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New multiple aperture arrangements for speckle photography

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Abstract

We propose a multiple exposure specklegram by using an optical system whose multiple aperture pupil changes between exposures. In particular, we analyze experimentally two arrangements and we show that it is possible to store the required information by employing a minimum number of registers if an adequate selection of the pupil is done. We study the effect of the decorrelation (among the stored speckle pattern) introduced by changing the multiple aperture pupil arrangements between exposures. The fundamentals and the relative benefits of the new scheme proposed are discussed on the basis of a fringe visibility analysis. © 2000 Published by Elsevier Science B.V.

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1. Introduction

Speckle photography is a well-known optical processing technique [1–4]. The principle of this technique is to determine the speckle displacement by coherent-optical processing of a specklegram, in which the speckle pattern before and after object deformation is recorded by double exposure. Speckle photography was first analyzed by Burch and Tokarski [5] and Archbold et al. [6,7].

This technique has been extended to multiplexing methods, which have been implemented by locating a proper mask immediately behind the imaging lens. In the method proposed by Kopf [8,9] the aperture of the lens is a slit and the image is composed of oriented speckles perpendicularly to the wider side of the slit. In that case, the spectrum of the registered image after processing shows diffracted light at large angles in the direction perpendicular to the oriented speckles. This method makes it possible to overlap photographs recorded with the slit apertures in different azimuthal positions and to separate them later by spatial filtering. This technique could be implemented with other pupil arrangements; the simplest may consist of two circular apertures symmetrically located with respect to the lens center [10]. In this case, it is possible to overlap some images if the double aperture is rotated after each recording. This

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double aperture method can be used in speckle photography, for measuring in-plane displacements. The distribution of fringes obtained has been examined theoretically by Bridko et al. [11]. Note that in the double aperture method is necessary to employ $2n$ registers to store n in-plane displacements.

Related techniques by using more than two apertures for recording have been scarcely studied. Chiang and Kethan [12] analyzed the double exposure technique by using for both registers the same multiple aperture pupils.

Recently we reconsidered the study of these techniques and we theoretically analyzed the use of different multiple aperture pupils for recording each image in speckle photography [13]. In this case, by considering different pupils for recording, the cross-correlation functions for the amplitudes and intensities were calculated in the image plane, on the basis of the statistical properties of the object. Also, the ensemble-average intensity in the Fourier plane was analytically derived and fringes visibility was investigated [13].

Based on that analysis, in this case we present a new multiple aperture geometry for speckle photography. We propose a multiple exposure specklegram by using an optical system whose multiple aperture pupil changes between exposures. In particular, we experimentally analyze two arrangements and we show that it is possible to store the required information by employing a minimum number of registers if an adequate selection of the pupil is done.

First, a five-exposure specklegram by using different pupil arrangements for each register is proposed. The pupils used for the second, third, fourth and fifth exposures are a subset of the pupil arrangement of the first exposure. This system allows to determine four in-plane displacements by using five exposures where all the displacements are referred to the original situation. In consequence, in term of the number of exposures this routine is more efficient than the double circular aperture method mentioned above.

Besides, another multiple exposure scheme with more than two apertures in each pupil is proposed. As a consequence of the pupil selection, the relative displacements among all possible pupil combination are obtained. In this case, four exposures are enough to store six in plane displacements.

The number of exposures can be reduced in comparison with the number of displacements to be determined depending on the pupils selected. In Ref. [13], the decorrelation introduced by changing the pupils arrangement between exposures is theoretically analyzed and the fringes visibility in the Fourier plane are derived in terms of the geometric features of the pupils. On the basis of that work now we analyze the effect of the decorrelation (among the stored speckle pattern) introduced by the new multiple aperture pupils scheme proposed.

It is well known that in speckle photography accurate measurement of the periodicity of the fringes is desirable. This feature stimulates us to optimaze the fringes visibility in our multiple exposure scheme. The fundamentals and the relative benefits of the new arrangements proposed are discussed in Section 3 on the basis of the study of the visibility.

2. Theoretical analysis

As it is depicted in Fig. 1, a conventional photographic procedure for recording and a coherent-optical processor for analyzing specklegrams are implemented. A diffuser is illuminated by a collimated He–Ne laser beam ($\lambda_R = 633$ nm) and imaged onto a high-resolution holographic film (Agfa-Gevaert 10E75) located at the X–Y plane. The distances from the diffuser R to the lens L_1 and from the lens L_1 to the camera are set to $Z_0 = 138$ mm and $Z_C = 382$ mm, respectively. A pupil mask P with multiple apertures is placed immediately in front of lens L_1 (u–v plane). Large speckles of characteristic size determined by the aperture diameter are formed in the image plane. As a result of the coherent overlapping of the beams emerging from each pair of apertures, the speckle grains are modulated by fringe systems oriented perpendicularly to the line joining the apertures. The frequency of each fringe system depends on the separation of each pair of apertures. Then, in the image appears several fringe systems with a frequency and orientation depending on the number and position of the apertures.

