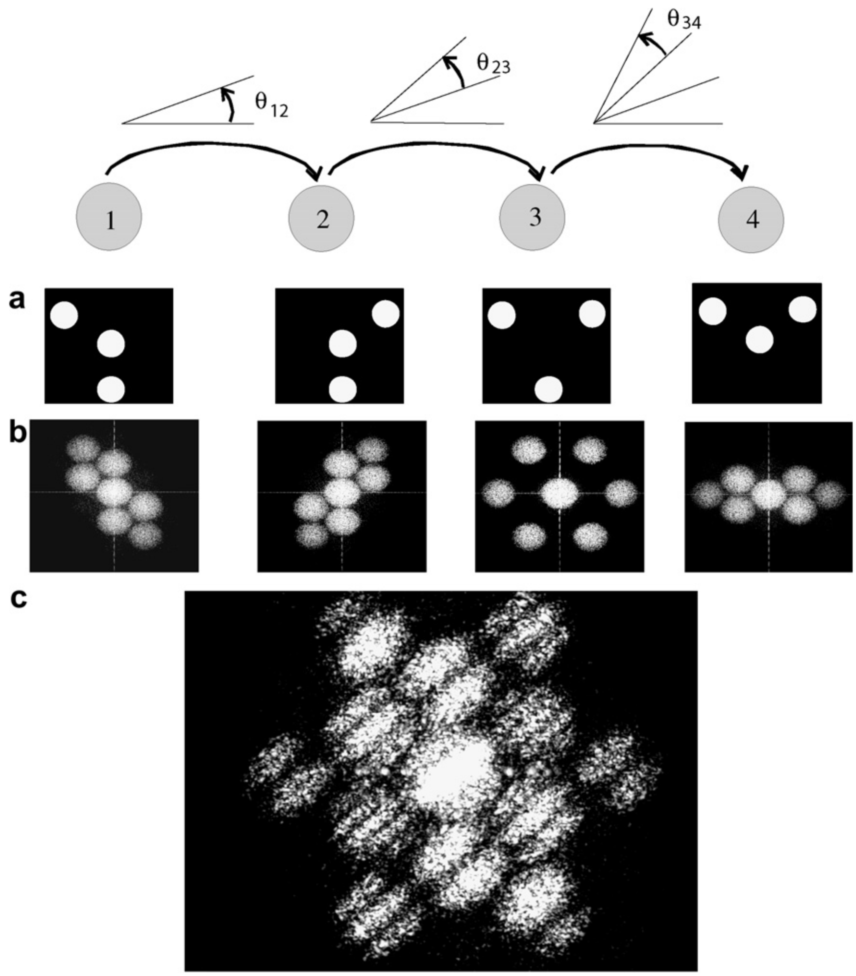

Fig. 5. (a) Schemes of the multiple aperture pupil employed in each exposure. The pupils are indicated by (**1**), (**2**), (**3**) and (**4**); (b) diffraction pattern corresponding to each pupil (c) diffraction pattern corresponding to a four exposure specklegram by in-plane rotating the diffuser an angle θ_{12}, θ_{23} and θ_{34} between exposures, respectively.

respectively. The former fringe system remains the same meanwhile two new systems of fringes associated with the rotations θ_{23} and $\theta_{12}+\theta_{23}=\theta_{13}=0.28°$ can be observed. As expected, fringes corresponding to the rotation θ_{13} present the highest frequency. Finally, in Fig. 5, a fourth exposure by using the pupil P^4 and by rotating an angle $\theta_{34}=0.20°$ between the third and the fourth steps is introduced. In this case, when analyzing the specklegram, three new fringe systems in the diffraction spots can be observed, corresponding to the rotations $\theta_{34}=0.20°$, $\theta_{23}+\theta_{34}=\theta_{24}=0.32°$ and $\theta_{12}+\theta_{23}+\theta_{34}=\theta_{14}=0.48°$.

