Distortion Compensation in Structured Lighting Systems

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Abstract – **The article discusses a modification of the structured lighting method. The difference between the proposed method and classical optical methods for measuring the profile of objects using structured illumination is that the phase of the projected images is demodulated taking into account the change in the intensity of the set of sinusoidal patterns projected onto the object when phase shifts of a known value are introduced. This improves the quality of the measurements. An experimental verification of the proposed method has been carried out.**

Index Terms – **Structured lighting, phase step, average brightness, measuring system.**

I. INTRODUCTION

MODERN MEASUREMENT technologies using structured lighting methods are based on the projection of images containing a system of stripes onto the surface of an object. The change in the shape of the bands recorded by the photodetector describes the surface relief [1-3]. Simple figures can act as such a system of stripes. For example, a collection of points or a set of lines. Lines are projected with special projectors. Often an LCD or laser projector is used as such a device. The optical axis of the photodetector is located at an angle to the optical axis of the projector. The photodetector registers the shape of the lines by which the relief of the measured surface is determined. However, this method of measuring the z-coordinate of an object corresponding to the surface relief does not allow registering its deformation with the required error.

Structured lighting methods, which use information about the phase of the projected stripes, is the same as the image projection methods [4]. Many authors consider them as a separate type of structured lighting method, which consists in the fact that an image of stripes with a sinusoidal profile is projected onto the surface of an object. Methods for measuring the phases of interference fringes inherent in holographic and, accordingly, interferometric measuring systems [5, 6], are also acceptable for methods of structured illumination in the case when the profile of the projected fringes has a sinusoidal form. Since in this case the intensity pattern is:

$$I_i(x,y) = I_0(x,y)\left[1 + V(x,y)\cos(\Delta\varphi(x,y) + \delta_i)\right], \quad (1)$$

where $I_0(x,y)$ is the average intensity, is the average visibility or contrast, $V(x,y)$ is the phase difference between the studied and ideal band distribution, and $\Delta\varphi$ is the known phase shift.

The profile change depends on the phase difference and the geometry of the optical installation. The method of phase steps for the purpose of interference measurements (PSI - Phase Shift Interferometry) was first proposed by Carre in 1966 [7] and immediately attracted the interest of engineers because it allowed performing phase measurements at a single point of the interference fringe [8, 9]. In this case, it is possible to avoid a global assessment of the interference pattern, which has local discontinuities. The phase step method consists in introducing phase shifts with a known value into the interference patterns. Usually a series of projection pictures with known phase steps is formed. The formula for the intensity of the bands along the horizontal x-axis is:

$$I_i(x,y) = a_0 + a\cos\left(\frac{2\pi N_p}{N_x}x - \delta_i\right), \quad (2)$$

where a_0 is the average luminance, a the amplitude projected on the object of bands, N_x the number of dots in the array, N_p - the required number of lanes, and δ_i phase shift.

To find the phase difference, which is proportional to the surface relief of the object, we project the system of bands (2) on the object, register and solve the system of equations (1) with respect to $I_i(x,y)$. A generalized algorithm for solving systems of transcendental equations (1) for arbitrary phase shifts is described in [10].

$$\varphi = \operatorname{arctg}\left(\frac{\vec{I}\cdot\vec{C}^{\perp}}{\vec{I}\cdot\vec{S}^{\perp}}\right), \quad (3)$$

here, $\vec{S}=(\sin\delta_0,\ldots,\sin\delta_{m-1})^T$ and $\vec{C}=(\cos\delta_0,\ldots,\cos\delta_{m-1})^T$ is a set of sines and cosines from known phase shifts δ, $\vec{C}^{\perp}$ - (a vector orthogonal to the vector $\vec{C}$) and $\vec{S}^{\perp}$ (a vector orthogonal to the vector $\vec{S}$).

