Paper Template for Digital Speckle Interferometry Method for Research of Dynamic Processes

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Abstract The new digital speckle interferometry method for research of processes in mechanics of fracture, fatigue and strength of solid materials and structures in real time is considered. The new method is based on simultaneous registration of information by the standard digital speckle interferometry method and registration of distribution of intensity in the single speckle. Such decision allows to investigate fracture processes in real time; to increase sensitivity and accuracy of measurements; to expand a range of measured displacements. Besides, an offered method of the analysis of distribution of intensity in the single speckle allows will get rid of own noise inherent of interferometric methods of coherent optics.

In work theoretical and experimental results on realization of an offered method are presented. The optoelectronic scheme the digital speckle interferometer for registration at the same time speckle interferograms and intensity distribution in the single speckle is presented. The algorithm of processing of speckle interferograms on an offered method is presented.

It is shown that dynamic displacements can be measured with high resolution, in large range of measured value of displacements and in the large frequency range and in real time by this new method.

Keywords Experimental mechanics, Dynamic processes, Optical methods, Digital speckle interferometry, Processing and analysis of images and signals

1. Introduction

One of the main problems of solid mechanics, both fundamental, and the applied character, in many respects of a strength and durability of elements of designs, research of dynamic tasks is defining. Development of technique sets a task of increase of reliability of created and already working elements of designs subjecting to dynamic loadings. Existing mathematical models of the mechanics of fracture and settlement methods of forecasting don't allow to consider all real service conditions of designs fully. Experimental researches are necessary for confirmation of mathematical models of the mechanics of fracture and ensuring demanded parameters of designs at dynamic and static loadings. It demands development of the experimental measuring means, allowing to receive both qualitative, and quantitative data at dynamic and static loadings.

Optical contactless methods of researches gain now the increasing scientific and applied importance. Contactless methods have no impact on research elements of designs when carrying out experimental measurements that leads to increase of accuracy and reliability of received results. Considerable interest causes application of nondestructive interferometric methods for research of dynamic processes, both fundamental, and applied character. Optical, including laser interferometers, demand performance of a number of conditions which limit their practical application: the reflecting studied surface has to be optically smooth; the rigid mutual adjustment and fixing of elements of optical system is required. It should be noted also that interferometric methods, at practical application, demand use of lasers with a large spatial and time coherence that imposes additional restrictions when using data of systems in actual practice.

At the present stage it is necessary first of all to allocate from interferometric methods the digital holographic and speckle interferometry [1-4]. However, it is well known that at application of the

holographic and speckle interferometry there is a number of restrictions, which connected with existence of own noise (speckles), which lead to reduction of sensitivity and accuracy of measurements. Besides, speckle noise leads to restriction of measurement of displacements with great values of a gradient. Also we will note that existence of own noise (speckles) complicates processing of interferential pictures, both in the holographic, and the speckle interferometry and becomes impossible at research of high-frequency vibrations, because the contrast of interference fringes is falls. A problem of processing of the holographic and speckle interferograms the huge attention is paid [5-7]. Standard methods of the digital holographic and speckle interferometry, as a rule, don't allow to observe dynamic processes of solid mechanics in real time as at researches are generally used: averaging method in time; method of two expositions or pulse method.
In this work the new method of registration dynamic displacements of a research surface of object in large range of measured value of displacements and in the large frequency range on the basis of the analysis of distribution of intensity in the single speckle is considered. Such decision allows to overcome restrictions which are connected with existence of own noise (speckles) in the holographic and speckle interferometry and to register dynamic displacements in real time.

2. Speckle and practical application

2.1. Speckle pattern

When lighting by coherent radiation a rough surface because of scattering of a coherent radiation in space the complicated interference pattern, which is called speckle pattern, is formed. The characteristic kind of speckle pattern is presented in Fig. 1.

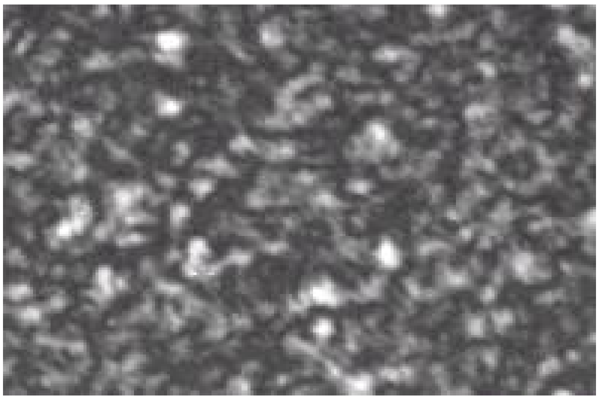

Figure 1. Photography of speckle patterns

Distinguish two kind of speckle patterns: a) the objective - formed in space at the expense of an interference of a large set of the reflected beams from a rough surface, and which can be registered directly without optical system on a photographic material; b) the subjective - formed and recorded on a photographic material by means of optical system in the plane of the image of a researched rough surface.
The sizes, longitudinal — *L* and transversal – *H,* of a speckle in objective and subjective speckle patterns are estimated on known formulas [1]:

