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M.N. Osipov
Samara National Research University, Samara, Russian Federation
E-mail: osipov7@yandex.ru. ORCID: https://orcid.org/0000-0002-8104-5002
R.N. Sergeev
Samara National Research University, Samara, Russian Federation
E-mail: romansr@yandex.ru. ORCID: https://orcid.org/0000-0002-7157-316X

EVALUATION OF THE APPLICATION OF DOUBLE-EXPOSURE SPECKLE PHOTOGRAPHY WITH DIFFERENT APERTURES IN EXPERIMENTAL MECHANICS

ABSTRACT

The article presents an experimental evaluation of the use of double-exposure speckle photography with circular and annular apertures in experimental mechanics using the example of determining the modulus of elasticity in tension. The description of the process of registration of speckle photography and its subsequent processing is given. Based on the results of calculations of the finite element model of the sample, the area where the boundary conditions do not affect its tension is determined. A description is given of the procedure for processing speckle photographs to determine the modulus of elasticity and the error in its measurement with different apertures.

Key words: double-exposure; speckle photography; circular and annular apertures; modulus of elasticity; measurement; tension; error; finite element method.

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© Osipov M.N., 2021
Mikhail N. Osipov — Candidate of Physical and Mathematical Sciences, head of the Department of Information Security, Samara National Research University, 34, Moskovskoye shosse, 443086, Russian Federation.
© Sergeev R.N., 2021
Roman N. Sergeev — laboratory assistant of the Educational and Scientific Laboratory of Mathematical Methods of Information Security, Samara National Research University, 34, Moskovskoye shosse, 443086, Russian Federation

Introduction

Elastic deformation has a significant impact on the subsequent development of inelastic processes both for the brittle state of bodies under processing and operation conditions, and for the plastic and highly elastic states of materials. This circumstance shows the practical importance of studying the elastic state of materials [1; 2].

In modern studies of the solid mechanics, as well as in modeling load-bearing structures for various purposes, numerical methods have been widely used in their design. The results of calculations using numerical methods completely depend on the adequacy of the specified loading conditions, design parameters, and the accepted material model. Often, when design a model of a calculated structure, the physical and mechanical parameters of the material are idealized [3]. Most often, the material is endowed with the properties of ideal elasticity, or ideal plasticity. The values of the parameters characterizing the properties of the material are taken according to reference values and are assumed to be the same within the entire structure, and their correspondence to real values is analyzed very rarely. This is mainly due to the standard approach to calculation, where it is assumed that for materials such as structural steel, for example, the variability of physical and mechanical properties is small and has little effect on the calculation results. This approach has developed from the concepts and types of problems in which the nonlinearity of the initial range of the stress-strain curve can be neglected [3; 4].

The existing situation can be changed by the presence of experimental information reflecting the real conditions of loading, fastening, as well as the physical and mechanical properties of the material of the investigated object. Experimental methods should have high metrological characteristics, provide the possibility of measuring the deformed state over the entire surface of the investigated object, and have a high level of automation and information capacity [5; 6].

These requirements are most fully met by coherent-optical methods, in particular holographic, as well as speckle photography and speckle interferometry, developed on its basis and separated into an independent direction. Speckle photography is the easiest to put into practice and interpret the results of the study.

Speckle photography is a method for measuring displacements, deformations, rotations and vibrations. The requirements for the mechanical stability of the optical scheme are significantly less than in holographic interferometry [7–10].

In this paper, the evaluation is made on the use of double-exposure speckle photography with standard (circle) and annular apertures in experimental mechanics on the example determining of the modulus of elasticity.

1. Double-exposure speckle photography

The method of double-exposure speckle photography is widely used to determine the displacement fields of the studied samples during deformation. The optical scheme for recording speckle photography is shown in Fig. 1.1. The surface under study, located in the x_1y_1 plane, is illuminated by the coherent light, at the distance d_1 from it there is a diaphragm and the optical system with the focal length f (plane x_2y_2). The photographic plate is located at the distance d_2 (image plane x_3y_3) from the optical system with the diaphragm.

