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HOLOGRAPHIC STUDY OF NON-STATIONARY STATES OF THIN-WALLED STRUCTURE ELEMENTS UNDER THERMAL AND THERMOMECHANICAL LOADING

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Abstract- Non-stationary deformed states of inhomogeneous shells and plates under thermal and thermomechanical loading are studied. The features and results of determining thermal unsteady displacements are presented: a round plate heated in the center; a cylindrical shell with a central rectangular cutout during cooling after uniform heating; a cylindrical shell with two holes to the contour of which heat is applied non-contactly; a vertically located cylindrical tank with two lateral central supports in the form of a frame when it is filled with heated liquid. The experiments use methods of averaged and combined holographic interferograms and low output power lasers (up to 50 mWt). Calculation formulas for the quantitative interpretation of the resulting interference patterns are given, as well as the general procedure for determining displacements. The results obtained clearly demonstrate the good effectiveness of the methods used and can be useful in improving the calculation models of these objects.

Keywords: Shells and Plates, Thermal and Thermomechanical Loading, Unsteady States, Holographic Research, Methods of Averaged and Combined Interferograms.

1. INTRODUCTION

Thin-walled structural elements are widely used in various industries. Such structures during operation, are subjected to loads that vary in physical nature and nature of action. For reasons of increasing specific strength and expanding functionality, in many cases these elements are also created to be heterogeneous in the distribution of the material and its properties. The implementation of these changes is accompanied by the appearance of welded, glued, riveted and other joints in finished products, as well as random imperfections. As a result, significant residual stresses often occur in products. During transportation, installation and operation, cracks, dents and other damage may be added to the indicated inhomogeneities.

Ensuring the load-bearing capacity of such structural elements with heterogeneous parameters is an important, multifaceted and quite complex problem that has received much attention all over the world.. To date, significant progress has been made in the research of structures of the class under consideration [1-6], in which a number of theoretical and experimental results were obtained characterizing the features of their deformation and destruction under the influence of various loads, a significant number of important scientific and practical problems were solved.

However, due to the multifactorial nature and complexity of the problems that arise, a number of urgent tasks remain insufficiently studied, in particular, those related to the processes of deformation of such elements under the influence of thermal fields. Theoretical solutions include solving the problem of thermal conductivity and further determining the parameters of the stress-strain state [1-6]. This is due to the need to introduce a whole series of assumptions regarding heat transfer coefficients, temperature distribution by thickness, etc. and significant mathematical difficulties even when using simplified hypotheses.

Experimental research in this area remains limited [4]. Electrotensometry, indicators of the clock type, etc. measurement methods and means here, as a rule, are ineffective or completely unacceptable. Contact with the surface under study and the locality of measurements by these methods of relatively complex thin-walled structures can lead to significant errors in experimental data and, as a consequence, to incorrect ideas about the behavior of the structure. In recent decades, when studying the parameters of inhomogeneous structures and their parts, methods of optical high-coherence interferometry have found increasing use [7-18]. Of these, holographic interferometry methods are considered the most developed and widely used. The unique advantages of holographic interferometry are high (fractions of microns) sensitivity to surface movements, non-contact measurements, and the possibility of simultaneous observation of a surface with an area of 10

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square meters or more, the absence of fundamental restrictions on the shape, surface condition and material of the test object.

The most effective area of application of holographic interferometry in mechanics is the diagnostics of the behavior of inhomogeneous thin-walled structures [11-13]. When studying complex large-sized products, holographic methods often turn out to be the only acceptable ones.

However, studying transient deformations using holographic methods is not always easy. Indeed, to study them using the two-exposure method, it is necessary to have an expensive pulsed laser. The real-time method allows one to obtain a "live" interference pattern of surface deformation, but the contrast of the observed bands is very low, which limits its use to qualitative analysis of dynamic processes. Relatively recently, two methods for analyzing transient surface displacements using the holographic time averaging method were developed - using averaged [12] and combined [10] interferograms. The purpose of this communication is to test these methods in studies of non-stationary temperature and thermomechanical deformation fields of shells and plates with some localized inhomogeneities.

