Processing of the output signal of the speckle interferometer on a single speckle at influence of a external noise

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Abstract. The influence of external noise on the processing of the output signal of a speckle interferometer on a single speckle is considered. The optical scheme of a speckle interferometer on a single speckle is shown. On the basis of theoretical studies, the main limitations imposed on the parameters of the optical circuit are determined. The proposed optical scheme allows simultaneously to determine both the vibration mode of the object under study and the amplitude of the vibrations from several nanometers to hundreds of microns and in a wide frequency range from zero Hz to tens of MHz. Theoretical and experimental studies of the influence of external noise on the output signal from the proposed speckle interferometer on a single speckle are presented. As a result of theoretical and experimental studies it was found that low-frequency noise does not affect the output signal from the speckle interferometer, especially when the amplitude of the information signal is greater than λ/8 (λ – is the wavelength of the laser radiation). Thus, the application of the proposed method of vibration registration of the investigated elements of mechanical structures makes it possible to use it in conditions close to industrial.

1. Introduction
To research the dynamic processes of elements of mechanical constructions used variety of research methods. These methods are classified as contact and noncontact. Contact methods investigating of dynamic processes are influence as on the frequency characteristics of the studied objects, especially at the study of small-sized structures and on the frequency characteristics of measuring sensors. It is must be taken into account in further experimental studies and mathematical modeling. Noncontact methods do not have these disadvantages. Therefore, it is necessary to pay great attention to the development of noncontact methods at research of dynamic processes of construction elements. Among the contactless methods it is necessary to distinguish the methods of coherent optics – holographic and speckle interferometry.

Interferometric methods such as holographic and speckle interferometry are unique noncontact measurement technologies that allow to simultaneously control the displacement of points along the entire observed surface of the object. In addition, holographic and speckle interferometry does not
impose strict requirements for the quality of the surface under study, unlike classical interferometry. Nevertheless these methods are inapplicable for the study of the frequency characteristics of elements of mechanical constructions in real time, because the main methods used in the studies are: averaging over time; a method of two exposures or an impulse stroboscopic method. In addition, the presence of own noise, when using coherent light (graininess interference patterns – speckle pattern), leads to restrictions on the measured range of displacements, as well as the accuracy and sensitivity of measurements. Also, due to the presence of own noise the research of the high-frequency vibrations and their mode shapes, as in holographic and speckle interferometry, become difficult or impossible because the contrast of the interference fringes decreases at high amplitudes and frequencies [1-7]. In the article [8] the method of minimization of own noise high resolution digital holographic microscopy is presented. The main feature is noise filtration due to the presence of noise in the recorded intensity distribution and the use of all orders of the hologram. Methods of contrast increasing of the interference patterns in digital holographic interferometry by numerical linear phase modulation and interpolation post-processing of digital focused-image holograms are discussed in the article [9].

It should be noted that the speckle interferometry uses its own noises as an information signal for studying the behavior of objects subject to various loads. This allows to significantly reduce the requirements for interferometric measurements in comparison with holographic interferometry [3-7]. In consequence of this speckle interferometry widely used in study of the dynamic processes of construction elements at the present time [10-14].

In the article [10] the combination of a high-speed TV holography system and a 3D Fourier-transform data processing is proposed for the analysis of multimode vibrations in plates. The individual vibration modes are separated in the 3D frequency space due to their different vibration frequencies and, to a lesser extent, to the different spatial frequencies of the mode shapes. In the paper [11] the high speed speckle interferometry system for the experimental analysis of transient and dynamic phenomena is presented. The system is based on an out-of-plane continuous wave speckle interferometry setup and integrates a fast camera that allows acquisition rates of over 26,000 frames/s. In the paper [12] the method and apparatus to measure surface vibrations by moving speckle interferometer are proposed. In the paper [13] the method incorporating amplitude-fluctuation electronic speckle pattern interferometry (AF-ESPI) with radial basis function (RBF) was proposed to investigate vibration characteristics of structures. The vibration patterns were obtained by AF-ESPI. A novel pre-filtering RBF method was presented to improve the quality of patterns. In the paper [14] several aspects of these two technologies are discussed. For the camera-based interferometry, the discussion includes the introduction of the carrier, the processing of the recorded images, the phase extraction algorithms in various domains, and how to increase the temporal measurement range by using multiwavelength techniques. For the detector-based interferometry, the discussion mainly focuses on the single-point and multipoint laser Doppler vibrometers and their applications for measurement under extreme conditions.

However, it should be noted that the problem of measuring the dynamic processes by speckle interferometry in real time is not solved completely at present.