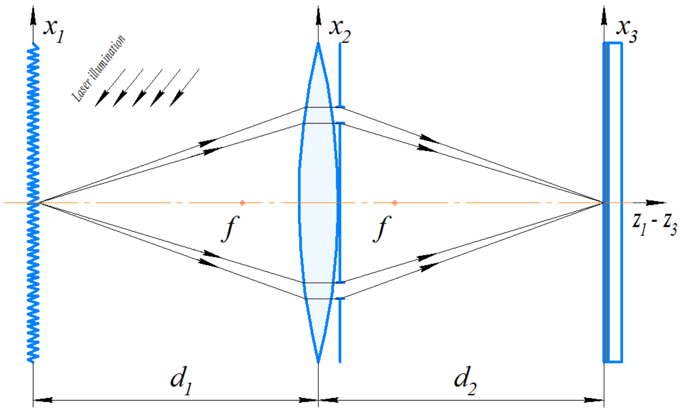


Fig. 1.1. Optical scheme recording the focused speckle photography

To obtain the focused image of the object under study in the image plane of the photographic plate, it is necessary to fulfill the well-known relation:

$$\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f}. \tag{1.1}$$

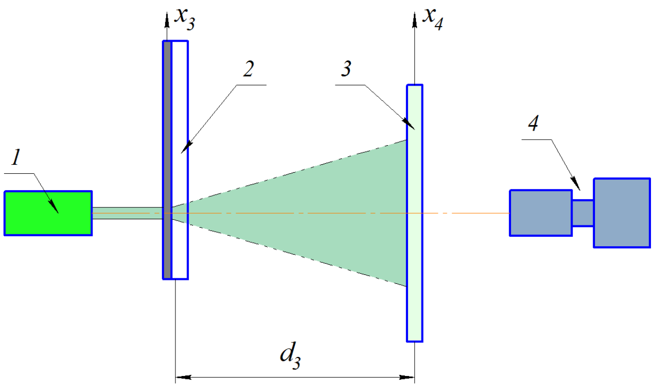
Recording on the photographic plate is made in two stages: first, the initial state of the sample is recorded, and then the deformed one, as a result of which the initial state of the speckle field changes under the influence of the load, thereby two complex irregular speckle-patterns displaced relative to each other are recorded on the photographic plate.

In works [11; 12], based on the method proposed by Vander Lugt [13], and the representation of the scattering surface as a set of point radiating sources described by the Dirac delta function [14], the expression was obtained for the intensity distribution recorded on the photographic material:

$$I(x_3,y_3)=I_0+I_L=|A_0|^2\iint\limits_{P_2}\iint\limits_{P_2'} e^{ikD_2x_3(x_2-x_2')}e^{ikD_1(u_nx_2-u_mx_2')}\times \\ \times e^{ikD_2y_3(y_2-y_2')}e^{ikD_1(v_ny_2-v_my_2')}\cos\left(\tfrac{k}{2}D_1L(x_2-x_2')\right)dx_2dy_2dx_2'dy_2', \tag{1.2}$$

where I_0 is the intensity of the initial state; I_L is the intensity of the deformed state; A_0 is the average intensity in the speckle pattern; L is the displacement value at some point of the surface under study between two exposures; $k=2\pi/\lambda$, (λ is the wavelength of laser radiation); $D_1=1/d_1$, $D_2=1/d_2$; u_n, v_n – coordinates of the n-th point of the investigated surface; u_m,v_m are the coordinates of the m-th point of the surface under study (n and m change from 1 to N – the number of point sources on the surface under study); x_2y_2 are the coordinates of the diaphragm surface used; P_2 and P_2' area of integration over the surface of the diaphragm used.

The deciphering of double-exposure speckle photography can be carried out by two methods: by point-by-point scanning (Young's method), or by optical filtering. Young's method is the most famous. The implementation scheme of Young's method is shown in Fig. 1.2, *a*. A double-exposure speckle photography *2* located in the x_3,y_3 plane is scanned by a narrow laser beam *1*. As a result of diffraction on the specklogram of the scanning laser beam, in the plane of the screen *3*, located at a distance d_3 from the screen, Young's interference fringes are formed, which are recorded by camera *4*.