A multiple exposure register is implemented. Each imaged speckle intensity distribution is sequentially recorded on the film and between consecutive expo-

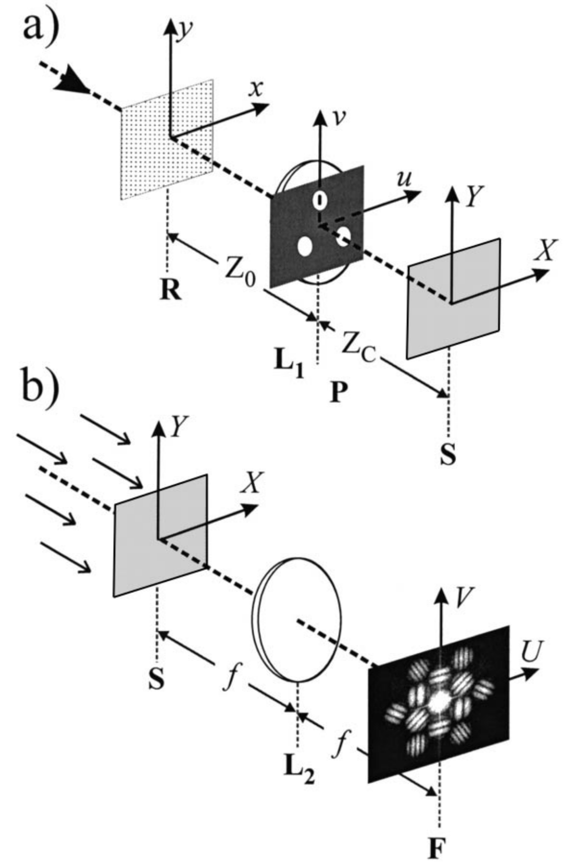

Fig. 1. Experimental set-up for (a) recording and (b) analysis of the specklegram. R: diffuser; L_1: imaging lens, P: pupil mask; S: specklegram; L_2: Fourier lens, F: Fourier plane.

sures an in-plane displacement of the diffuser is done.

By referring to Fig. 1, the registered specklegram is illuminated by a collimated laser beam, which impinges perpendicularly to the X–Y plane. Afterwards, the transmitted light is Fourier transformed by means of lens L_2 of focal length f and the intensity distribution is observed at the focal plane (U–V plane).

If the diffuser is uniformly displaced between exposures, when the specklegram is read-out, straight equispaced fringes appear in the diffraction plane whose orientation is perpendicular to the direction of the displacement. Thus, by analyzing the Young fringes, the distribution of the speckle displacements can be evaluated.

When using a multiple aperture pupil for recording, several separated spots are observed in the Fourier transform plane U–V. Furthermore, by considering a double exposure specklegram both with the same pupil, the average intensity distribution in the U–V plane is the well-known expression [13]:

$$\langle I_f(U,V)\rangle = 4\cos^2\left(\frac{\pi}{\lambda_R f}\left[U\Delta X^{12}+V\Delta Y^{12}\right]\right) \times \Im\left\{\left|\Im\left\{P^{12}(u,v)\right\}(X,Y)\right|^2\right\}(\vartheta U,\vartheta V) \quad (1)$$

where $(\Delta X^{12},\Delta Y^{12})$ is the image displacement and the function P^{12} represents the common region of the pupils P^1 and P^2 (in this case $P^1=P^2=P^{12}$). Besides, the factor $\Im\{|\Im\{P^{12}(u,v)\}(X,Y)|^2\}(\vartheta U,\vartheta V)$ describes the form of the respective diffraction halo of a single exposed speckle pattern and $\Im$ indicates a two dimensional Fourier transform where $\vartheta=(\lambda_W Z_C/\lambda_R f)$. This general expression does not depend on the shape of the apertures. In this case only a fringe system modulates the whole diffraction pattern.

Eq. (1) must be generalized to consider a multiple exposure routine and the use of different multiple aperture pupils P^k $(k=1,\ 2\ldots N)$ for recording. Theoretical arguments and experimental evidences suggest that the average intensity distribution in the U–V plane of a specklegram of N exposures is [13]:

$$\langle I_f(U,V)\rangle = \sum_{k=1}^{N}\Im\left\{\left|\Im\left\{P^k(u,v)\right\}(X,Y)\right|^2\right\}(\vartheta U,\vartheta V) + 2\sum_{\substack{k,l=1\\(k<l)}}^{N}\cos\left(\frac{2\pi}{\lambda_R f}\left[U\Delta X^{kl}+V\Delta Y^{kl}\right]\right) \times \Im\left\{\left|\Im\left\{P^{kl}(u,v)\right\}(X,Y)\right|^2\right\}(\vartheta U,\vartheta V) \quad (2)$$

where the first term describes the overlapping of all the smoothed diffraction halos corresponding to an individual single exposure recording and in consequence does not contribute to the fringe formation. The second term is related to the common part P^{kl} of the pupils P^k and P^l, when a relative diffuser displacement between exposures is produced. This term describes a rather complex pattern, which results from the selective overlapping of fringe-modulated spots.