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II. Solution Of The Problem

It follows from expressions (1) - (3) that correct phase reconstruction requires knowledge of the actual value of the average brightness and amplitude of the bands projected on the object. Since the expression (2) under the specified conditions takes the form

$$I_i(x,y) = a_i + b_i \cos\left(\frac{2\pi N_p}{N_x}x - \delta_i\right). \qquad (4)$$

Given the dependence of the coefficients a_i and b_i the expression (1) is convenient to rewrite in the form

$$I(x,y) = \left(a_r^2 + a_p^2\right) + 2a_r a_p \cos(\varphi), \qquad (5)$$

where a_p and a_r are the amplitudes of the reference and object beams, respectively, and a is the phase of the sinusoidal fringes.

By changing the intensity of the average brightness of the system of sinusoidal bands projected on the object to known values a system of equations can be obtained

$$\begin{cases} I = a_r^2 + a_p^2 + 2a_r \cdot a_p \cos\varphi \\ I(k) = (ka_r)^2 + a_p^2 + 2ka_r \cdot a_p \cos\varphi \end{cases} \qquad (6)$$

from which are the actual values of the amplitudes a_p and a_r - of the reference and object beams, respectively. However, the direct solution of this problem requires knowledge of the phase φ, which is calculated with an error due to the variability of values and when making a phase shift. We show that this effect can be eliminated. Let three sinusoidal patterns with different values be formed for each phase shift

$$\begin{cases} I_1 = a_r^2 + a_p^2 + 2a_r \cdot a_p \cos\varphi \\ I_2 = (ma_r)^2 + a_p^2 + 2m \cdot a_r \cdot a_p \cos\varphi, \\ I_3 = (na_r)^2 + a_p^2 + 2n \cdot a_r \cdot a_p \cos\varphi \end{cases} \qquad (7)$$

here m and n the known attenuation coefficients of the reference beam.

By subtracting the first equation multiplied by the corresponding attenuation coefficient of the reference beam from the subsequent equations of the system (7). it is possible to form a system of equations that does not contain terms containing the phase φ

$$\begin{cases} mI_1 - I_2 = m(1-m)a_r^2 + (1-m)a_p^2 \\ nI_1 - I_3 = n(1-n)a_r^2 + (1-n)a_p^2 \end{cases}. \qquad (8)$$

Then solving the system of equations (8) with respect to the unknown a_r^2 and a_p^2 we get

$$\begin{cases} a_p^2 = \dfrac{m \cdot n(m-n)I_1 + n(n-1)I_2 - m(m-1)I_3}{(m-n)(m-1)(n-1)} \\ a_r^2 = \dfrac{(m-n)I_1 + (n-1)I_2 - (m-1)I_3}{(m-n)(m-1)(n-1)} \end{cases}. \qquad (9)$$

Performing the specified operations (7) - (9) for each phase shift, we can obtain expression (3) with constant coefficients by normalizing the sinusoidal bands projected on the object (4)

$$\tilde{I}_i(x,y) = \frac{I_i(x,y) - \left(a_r^2 + a_p^2\right)}{2a_r a_p} = \cos(\varphi). \qquad (10)$$

The accuracy of determining the amplitudes depends directly on the true values of the attenuation coefficients. Therefore, there is no doubt that they need to be calibrated. Let's look at the process of calibration of transmission coefficients.

The transmission coefficient of a neutral filter can be determined by calculating the upper expression (9) at several points in the interference pattern. the difference between these values depends only on the transmission coefficients. For example, for two points i and j we get the following expressions

$$\frac{(m-n)I_{1i} + (n-1)I_{2i} - (m-1)I_{3i}}{(m-n)(m-1)(n-1)} - \frac{(m-n)I_{1j} + (n-1)I_{2j} - (m-1)I_{3j}}{(m-n)(m-1)(n-1)} = 0, \qquad (11)$$

$$\frac{m \cdot n(m-n)I_{1i} + n(n-1)I_{2i} - m(m-1)I_3 i}{(m-n)(m-1)(n-1)} - \frac{m \cdot n(m-n)I_{1j} + n(n-1)I_{2j} - m(m-1)I_3 j}{(m-n)(m-1)(n-1)}. \qquad (12)$$