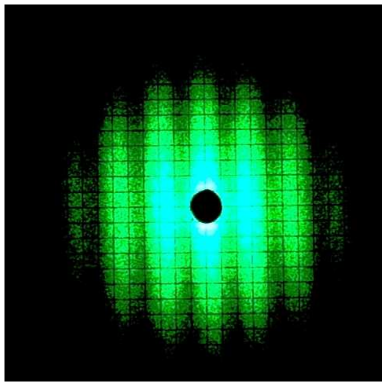


Fig. 1.2. Decoding scheme of the double-exposure speckle photography by Young's fringes method (*a*), photography of observed Young's fringes (*b*)

In works [11; 12], the expression was also obtained that describes the intensity distribution in the diffraction halo, which is the Fourier transform of the amplitude transmission of the double-exposure specklogram:

$$I(x_4,y_4)=|A_0|^4\left(\frac{\lambda}{D_2}\right)^2\left|\cos\left(\frac{k}{2}\frac{D_1D_3}{D_2}Lx_4\right)\right|^2e^{-ik\frac{D_1D_3}{D_2}u_mx_4}e^{-ik\frac{D_1D_3}{D_2}v_my_4}\times \\ \times\iint\limits_{P_2}\iint\limits_{P_3}e^{-ikD_1\{x_2(u_n-u_m)+y_2(v_n-v_m)\}}dx_3dy_3dx_4dy_4, \tag{1.3}$$

where $D_3=1/d_3$.

This expression describes the formation of Young's fringes. It should be noted that in these works, to simplify the calculations, the coordinate system was chosen in such a way that the displacement L at the studied point of the surface coincided with the x axis, which does not affect the calculations in the general case.

From the equation (1.3) it is possible to determine the amount of displacement L in the scanning area by the narrow laser beam, which is determined with the following equation:

$$L=\frac{\lambda d_3}{mp}, \tag{1.4}$$

where $p=2x_4$ is the period of Young's fringes, $m=D_1/D_2$ is the magnification of the optical system when recording double-exposure speckle photography.

Since the coordinate system was chosen in such a way that the displacement L at the studied point of the surface coincided with the x axis, it follows from Eq. (1.3) that the displacement L at the studied point is perpendicular to the Young's fringes. Thus, from Young's fringes, we can determine the magnitude and direction of displacement in the region of a scanning narrow laser beam. It should be noted that the sign of the displacement L at the point under study is not determined by Young's fringes, but which can be estimated in the course of the experiment. Thus, knowing the period of the Young's fringes and their orientation relative to the selected coordinate system associated with the sample under study, it is possible to determine the displacement field of the surface under study. The influence of the diameter of the scanning narrow laser beam, when decoding double-exposure specklograms, on the experimental results is given in work [15].

In papers [11; 12] present theoretical and experimental results on the influence of the aperture type of optical systems on the formation of subjective speckle structures. It is shown that the use of an annular aperture leads to a decrease of the average size of speckles in the recorded speckle patterns and, consequently, to an increase in the size of the diffraction halo when decoded by the Young's method. This makes it possible to increase the sensitivity and expand the range of measured displacements by the method of the double-exposure speckle photography. In addition, it is shown that the quality of the Young's fringes is higher in comparison with the Young's fringes obtained by decoding double-exposure speckle photography recorded using a standard circular aperture, that also improves the measurement accuracy of a displacement field.

Let us conduct an experimental evaluation of the use of double-exposure speckle photography which used the optical system with different apertures in experimental mechanics on the example of determining the modulus of elasticity of a material.

2. Teachnique for determining the elastic modulus

The technique for determining the modulus of elasticity in tension of a plane sample is well known. This is based on the hypothesis of plane sections, according to which the stresses in the cross-sectional area (having a constant section with area S) loaded with a constant normal force F are uniformly distributed, and is determined by the expression [1; 2; 16]:

$$E = \frac{Fl}{S\Delta l}, \tag{2.1}$$

where Δl is the absolute elongation of the sample over the length l.