2. THEORETICAL FOUNDATIONS OF USED HOLOGRAPHIC METHODS

Let some point (x, y, z) on the surface move with speed $\bar{V}(\tau)$, here τ is time. If the recording medium is exposed to the unsteady a period of time T, we obtain an averaged interferogram of the surface. The illumination indicators of a point in the image, reconstructed from this interferogram, are described according to the given in Equation (1) [12].

$$I \approx I_0 \left| \frac{1}{T} \int_{t_0}^{t_0+T} \exp\left[-i \int_{t_0}^{t} \left(\bar{K} \times \bar{V}(\tau) \right) d\tau \right] dt \right|^2 \tag{1}$$

where, I_0 is the illumination of the image of a surface point in a stationary state; t is time; t_0 is exposure start time; i is imaginary unit; $\bar{K}(x,y,z)$ is vector, the components of which are the sensitivity parameters of the optical circuitt. To obtain a combined interferogram of a surface, it is necessary to expose its static state of time $T_0 = \alpha T$, and then for a period of time $T_H = (1-\alpha)T$ is unsteady state. The expression for the illumination of a point in the image reconstructed from such an interferogram has the form [10]:

$$I \approx I_0 \left| \alpha + \frac{1}{T} \int_{t_0}^{t_0+T(1-\alpha)} \exp\left[-i \int_{t_0}^{t} \left(\bar{K} \times \bar{V}(\tau) \right) d\tau \right] dt \right|^2 \tag{2}$$

where, α is the coefficient; $T = T_0 + T_H$ is exposure duration. Obviously, when α=0 from Equation (2) we obtain Equation (1). Let us analyze Equation (2) under some characteristic laws of motion of the holographic surface.

2.1. For the Case of Displacement of Surface Points at a Constant Speed

The $\bar{V}(\tau) = \bar{V}(x, y, z, \tau) = \bar{V}$ in Equation (2) takes:

$$I \approx I_0 \left| \alpha^2 + \alpha \frac{\sin\left[2(1-\alpha)X\right]}{X} + \frac{\sin^2\left[(1-\alpha)X\right]}{X^2} \right| \tag{3}$$

where, $X = \bar{K} \times \bar{V}\, T/2$. Figure 1 shows the dependencies $I(X)/I_0$ in accordance with Equation (3).

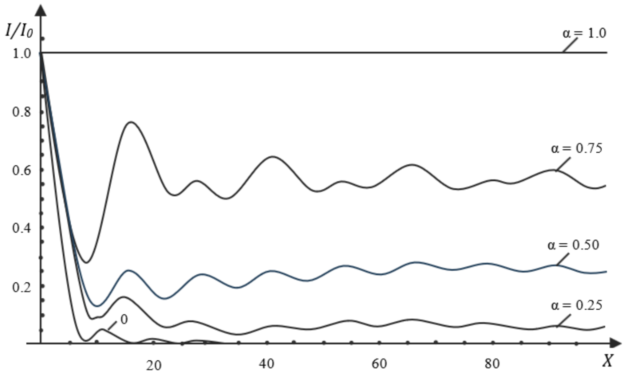

Figure 1. Functios of illumination of a point on averaged ($\alpha = 0$) and combined ($\alpha \neq 0$) interferograms of a surface when its points move at a constant speed

From Figure 1 it follows that the illumination of a point depends on the values of the parameter X and coefficient α. The maximum brightness of a point image decreases with increasing parameter X, and the number of distinguishable peaks (bands) at $\alpha = 0.4 \div 0.6$ is 5 times greater than at α=0.

2.2. For the Case when Each Point of the Observed Surface is Displaced According to the Law

The $\bar{L}(x,y,z,t) = \bar{A}\left(1 - e^{-\beta t}\right)$, $\bar{A}(x,y,z)$ are the displacement amplitude; x,y,z are coordinates of surface points; β is coefficient. Considering that $\bar{V}(\tau) = \bar{A}\,\beta\, e^{-\beta t}$, from Equation (2) we obtain.

$$I \approx I_0 \left| \alpha^2 - \frac{2\alpha}{\beta T}\left\{ \Omega_1 \cos(X \times \kappa_1) + \Omega_2 \sin(X \times \kappa_1) \right\} + \frac{1}{(\beta T)^2}\left[\Omega_1^2 + \Omega_2^2 \right] \right| \tag{4}$$

where, $\Omega_1 = Ci(X \times \kappa_2) - Ci(X \times \kappa_1)$

$X = \bar{K} \times \bar{A};\ \Omega_2 = Si(X \times \kappa_2) - Si(X \times \kappa_1)$

$Ci(\cdots)$ and $Si(\cdots)$ are integral cosine and sine; $\kappa_1 = e^{-\beta t_0}$; $\kappa_2 = e^{-\beta\left[t_0 + T(1-\alpha)\right]}$.