Fringes are observed only in those regions of the Fourier plane that coincide with the diffraction halo of the common part of the pupils. Note that, the common part of the pupils determines not only the correlation properties of the two speckled images, but also the loci of fringes in the transform plane. In particular, fringes do not appear when two completely uncorrelated speckled images are recorded; that is when the images are obtained by employing pupils whose apertures do not coincide at all. This condition must be taken into account when the pupils are designed.

In the following, we consider that each pupil P^k $(k = 1, 2, \ldots N)$ to be employed consists of an array of q^k identical apertures. Besides, it is assumed that by comparing any pair of pupils P^k and P^l, some of their apertures coincide exactly while the other apertures do not overlap at all. The function $P^{kl}(u,v)$ can be associated with a pupil P^{kl} whose transmission area corresponds to the transmission area that P^k has in common with P^l. The function P^{kl} is referred to as the common part of P^k and P^l.

In particular, if a mask with circular apertures of equal diameter D placed in the u–v plane is considered, then:

$$\Im\left\{\left|\Im\{a(u,v)\}(X,Y)\right|^2\right\}(\vartheta U,\vartheta V)$$

$$= \aleph(U,V) = \frac{D^2}{2}\left\{\arccos\left(\frac{2\rho}{D'}\right) - \left(\frac{2\rho}{D'}\right)\right.$$

$$\left.\times\left[1-\left(\frac{2\rho}{D'}\right)^2\right]^{\frac{1}{2}}\right\}\mathrm{cyl}\left(\frac{\rho}{D'}\right) \qquad (3)$$

where the function $a(u,v)$ defines the circular aperture, $\rho = \sqrt{U^2+V^2}, D' = (2f/Z_C)(\lambda_\mathrm{R}/\lambda_\mathrm{W})D$ and

$$\mathrm{cyl}(\rho/D') = \begin{cases} 1 & \text{if } 0 \le \rho \le D'/2 \\ 0 & \text{otherwise} \end{cases}$$

.The function $\aleph$ $(U–\alpha,V–\beta)$ stands for a (smoothed) circular diffraction spot of diameter D′, centered at the generic point (α,β).

For a multiple exposure by using several circular apertures of equal diameter D for each register, the expression for the average intensity distribution of a diffraction spot centered at point (α,β) in the Fourier plane is given by [13]:

$$\langle I_{\alpha\beta}(U,V)\rangle$$

$$= \left\{\sum_{k=1}^{N} q_{\alpha\beta}^{k} + 2\sum_{\substack{k,l=1\\(k<l)}}^{N} q_{\alpha\beta}^{kl}\cos\left[\frac{2\pi}{\lambda_\mathrm{R} f}(U\Delta X^{kl}\right.\right.$$

$$\left.\left.+V\Delta Y^{kl})\right]\right\}\aleph(U-\alpha,V-\beta). \qquad (4)$$

The number $q_{\alpha\beta}^{k}$ represents the number of aperture pairs in the pupil P^k that are responsible for a spot formation at the point (α,β). Then, the first term of this equation is not associated with fringe formation in the spot at the position (α,β). The number $q_{\alpha\beta}^{kl}$ is the number of different pairs of shared apertures of the pupils P^k and P^l responsible for the spot formation. Besides, $q_{\alpha\beta}^{kl}$ in the second term is a weighting factor, which determines the magnitude of the contribution of the pupil P^{kl} to fringe formation. However, the numbers $q_{\alpha\beta}^{k}$ and $q_{\alpha\beta}^{kl}$ are proportional to the aperture transmission area of the pupils P^k and P^{kl} respectively, only for the zero order.

Let us compare the diffraction patterns corresponding to any pair of pupils, for instance P^k and P^l. We assume that the loci of some spots of the diffraction pattern of P^k coincide exactly with some spots of the pattern associated with P^l, while the remaining spots do not overlap at all. In the same sense it is possible to define the common and non-common apertures. But it should be pointed out that there is not a one-to-one correspondence between common and non-common apertures and common and non-common spots. Note that it is possible to generate common spots by means of non-common apertures. Besides, the information associated to non-common apertures does not contribute to fringe formation, thus reducing the visibility of the correlation fringes generated by the information corresponding to common aperture pairs. In consequence if common and non-common apertures contribute to a determined diffraction spot the fringe visibility is not the highest one. Thus, it is very important a judicious selection of the pupils in order that the spectral information in different spots solely corresponds to diffracted light associated with the aperture pairs the pupils have in common.

