Research of strength characteristics and optimization of parameters of case structures using holographic interferometry

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Abstract. The article presents a method for studying the strength characteristics and optimizing the parameters of the casings of pumping and compressor equipment, gearboxes, motors, etc. structures by the reduced density of stripes on their holographic interferograms. It was used to study the properties of a cylindrical shell with an optimal reinforcing pad in the zone of action of a radial concentrated force. A rational redistribution of the material of the ribbed plate, bent by a transverse concentrated force, has been carried out. The deformation of the crankcase of the gearbox and clutch of a car in all gears is investigated, recommendations are given for the rational redistribution of its material. The results show that holographic interferometry makes it possible to assess the advantages of the optimal designs obtained, allows to significantly expand the class of hull structures, for which a high level of design solutions can be effectively implemented to ensure their rational parameters.

1. Introduction

Cases of turbomachines, compressors, pumps, engines, gearboxes and gearboxes in mechanical engineering, chemical and other industries are usually shell-plate constructions. Reducing the material consumption of structures of this class is one of the most important design tasks. Optimization of their strength properties in many cases leads to a significant redistribution of the material with a large number of control parameters and the need to study models with irregular stiffness. Moreover, the results significantly depend both on the effectiveness of the used optimization methods and algorithms, and on the accuracy and efficiency of the method for determining the stress-strain state (SSS).

Traditionally, theoretical methods with a further analysis of the results obtained numerically predominate in the problems of structural optimization [1,2]. The results indicate significant advantages of optimal projects, but the question of their practical use often remains open. This is due to the multifactorial nature of the task and the obvious insufficiency of the necessary experimental studies. As a result, the problem of reliable provision of rational parameters of hull structures remains among the relevant ones.

Recently, when solving problems of optimizing shell-plate constructions, holographic interferometry, which is most effective in estimating the SSS of inhomogeneous structures
[3,4,5], has been increasingly used. However, a qualitative approach to the interpretation of interferograms (according to the characteristics of interference fringes) is applicable only in cases where the influence of the geometry of the surface under study and the optical scheme on the analysis results can be neglected. A quantitative approach (with the determination of all components of the displacements of the surface of the test sample) with satisfactory accuracy of the results is unreasonably time-consuming.

The method that allows you to obtain clear and acceptable accuracy results in the study and optimization of the stiffness and strength properties of hull structures using new techniques for analyzing their SSS by holographic interferograms in the article are presented. The results of testing the approach are presented.

2. The method of researching the properties and redistribution of material construction

This method applies to structures whose SSS is reliably estimated by the deflections of the middle surface, and consists in the following.

According to the test scheme with maximum sensitivity to deflection, a test holographic interferogram (THI) of the design is obtained – a two-exposure interferogram with control values of the current load and its increment. Further, the most and least deformable zones and control sections in them are determined by THI [3].

It should be noted that in studies of the stress-strain mill (SSS) of structures, the greatest interest is most often not the full fields of deformations and stresses, but only the zones of their extrema. These zones judge the strength properties of the structure, evaluate the reserves and directions of the steps at its optimization improvements.

In order to increase the efficiency of identifying and assessing the extrema of the design SSS of construction, the analysis method THI using the reduced band density is used [6]. Its peculiarity lies in the fact that when assessing i-th the non-uniformity of the SSS, it is determined not the maximum value of the directly observed density of the bands on the i-th section of the THI of the studied surface, as in the qualitative interpretation of interferograms, but the reduced value of the maximum density of the bands on this section.

For this, at the THI to fined zones of extrema of the density of interference fringes and, thus, places of localization of heterogeneities of the SSS design. In these zones, local band density values are recorded normal to the bands $\rho_{ji}$ and tangent $\rho_{ji}$. Next, the magnitude and direction of the maximum density are calculated by the formulas $\rho_{i\max} = \sqrt{\rho_{ji}^2 + \rho_{ji}^2}$ and $\alpha_i = \arctan(\rho_{ji}/\rho_{ji})$ [3], respectively. Then, the reduced value of the maximum band density in the i-th zone $\rho_{i\max}^*$ is found. For this, the value $\rho_{i\max}$ is divided by the local optical-geometric coefficient $k_i$, which takes into account the shape of the investigated surface, the parameters of its lighting and observation, and in the general case it is determined by the formula

$$\theta$$ is half the angle between the directions of lighting and observing the surface at a given point; $\psi$ is the angle between the displacement vector and the bisector of the angle $2\theta$ at this point. Thus, the results are the same in accuracy (both in the center and on the periphery of the interferogram).