We come to the same formula if the point moves according to the law $\bar{L}(x,y,z,t) = \bar{A}\, e^{-\beta t}$. From the graphs of function (4) (Figure 2) it follows that in this case, preliminary exposure makes it possible to increase the number of distinguishable interference peaks by 4 times (at $\alpha = 0.5$).

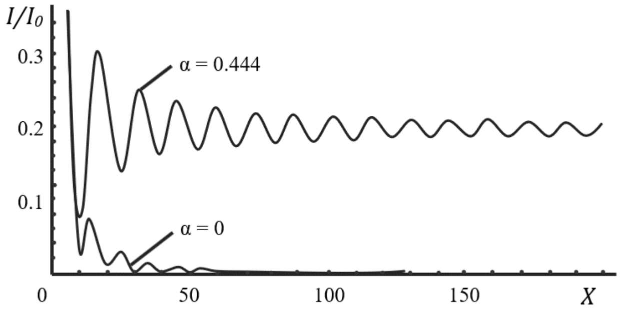

Figure 2. Dependencies characterizing the illumination of a point on the averaged ($\alpha = 0$) and combined ($\alpha = 0.444$) interferograms of the surface when its points move according to an exponential dependence ($t_0 = 5$ s , $T = 45$ s , $\beta = 0.029$)

2.3. Movement Along a Complex Dependence

Let us assume that each point (x, y, z) of the observed surface moves according to a complex relationship defined by the formula.

$$\overline{L}(x, y, z, t) = \overline{k}\left[a_1(t - t_0) + a_2\left\{1 - e^{-\beta(t-t_0)}\right\}\right] \quad (5)$$

where, $\overline{k}\ (x, y, z)$ is unit displacement vector; a_1, a_2, β are the coefficients. Such movement can occur under the simultaneous influence of a local heat source in the contact zone and a moment in the contact plane that includes this zone.

The dependences for determining the illumination of a point on the reconstructed surface image (2) after integration and identical transformations takes the form (6) and are presented graphically in Figure 3.

$$I \approx \frac{I_0}{T^2} \times \times\left\{(\alpha T)^2 + 2\alpha T\left[\int_1 \times \cos(XC) + \int_2 \times \sin(XC)\right] + \int_1^2 + \int_2^2\right\} \quad (6)$$

where, $X = \overline{K} \times \overline{k}$; $C = (a_2 - a_1 t_0)$; $\xi = a_1 t - a_2 e^{-\beta(t-t_0)}$;

$$\int_1 = \int_{t_0}^{t_0+T(1-\alpha)} \cos(X\xi)\ dt; \quad \int_2 = \int_{t_0}^{t_0+T(1-\alpha)} \sin(X\xi)\ dt.$$

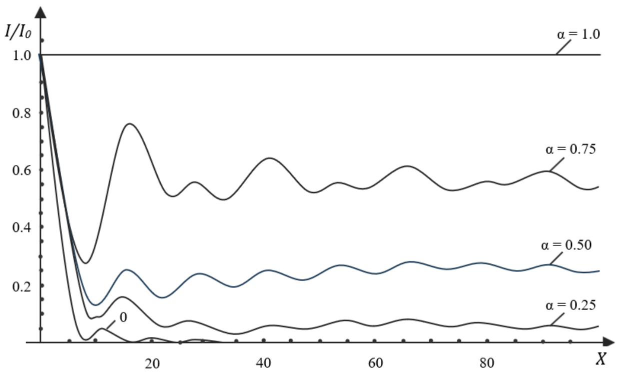

Figure 3. Change of illumination of a point on the image of a surface moving according to Equation (5)

And in this case, preliminary exposure to the static state of the surface also increases at $\alpha = 0.5$ by 3 times the number of distinguishable peaks (visibility of higher-order bands) in its combined interferogram.

These results can be generalized to many other predetermined laws of point displacement during holography using changes in the illumination of a point on the surface image reconstructed with its combined interferogram. At the same time, the use of computer mathematics tools is very convenient and significantly reduces labor costs.