3. Experimental analysis

First, we consider a double-exposed specklegram obtained by using the pupil arrangements schematized in Fig. 2(a). Besides, the spectra corresponding to a single and a double exposure are depicted in Fig. 2(b) and Fig. 2(c), respectively. Both experiments employ the pupil of Fig. 2(a). In the double exposure case an uniform horizontal in-plane displacement of the diffuser between the registers is done. It should be pointed out that this result was obtained by Kethan and Chiang [12]. As predicted by Eq. (1), it is observed in all diffraction orders the same frequency fringe system with the highest visibility. In consequence, the information stored in all the spots is the same and this scheme does not represent an advantage in comparison with the double aperture arrangements analyzed by Duffy [10]. Besides, it is possible with the double aperture scheme to storage multiple in-plane displacements by just rotating the pupil [14]. In this case, it is necessary to employ $2n$ registers to store n in-plane displacements. As a new approach, let us propose a multiple exposure scheme where different pupil arrangements are used in each register.

We propose a five-exposure specklegram by using the pupils shown in the first row of Fig. 3. We label the pupils associated to the first, second, third, fourth and fifth exposures as (1), (2), (3), (4), (5), respectively. Notice that the pupil used for the second, third, fourth and fifth exposures are a subset of the first exposure pupil.

The diffraction pattern corresponding to each pupil is schematized in the second row of Fig. 3. By comparing the diffraction pattern corresponding to the pupil (1) with the pattern associated with the others pupils, it is clear that only a region of the diffraction pattern of pupil (1) coincides with the diffraction pattern generated by the other pupils. Besides, the pattern associated to pupils (2), (3), (4) and (5) do not overlap each other. The information associated to the first exposure overlaps with the information associated to the following exposures only in those parts that the first pattern has in common with the pattern corresponding to the remaining exposures. We referred to those parts as common regions. Of course, the zero order is always a common diffraction spot, irrespective the pattern observed.

If in-plane displacements of the diffuser between consecutive exposures are done, then in the common regions of the multiple exposure spectrum appear a fringe system associated to the respective diffuser displacements with respect to the initial position. In the example proposed, a uniform vertical (to the top) 30 μm displacement of the diffuser was imple-

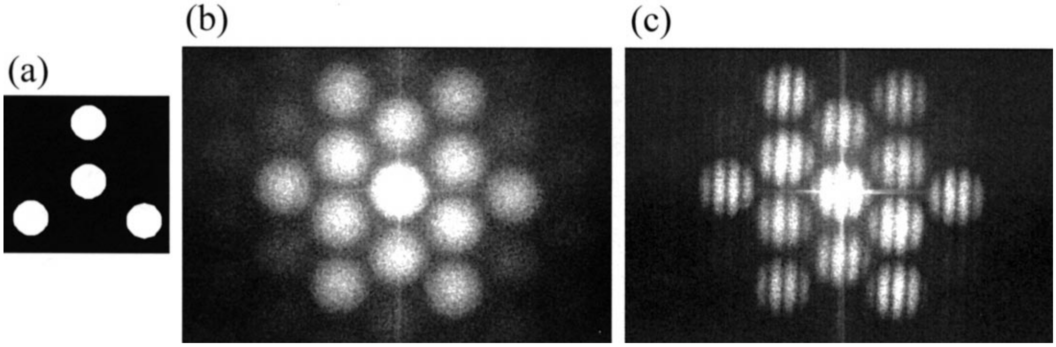

Fig. 2. (a) Scheme of the multiple aperture pupil; (b) single-exposed specklegram with the pupil shown in (a); and (c) double-exposed specklegrams by using the same multiple aperture pupil for both registers.

