2019 14th International Forum on Strategic Technology (IFOST)

Proceedings of IFOST-2019
October 14-17, 2019
Tomsk, Russia

Organized by
National Research
Tomsk Polytechnic University (Russia)

In association with
University of Ulsan (Korea)
Novosibirsk State Technical University (Russia)
Mongolian University of Science and Technology (Mongolia)
Harbin University of Science and Technology (China)
Chemnitz University of Technology (Germany)
43. Intelligent Analysis of Digital Economy Competencies in Agriculture Labor
Anastasiia Kaida, Sergey Kuznetsov, Lev Igumnov and Nataliya Maksimova

44. SWC Mapping For Automotive Systems
Anna Aletdinova, Maxim Bakaev and Viktor Astapchuk

45. Road Pavement Crack Detection Using Deep Learning with Synthetic Data
I.A. Kanaeva and Ju.A. Ivanova

46. Using an Interdisciplinary Approach to Manage Traffic in Modern Telecommunication Systems
Alexey Ermakov, Andrey Levakov and Nikolay Sokolov

47. A Machine Learning Based Energy-Efficient Non-Orthogonal Multiple Access Scheme
Rabia Khan, Dushantha Nalin K. Jayakody, Vishal Sharma, Vinay Kumar, Kuljeet Kaur and Zheng Chang

48. On the self-testing (m,n)-code checker design
Natalia Butorina, Yulia Burkatovskaya and Elena Pakhomova

49. A Hybrid RF/FSO and Underwater VLC Cooperative Relay Communication System
Mohammad Furqan Ali, Tharindu D. Ponnimbudage Perera, Sumali S. Morapitiya, Dushantha Nalin K. Jayakody, Stefan Panic and Sahil Garg

50. UAV Trajectory Optimization in Modern Communication Systems: Advances and Challenges
Alessandro Visintini, Tharindu D. Ponnimbudage Perera, Nalin Dushantha K. Jayakody and Ioannis Pitas

51. Compressive Sensing in the Problems of the Ultrasonic Signal Processing
Olesya A. Kozhemyk, Oleg V. Stukach and Alexey I. Soldatov

52. Outage Probability Analysis of Downlink UAV-assisted Cellular Systems
Anandpushparaj. J, Gattu Laxman Nadiminti, Muthuchidambaranathan, Maurizio Magarini and Dushantha Nalin K. Jayakody

53. Using artificial neural networks to solve text classification problems
Popova Ekaterina, Spitsyn Vladimir and Julia Ivanova

54. Algorithm for markers detection on fringe images
Aleksey Ubert

55. Mechanical Engineering, Robotics, and Automation

<table>
<thead>
<tr>
<th>№</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Machine learning for stabilizing quadrotor’s single axis using classifier decision boundary</td>
<td>371</td>
</tr>
<tr>
<td></td>
<td>Tserendondog Tengis, Luvsansambuu Uurtsaikh and Amar Batmunkh</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Measuring system for real-time holographic interferometry with an extended measurement range</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>V.I. Guzhov, S.P. Ilinykh and G.A. Pozdnyakov</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Automation of the Monitoring System for Surface Contamination with α-Active Radioisotopes</td>
<td>379</td>
</tr>
<tr>
<td></td>
<td>Valeriy A. Khan, Vyacheslav F. Myshkin, Dmitriy A. Izhoykin, Dmitriy M. Khorokhorin, Anna N. Panamaryova, Michail S. Kuznetsov and Laura A. Rakhimzhanova</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Optimization Fuel Consumption of Diesel-LPG Dual Fuel</td>
<td>383</td>
</tr>
</tbody>
</table>
Measuring system for real-time holographic interferometry with an extended measurement range

V.I. Guzhov
Novosibirsk state technical university,
NSTU
Novosibirsk, Russia
vigguzhov@gmail.ru

S.P. Ilinykh
Novosibirsk state technical university,
NSTU
Novosibirsk, Russia
isp51@yandex.ru

G.A. Pozdnyakov
Novosibirsk state technical university,
NSTU
Novosibirsk, Russia
worlaff@gmail.com

Abstract—This article describes a method for expanding the dynamic range of digital holographic interferometry. Two series of holograms were obtained by the method of two exposures: one for the initial state of the object, the other for the object after its deformation. Then, from these holograms, four interferograms of the object phase difference before and after the load were calculated. The quality of restoring information about the phase difference between the two states of the object is not inferior to the methods of classical holographic interferometry with angles of the order of 30-60 degrees, but in this case there is no need to use hologram recording using photocarriers.

Keywords—digital holographic interferometry, step-by-step phase shift, two-exposure method

I. INTRODUCTION

Holographic interferometry is the acquisition and interpretation of interference patterns in several states of an object, with one or several states of the object being recorded and reconstructed using holography. According to the results of the analysis of holographic interferograms, it is possible to determine the difference between the two states of the object, and therefore build a model of changes that have occurred with the object. Holographic interferometry provides a non-contact, non-destructive measurement method with sensitivity of the order of one-hundredth of a wavelength. This is an effective measurement method for determining changes in the optical path length caused by deformation of a solid or a change in the refractive index in transparent media [1]-[7].