2.4. The Procedure for Determining Movements

Let, for example, the movement of a point be described by the expression $\overline{L}(x, y, z, t) = \overline{A}\, e^{-\beta t}$. If the corresponding calculated graph of the illumination of a point (interference fringes) is constructed using Equation (4), then the magnitude of the vector $\overline{L}$ at the point $M(x, y, z)$ at a time t_1 is found as follows:

a) first according the received from interferogram are determinate the order of the interference fringe at an arbitrary point (ξ_M);

b) next, the corresponding value of the argument (X_M) is determined using a graph similar to that shown above;

c) based on the obtained value of X_M the amplitude $\left|\overline{A}_M\right| = X_M\ \lambda/(4\pi \cos\theta \cos\psi)$ is calculated, while $X = \overline{K} \times \overline{A} = \left|\overline{K}\right| \times \left|\overline{A}\right| \cos\psi$, where ψ is the angle between $\overline{K}$ and $\overline{A}$, the value $\left|\overline{K}\right|$ is known;

d) the displacement value at the moment is considered $t_1 : \left|\overline{L}_M(t_1)\right| = \left|\overline{A}_M\right| e^{-\beta t_1}$.

3. FEATURES OF THE METHOD AND RESULTS OF EXPERIMENTAL STUDY OF NON-STATIONARY MOVEMENTS OF MODEL SAMPLES

The experiments investigated the unsteady deformed states of model inhomogeneous shells and plates under thermal and thermomechanical loading. Continuous radiation lasers of low output power (up to 50 mWt), a UIG-23 holographic installation, strain gauges and the «Mathematika» computer system were used to approximate strain gauge measurement data and construct calculated illumination graphs. Below are the features and results of the study.

3.1. Cylindrical Sheet Steel Shell with a Central Square Cutout when Heated

The shell with rigid frames at the ends was uniformly heated from 21 °C to 60 °C from the inside (using a cylindrical container filled with hot water) and then cooled freely to 25 °C. In these two modes, characteristic combined holographic interferograms of non-stationary states of the shell were obtained (Figure 4). Analysis of interferograms provides a visual representation of the nature of the deformation of the shell during its heating and cooling and shows qualitative differences in the thermally stressed states of the shell in these cases.

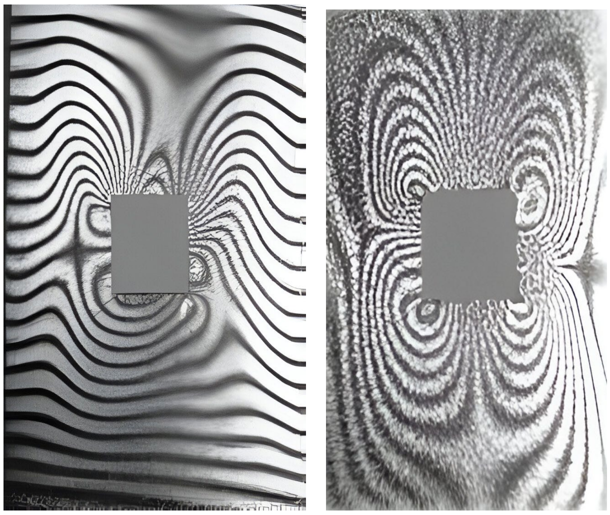

Figure 4. Combined interferograms of a steel shell with a cutout when it is uniform heating from 21 °C to 60 °C (left); with its free cooling from 60 °C to 25 °C (right)

3.2. A Round Plate with a Central Hole for Non-Contact Local Heating

The plate was heated for 105 seconds with an adjustable heat source located in its central part from 20 °C and from the moment t_0 = 60 s, it was holographed for 45 sec as Figure 5. In this way, an averaged interferogram of its unsteady temperature deflections of the plate was obtained.

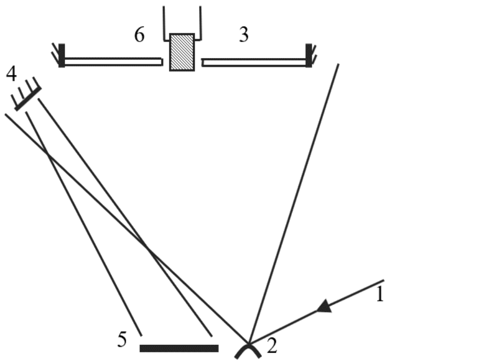

Figure 5. Loading and holographic schemes of the plate
1- direction of laser beam; 2- spherical mirror; 3- ring plate; 4- flat mirror; 5- photographic plate; 6- adjustable heat source; 7- lens

It was established that the "deflection - time" curves of the plate satisfactorily superimposed on the graphs $W(t) = A\left(1 - e^{-0.005\,t}\right)$. Moreover, at point of the central vertical section at moment $\tilde{r} = r/R = 0.5$ $t = 0.5 = 105$ s, the deflection was +7 µm. To construct a calculated graph of the illumination of a point, formula (4) was used at $\alpha = 0$. Typical experimental results are presented in Figure 6. We see that the value of the holographic determination of the deflection at a point $\tilde{r} = 0.5$ is equal to 7.3 µm and coincides with the result of strain gauge measurements (7 µm).

