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Eliminating the diffraction halo effect in speckle photography

J. Georgieva

Department of Physics, Higher Institute of Architecture and Civil Engineering, 2, Chr. Smirnenski Blvd, Sofia 1421, Bulgaria.

A method to eliminate the diffraction halo effect in speckle photography is derived which does not demand any knowledge of the halo intensity distribution. Both maxima and minima positions in Young's fringe pattern may be used. Experiments are performed to verify the applicability of the proposed procedure.

1. Introduction

Speckle photography has now become a common technique for non-destructive strain analysis in static and dynamic problems [1]. The method is based on the correlation of two random patterns (both coherent and incoherent ones may be used) of an object recorded on the same photo emulsion before and after the object is affected. The specklegram is then optically processed by a whole field or (more often) by a pointwise filtering. The last procedure consists in illuminating a small region of the speckle photograph at normal incidence with a converging beam of laser light. In the Fourier plane where the beam comes to focus a diffraction halo appears modulated by a parallel equispaced fringes similar to Young's fringes. The displacement vector of the point of consideration is determined from the spacing and the angle of these fringes.

It has been found that the halo intensity variation changes the slope of the fringes and as a result the minima move to the edge of the pattern and the maxima – to its centre. So the values determined from maxima or from minima positions turn to be different from their real values [2]–[4]. The effect is significant when the fringe density is low, *i.e.*, near the lower limit of measurable displacement d_{min} and experiments with laser speckle photography show that measured displacement values less than $5d_{min}$ and $3d_{min}$ when using maxima and minima, respectively, are highly inaccurate and necessitate compulsory corrections to obtain reliable results [5].

Different methods are suggested to correct the results and to remove the diffraction halo effect for the occasion when displacements and vibrations are measured [6]–[9]. Most w them are based on theoretical models for diffraction halo intensity distribution. But the actually observed halo profile may be quite different from the predicted one. This is valid especially in white light speckle photography where the diffraction halo is affected by many factors that usually cannot be taken into account. In all these cases the above-mentioned procedures are inapplicable.

The experimentally observed diffraction halo shape also may be used to correct the results. In this case, some additional experiments are necessary to obtain the real halo function [10]–[12].

In this work, we present a simple method to eliminate the diffraction halo effect in speckle photography. Both maxima and minima positions in Young's fringe pattern may be used and no assumptions about the halo intensity distribution are needed.

2. Method for removing the diffraction halo effect

The light intensity distribution in the Fourier plane with point-by-point filtering is

$$I(x) = I_0(x)\cos^2\frac{\pi x d M}{\lambda L} \tag{1}$$

where x is the co-ordinate in the direction perpendicular to the fringes, $I_0(x)$ is the diffraction halo intensity distribution, d is the displacement in the object plane, λ is the wavelength used for filtering, L is the distance between the specklegram and the Fourier plane, and M is the magnification factor. Here we assume that the image is integrated along lines parallel to the fringes to create a one-dimensional function. As the fringe positions are slightly affected by the visibility factor v, we accept $v = 1$.

The displacement values are usually obtained using n-th maximum $(x_n)_t$, (or minimum $(x_n^0)_t$) of the periodic function $\cos^2\dfrac{\pi d x M}{\lambda L}$ and the positions of the peaks x_n (or of the gaps x_n^0) of the actual intensity distribution in the Fourier plane, *i.e.*

$$d = \frac{\lambda L n}{M x_n}, \quad n = 1,\ 2,\ 3,\ \dots, \tag{2}$$

$$d = \frac{\lambda L(n+1/2)}{M x_n^0}, \quad n = 0,\ 1,\ 2,\ 3,\ \dots, \tag{3}$$

from where the following expressions are expected:

$$d\,\frac{x_n}{n} = d\,\frac{x_n^0}{n+1/2} = \frac{\lambda L}{M} = \text{const.} \tag{4}$$

But as the diffraction halo shifts maxima and minima positions

$$x_n \neq (x_n)_t, \quad x_n^0 = (x_n^0)_t,$$

and as a result this is valid only for constant intensity halo or when the displacements are sufficiently big.