Expressing the variable n from expression (11) and substituting it into expression (12), we obtain the value of the transmission coefficient *m*

$$m = \frac{I_{2i} - I_{2j}}{I_{1i} - I_{1j}} \qquad (13)$$

Similarly expressing the variable m we get the value of the transmission coefficient *n*

$$n = \frac{I_{3i} - I_{3j}}{I_{1i} - I_{1j}}. \qquad (14)$$

The algorithm was checked using the following method

III. Experimental Results

As the object under study, a pinched cantilever beam is used, one end of which is fixed, and some load is applied to the other end of the beam. This measurement scheme is well studied, so it allows you to compare experimental data with the results of theoretical calculations. A pressed profile made of aluminum alloys is used as a beam (Fig. 1).

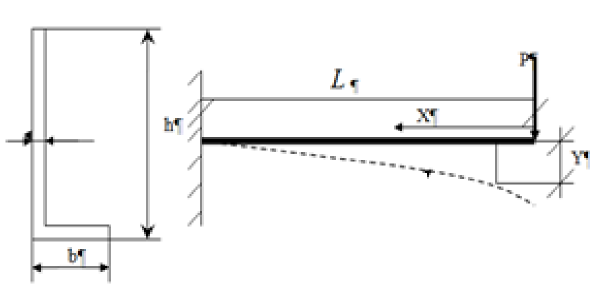

Fig. 1 form and scheme of object loading.

Its cross-section has the form of an uneven corner with the dimensions of the shelves: $h = 65$ mm and $b = 10$ mm, the thickness of the profile $\Delta = 1.2$ mm. Elastic modulus of the beam material $E = 7 \cdot 10^9$ P. Length $L = 0.5$ m. The moment of inertia of the section $I = 5.194 \cdot 10^{-8} \text{m}^4$, the value of the concentrated force applied at the end of the beam is equal to 4.5 N, the moment of inertia of the section $I = 5.194 \cdot 10^{-8} \text{m}^4$. The loading device is a serial micrometer, which also serves to control the amount of bending of the free edge of the beam (Fig.2).

The optical measurement scheme and the measuring system that implements them are shown in Fig. 3, 4. here the distance between the projector and the camera is 1.5 m, $L = 2$ m the distance from the projector to the object plane is the length of the beam - $EF = 500$ mm. To reduce the size of the period of the projected sinusoidal pattern, projectors with a large spatial resolution are required.

This work uses a 4K projector VPLVW260ES, which provides a resolution of 4096 by 2160 pixels. To register, use a CANON EOS M50 camera paired with a computer. The Canon EOS M50 has a CMOS image sensor with a resolution of 24.1 MP and a physical size of 22,3x14,9 mm (APS-C format). The maximum resolution when entering a single frame is 6000x4000.

Thanks to the new DIGIC 8 processor support for 4K video recording is provided. The maximum video resolution is 3840x2160 pixels at 25 frames per second.

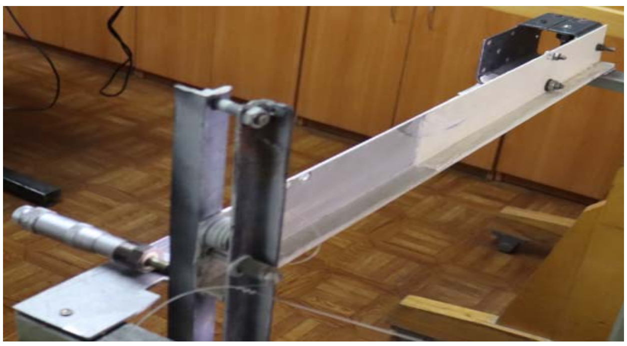

Fig. 2. loading Scheme of the test sample.