The plane samples of the aluminum alloy AMg of standard form for determine of the elasticity modulus were used (Fig. 2.1).

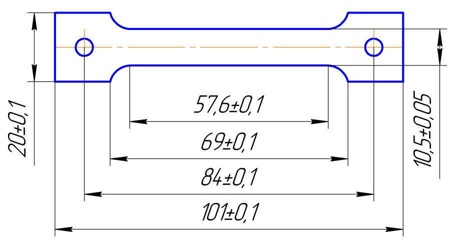
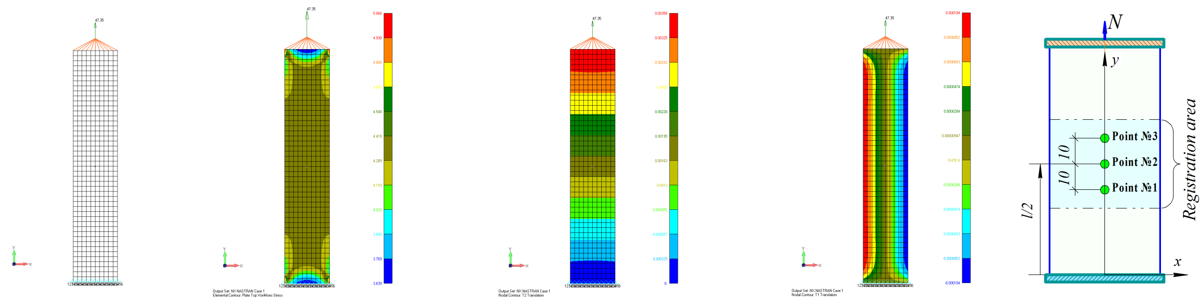


Fig. 2.1. Sketch of the plane sample

The plane sample of aluminum alloy has the following dimensions: length 57.6 ± 0.1 mm, width 10.5 ± 0.05 mm, thickness 0.97 ± 0.01 mm. To select the working area to determine the elastic modulus of the aluminum alloy by double-exposure speckle photography, a calculation was carried out on the basis of a finite element model (FEM).

In accordance with the nominal geometric parameters and reference values of the physical and mechanical characteristics of the aluminum alloy (modulus of elasticity 69000 MPa, Poisson's ratio 0.3), a finite element model of the sample was created (Fig. 2.2, *a*). The results of the FEM calculations made it possible to obtain the stress-strain state of the entire sample (Fig. 2.2, *b, c, d*). Based on the results of calculations of the stress-strain state of the sample, the boundaries of the central region were determined, in which the stresses are distributed uniformly, without a significant influence of the boundary conditions. This area extends from the center by a value of ±20 mm. Based on these calculations, for the experimental determination of the elastic modulus, a region of ±10 mm from the center of the sample was selected. This computational domain (Fig. 2.2, *e*) was adopted for point-by-point scanning of the double-exposure specklograms using the Young's method.



a *b* *c* *d* *e*

Fig. 2.2. Finite element model: general view (*a*); stress field distribution according to vonMises (*b*); displacement field in the longitudinal (*c*) and transverse (*d*) directions; measuring points placement (*e*)

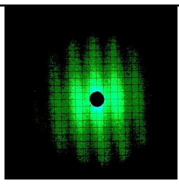
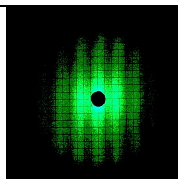
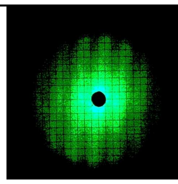
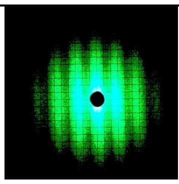
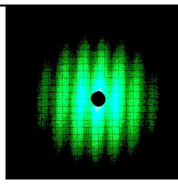
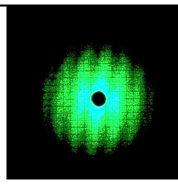
3. Experimental determination of the elastic modulus