Results of Figs. 3–5 are obtained under similar experimental conditions. In the recording step, the optical system magnification is about 2.2, the diameter of each aperture is 8 mm and the distance between the closer apertures is 16 mm. Consequently, the speckle average transversal diameter is about 49 μm. The speckles internal modulation fringes period ranges between 12 μm and 20 μm, which implies an average number of fringes in each speckle ranging from 4.1 to 2.4, respectively. To address the analysis of the specklegrams, an interrogating beam whose diameter is 1 mm impinges over a diagonal at a distance 12.7 mm from the optical axis. Then, the diameter of the interrogating beam is 20 times the average speckle transversal diameter. In this case, the focal length f_2 is 40 mm. According to the geometrical characteristics of the pupils, the distances between spots are minimized so that there is no overlapping among them. The actual spot diameter is 1.2 mm that coincides with the smallest separation between spots.

Fig. 5 shows that six different angles corresponding to all relative rotations between the four speckled images are obtained. Then, a comparison of relative local speckle displacements between non-consecutive recorded images is possible. This result stands for an extension of the speckle photography technique, to depict simultaneously in a single frame several systems of Young fringes corresponding to different local in-plane displacements between speckled images. Each pair of spots depicts a different system of fringes, minimizing thereby the redundancy.

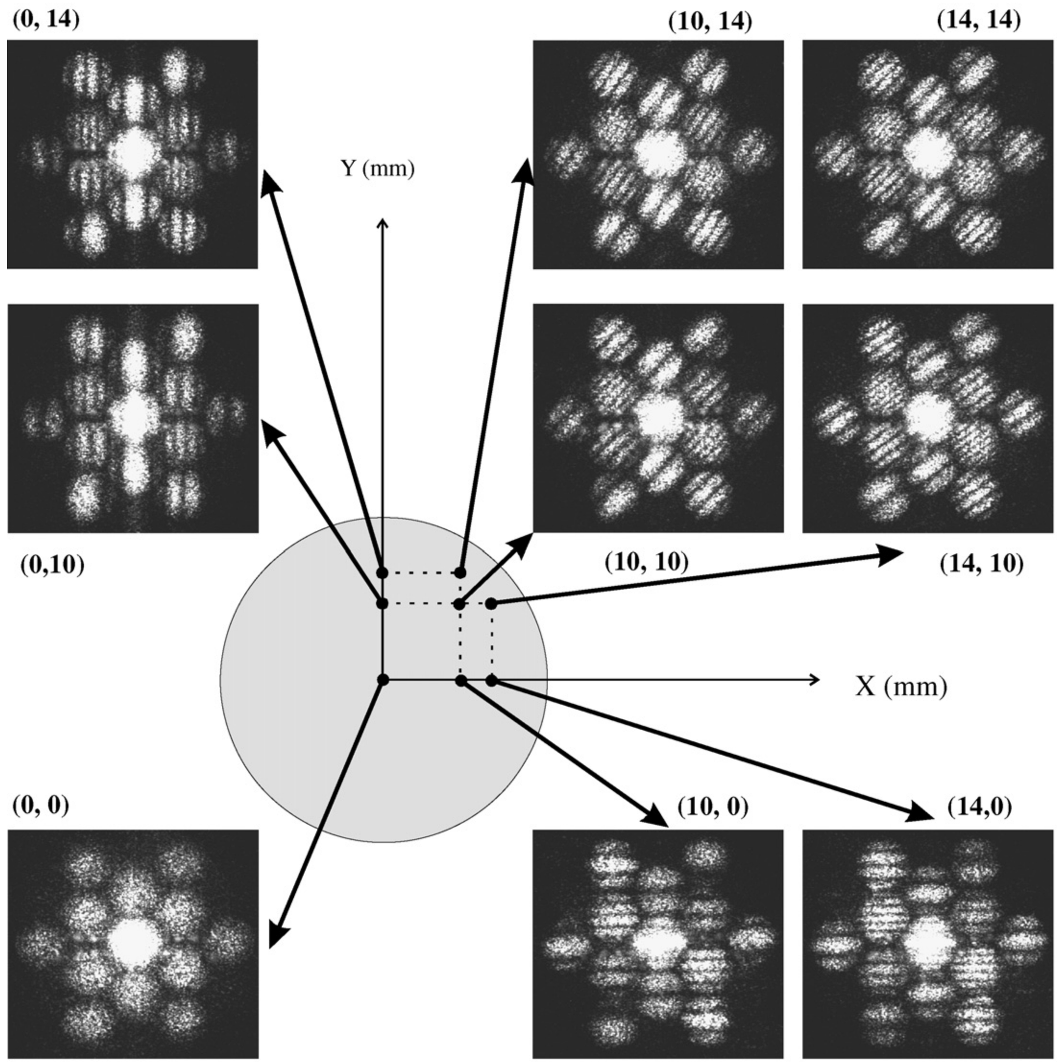

Fig. 6. Diffraction patterns corresponding to different impinging points of the interrogating beam to a multiple exposure scheme by using the pupils described in Fig. 5.