Let us assume that

$$d = \frac{x_n}{n} f(x_n) = \frac{\lambda L}{M} = \text{const} \tag{5}$$

where the correcting function $f(x_n)$ is given by

$$f(x_n) = \frac{(x_n)_t}{x_n}. \tag{6}$$

If known, $f(x_n)$ may be used to correct displacement values calculated from (2) and (3).

The correcting function $f(x_n)$ was obtained using a theoretical model for halo intensity distribution as accepted in [13]

$$I_0(r_0) = \frac{2}{\pi}\left[\arccos\frac{r}{r_0} - \frac{r}{r_0}\sqrt{1-\left(\frac{r}{r_0}\right)^2}\right] \tag{7}$$

where r is the distance from the centre of the halo, and r_0 – its radius.

The values of x_n and $(x_n)_t$ were estimated for $n = 1, 2, 3$ for different displacement values near the lower limit of measurable displacements. The results are presented in Fig. 1, where $f(x_n)$ is plotted versus the peak position x_n. The same figure shows

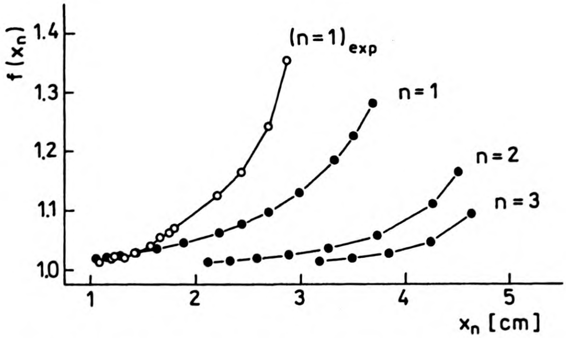

Fig. 1. Correcting function $f(x_n)$ versus n-th maximum position. • – theoretical, o – experimental

$f(x_1)_{exp}$ determined from experimentally observed fringe pattern with the same λ, M, L, and F-number of the recording camera. The deviation of $f(x_1)_{exp}$ from the theoretical curve is considered to be due to the fact that in a real experiment the halo intensity profile may differ from that given in Eq. (7). Some of the possible reasons are discussed in [13], [14].

The correcting function may be different according to the specific experimental conditions and may be determined for a given experiment by processing a number of double exposed specklegrams recorded with known displacement values and appropriate approximation.

3. Experimental results

The validity of the proposed procedure was verified experimentally for white light speckle photography, where the diffraction halo is much more sensitive. A plane white object with an artificially created speckle pattern was illuminated with a flash lamp and imaged by an ordinary 35 mm camera. Between the two exposures a camera translation of a known value perpendicular to the optical axis of the lens was introduced. The specklegrams were analysed by pointwise filtering. The correcting function was estimated by polynomial approximation of different degree and using different number of initial values from first maxima positions. Figure 2

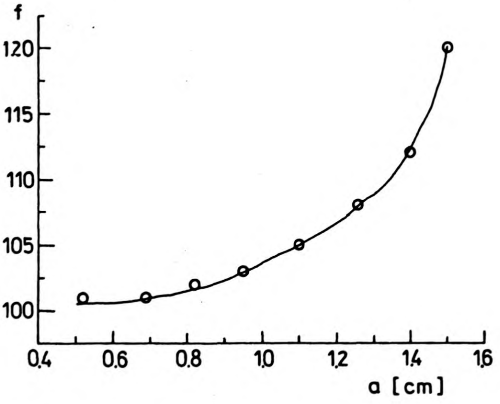

Fig. 2. Experimentally determined correction function versus the first maximum position. o – points used for polynomial approximation

shows experimentally determined correction function versus first maximum position. To obtain it, known displacement values in the range of 300–700 μm are introduced to the recording camera. It is seen that values calculated by means of Eq. (2) need corrections up to 20%.