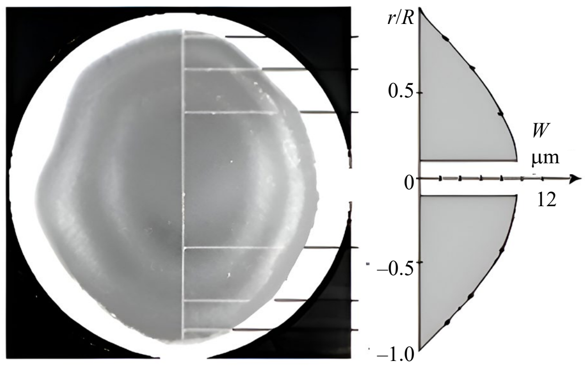

Figure 6. Averaged interferogram and distribution of deflection along the central section of the heated plate at moment t = 105 s

3.3. A Cylindrical Shell with Central and Off-Centre Holes, Non-Contact Heated through Off-Centre Hole

A combined interferogram of the shell was obtained (Figure 7a) by exposing it for 20 s at a temperature of 20 °C and further heating and exposure for 25 s at α= 0.444. It was established that the deflection at the point $\tilde{x} = x/L = 0.15$, $\tilde{s} = s/\pi D = 0$ at the heating time $t = 50$ s was 9 µm and the curves "shell deflection-time" were described by functions $y(t) = A\left(1 - e^{-0.029\,t}\right)$. The deflection at this control point was also determined using strain gauge measurements and amounted to 8.7 µm, which agrees well with the data of holographic studies (9 µm). The calculated graph of strip illumination obtained using Equation (4) is shown in Figure 2. The results of the experiments are presented in Figure 7c.

3.4. A Vertically Located Cylindrical Tray with Two Side Supports when Filled with Heated Liquid

For transportation and storage of heated bulk or liquid substances in metallurgy, the chemical industry, and other areas of modern technology, tanks in the form of a vertically located rotation shell with additional lateral supports are used. The strength and functionality of such tanks, as a rule, are determined by their transient (unsteady) stress-strain states of the stress-strain state during the loading process.

Despite the abundance of publications on studies of the interaction of shells with additional supports, as well as methods and results for solving numerous practical problems in this area [2-4], when determining the unsteady thermomechanical stress-strain state of such structures using known methods and means, a number of fundamental difficulties arise, primarily due to, multifactorial task. One of the ways to solve this problem is to obtain, using holographic interferometry, new reliable data on the thermoelastic deformation of the structural elements under consideration. In this experiment, a duralumin cylindrical shell with an inner diameter D=0.180 m, a working length L=0.180 m and a wall thickness h=3×10^{-3} m was used, which was made by turning from a workpiece.