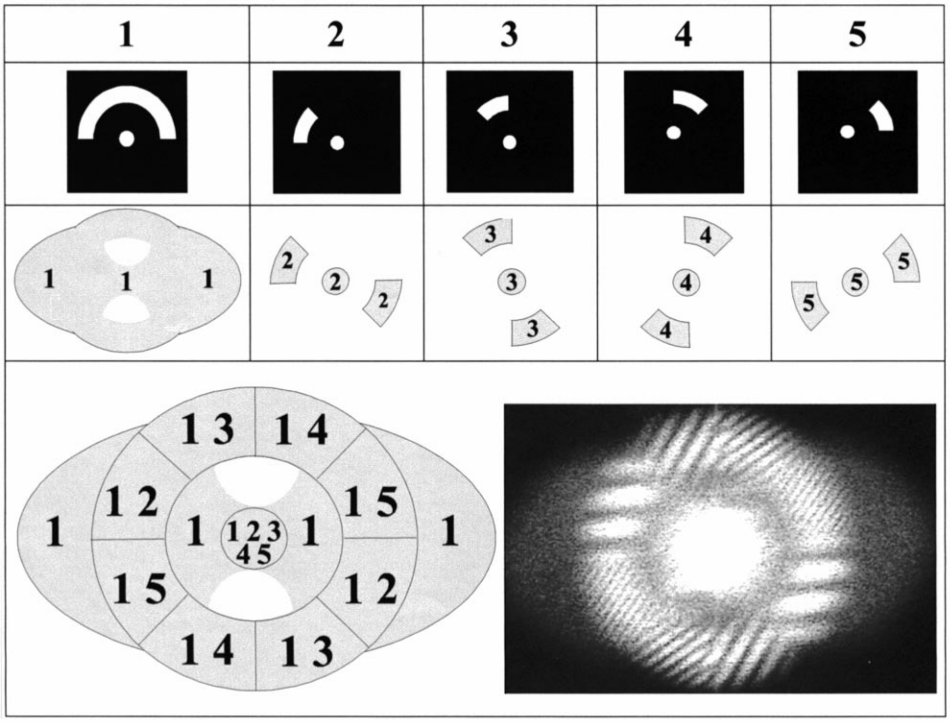

Fig. 3. Five exposed specklegram. In the first row is shown the schema of the pupil employed. In the second row are schematized the diffraction pattern corresponding to each spot. In the third row is shown the schema of the multiple exposure and the respective image when uniform in-plane displacements between images recorded is done.

mented between the first and the second exposure. Afterwards, a horizontal (to the left) 30 μm displacement was done between the second and the third exposure. Between the third and the fourth image an additional vertical (to the top) 30 μm displacement was done. Thus, the diffuser is 60 μm vertically and 30 μm horizontally displaced for the fourth image with respect to the first exposure. Between the fourth and the fifth images a new horizontal (to the left) 30 μm displacement was done that implied a vertical 60 μm and a horizontal 60 μm displacement of the fifth exposure with respect to the first exposure.

The spectral amplitude components corresponding to a pair of exposures are added into the common part of the diffraction spots. The diffraction patterns of the selected pupil arrangements (2), (3), (4) and (5) do not overlap each other but they all have a common part with the diffraction pattern corresponding to the pupil (1). In consequence, the information corresponding only to a pair of exposures is overlapped in each region of the diffraction pattern corresponding to the five-exposure routine. This feature allows to obtain multiple in-plane displacements all referred to the first situation without overlapping the information.

In the third row of Fig. 3 the scheme and the diffraction pattern obtained with the five-exposure routine by using pupils (1), (2), (3), (4) and (5) is depicted. The scheme shows which pupil contributes to the diffraction pattern in each region. The fringes observed in a determined region of the Fourier plane correspond to a relative in-plane displacement between the pupils that contribute there as can be determined by Eq. (2). The region with fringes coincides with the diffraction halo of the common part of a pupil pair.

In summary, by the arrangement proposed is possible to combine selectively the spectral information of a pair of exposures in determined regions of the diffraction pattern and in consequence to store four in-plane displacements by using five exposures, all referred to the original situation.

In speckle photography applications, some advantage can be accomplished if separated diffraction spots are observed in the Fourier plane, for example to avoid cross-talk effects in a variety of image multiplexing approaches. Note that in the approach just discussed, the fringes are too close each other and in consequence it should be convenient to separate them. To this purpose, we propose a new multiple exposure routine, which uses a pupil arrangement where the fringe systems carrying information of relative displacements do not overlap. The pupil schemes are shown in the first row of Fig. 4. In this case, the arrangements have more than two separated apertures. Besides, the shape of all the aperture pupils is circular and identical. Then, the diffraction pattern in the Fourier plane of each pupil arrangement consists of separated circular spots separated each other.

The speckle intensity distributions corresponding to each pupil arrangement imaged onto the film are shown in the second row of Fig. 4. We label the pupil associated to the first exposure as (A), to the second as (B), to the third as (C) and to the fourth as (D). Note that the speckles displayed are modulated by three fringe systems in each case. In particular, the patterns associated to the pupils (A), (B) and (C) exhibits two systems with the same frequency and the third system has a higher frequency which coincides with the frequency system that modulate the last pattern (pupil (D)).

In the third row of Fig. 4, the diffraction pattern of each pupil is schematized. Let us compare two diffraction patterns corresponding to any pair of the pupils employed. It is observed that the loci of some spots of one of the pattern coincide exactly with some diffraction spots of the other pattern, while the remaining spots do not overlap at all. Then, isolated common and non-common diffraction spots can be identified by comparing the patterns that any pair of

