Determination of frequency characteristics of mechanical constructions in real time by speckle interferometry

Michael Osipov\textsuperscript{a,*}, Nikita Sharafutdinov\textsuperscript{a}, Yury Sheglov\textsuperscript{a}, Ivan Falileev\textsuperscript{a}, Mariya Fedina\textsuperscript{a}

\textsuperscript{a}Samara State University, 1 Akademika Pavlova st., Samara, 443011, Russia

Abstract

In this article, method for determining in real time the frequency characteristics (amplitude, frequency, and etc.) of mechanical constructions subjected to dynamic loads is presented. This method is based on the analysis of the behavior of the intensity of a single speckle. The optical scheme in which a simultaneous registration of a standard digital speckle interferogram on the CCD-matrix and the behavior of the intensity distribution in a single speckle with using high-speed point photodetector is presented, that allows to simultaneously determine the shape and amplitude of the resonant vibrations of the mechanical structures in real-time. The results of experimental researches are presented.

1. Introduction

The methods of coherent optics - holographic and speckle interferometry - are the unique non-contact measuring technology that allows to control the simultaneous displacement of points throughout the observable object surface. Classical implementation of interferometric measurements expects ensuring of strict conditions of measurement excluding various kinds of noise. As a rule, interferometric devices are stationary and often require mechanical contact with the controlled object, which leads to a distortion of registered information. From this it follows that the development of automated interferometric devices and methods of interferogram decoding is an important task for

* Corresponding author. Tel.: +7-927-263-5777; fax: +7-846-334-3517.

E-mail address: osipov7@yandex.ru
experimental research in mechanics.

Special attention is now being given to the expanding of the scope of the coherent optics methods, and in particular, interferometric techniques based on the speckle interferometry.

The standard methods of the holographic and speckle interferometry are usually not for investigating of the frequency characteristics of mechanical structures in real time, because in research are mainly used: method of the time-averaging [1]; method of the two exposures or strobe pulse method [2, 3]. Also, because of the presence of the own noise (graininess interference patterns - speckle patterns), there are restrictions of the measured displacement range, as well as the accuracy and sensitivity of measurements [4]. In addition, these noises hamper the processing of the speckle interferograms. It should be said that the research of the high-frequency vibrations and their mode shapes, as in holographic and speckle interferometry, become difficult or impossible due to the fact that the contrast of the interference fringes decreases at high amplitudes and frequencies. It should also be noted that industrial application of speckle interferometry requires the establishment of specialized expensive stands, and furthermore, research may be carried out mainly with the small-sized constructions [5].

Processing of the experimental holographic and speckle interferograms is an extremely time-consuming process, which may appear ambiguous results.

Great attention is paid to processing of the speckle interferograms in works [6-11]. Various methods based on Fourier and wavelet transformations, creating of virtual speckle pictures, statistical image processing techniques have been offered to decode the speckle interferograms that can improve the quality of the interferogram processing. However, the methods proposed in these papers solve partially the problem of the holographic and speckle interferometry.

Note also that the problem of measuring the dynamic processes by speckle interferometry in real time is solved not completely at present.

To solve these problems, this paper presents an automated system of the optoelectronic noiseproof speckle pattern interferometer (OESPI) to determine the mode shapes and frequency characteristics of the construction elements in real time under dynamic loads on the basis of analyzing the behavior of the intensity of a single speckle.

2. Optoelectronic noiseproof speckle pattern interferometer

Developed optoelectronic speckle pattern interferometer (OESPI) is shown in Fig. 1a. 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 μm, 1392x1040 pixels resolution and recording speed 7.7 Hz [12]. The optical scheme OESPI is presented in Fig. 1b.

![Fig. 1. (a) photo OESPI; (b) optical scheme OESPI.](image)

One of the features of developed OESPI is the using of diffusely scattered laser light as the reference signal. The relative distribution of intensity in the speckle pattern of the reference and object beams can be controlled with this optical scheme, and therefore no strict requirements on the smoothness of the wave front of the reference wave. To
obtain the interferogram of acceptable quality, the intensity of the reference beam must be agreed with the intensity of the object beam.

To implement these requirements in the developed software, the special function to determine and display the corresponding histograms of brightness of object and reference beams is available. Figures 2a and 2b present the histogram of the signal of the reference and object beams, which are not the same brightness, so they need adjustment.

![Figure 2](image_url)

To equalize the brightness the device has a regulation of intensity of the reference beam by an attenuator and regulation of intensity of the object beam by the aperture diaphragm of the lens.

Developed optoelectronic noiseproof speckle pattern interferometer enables the investigation of displacement fields, as at the static and dynamic tests of the various construction elements in the presence of external noise. However, the presence of own noise – speckle-structures - limits the measurement range of the frequency characteristics of vibrations of the studied construction elements in both amplitude and frequency. To solve this problem was the high-speed point photodetector in the design OESPI additionally introduced.

The principle of operation OESPI is as follows (see. figure 2): laser light by means of the beam splitter (BS1) is divided into two beams, one of which (object) by optical system (L1) illuminates the investigated object at researches. The scattered light from the object by means of the optical system (L2) (camera lens) forms images of the investigated surface in the plane of a CCD matrix of a video camera (Cam) 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 transverse dimension of a single speckle $H$ is defined by the well-known equation [13]:

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

where $\lambda$ - the wavelength of the laser; $\alpha$ - the ratio of the diameter of the objective aperture to the focal length of the optical system.