$$L = \frac{4\lambda}{\alpha^2}, \tag{1}$$

$$H = 1{,}22\frac{\lambda}{\alpha}, \tag{2}$$

where λ is the wavelength of a laser, α – the relation of diameter of the lighted area of a research surface to distance from a research surface to a point of registration of the speckle for objective speckle pattern; α – the relation of diameter of an entrance aperture to focal length of optical system for subjective speckle pattern.
The dynamic processes arising on a surface of research object, lead to change of parameters speckle pattern (size and intensity) in space and in time that is connected with change of a phase of the reflected secondary spherical waves. Therefore, according to the analysis of existential behavior of the speckle pattern it is possible to investigate the dynamic and static processes of a research surface.

2.1. Proposed solution

As it was noted, parameters of the speckle pattern, changing in space and in time, are: longitudinal and transversal sizes; distribution of the intensity.
Let's estimate possibility of research of dynamic processes at the expense of measurement of parameters of the speckle pattern.
From Eq. (1) and (2) follows that the sizes of the subjective speckle pattern don't depend on dynamics of a research surface as α is a constant, and are therefore connected only with characteristics of optical system. Thus, the subjective speckle pattern doesn't allow to register displacements of a research surface, at the expense of measurement of the sizes speckle. On the other hand, registration subjective speckle pattern allows to tie rigidly its spatial arrangement in the image plane to a concrete point of a research surface. For registration of displacements in it cases are used methods of two expositions or averaging in time with the subsequent processing of interferograms.
Let's carry out a similar assessment for the objective speckle pattern. At dynamic displacements of a research surface of change of the sizes of a speckle for objective speckle pattern according to Eq. (1) and (2) will be defined by the following ratios:

$$L = \frac{4\lambda(r \pm \Delta r)^2}{D^2}, \tag{3}$$

$$H = 1{,}22\frac{\lambda(r \pm \Delta r)}{D}, \tag{4}$$

where r – distance from a research surface to a point of registration of the speckle; $\pm\Delta r$ – the value of displacement of a research surface; D – diameter of the lighted area of a research surface.
From the analysis of Eq. (1) and (2) follows that the transversal and longitudinal sizes of a speckle will change at very small value, as under real conditions of measurements $\Delta r/r \approx 0$. Therefore, as well as in a case with the subjective speckle pattern to define dynamics of a research surface at the expense of measurement of the sizes objective speckle pattern also it is almost impossible.
Let's consider possibility of definition of dynamics of a research surface, at the expense of registration of change of intensity of the speckle.
Change of intensity of a speckle occurs at the expense of change of its phase which depends on change of an optical way at displacement of a research surface. Change of value of a phase of the speckle on $\pm\pi$ $(2n+1)$, (where n=0,1,2. …) leads to change of intensity of the speckle from the minimum value to maximum or on a turn.
For registration of change of a phase of the speckle is necessary to use the reference beam of a laser radiation which is imposed on the speckle pattern, and therefore the secondary interference pattern in the form of fringe pattern is formed. Width of secondary interference fringes d is defined by well-known equation [8]:

$$d = \frac{\lambda}{2\sin(\frac{\Theta}{2})}, \tag{5}$$

where Θ – angle between the reference beam of a laser radiation and the focused scattered laser radiation from a research surface which forming image of this surface with speckle pattern in the plane of the photodetector.
The kind of speckle pattern with the secondary interference pattern is presented in Fig. 2.