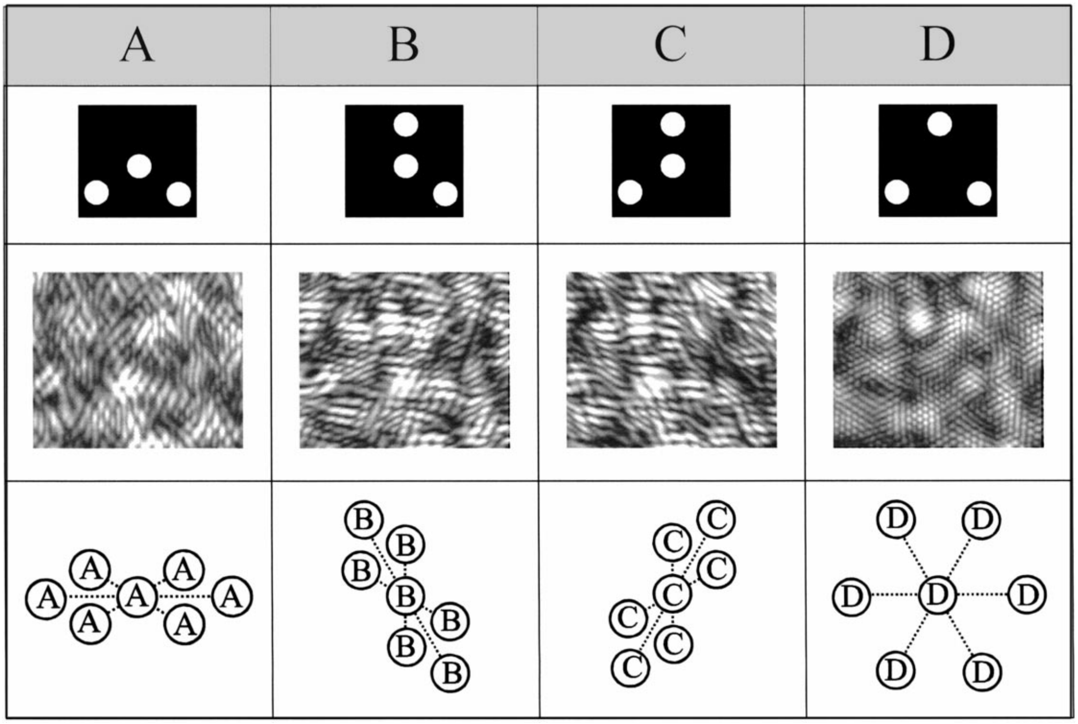

Fig. 4. In the first row is shown the schema of the pupil. In the second row is intensity distribution in the image plane corresponding to each pupil employed. In the third row is shown the diffraction pattern schemes corresponding to each pupil.

pupils generate. Note that in this case the common spots are associated to a common aperture pair. In consequence, the adequate selection of different multiple aperture pupils allows to isolate selectively or combine the spectral information of several multiplexed images in separated parts of the diffraction plane.

In Fig. 5 are shown a single, double, triple and quadruple exposure routines by using the pupils of Fig. 4. In the first row of Fig. 5 a single exposure