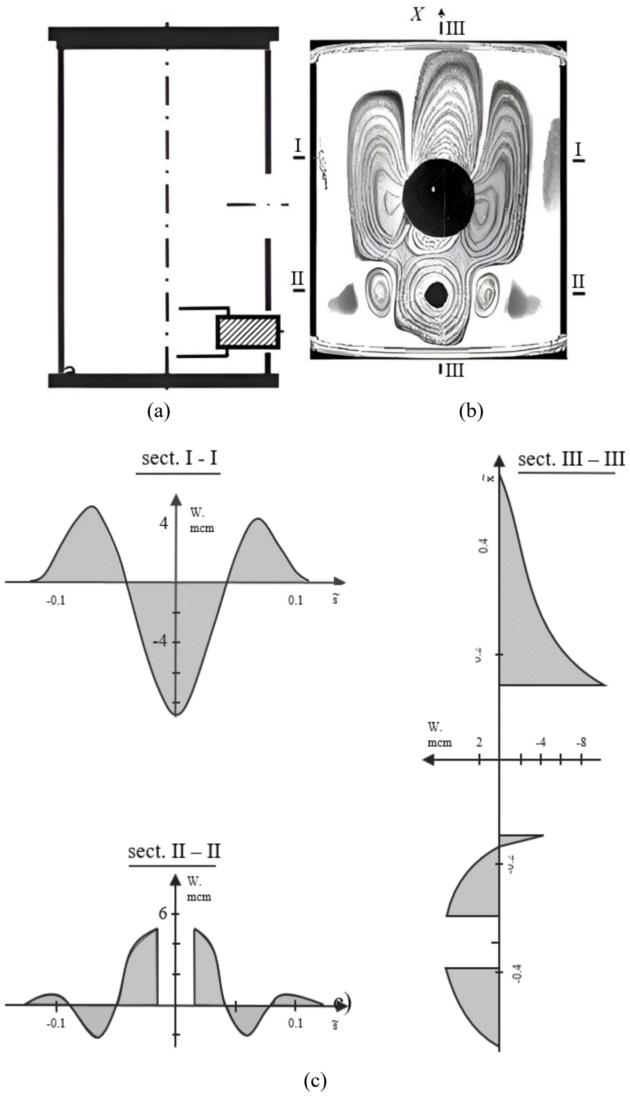

Figure 7. a) Shell loading diagram, b) its combined interferogram, c) distribution of deflections across sections at moment $t = 50$ s of heating

At both ends, the shell had reinforcement in the form of "weak" frames. One of the ends of the shell was free, the other was rigidly pinched with the help of a special device (Figure 8).

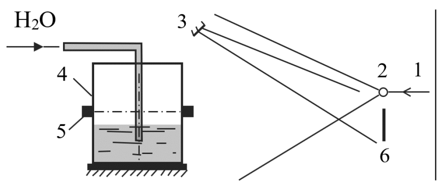

Figure 8. Scheme of loading and holography of the shell with lodgements, 1- direction of laser beam, 2- lens, 3- mirror, 4- shell, 5- lodgments, 6- photographic plate

The sample was placed on the working plate of the installation in a vertical position, resting on the pinched end face, and was fixed along the central cross section with two symmetrically arranged thermal insulation lodgments with a girth angle φ=90 °C.

The contact area of the shell and the base was $S = 23 \times 142 \times 10^{-6}$ m^2. The deformation of the shell was studied in various modes of its filling with heated water. The magnitude of the temperature difference, the level of filling of the shell with water and the rate of supply of the latter changed. For the means used in the experiments, the following method turned out to be optimal: first, the shell was exposure for 60 seconds at temperature 19 °C, then the shell was filled with water heated to 29 °C at a speed of $V = 0.114$ l/s and exposure a second time at 70 s.

The second exposure began after $t_0 = 5$ s the start of filling; as a result, a combined holographic interferogram of the transient deformation of the shell was recorded. Additionally, the dependence of sample deflections on time was determined under various loading modes. When approximating the obtained discrete data on deflections, it was believed that transient deformations of the shell can be considered as deformations from the action of a local heat source that moves upward at a constant speed, and the coordinate components of these movements are related by the relation $\left|\bar{V}\right| = \eta \left|\bar{A}\right|$, where $0 \le \eta \le 1$.

Therefore, the approximating function was found in the form of a sum of deflection functions corresponding to each of these movements - exponentially and at a constant speed. In particular, it was found that deflections are described by the function $W = A(x, y, z)\left[1 + 0.011(t-5) - e^{-0.0332(t-5)}\right]$; where $\eta = 0.011$. With such a deflection function, using Equation (7), a graph of the illumination of a point on the surface image was constructed (Figure 9).

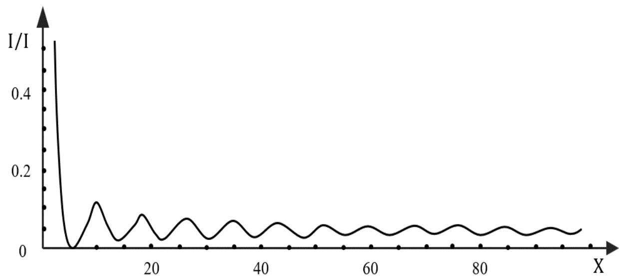

Figure 9. Distribution of illumination of stripes on the surface of the shell at $\eta = 0.011$, $\beta = 0.0332$, $\alpha = 0.462$, $T = 130$ s, $X = \bar{K} \times A$

The $\bar{A}$ is vector of the amplitude displacement of the point; $\bar{K}$ is sensitivity vector of the optical circuit $t_0 = 5$ s. Using this graph, distributions of transient deflections were plotted along characteristic sections of the shell at a given moment of its deformation (Figure 10). The deflection at the control point (22.3 µm) is in satisfactory agreement with the data of strain gauge measurements (19 µm).