For the first time, the new 14-bit RAW — CR3 format was used for EOS cameras

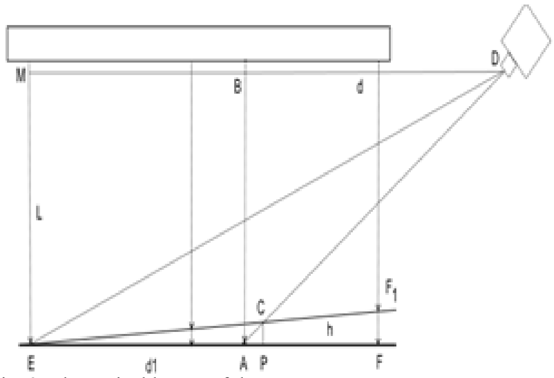

Fig. 3. The optical layout of the system.

Fig 4. General view of the measurement system.

Fig. 5 shows sinusoidal patterns projected onto the surface of the object under study.

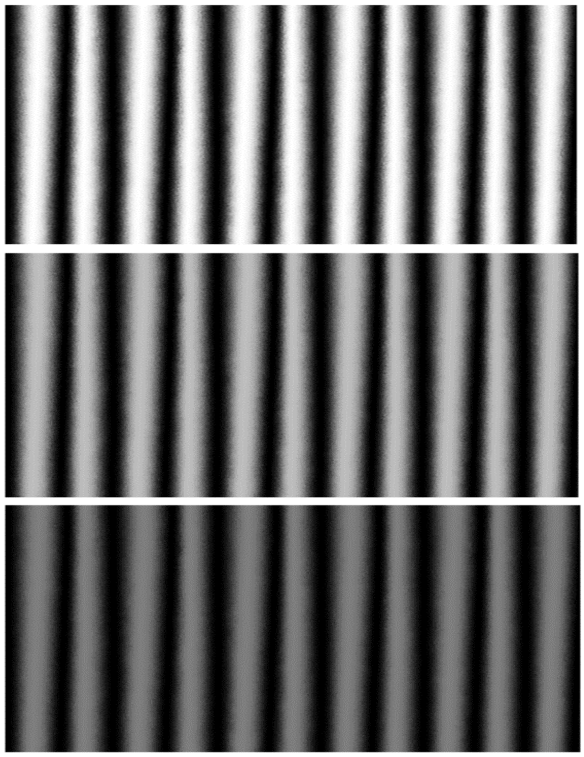

Fig. 5 Sinusoidal patterns projected on the object under study.

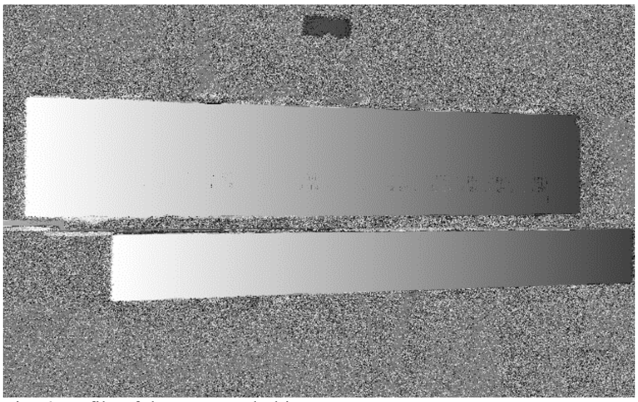

Fig. 6 Profile of the measured object.

The interference pattern was normalized using equations (7) - (10). This eliminates the influence of distortions caused by the variability of the average brightness of the interference pattern when making phase shifts. A total of 9 interference patterns were formed at three phase shifts. After that (Fig 6.), the phase distribution was demodulated according to the formula (3).
The use of this algorithm allowed to increase the accuracy of measuring the profile of the object under study with a size of half a meter to values of the order of 2-3 microns.

VI. CONCLUSION

The article considers the possibility of improving the quality of phase demodulation in the structured lighting method by taking into account changes in the uneven illumination of the measured object when making phase shifts. Taking into account the influence of the amplitude distribution of the reference and object beams significantly increases the quality of phase measurement.

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