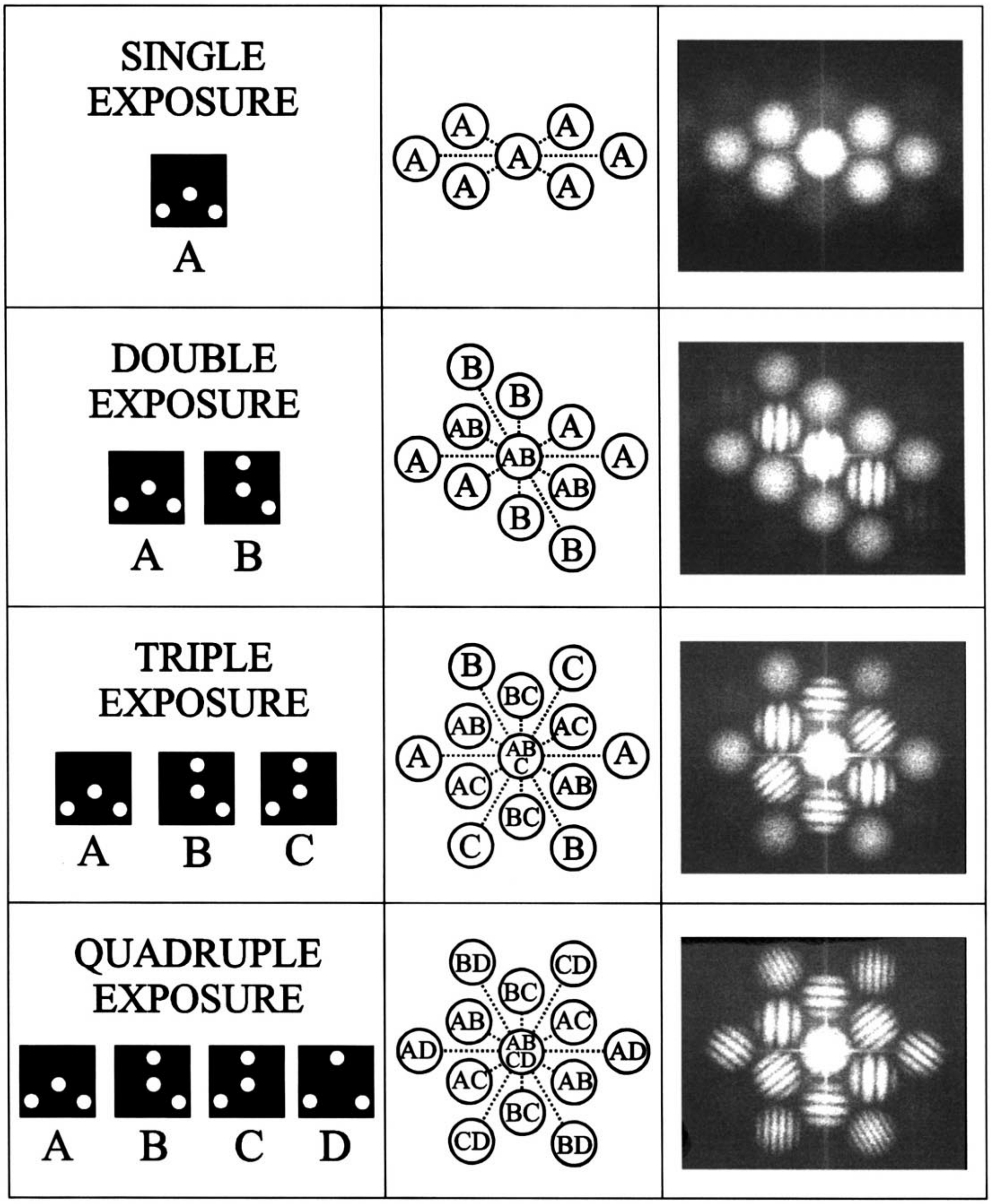

Fig. 5. Single, double, triple and quadruple-exposed specklegrams through pupils schematized.

through the pupil (A) is depicted. In this case, fringes do not appear because it corresponds to an individual single exposure.

In the second row of Fig. 5, the diffraction pattern corresponding to a double-exposure through the pupils (A) and (B) are shown. Between the first and the second exposures, a horizontal (to the right) 40 μm diffuser displacement was done.

The spectral amplitude components for a pair of exposures are added into the common diffraction spots, while their individual spectra are isolated in the non-common spots. Eq. (2) states that if an in-plane displacement between two exposures is done, a fringe system appears in the common diffraction spots. This result can be confirmed by observing the diffraction pattern corresponding to a double exposure routine as it is shown in the second row of Fig. 5. In the spots without fringes, light diffracted by one pupil alone concentrates there. It is clear that there are non-common aperture pairs in the pupils responsible for such spot formation. Besides, the common apertures of the pupils are responsible for the diffracted light into the common spots. In the double exposure specklegram, the pattern only has a pair of spots in common and one couple of lateral diffraction spots is fringe modulated. Let us compare the scheme of the diffraction pattern depicted in the second column of Fig. 5 with the corresponding picture of the third column. It is observed that the fringes only appear in the region where the information corresponding to both registers is overlapped. In the zero order, the spectra of both images are overlapped and fringes are observed because the pupils have two apertures in common, respectively. In case that the common spots would not been associated to a common aperture pair in both registers, then fringes do not appear because in this case the speckle patterns are not correlated [13].

The specklegram of the third row in Fig. 5 corresponds to a triple exposure with pupils (A), (B) and (C). As mentioned above, between the first and the second exposure, a horizontal (to the right) 40 μm displacement of the diffuser was implemented. Afterwards, a vertical (to the bottom) 40 μm displacement was done between the second and the third exposure. Thus, the third image was both horizontally and vertically displaced with respect to the first image. In this case, new pairs of diffraction spots are fringe modulated. The fringes in these spots are associated to the in-plane displacements between the first and the third and between the second and the third exposure.

In the central spot, the spectra of the three images are overlapped. Furthermore, a rather complex spatial modulation appears because horizontal, vertical and diagonal fringes are overlapped there.

In the fourth row a four-exposure routine is depicted. In this case, an additional exposure by using the pupil (D) was done. Between the third and the fourth exposure, the diffuser was displaced horizontally (to the left) 80 μm which implies a 40 μm (to the left) displacement with respect to the first exposure. Then, three new fringe systems appear as a consequence of the overlapping of the spectral components of the fourth image with the first, the second and the third image, respectively. In fact, these fringes refer to the relative displacement between the respective images. As in the previous examples, the zero order contains spectra components belonging to the four images.

By comparing the five and the four-exposure schemes proposed, it is apparent that more in-plane displacements are stored in the last case meanwhile the number of exposures is reduced. Nevertheless this is not the only feature to be taken into account. The change of the pupil arrangement between exposures can introduce a decorrelation effect, which reduces the fringe visibility as analyzed in terms of the geometric characteristics of the pupils in Ref. [13].

Remember that common apertures generate always common diffraction spots but common spots are not necessary associated to common apertures. Let us return to the expression of the average intensity distribution of a generic diffraction spot centered at point (α,β) in the Fourier plane given by Eq. (4). Note that the second term in this equation is associated to the common parts of the apertures and in consequence is responsible for the fringe formation. The first term in Eq. (4) corresponds to non-common apertures and it is not associated with fringe formation in the spot. Then, if common and non-common apertures contribute to a spot, both terms in Eq. (4) are not null thus reducing the fringe visibility.