In connection with the development of digital means of recording, the growth of computing power, the emergence of new methods for obtaining and decoding holograms, classical holography is being transferred to digital, in which the interference pattern of the object diffraction field and the reference wave is recorded in digital form. Other important advantages of digital holography are:
- the ability to determine information at once across the entire field of the object;
- the ability to automatically determine the sign of movement;
- the ability to measure ultra-small movements that do not lead to the appearance of interference fringes;
- the possibility of computer processing of individual fragments of holograms;
- the possibility of combining in one computer program measurements of the displacement field and the development of digital interferometry numerical method for analyzing the stress-strain state. Method allows us to hope for a revival of interest in measuring holographic systems and will allow them to be introduced into the practice of experimental research in the near future.

II. PROPOSED APPROACH

In a digital holographic interference system, it is necessary to obtain digital holograms before and after loading to measure the parameters of an object.

Obtaining digital holograms includes the following steps [8]-[12]:
- obtaining digital holograms using optical installation;
- registration of holograms with step-by-step phase shift;
- obtaining a mathematical hologram;
- recovery of useful information from a mathematical hologram.

The first two steps are carried out on an optical installation. The last two steps were performed programmatically.

The measuring system for obtaining digital holograms consists of an optical subsystem, a hologram recording means, a computer and software. To obtain holograms with step-by-step phase shift [15], the system contains a control device that allows setting the phase shifts of the reference beam.

The basis for the holographic experiments is an interferometer, in which the light beam is divided into two beams, which are subsequently reduced at one point. As a result of the interference of the beams, a hologram is formed, which is recorded digitally with the help of a camera and transmitted to a computer for further processing.

Let \( R(x,y) \) be a smooth reference wave, and \( U(x, y) \) be the object wave emanating from the object. Then the intensity recorded on the matrix of the receiving camera is described by the expression:

\[
I_0(x,y) = |R_0(x,y)|^2 + |U_0(x,y)|^2 + R_0(x,y) U_0^*(x,y) + R_0^*(x,y) U_0(x,y),
\]

(1)

where \( H_0 \) is the index denoting the plane of the hologram, and the index * denotes complex conjugation. The intensity described by equation (1) is recorded as an array of pixels \((M \times N)\), with dimensions \((\Delta x \times \Delta y)\) which allows you to record the intensity value as a function of \( I_0(m\Delta x, n\Delta y) \), where \( m \) and \( n \) - whole numbers. The last two terms of equation (1) contain information about the amplitude and phase of the object wave. This information can be extracted using the Fresnel transform method. To obtain the distribution of the field in the plane of the object, it is necessary to conduct the Fresnel transform above the mathematical hologram.
\[ U(x,y) = \alpha_0(x,y) \exp(\phi_0(x,y)), \] (2)

where \( \alpha_0(x,y) \) is the field amplitude, \( \phi_0(x,y) \) is the phase of the field propagated from the object in the plane of the hologram. To form a mathematical hologram (2), the technology of step-to-step phase shift is used \[13\]. In this method, a series of interferograms with various phase shifts \( \Delta \) is recorded, which determines the phase and amplitude corresponding to the profile of the object.

\[ U(x,y) = \alpha_0(x,y) \exp(\phi_0(x,y) + \Delta_i). \] (3)

From the complex amplitude \( U_i(m\Delta x, n\Delta y) \) obtained in digital form, the local phase \( \phi_{ih} \) of the wavefront of the object wave in the range of \( 0 \leq 2\pi \) can be calculated by the following relations

\[ S_y = \text{Im}[U_i(m\Delta x, n\Delta y)], \]
\[ S_x = \text{Re}[U_i(m\Delta x, n\Delta y)] \] (4)

and

\[ \phi_{H0}(m\Delta x, n\Delta y) = \arctan(S_y/S_x), \]
\[ \phi_{H0} = \arctan(S_y/S_x), \] (5)

where \( \text{Re} \) and \( \text{Im} \) denote the real and imaginary parts of the complex number, respectively.

The absolute value of the total phase \( \phi \) is determined by taking into account the number of the interference band \( N \).

\[ \phi = \phi_{ih} + 2\pi N. \] (6)

By subtracting the phase values of the object field calculated for the two states of the object (before the load is applied and after), you can get the value of the absolute phase difference, which allows you to calculate the displacement of object points \( d \) as a result of applying the load in the \( s \) direction using the formula

\[ \Delta \phi = (2\pi/\lambda)d \cdot s, \] (7)

where \( \lambda \) is the wavelength of the laser radiation, \( s \) is the sensitivity vector of the interferometer, defined by the expressions \( k_x \cdot k_y \), where \( k_x \) and \( k_y \) are the unit lighting and observation vectors, respectively.

In the case when the measurement range significantly exceeds the laser wavelength, it is necessary to eliminate phase ambiguity by taking into account phase transitions. However, it is difficult to determine the exact value of the phase for diffuse objects, which greatly complicates this task. This leads to a decrease in the measuring range.