A new method of determining the frequency characteristics of mechanical construction in real time using speckle interferometry of a single speckle is presented in works [15,16]. In these works it was shown that the changes in light intensity of a single speckle is recorded by a high-speed point photodetector. This allows measurements of the frequency characteristics of mechanical constructions in real time and in wide range of amplitudes and frequencies. However, these works did not study the influence of an external noise on the results of processing output signal of a speckle interferometer on a single speckle.

In this work, the influence of external noise on the processing of the output signal of the speckle interferometer on a single speckle when measuring the frequency characteristics of construction elements is subjected to investigation.
2. Experimental setup and fundamentals

The optical scheme of a speckle interferometer was developed to implement the proposed method for determining the frequency characteristics of mechanical structures in real time using speckle interferometry of a single speckle. The optical scheme presented in Figure 1.

Let us consider the principle of operation of this optical scheme. Laser light by means of the beam splitter (BS1) is divided into two beams, one of which (object beam) by optical system (L1) illuminates the investigated object at researches. The scattered light from the object by means of the optical system (L2) (lens) forms images of the investigated surface in the plane of a CCD matrix of a video camera and in the plane of the high-speed point photodetector (PD). The investigated surface image, as is well known, is covered with subjective speckles. The second beam (reference beam) by means of the beam splitters (BS1), (BS2) and optical system (L3) (lens) is superimposed on the object beam forming the secondary interference pattern in the plane of the CCD-matrix of a video camera and in the plane of the high-speed point photodetector (PD). The kind of the resulting interference pattern is shown in Figure 2.

![Figure 1. The optical scheme of the speckle interferometer on a single speckle.](image1)

![Figure 2. Photo of a resulting interference pattern.](image2)

The photo (Figure 2) shows that the resulting interference pattern consists of speckle structures that characterize of the surface of the object and which are covered by secondary interference fringes formed by superimposing a reference wave. As a result, in this optical system by the high-speed point photodetector (PD) of the change intensity of a single speckle and by the video camera (CCD) the speckle interferogram defining the mode shapes are recorded simultaneously.

The angle $\beta$ between the direction of illumination and observation in this optical scheme determines the sensitivity of the optical system. When angle between the direction of illumination and observation $\beta = 0$ the sensitivity of this optical system is maximal [1,2,4]. This condition for the proposed optical scheme is performed with great accuracy, since the laser emitting and receiving elements (CCD) of the optical circuit are at a minimum distance, and the distance to the object under study is much larger than the distance between the emitter and the receiver.

In works [15,16] it was shown that for effective registration of the intensity changes of a single speckle requires the following requirements: the width of the fringes of the secondary interference pattern should be larger than the transverse size of a single speckle, and the size of a high-speed point photodetector (PD) should be smaller than the single speckle size. These conditions are fulfilled by the
selection of the optical scheme parameters – aperture, focal length, angle of convergence between the reference and object beams [15,16].

It should also be noted, since in this optical scheme subjective speckle patterns are recorded, then each speckle is rigidly associated with the concrete point of investigated surface.

Thus, the study of the behavior of the change intensity of a single speckle gives the information about the dynamics of the concrete point of investigated surface. Any changes of the vibrating surface lead to a change intensity of the speckle structure in the image plane.

3. Influence of external noise on the output signal of a speckle interferometer

Let us consider for the offered optical scheme theoretically the light intensity change of the image of the investigated object in the registration planes – video camera (CCD) and high-speed point photodetector (PD). Write down values of vectors of electric intensity in the registration planes PD for waves passed through both optical paths (object and reference beams) in the following kind:

\[
\vec{E}_1 = E_0 e^{i(kx_1 - \omega t + \varphi)} ,
\]

\[
\vec{E}_2 = E_0 e^{i(kx_2 - \omega t + \varphi)} ,
\]

(1-2)

where \(E_0\) – amplitude of electric intensity of an electromagnetic field (we assume for simplification of calculations that it is identical in both optical paths); \(k = 2\pi/\lambda\) – wave number; \(\lambda\) – wavelength of a laser; \(\omega\) – circular frequency of laser; \(\varphi\) – an initial phase which also is considered identical to both optical paths; \(x_1\) – optical path of reference beam – distance from beam splitter (BS1) to the registration planes (high-speed point photodetector (PD) or CCD matrix); \(x_2\) – the optical path of the object beam – the distance from beam splitter (BS1) to the object and from the object to the registration planes (high-speed point photodetector (PD) or CCD matrix).