To analyze the fringe visibility of the five-exposure scheme, we can adopt a simple model. Let us assume that the half ring slit area of the pupil (1) is approximated by a set of adjacent circular apertures whose diameter coincides with the ring slit width. The same assumption is done when considering pupils (2), (3), (4) and (5). Under this approach let us observe pupils (1) and (2). It can be inferred as depicted in Fig. 6(a) and Fig. 6(b) that there are common and non-common circular aperture pairs. The highlighted common aperture pairs generate the diffraction spots pair indicated in Fig. 6(c). Moreover the non-common aperture pair depicted in Fig. 6(a) also contributes in building up to the same diffraction spot pair. This is a consequence of translation invariance properties of the Fourier transform. Pupil (1) was employed in the first exposure and it was replaced by pupil (2), after an in-plane displacement of the diffuser. According with Eq. (4) the highlighted diffraction spots in Fig. 6(c) will exhibit fringes associated to the common aperture pairs but its visibility will be reduced as a consequence of the contribution of the non-common aperture pair depicted in Fig. 6(a). The same analysis is appropriated with the pupil (3), (4) and (5). Then, the selection of pupils in the five exposure scheme is rather less adequate because the visibility does not reach the highest.

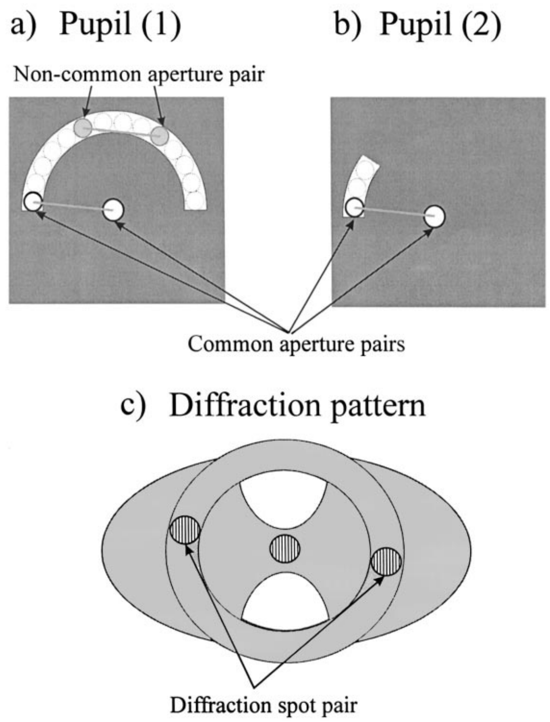

Fig. 6. Model for analyzing fringe visibility. In (a) and (b), schemes of the pupils (1) and (2) indicating the common and non-common aperture pairs. In (c), scheme of the diffraction pattern for the corresponding double exposure register.

To obtain fringes with maximum visibility it is necessary that the first term in Eq. (4) that is associated to non-common apertures must be nule. This situation is fulfilled in the second arrangement proposed. There all the diffraction spots have the highest fringe visibility because in each fringed spot is only overlapped the information corresponding to a pair of apertures carried by speckle patterns that are fully correlated [13]. Its means that only common aperture contributes in any position in the Fourier plane.

4. Conclusions

In this paper, we proposed an extension of the speckle photography technique based on a multiplexing method by employing pupil arrangements, which change between the multiple exposures implemented.

The introduction of spatial frequency carriers through the internal modulation of speckles allows to concentrate selectively the spectral components in determined region in the Fourier plane. Then, we take advantage of these features by employing a multiple exposure routine allowing to gather transforming plane the information of different images.

In particular, we analyzed two experiments. First, a five-exposure routine by using a different pupil arrangement with two apertures in each register is proposed. Notice that the pupils used for the second, third, fourth and fifth exposures are a subsets of the first exposure pupil. This system allows to determine in a single frame four in-plane displacements referred all to an original position.

Besides, another multiple exposure scheme is proposed with more than two apertures in each pupil. In this case, only four recording steps are needed to store six in-plane displacements and the relative displacements among all possible pupil combination is displayed.

In the proposed cases is apparent that the adequate selection of the pupil arrangements is an important feature to obtain maximum fringe visibility. We can observe that the second case analyzed fulfilled the requirement to obtain the highest visibility while the first experiment is constrained to reach only a low visibility. By considering both cases we can concluded that high visibility is obtained when the spectral information in different spots corresponds solely to diffracted light associated with the apertures pairs that the pupil have in common. Then, the second case not only allows to display all possible relative in-plane displacement with only four exposures but the fringes that store this information have the maximum visibility. This is a consequence of satisfying the condition stated above.

Besides, this multiple aperture pupil multiplexing technique is not restricted to the transmission arrangement geometry, but also it could be used for a properly illuminated rough reflecting surface. Thus, other applications that require to minimize the number of exposure and an efficient display of the stored information can be implemented by following this approach, for both real-time image processing and metrology

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