An approximation by polynom of the 4-th degree based on the points marked in Fig. 2 seems to be good enough to be used for corrections which can be seen in Fig. 3. Two curves are presented in the figure – the values calculated by means of Eq. (2) and the real displacement values against the maxima positions. The values

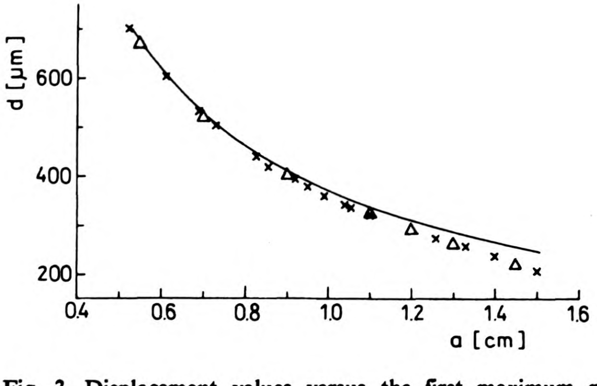

Fig. 3. Displacement values versus the first maximum position. —— – calculated by means of Eq. (2), × – real values, Δ – corrected by means of polynomial approximation

estimated using the procedure described are plotted as well and they agree very well with the real displacement values. Displacement values corrected by polynomial approximations of 3, 4 and 5 degree of the correcting function are given in the Table.

Displacement values correted by means of polynomial approximation: d_0 – calculated from Eq. (2), d – real values, d_i – corrected by polynomial approximation of i-th degree

N	d_0 [μm]	d [μm]	d_3 [μm]	d_4 [μm]	d_5 [μm]
1	705	700	702.6	699.8	700.4
2	536	532	528.0	532.8	531.0
3	449	440	439.3	439.7	440.9
4	402	394	392.3	390.3	391.5
5	356	341	343.6	341.2	340.9
6	336	321	322.3	320.6	319.7
7	294	272	271.9	272.4	272.5
8	278	256	251.8	253.6	253.9
9	264	236	232.7	234.2	235.1
10	247	205	206.8	205.8	205.5

The procedure described could be useful in a variety of practical situations. We applied it when investigating in-plane strain of models of thin-wall structures by white light speckle photography, which was performed simultaneously with their engineering testing. Displacements in a wide range of points had to be measured and models were loaded many times. No one of the known methods seemed to be suitable to correct lower displacement values influenced by the diffraction halo slope. We need not to discuss in detail here the experiments and shall only note that in several points of the model the vertical components of the displacement vector were measured independently. Before the models were

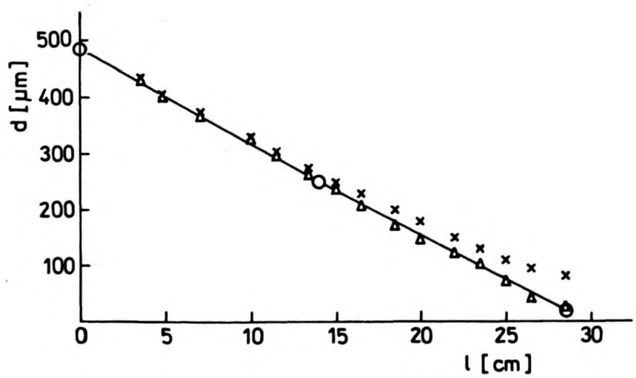

Fig. 4. Comparison between uncorrected (×) and corrected (△) displacement values. o – independently measured displacement values

loaded known lateral displacements were introduced to the recording camera and were used afterwards for polynomial approximation.

An example of the results is presented in Fig. 4, where the vertical displacement components are plotted against the model length. It is seen that polynomial approximation permits obtaining trustworthy displacement values.

4. Conclusions

The proposed procedure eliminates the diffraction halo effect in speckle photography in a very simple way. Although we prefer to use for it maxima positions, minima may be used in the same way. It should be noted that no information about the halo shape is needed and hence it may be applied without any restrictions in most practical cases of speckle photography.

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