Since in this optical scheme the angle \(\beta\) between the direction of illumination and observation is very small, the optical path of the object beam is written in the following form:

\[
x_2 = r_0 + r \pm 2\Delta r(t) ,
\]

(3)

where \(r_0\) – distance from beam splitter (BS1) to a research surface; \(r\) – distance from a research surface to the registration planes (high-speed point photodetector (PD) or CCD matrix); \(\pm \Delta r(t)\) – the value of displacement of a research surface in time.

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:

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

(4)

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

As follows from the equation (4), the speckle intensity changes from the minimum to the maximum value (or vice versa) when the value of its phase changes by \(\pm \pi (2n + 1)\), (where \(n = 0,1,2,..\)), which is related with the dynamics of the a research surface, that is, with the change of \(\Delta r(t)\) in time.

Change of a light 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. 4) can be expressed as follows:

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

(5)

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 optoelectronic scheme; \(\varphi(0) = k(x_1 - r_0 - r)\) – 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; \(\varphi(t) = \pm 2\Delta r(t)\) 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 the research surface.
As follows from the Eq. (5), the change in value of the phase speckle \( \phi(t) \) to \( \pm \pi(2n+1) \) (where \( n=0,1,2,... \)) leads to the change in the intensity of the speckle, and hence the change in the output voltage of the photodetector (PD) from minimum value \( u(t)_{\text{min}} \) to maximum value \( u(t)_{\text{max}} \) or vice versa. Changing of the speckle phase to \( \pm \pi(2n+1) \) in this optical scheme corresponds to displacements of the research surface at a value equal \( \Delta r(t) = \pm \lambda/4 \). As shown in works [14,15], when the displacements of the investigation surface by less than or equally \( \lambda/8 \), then the output voltage of the photodetector is fully identical with this displacements if to choose \( \phi(0) \) equal \( \pi(2n+1)/2 \). This condition means that at the initial time of measurement the output voltage from the photodetector must be installed so that it corresponds to a value equal to half-sum of the maximum \( u(t)_{\text{max}} \) and minimum \( u(t)_{\text{min}} \) voltages. Therefore the following ratio has to be carried out: \( u(0) = (u(t)_{\text{max}} + u(t)_{\text{min}})/2 \). This choice of the initial phase difference is achieved by a suitable arrangement in the image plane of the high-speed point photodetector (PD) around of selected image of the investigated point of surface. It should be noted that under this condition the maximum sensitivity of the offered optoelectronic system is reached.

When displacements more than \( \lambda/8 \), then the output voltage of the photodetector have a complicated form and represent a set of oscillating packets. At researches of the natural vibrations, the form of oscillating packets of output voltage of the high-speed point photodetector PD is periodic.

In these works did not study the influence of an external noise on the results of processing output signal of a speckle interferometer on a single speckle. Let’s consider the influence of an external noise on the behavior of the output signal of a speckle interferometer. Assume that the vibration of the research surface is performed according to the harmonic law. Influence of an external noise also occurs according to the harmonic law. In this case, \( \phi(t) \) will be written as follows:

\[
\phi(t) = 2\pi \left[ a \sin(\Omega t) + b \sin(\Omega_1 t) \right], \tag{6}
\]

where \( a \) – amplitude of vibrations of the research object under the influence of the exciting load; \( \Omega \) – vibration frequency of the research object; \( b \) – amplitude of vibrations of the research object under the influence of an external noise; \( \Omega_1 \) – vibration frequency of the research object under the influence of the external noise.

Figure 3 illustrates the theoretical curve of the output voltage behavior of the photodetector \( u(t) \) at the absence of the external noise \((b=0, \Omega_1=0)\) for the values \( a = \lambda/12 \) and \( \Omega = 300 \) Hz.

Figure 4 illustrates the theoretical curve of the output voltage behavior of the photodetector \( u(t) \) at the presence of the external noise \((b = 5\lambda, \Omega_1 = 10 \) Hz\) for the same values \( a \) and \( \Omega \).

Figure 5 illustrates the theoretical curve of the output voltage behavior of the photodetector \( u(t) \) in the absence of the external noise \((b=0, \Omega_1=0)\) for the values \( a = \lambda \) and \( \Omega = 300 \) Hz.

Figure 6 illustrates the theoretical curve of the output voltage behavior of the photodetector \( u(t) \) in the presence of the external noise \((b = 5\lambda, \Omega_1 = 10 \) Hz\) for the same values \( a \) and \( \Omega \).

**Figure 3.** Output voltage from the photodetector under vibrations of the investigated surface with amplitude \( a = \lambda/12 \) and frequency \( \Omega = 300 \) Hz at the absence of the external noise: \( b = 0, \Omega_1 = 0 \) Hz.