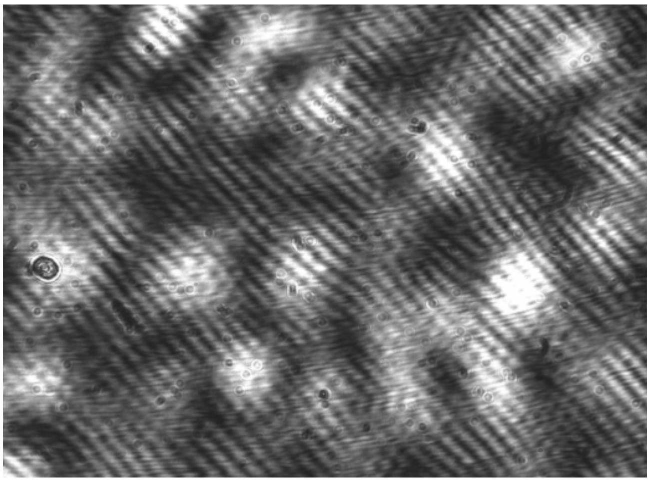

Figure 2. Photography of the speckle pattern with the secondary interference pattern

It is offered for effective registration of change of intensity of the single speckle to satisfy the following conditions: width of secondary interference fringes has to be agreed with the transversal size of the single speckle, and also with size of a sensitive cell of the photodetector.
For agreement of the transversal size of the single speckle with size of a sensitive cell of the photodetector it is necessary that the following ratio was carried out:

$$H \geq h, \tag{6}$$

where h – size of a sensitive cell of the photodetector.
Performance of this condition is achieved by sampling of the parameter α of a optical system, as appears from of Eq. (2).
In order that the sensitive cell of the photodetector could measure change of a phase of the single speckle it is necessary that width of secondary interference fringes d was more or equally of the size of a sensitive cell of the photodetector that is the following ratio was carried out:

$$d \geq h, \tag{7}$$

Performance of this condition is achieved by sampling of a angle of a convergence Θ between the reference beam and the focused scattered laser radiation from a research surface which forming image of this surface with speckle pattern in the plane of the photodetector, as appears from Eq. (5).
Performance of conditions – Eq. (6) and (7) – leads to that intensity of the single speckle, as whole, will change from minimum to the maximum value (or on the contrary) depending on displacements of a research surface.
Thus, measurement of intensity of the single speckle allows to investigate dynamic processes in a solid mechanics. Application in the offered method of high-speed photodiodes expands the frequency range of measured dynamic displacements.

2. 2 Measurement system

Realization of this method, based on the analysis of change of intensity of the single speckle, for measurement of dynamic processes in solid mechanics it is offered to carry out according to the optical scheme presented in Fig. 3.
By means of optical system L2 the rough surface of a research object O is lighted with laser radiation and is focused on the CCD TV. Let's emphasize, that as it was noted above, in the plane of a CCD matrix the image of object covered speckles is fixed. That allows to record on CCD TV a image of the research object with binding speckles to concrete points of this object.
If to direct the reference beam (in Fig. 3 it isn't shown) on a CCD matrix, as a result, we will receive standard the digital speckle interferometer which allows to make measurements of displacements with restrictions indicated in Introduction.

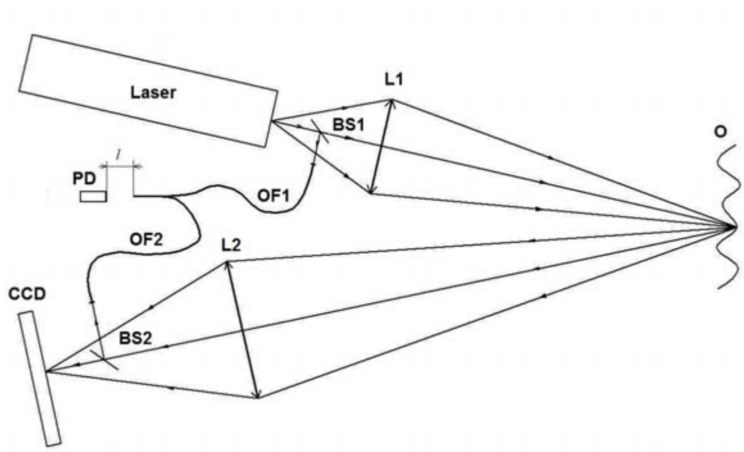

Figure 3. Optical scheme for dynamic measurement

Measurement of dynamic processes in solid mechanics is offered to be carried out according to the analysis of change of intensity of the single speckle. Standard CCD matrixes, as a rule, aren't the high-speed photodetector. Therefore they aren't capable to register of change of intensity of the single speckle in the wide frequency range. For overcoming of this restriction in the optical scheme it is offered to use in addition the high-speed photodetector PD, allowing to analyze of intensity of the single speckle in the wide frequency range.
For allocation single speckle, by means of the beam splitter BS2 the image of the single speckle goes on an entrance end face of an optical fiber OF2 which output end face is agreed with the high-speed photodetector PD. Diameter of a core of an optical fiber of OF2 has to be agreed with the transversal size of a speckle, that is the ratio (Eq. 6) has to be carried out.
For creation of a reference beam by means of the beam splitter BS1 the part of radiation of the laser L goes on an entrance end face of an optical fiber OF1 which output end face is also agreed with the high-speed photodetector FD. The output ends of optical fibers OF1 and OF1 are combined so that conditions (Eq. 6 and Eq. 7) were satisfied. The change of intensity of the single speckle is registered by the photodetector PD and is recorded in the PC for processing and visualization.