Experimental studies to determine the elasticity modulus based on double-exposure speckle photography were carried out according to the optical scheme shown in Fig. 1.1. A lens with an aperture of 70 mm in diameter and a focal length of 170 mm was used as an optical system. When recording the double-exposure speckle photography with an annular aperture, a diaphragm with an outer diameter of 70 mm and an inner diameter of 56 mm was used. Double-exposure specklograms of the investigated plane sample of aluminum alloy AMg were recorded with an optical image magnification $m = 1$. The sample dimensions in the previous section are presented. The samples were loaded stepwise, during the first exposure, the loaded state was recorded, and during the second exposure, the unloaded state.

The interpretation of the double-exposure specklograms was carried out by the Young's method according to the optical scheme shown in Fig. 1.1. For the most accurate positioning of the scanned points on the sample (Fig. 2.2, *e*), an opaque template was made, with strictly located transparent holes 2 mm in diameter, at a distance of 10 ± 0.05 mm each from each other, thereby forming the basis for measuring the elongation l in accordance with equation (2.1). During scanning, the template was tightly attached to the emulsion of the photographic plate. Characteristic speckle photographs of Young's fringes, obtained by tension a sample with circular and annular apertures, are shown in Tab. 3.1.

Table 3.1

Young's fringes patterns

Aperture Form	Point No. 1	Point No. 2	Point No.3
Annular			
Circle			

To quantify the elasticity modulus in accordance with equation (2.1), it is necessary to determine the elongation of the base under a certain load. Base elongation is defined as the difference between the displacements of two adjacent points (No.1 - No.2 or No.2 - No.3, see Fig. 2.2, *e*). The amount of displacement in the investigated scanned point is determined by Young's fringes based on equation (1.4).

When the sample is lengthened, both longitudinal and transverse displacements occur due to the Poisson's effect. As described above, a feature of the speckle photography method is that the displacement vector is registered without taking into account the sign of the displacements. Therefore, when determining the longitudinal component from the patterns of Young's fringes, it is necessary to take into account the angle of their inclination.

Image processing was carried out using the *Image-Pro Plus* program. The result of this image processing of the Young's fringes paintings was to create three named *Excel* files (with a total of 72 files). One file contains a selection of 15 dimensions according to the size grid, with the aim of subsequently linking the pixel size to the actual size in the image. Another file contains a sample of 15 stripe pitch measurements, in pixels. The third file contains a selection of 15 measurements of the angle of inclination of the fringes, in degrees.

To automatically process the generated *Excel* files, the *YoungModule.py* program was developed in the *Python* programming language. This program performs statistical processing [16; 17] of all values used to calculate the elastic modulus and its error.

The result of the *YoungModule.py* program for processing experimental values for the plane sample of aluminum alloy AMg is presented in Table 3.2.

Table 3.2

The results of determining the modulus of elasticity

	Annular Aperture	Circle Aperture
474	85907±394	99879±488
710	74408±465	147724±539
919	62219±594	141783±605
1203	58371±698	60964±913

The experimental stress-strain curve of the plane sample of aluminum alloy AMg for two forms of apertures is shown in Fig. 3.1.