Diffraction patterns in Fig. 6 are obtained from the same specklegram employed to obtain the results of Fig. 5. Each pattern in Fig. 6 corresponds to a different position of the interrogating beam. As expected, by varying the interrogation point, the fringe systems in the diffraction pattern change accordingly. Note that for each interrogating beam position, all the fringe systems in the diffraction pattern are parallel each other and perpendicular to the direction of the local speckle displacements at this point. The frequency of the fringes that modulates each pair of diffraction spots corresponds to the relative diffuser rotation between the respective exposures whose spectral information goes there. Note that the ratio between the fringe frequencies coincides with the ratio between the respective rotation angles. Moreover, frequencies increase monotonically in proportion to the distance between the optical axis and the interrogating point.

Let us consider the diffraction pattern corresponding to the interrogating position $U = 14$ mm and $V = 14$ mm. For this position, the average intensity profiles along a direction perpendicular to the fringes are depicted for each pair of diffraction spots (see Fig. 7). The fringes in each spot give information about the relative diffuser rotation through its period measurement. By using this information, the predicted rotating angles are: $\theta^*_{12} = 0.17°$; $\theta^*_{13} = 0.28°$; $\theta^*_{14} = 0.49°$; $\theta^*_{23} = 0.13°$; $\theta^*_{24} = 0.32°$; $\theta^*_{34} = 0.21°$. These values coincide up to 0.01° with the actual ones. The approximate values allow us to relay on the validity of the proposed method. It is apparent that the accuracy and precision of our proposal is not different than those we can achieve in conventional speckle photography. In this sense, Young fringes visibility remains one of the main concerns to improve the accuracy of local measurements. To achieve it, the most important parameter is the average number of speckles in each fringe $N = \Lambda/2r_0$. This parameter N ranges from 3 to 11 in the case $U = 14$ mm and $V = 14$ mm.