3. Theory

Let's consider for the offered optical scheme formation of distribution of intensity in the single speckle when performing conditions (Eq. 6 and Eq. 7). Let's write down values of vectors of electric intensity on the photodetector PD for waves passed through both optical fibers in the following kind:

$$\vec{E}_1 = \vec{E}_0 e^{i(kx_1 - \omega t + \varphi)}, \qquad (8)$$

$$\vec{E}_2 = \vec{E}_0 e^{i(kx_2 - \omega t + \varphi)}, \qquad (9)$$

where – E_0 amplitude of electric intensity of an electromagnetic field (we assume for simplification of calculations that it is identical in both optical fibers); $k=2\pi/\lambda$ – wave number; ω– circular frequency of laser radiation; φ– an initial phase which also is considered identical to both optical fibers; x_1 – distance from beam splitter BS1 to the photodetector PD on optical fiber OF1; x_2 – distance from beam splitter BS1 to the photodetector on optical fiber OF2.

Distance from beam splitter BS1 to the photodetector on an optical fiber OF2 recorded in the following kind:

$$x_2 = r_0 + r \pm 2\Delta r, \qquad (9)$$

where r_0 – distance from beam splitter BS1 to a research object O; r – distance from a research object O to the photodetector PD on optical fiber OF2; $\pm\Delta r$ – the value of displacement of a research surface.

As the photodetector registers intensity, than the distribution of the intensity in an interference pattern of the single speckle will record in the following kind:

$$I(x,t) = \left| \left(\vec{E}_1 + \vec{E}_2\right)^{+} (\vec{E}_1 + \vec{E}_2) \right|^2 \approx 2E_0^2 \{1 + \cos[k(x_1 - r_0 - r \mp 2\Delta r)]\}, \qquad (10)$$

where the top index (+) means that vector value of electric intensity of an electromagnetic field is transposed and in a complex interfaced.

As appears from Eq. (10), and as it was noted above, intensity of a speckle changes from minimum to maximum values (or on the contrary) at change of value of a phase baked on $\pm\pi$ ($2n$+1), (where n=0,1,2…) which is connected by dynamics of a research surface, that is with change Δr in time.

Change of intensity of the single speckle on an entrance of the photodetector it will be transformed to change of output signal of the photodetector which (see Eq. 10) can be expressed as follows:

$$u(t) = A + B\cos[\varphi(0) - \varphi(t)], \qquad (11)$$

where $u(t)$ – the output voltage of the electrical scheme of the photodetector; A – the output bias voltage which is related to the average intensity of the single speckle; B – amplitude of useful output voltage which is defined by parameters of the optoelectronic scheme which related to a displacement of a research surface and kind of the optical scheme; $\varphi(0) = k(x_1\text{-}r_0\text{-}r)$ – initial value of a phase difference between the reference beam and the object beam forming speckle pattern in plane of a optical image. This phase difference can change but remains to constants in the time of measurements; $\varphi(t) = \pm 2k\Delta r$ is the change of a phase in single speckle related with change of the optical path in the object arm of a optical scheme at dynamic displacements of a research surface.

From the analysis of a Eq. (10) and (11) follows that change of output voltage of the photodetector depends on phase change $\varphi(t)$ characterizing dynamics single speckle related with movement of a research surface. As intensity single speckle changes from minimum to maximum or on the contrary, respectively and output voltage from the photodetector changes from the minimum value – $u(t)_{min}$ to the maximum value – $u(t)_{max}$ or on the contrary.

The theoretical results of behavior of the output voltage $u(t)$ in respect of vibrating displacements of the investigation surface are demonstrates in Fig. 4. The dashed curve represents the vibrations of the investigation surface with amplitude increasing in time. The solid curve represents the theoretically calculated output voltage signal.