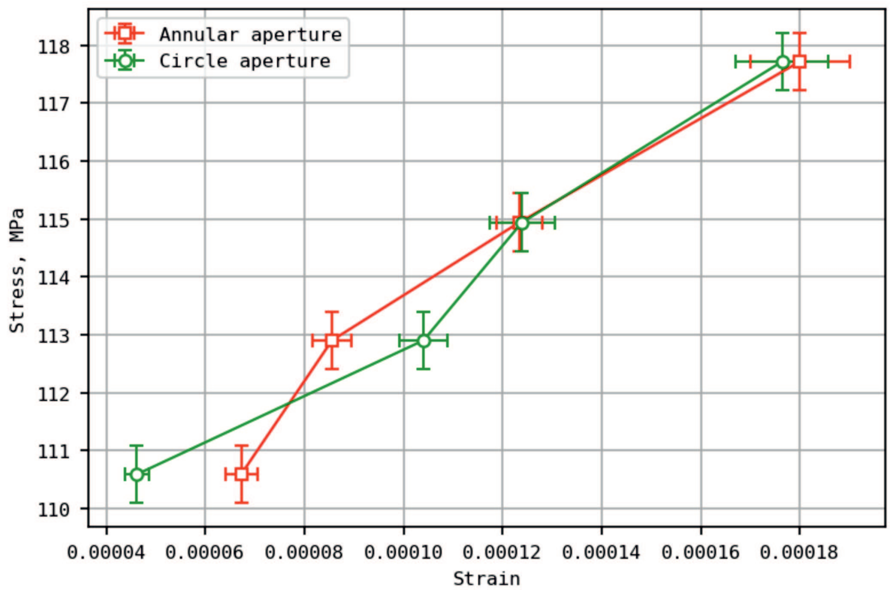


Fig. 3.1. Stress-strain curve

From Tab. 3.2 it is possible to determine the average value of the elasticity modulus of the aluminum alloy in the area of application of the load from 474N to 1203N. The average value of the elasticity modulus determined by the optical scheme with an annular aperture is E= 70227 ± 540 MPa aperture is E = 112588± ±640 MPa.

The average value of the elasticity modulus, obtained when recording with an annular aperture, shows that the experimental modulus of elasticity coincides with the reference values for aluminum alloys AMg lying within 69000...71000 MPa with a sufficiently high degree of accuracy. The average value of the modulus of elasticity, obtained when recording with a standard circular aperture, shows that the experimental modulus of elasticity in this case differs significantly from the reference values for aluminum alloys.

Conclusion

The experimental evaluation of the use of speckle photography with different apertures for measuring the elastic modulus showed that the use of an annular aperture makes it possible to increase the measurement accuracy.

Theoretical and experimental studies [11, 12] show that the use of annular apertures also leads to an increase in the sensitivity of speckle photography and an extension of the range of displacements measured by this method compared to the standard circular aperture.

Acknowledgments

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М.Н. Осипов
Самарский национальный исследовательский университет
имени академика С.П. Королева, г. Самара, Российская Федерация
E-mail: osipov7@yandex.ru. ORCID: https://orcid.org/0000-0002-8104-5002
Р.Н. Сергеев
Самарский национальный исследовательский университет
имени академика С.П. Королева, г. Самара, Российская Федерация
E-mail: petr2021@mail.ru. ORCID: https://orcid.org/0000-0002-7157-316X

ОЦЕНКА ПРИМЕНЕНИЯ ДВУХЭКСПОЗИЦИОННОЙ СПЕКЛ-ФОТОГРАФИИ С РАЗЛИЧНОЙ АПЕРТУРОЙ В ЭКСПЕРИМЕНТАЛЬНОЙ МЕХАНИКЕ

АННОТАЦИЯ

В статье приводится экспериментальная оценка применения двухэкспозиционной спекл-фотографии с круговой и кольцевой апертурами в экспериментальной механике на примере определения модуля упругости при растяжении. Приводится описание процесса регистрации спекл-фотографии и ее последующей обработки. По результатам расчетов конечно-элементной модели образца определяется область, где граничные условия не влияют на его растяжение. Приводится описание процедуры обработки спекл-фотографий для определения модуля упругости и погрешности при его измерении с различными апертурами.

Ключевые слова: метод двойной экспозиции; спекл-фотография; круговая и кольцевая апертуры; модуль упругости материала; измерение; растяжение образца; погрешность измерения; конечно-элементный метод.

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Осипов Михаил Николаевич — кандидат физико-математических наук, доцент, заведующий кафедрой безопасности информационных систем, Самарский национальный исследовательский университет имени академика С.П. Королева, 443086, Российская Федерация, г. Самара, Московское шоссе, 34.
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Сергеев Роман Николаевич — лаборант учебно-научной лаборатории математических методов защиты информации, Самарский национальный исследовательский университет имени академика С.П. Королева, 443086, Российская Федерация, г. Самара, Московское шоссе, 34.

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