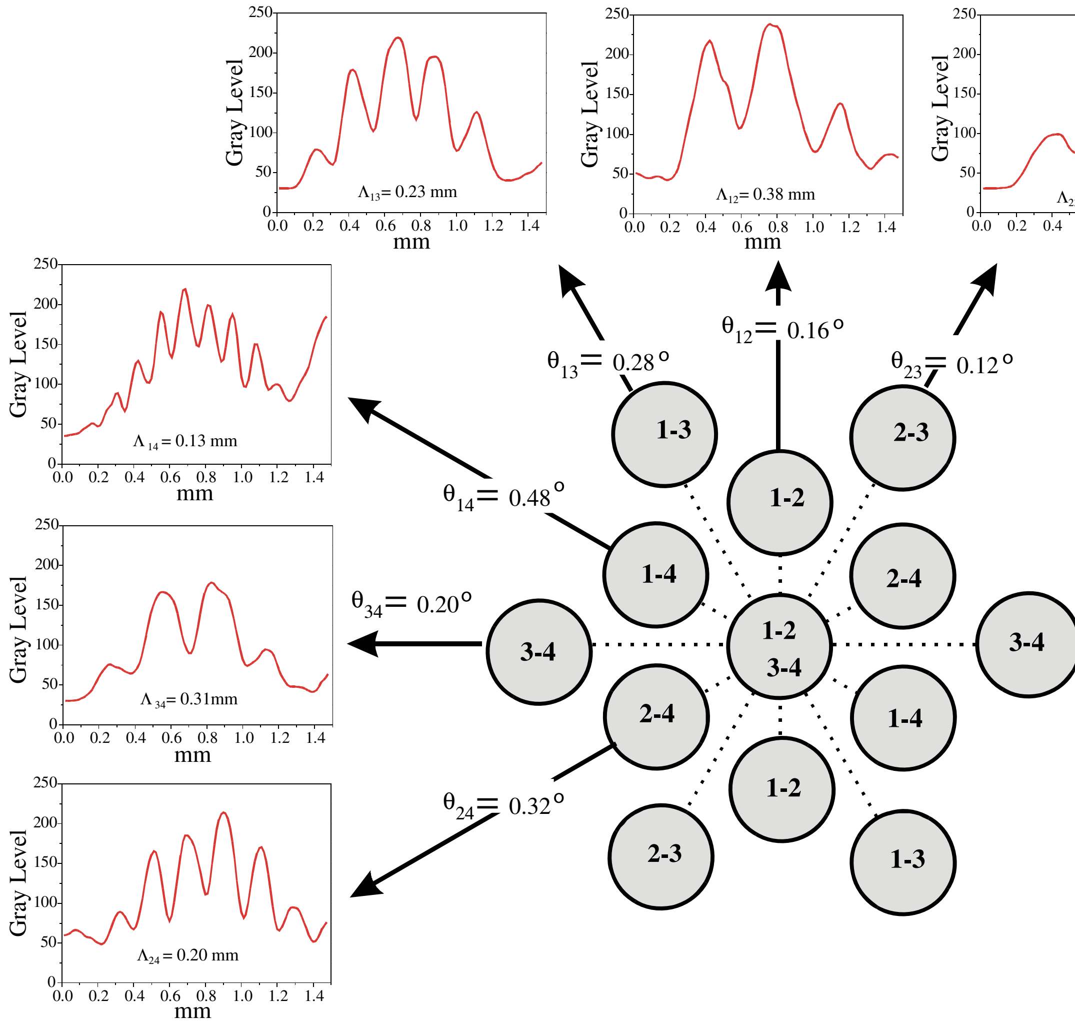

Fig. 7. Scheme of the diffraction pattern corresponding to a multiple exposure scheme by using the pupils described in Fig. 5. Experimental average intensity profiles along a direction perpendicular to the fringes for each pair of diffraction spots and corresponding to the interrogating beam position $U = 14$ mm and $V = 14$ mm.

3. Conclusions

In the present paper, we present an extension of the conventional speckle photography technique by using different multiple aperture pupils in a multiple exposures scheme. We demonstrate that it is possible to employ the proposed technique as an efficient metrological tool. We analyze the technique capability by testing the arrangement in local displacement measurements resulting from in-plane rotations. We experimentally demonstrate that it is possible to depict simultaneously in a single frame several systems of Young fringes corresponding to different local in-plane displacements between speckled images. The proposed pupil arrangement allows minimizing the redundancy in relation to the object status. Note that, with four exposures, six relative angles are determined with high precision and accuracy. In consequence, we maximize the information that can be drawn from the given set of exposures.

The accuracy and precision of our proposal is not different than those we can achieve in conventional single aperture speckle photography case. The technique by using different multiple aperture pupils in a multiple exposure scheme is not restricted to the transmission arrangement geometry, but also it could be employed for a properly illuminated rough reflecting surface.

In summary, it seems valid to revitalize this speckle photography technique based on a well established procedure to encompass multiple local displacement measurements with high accuracy.

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