The second beam (reference), passing through the diffuser (D) and by means of the beam splitter (BS2) is superimposed on the object beam forming the secondary interference pattern in the plane of the CCD-matrix of a video camera (Cam) and in the plane of the high-speed point photodetector (PD). The period $d$ of the secondary interference fringes is determined by the well-known equation [14]:

$$d = \frac{\lambda}{2 \sin \frac{\theta}{2}} \tag{2}$$
where $\theta$ – the angle of convergence between the reference and object beams.

As a result, in this optical system by the high-speed point photodetector (PD) the single speckle intensity changes and by the video camera (Cam) the speckle interferogram, defining the mode shapes, simultaneously are recorded.

The dimensions $h$ of the working surface of the high-speed point photodetector (PD) must be agreed with the size of a single speckle $H$ of the subjective speckle structure and with the period $d$ of the secondary interference fringes formed in the plane of the photodetector (PD). The following relationship must be carried out:

$$d \geq H \geq h$$

(3)

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].

It should also be noted, as in this optical system are recorded subjective speckle patterns that each speckle rigidly associated with the concrete point of investigated surface.

Thus, the study of the behavior of the intensity of a single speckle gives the information about the dynamics of the specific point of investigated surface.

3. Processing of speckle interferograms

The principle of the speckle interferograms processing, implemented in the developed software, is to model a virtual wave with smooth curvilinear wave front – spline, which, interfering with the plane wave would produce an interference pattern, coinciding with the experimental interferogram on the location of interference fringes. We will call such interferograms the pseudo-interferograms. Thus obtained pseudo-interferogram is superimposed on the experimental interferogram. Fig. 3 shows the corrected pseudo-interferogram on the background of the experimental interferogram.

![Fig. 3. Experimental speckle interferogram with a plot of superposed pseudo-interferogram.](image)

The software of the developed optoelectronic speckle interferometer allows "align" the spline so that the median lines of fringes of the pseudo-interferogram are in the middle of interference fringes of the original experimental interferogram, as it is shown in Fig. 3. This solution allows to expedite the processing of speckle interferograms and to increase the accuracy of determining the displacement fields.

In works [16,17] is theoretically and experimentally shown that the change of the intensity of a single speckle and therefore the change of the output voltage $u(t)$ of the registration high-speed point photodetector (PD) is described by equation:

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

(4)
where $A$ - the output bias voltage which is related to the average intensity of the single speckle; $B$ - amplitude of the desired output voltage, which is determined by the parameters of optoelectronic and optical schemes; $\varphi(0)$ – the initial value of the phase difference between the reference and object beams in planes of the optical image of the investigated surface (Cam) and (PD); $\varphi(t)$ – the change of a phase in single speckle which related with change of the optical path in the object arm of a optical scheme at dynamic displacements of the investigated surface.

As follows from the Eq. (4), the change in value of the phase speckle $\varphi(t)$ 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 investigated surface at a value equal $\pm \lambda/4$.

Changing of the input voltage is recorded in the memory of a personal computer or by a storage oscilloscope.

The behavior of the output voltage from the photodetector is complex. At researches, as shown in [15,18], when the displacements of the investigation surface by less than or equal $\lambda/8$, then the output voltage of the photodetector is fully identical with this displacements. 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 photodetector is periodic.

From the analysis of the Eq. (4) 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.

For registration of vibrations without additional processing of the output signal, as follows from Eq. (4), it is necessary to choose $\varphi(0)$ equal $\pi (2n+1)/2$ (where $n=0,1,2,...$) therefore measurements are performed for displacements less than or equal $\lambda/8$. 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 and minimum 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 of the investigated point of surface.

4. Experimental researches

Developed optoelectronic noiseproof speckle interferometer is used to study the displacement fields, as in the static and dynamic tests of various construction elements in the presence of external noise.

In figure 4 presented speckle interferograms of the vibrations of a thin circular metal membrane with the rigid pinching and excited on natural frequencies. These speckle interferograms of the mode shapes recorded by the developed OESPI with use of a method of averaging in time.

![Fig. 4. Photos of speckle interferograms of the natural vibrations of the thin circular metal membrane.](image)

As seen from the photographs (Fig. 4) developed OESPI allows to record the mode shapes of natural vibrations. These pictures confirm what has been said above that the presence of own noise - speckle-structures, limits the
measurement range of the amplitude of vibrations of the investigated structures, as the number of resolvable interference fringes is limited by the size of the speckles.

In figure 5 a typical form of oscillating packets of the output voltage of the high-speed point photodetector (PD) for various natural vibrations of the investigated point of surface are presented.

![Oscillograms](image)

**Fig.5.** The oscillograms of the output voltage: (a) vibration with frequency 50 Hz; (b) vibration with frequency 100 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 surface in the first case (Fig. 5a) is about $7\lambda/4$, in the second case (Fig. 5b) is about $15\lambda/8$.

The sensitivity of the amplitude measurement by means OASI is determined by the parameters of the optoelectronic circuit which processes the output signal of the photodetector, and also the sensitivity of the photodetector. Thus the sensitivity can be order of some nanometers.

The upper limit of the measurement of the vibrations amplitude is determined by the high-speed point photodetector, high-speed memory and its capacity and may be some millimeters.

**Conclusion**

Theoretical and experimental researches have confirmed that the developed optoelectronic noiseproof speckle interferometer allows simultaneously to record the mode shapes of natural vibrations and to determine the frequency and amplitude of these vibrations for various construction elements under dynamic loads.

Theoretical and experimental researches have also shown that the proposed method of recording changes of the intensity of a single speckle allows measurement of vibration parameters (frequency, amplitude) of diffusely reflecting surface in real time and in a wide range - from nanometers to some millimeters.

**Acknowledgements**

The reported study was partially supported by RFBR, research project No. 12-08-00390-а и No. 13-01-97009.

**References**