From the theoretical curves of the output voltage oscillations of the photodetector \( u(t) \) (Figures 3 and 4) it follows that at the amplitudes of the harmonic vibrations of the investigated surface less than or equal to \( \lambda/8 \), the form of the output voltage oscillations does not fully correspond to the form of
vibrations of the investigated surface, therefore the external noise influence on the form of the investigated vibrations. The analysis of these results shows that in the presence of external noise, the amplitude of the output voltage oscillations of the photodetector fully corresponds to the amplitude vibrations of the investigated surface.

**Figure 4.** Output voltage from the photodetector under vibration of the investigated surface with amplitude $a = \lambda /12$ and frequency $\Omega = 300$ Hz at the presence of the external noise $b = 5\lambda$, $\Omega_1 = 10$ Hz.

**Figure 5.** Output voltage from the photodetector under vibration of the investigated surface with amplitude $a = \lambda /12$ and frequency $\Omega = 300$ Hz at the absence of the external noise: $b = 0$, $\Omega_1 = 0$ Hz.

**Figure 6.** Output voltage from the photodetector under vibration of the investigated surface with amplitude $a = \lambda$ and frequency $\Omega = 300$ Hz at the presence of the external noise: $b = 5\lambda$, $\Omega_1 = 10$ Hz.

However, the oscillation frequency of the output voltage of the photodetector does not correspond to the frequency vibrations of the investigated surface. Thus, the amplitude of the oscillations output voltage of the photodetector allows to fully determine the value of the amplitude vibrations of the investigated surface at amplitudes vibrations less than or equal to $\lambda/8$. However, the determination of the frequency vibrations remains an open question.

At the vibrations amplitudes of the investigated surface more than $\lambda/8$, the output voltage
The oscillations of the photodetector PD (Figures 5 and 6) have a complicated form and represent a set of oscillating packets as said above. From the analysis of Eq. (5) it follows that the number of oscillations within packets is proportional to the doubled amplitude of natural vibrations, and the period of the oscillating packets corresponds to the doubled frequency of the natural vibrations of the investigated point of surface. Thus, from the theoretical curves of the output voltage oscillations of the photodetector \( u(t) \) (Figures 5 and 6) it follows that at the vibration amplitudes of the investigated surface more than \( \lambda/8 \) the external noise does not significantly influence on the determination of the frequency and amplitude of vibrations of the investigated surface.

In figure 7a the experimental photo of the oscillogram of the output voltage behavior of the photodetector at investigation of the natural vibrations of the object at the absence of the external noise is presented. In figure 7b the experimental photo of the oscillogram of the output voltage behavior of the photodetector at investigation of the natural vibrations of the object at the presence of the external random noise is presented.

![Figure 7. Photo of the oscillograms: a) – natural vibrations of the surface at the absence of the external noise; b) – natural vibrations of the surface at the presence of the external noise.](image)

Experimental studies were carried out according to the optical scheme presented in Figure 1. The main elements of the speckle interferometer are: laser module LCM-S-111-50-NP25 (wavelength 532 nm, power 50 mW, the coherence length of more than 50 m); CCD camera VIDEOSCAN-285 / P-USB with a pixels size of 6.45x6.45 \( \mu \)m, 1392x1040 pixels resolution and recording speed 7.7 Hz. For the measurement of change of the light intensity of the single speckle with very high frequency the p-i-n photodiode module FPМ-34MA with frequency range 20 MHz was used.

The object of the study was the membrane of the microphone excited at various frequencies. The figure 7 shows the vibrations of the membrane at a frequency of 300 Hz. From told above it follows that for this optical scheme one full oscillation within oscillating packets corresponds to the displacement of the investigated point of surface by the amount \( \lambda/2 \). Thus, the amplitude of vibrations of the investigated point of the membrane surface is about \( 13\lambda/8 \). Since in the experiment is used a laser with a wavelength 532 nm, then the measured amplitude vibrations is about 865 nm.

The comparison of experimental results shows that for vibrations with amplitude more than \( \lambda/8 \), external noise does not significantly influence on the measurements. As told above it follows that the following frequency of the oscillating packets completely corresponds to the doubled exciting frequency both in the absence and in the presence of external noise. The number of oscillations in oscillating packets remains the same both in the presence and in the absence of external noise.

Thus, the experimental results confirm the theoretical conclusions presented above.

4. Conclusion
The presented theoretical and experimental studies on the application of a new method for measuring the frequency characteristics of construction elements based on speckle interferometry of a single speck showed that the proposed method is applicable in the presence of external noise that is very important from the point of view of industrial use.
5. References

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