The following describes the algorithm according to which,

\[ \Delta \phi = (2\pi/\lambda)d \cdot s, \] (7)

difference between the two states of the object is found directly, excluding the need for the operation to eliminate phase ambiguity:

1) We obtain mathematical holograms for the first state of the object with step-by-step phase shifts.
2) Then we get four mathematical holograms for the second state with step-by-step phase shifts (a total of 8 holograms).
3) Add the complex fields immediately after the hologram (mathematical holograms) for each of the states of the object obtained with shifts \( \Delta_0, \Delta_1, \Delta_2, \Delta_3 \). Multiply by the complex field corresponding to the reference wave.
4) We restore the amplitude of the complex field in the image area. For this, it is necessary to perform the Fresnel (Fourier) transformation depending on the distance above the wave front.
5) The amplitude of the complex field (3) forms an interferogram. Thus, we synthesize the first holographic interferogram.
6) To obtain the second interferogram, we add the complex field for the first state obtained with the same shifts \( \Delta_0, \Delta_1, \Delta_2, \Delta_3 \) and for the second state, when determining the mathematical hologram, we use the already existing holograms with shifts in a different order \( -\Delta_1, -\Delta_2, -\Delta_3, \Delta_0 \). To obtain the third for the second state, we use holograms with shifts \( -\Delta_2, -\Delta_3, -\Delta_1, \Delta_0 \). For the fourth with shifts of \( \Delta_3, \Delta_0, \Delta_1, \Delta_2 \). As a result, we obtain a series of holographic interferograms with phase shifts \( \Delta_0, \Delta_1, \Delta_2, \Delta_3 \). Deciphering the resulting series of interferograms, we obtain the phase difference for the two states of the object.

The advantage of the proposed method of digital holographic interferometry is that arbitrary wave fields are actually compared.

III. EXPERIMENT

The laser radiation is divided into an object beam, illuminating the object and the reference beam, directly arriving at the receiving sensor of a digital camera. The object beam illuminates the object in the direction of \( k \). The part of the light reflected by the object in the \( k \) direction, called the “direction of observation”, passes through the optical focusing system and forms an image of the object on the receiving sensor of the digital video camera. The hologram of the focused image is formed on the matrix of a digital camera as a result of interference between the reference and object beams. The diaphragm serves to limit the spatial frequencies of the arising interference structure and bring it in line with the resolution of the receiving sensor. The imposition of the reference and object beams on the receiving matrix of the camera is performed using a beam-splitting cube, which is set so that the reference beam proceeds in the direction of the camera sensor from an imaginary source located near the aperture (Fig. 1). To obtain holographic interferograms, a metal membrane loaded in the center was placed as an object in the interferometer circuit (Fig. 2).
To register holograms, a Canon EOS 650D camera was used with a maximum resolution of 5184x3456 pixels and a matrix of photodetectors of 22.3 x 14.9 mm (the pixel size in the matrix is 4.3 μm). The image of the object was projected directly onto the photodetector matrix without a lens. The illumination was performed with a LS-1-SLM-532-100 semiconductor laser with a wavelength of 532 nm.

Using modern technology calculations on the GPU (graphics processing unit), you can achieve higher speed reconstruction and analysis of digital holograms. When using the NVIDIA GTX 1070 graphics accelerator, we were able to obtain holograms and restore them to real-time images. The speed of recording digital holograms, calculating a mathematical hologram from them and recovering images is about 30 cycles per second.

Unfortunately, for diffuse objects, phase information cannot be determined from a single hologram. This is due to phase transitions through at neighboring points, due to a change in the relief of a diffuse object at these points of a longer laser wavelength used for illumination.

Using the principles of holographic interferometry eliminates this disadvantage. Two states of the object are compared before and after loading. In this case, the relief and shape of the surface are irrelevant. The main condition for the formation of interference fringes is a small amount of displacement.

Further, a mathematical hologram was obtained for an object with no load (Fig 3). Then the object was loaded, and the second series of holograms was recorded (Fig 4).

Comparison of the recovered fields in the image area was carried out on a computer. In order to expand the dynamic range, quadrature components of the phase difference [13]–[16] were formed from mathematical holograms before and after loading, from which the difference between the states of the object was directly calculated. The dynamic range of displacement of the object was 0.5 mm. In real-time, one can observe holographic interference bands corresponding to disk deformations (Fig. 5).

Fig 1. Optical scheme (a) and photograph setup (b). 1 is a laser; 2 - an object with a load, 3 - beam expander, 4 - light filters for leveling the intensity level, 5 - a support mirror mounted on piezo ceramics, 7 - a light beam divider; 8 - aperture; 9 the - camera

Fig. 2. Metal membrane with variable load in the center.

(a)
(b)
(c)
(d)

(a) (b) (c) (d)

Fig 3. Digital holograms with a change in phase shift angle before loading. Phase shift: (a) - 0°, (b) -90°, (c) - 180°, (d) -270°.
IV. CONCLUSION

A new method for measuring displacement fields independent of the complexity of the relief of the object (with elevations for diffuse objects significantly exceeding the laser wavelength radiation). The quality of restoring information about the phase difference between the two states of the object in the proposed approach is not inferior to the methods of classical holographic interferometry.

REFERENCES