Further along the direction $\rho_{i\max}^*$, the relative magnitude of the change in the stripe $s_j$ step $\Delta s_j = |s_j - s_{j+1}|/s_{j+1}$ (where $j$ is the number of the interference band) is calculated.

Assessment of the $i$-th heterogeneity (extremum) of the SSS is given by the parameters $\rho_{i\max}^*$, $\alpha_i$ and $\Delta s_j$. In particular, the control sections in the extremum zones coincide with the direction of the perpendicular to the direction of the local maximum density of the bands (the most probable direction of the initial microcrack).
Then, in the control cross-sections, the second derivatives of the deflection in two main directions are determined, and the values of the main curvatures $\kappa_1$ and $\kappa_2$ the deformed surface are found from them. In determining $\kappa_1$ and $\kappa_2$, the general character of the change $\kappa_1$ and $\kappa_2$ along the control cross-section and their value in a first approximation are estimated. Then, for a more accurate determination $\kappa_1$ and $\kappa_2$, a quantitative interpretation of the THI is performed along this section in the main directions, followed by approximation of the discrete results by splines and differentiation of the latter. In this case the magnitude of the deflection $w$ is determined by the formula

$$w = 0.5 \lambda \cdot N (\cos \theta \cdot \cos \psi)^{-1};$$

(2)

where $N$ is the order of the interference band at a given point, $\lambda$ is the wavelength. Correctness of smoothing is ensured by using data obtained by the moiré method.

The local principal stresses $\sigma_{1\text{max}}$, $\sigma_{2\text{max}}$ and the bending stiffness $D(x, y)$ of the wall of the structure are estimated by the values of $\kappa_1$ and $\kappa_2$. The calculation is performed according to the formulas:

$$\sigma_{1\text{max}} = \pm C_z h (\kappa_1 + \mu \kappa_2); \quad \sigma_{2\text{max}} = \pm C_z h (\kappa_2 + \mu \kappa_1); \quad D(x, y) = C_z h^3 / 6,$$

(3)

where $h = h(x, y)$ is the variable thickness; $C_z = E \left[ 2 \left( 1 - \mu^2 \right) \right]$; $E$ and $\mu$ – material characteristics.

If it is necessary to make recommendations on the rational redistribution of the material of the structural wall in order to improve its strength and stiffness properties, the lower boundaries of the local wall thickness $h_*(x, y)$ and stiffness $D_*(x, y)$ are determined by the found values of the principal stresses using one of the strength theories. Equivalent stresses in the structure are evaluated, and in proportion to these stresses, the material is removed and builds up, respectively, in the underloaded and overloaded sections.

In an improved sample, equivalent stresses are similarly determined. Based on the results of this analysis, removal or augmentation of its material is carried out in the relevant areas. The process stops when the determined stresses or bending stiffness at all control points of the structure become close to the specified values.

Below are some results of testing the presented method.

3. The research of the properties of a cylindrical shell with a reinforcing pad in the area of action of the radial concentrated force

To strengthen the shells of rotation in the area of application of the local transverse load, local thickenings in the form of overlays are often used, which causes practical and scientific interest in the development of optimal design methods and experimental studies of structures thus reinforced.

The experiments were performed on 3 samples of a shell clamped at the ends of a radius of $R = 0.057$ m and a working length of $L = 2R$ made of sheet steel Kh18N9n with a thickness of $h_0 = 2.8 \times 10^{-4}$ m. The first sample was without reinforcement, the second – with a square plate with a thickness of $h_0$, the third – one with an optimum weight plate (Figure 1). Linings of shell were made of the same steel.

![Figure 1. Optimal distribution of shell thickness in the zone force action in longitudinal (left) and circumferential (right) sections.](image-url)
The dimensions of the square lining (0.08×0.08 m²) were determined experimentally – by visual analysis of the interferograms of an unsupported sample in order to smooth out its deformed state. Therefore, the overlay covered the three central half-waves of the deflection field of the shell (Figure 2). The weight-optimal configuration of the lining (thickening of the wall of the cylindrical shell as a variable in two directions of stiffness, represented by curved lines in Figure 1) was determined in [6] using the discrete-continuous calculation model and the necessary optimality conditions in the form of the Pontryagin maximum principle. Its weight turned out to be 48 times less than the weight of the first (square) pad of zero approximation. In the experiment, the optimal lining was modeled with three layers of thickness $h_0$ (shown in rectangles in Figure 1), connected by glue. The linings were also attached to the shell using adhesive bonding.