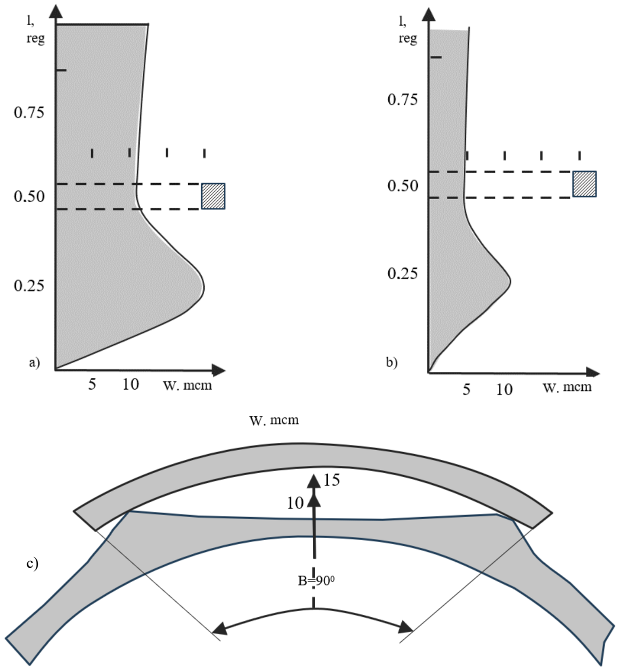

Figure 10. Distributions of transient deflections of the shell in longitudinal and cross sections at a moment *t*=65 s, a) near the end of the support, b) in its center, c) along its lower edge

It is also noted that when the temperature difference between the water and the shell is more than 10 °C, the weight component of the load becomes negligible. In transient deformed states, in contrast to the steady state, the deflection field of the shell near the free end has a wave-like component, the presence of which indicates that the shell in these states may temporarily experience a loss of stability at the free end.

4. CONCLUSION

The work obtained visual qualitative and fairly accurate quantitative data on the non-stationary deformed states of a number of inhomogeneous shells and plates when exposed to temperature and thermomechanical fields. The research results in general suggest that two effective methods have been developed for analyzing transient thermoelastic deformations of inhomogeneous plates and shells using holographic interferometry of time averaging. It is shown that the use of the proposed methodology allows obtain a wide range of data on displacements of the surface of shell elements under conditions of transient thermal and thermomechanical influences in a wide range of their changes using conventional low-output continuous-wave lasers.

It has been demonstrated that the use of combined holographic interferograms provides an increase in the range of measured displacements by 2-5 times, which is of great importance when studying the transient stress-strain state of thin-walled structures with local features of the distribution of physical and mechanical characteristics, boundary conditions and load.

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Research Interests: Solid Mechanics; Strength, Stability and Mechanics of Composite Materials, Experimental Mechanics
Scientific Publications: 98 Papers, 2 Monographs, 3 Textbooks

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Ph.D.: Tech., Aircraft Strength, Dnipro State University, Dnipro, Ukraine, 1985
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The Last Scientific Position: Prof., Oles Gonchar Dnipro National University, Dnipro, Ukraine, Since 2017
Research Interests: Experimental of Deformed Solid Mechanics, Interference-Optical Methods of Mechanics, Strength, Stability, Oscillations of Inhomogeneous Thin-Walled Structures
Scientific Publications: 130 Papers, 4 Monographs, 5 Patents, 50 Theses

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Ph.D.: Tech., Azerbaijan Scientific Research Institute of Economics and Agricultural Organization, Baku, Azerbaijan, 2006
The Last Scientific Position: Assoc. Prof., Department of Land Reclamation and Water Management Construction, Faculty of Engineering Communications and Water Management, Azerbaijan University of Architecture and Construction, Baku, Azerbaijan, Since 2016
Research Interests: Mechanics, Hydromechanics, Hydraulic Structures, Hydrology
Scientific Publications: 65 Papers, 2 Monographs, 4 Book, 16 Theses