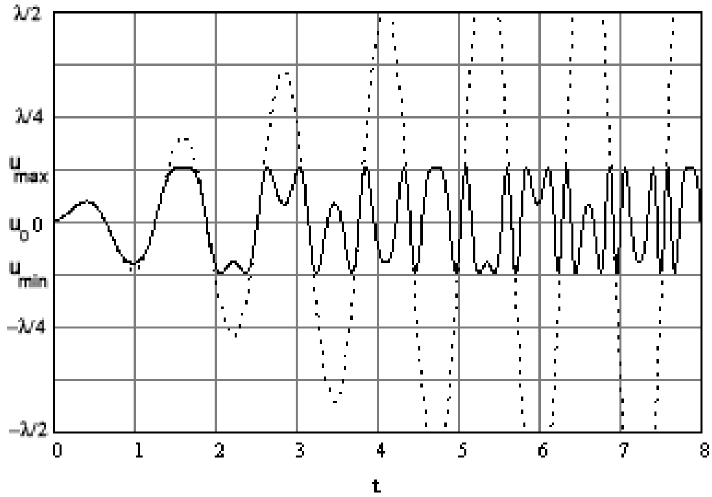

Figure 4. Theoretical curves of behavior output signal *u(t)* at the increasing amplitude of the investigation surface

3.1. Assessment of range of measurements

From the analysis of Eq. (10) and (11) follows that change of output voltage from minimum to the maximum corresponds to displacements of the investigation surface at a value equal $\lambda/4$.
Then, when demonstrate the constant direction - not sign-variable - for determination of value of full movement it is enough to define number of changes of the output single from maximum to the minimum. At sign-variable movements that corresponds to vibration loadings, character of an output signal of the photodetector has features.
The analysis of Eq. (10) and (11) shows that at vibrations of the investigation surface with amplitudes it is less or equally $\lambda/8$ the output voltage of the photodetector corresponds to a form of vibrations of this surface. With amplitudes of vibrations of the investigation surface more $\lambda/8$ the output voltage of the photodetector won't correspond to a form of vibrations of this surface that as it is visible in Fig. 4. In this case development of additional algorithm of interpretation of an output signal of the photodetector is required.
For registration of vibrations without additional processing of an output signal, as appears from Eq. (10) and (11), it is necessary to choose $\varphi(0)$ equal $\frac{\pi}{2}(2n+1)$ (where n=0,1,2…). This condition means that at the initial moment of measurements output voltage from the photodetector has to be established so that its value corresponded to value equal:

$$u(0) = \frac{u_{\max} + u_{\min}}{2} = A \qquad (12)$$

It is reached by corresponding change of a phase of the reference beam. Under these conditions amplitude B of measured vibrations of the investigation surface will correspond to value equal $\lambda/8$.

4. Results and conclusion

Realization of this method, based on the analysis of change of intensity of the single speckle, was used for the investigation of wave processes in a plate subjected shock loading. Fig. 4 shows the experimental behavior of the output voltage *u(t)* of the photodiode, which is obtained on high-speed storing oscillograph at the investigation of wave processes in a plate subjected shock loading. The comparison of the theoretical and experimental results allows us to make a conclusion that the represented above assumptions are valid.

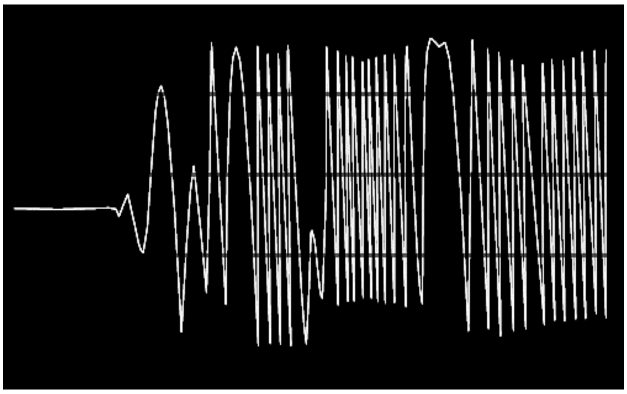

Figure 5. Experimental oscillogram of the output signal from the photodetector

In the experimental arrangement laser LCM-S-111-50-NP25 with wavelength λ = 532 nm and coherence length more 50 m is used. For the measurement of the dynamic displacements with very high frequency p-i-n photodiode with frequency range 20 MHz.

Thus, the new method of registration dynamic displacements of the investigation surface of object in large range of measured value of displacements and in the large frequency range on the basis of the analysis of distribution of intensity in the single speckle is considered.

Advantage of the offered method is that its use doesn't demand a careful adjustment of elements of optical system and allows to overcome restrictions which are connected with existence of own noise (speckles) in the holographic and speckle interferometry and to register dynamic displacements in real time.

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