The load was set with the help of measured weights, block and flexible traction. To record interferograms, an optical scheme was used with a predominant sensitivity to shell deflections. Figure 2 shows the THI of the tested samples. The distributions of the deflections and their second derivatives along the longitudinal and transverse sections passing through the point of application of force are shown in Figure 3.

![Figure 2. THI tested shell samples.](image)

![Figure 3. Distributions of deflections (left) and their second derivatives (right) for shells without overlays (solid curves) and with optimal overlays (dashed curves); dots show the results of decoding THI.](image)
From an analysis of these interferograms and graphs, it follows that a square patch with a thickness of \( h_0 \) and a width of 0.5 \( L \) (into three central half-waves of the deflection field of an unsupported shell) did not significantly affect the change in the nature of this field. The absolute values of the deflections (the number of bands), as expected, decreased by half. The optimal pad with many times less material consumption for its manufacture affected the maximum deflections in almost the same way. In addition, in the zone of action of the force, the maximum values of the derivative deflections that characterize the stress distribution decreased by 3 times. This indicates a significant improvement in the SSS parameters of the design as a whole.

The above research results allow us to conclude that holographic interferometry makes it possible to evaluate the advantages of the resulting optimal designs, to demonstrate the effectiveness and feasibility of their wider use in design practice.

4. The rational distribution of the material of the ribbed plate, bent by a transverse concentrated force

This section shows that in certain cases, acceptable results on the rational distribution of the material of inhomogeneous structures can be obtained directly by the holographic method described in section 2.

The weight refinement of a model rectangular organic glass plate supported by stiffeners was performed. The long sides of the plate were rigidly pinched, the short ones were free. The plate through one of the fins nodes was loaded with normal concentrated force \( P \). An optical scheme was used with maximum sensitivity to its deflections. The fins and THI diagrams for this plate are shown in Figure 4 on the left.

The interpretation of the interferogram was carried out according to the formula (2). When approximating the obtained data on displacements and their derivatives, the results of express analysis of THI using the modernized moiré method were used [3]. The distributions of deflections, their derivatives, and also equivalent stresses are obtained according to the fourth theory of strength along coordinate axes. The distribution of deflections and stresses along the \( x \) axis is shown in Figure 5, where the dots show the interpretation data of the interferogram.

Redistribution of the plate material from technological considerations was carried out only by decreasing or increasing the height of their cross section linear along the length of the ribs. After the third redistribution step, the weight of the fins was reduced by 39%. Figure 4 on the right shows the general view and THI (on the back side) of this model. According to the THI, the distributions of the deflections of the model, their derivatives, and also equivalent stresses along the coordinate axes were also constructed. Graphs of the distribution of deflections and equivalent stresses are shown in Figure 5.

![Figure 4](image.png)

**Figure 4.** Plate finning diagram and TGIs on the smooth side of the plate in the initial state (left) and after the third change in the cross sections of the ribs (right).
Figure 5. Distribution of $w$ and $\sigma_{equ}/C$ plate along the $x$ axis in the initial state (solid lines) and after the third redistribution of material (dashed lines).

From figure 5 it follows that the fields of deformations and stresses on the surface of the sample were leveled, while the largest equivalent stresses somewhat decreased. Obviously, there are still considerable reserves of further improvement of the design.

5. The study of the deformation of the crankcase gearbox and vehicle clutch

Optimization of more complex material distribution and manufacturing technology of shell-plate case structures using this method was performed using the full-scale case of the gearbox and vehicle clutch as an example. Using a special device for loading, THIs of the crankcase were obtained in all gears. THI of the crankcase at the most “heavy” (reverse) gear is shown in Figure 6. Using them, the distributions of the increments of the deflections in the zones of greatest and least strains are constructed, and the corresponding distributions of equivalent stresses are obtained. Using these data, recommendations were made on the rational redistribution of crankcase material.

At the same time, it should be noted that the redistribution of its material requires the replacement of an expensive mold, which becomes one of the barriers to the implementation of the results.

In this regard, in our opinion, the development of the method discussed in Section 2 using the mock-ups of a hull structure printed on a 3D printer even during its design seems promising.

Figure 6. THI of the crankcase in the reverse gear. The most and least deformable zones of the crankcase are highlighted by solid and dashed lines, respectively. The solid and dashed arrows indicate the location and direction of the maximum or minimum change in the density (step) of the bands on the observed surface, respectively.

Output. The approach presented in this work, based on the use of holographic interferometry, allows one to significantly expand the class of body structures of machines, pump and compressor equipment, other mechanisms and their elements, for which a high level of design decisions to ensure their rational parameters can be effectively implemented.

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