Using diffractive optical elements for industrial products geometrical parameters inspection

P S Zavyalov¹, L V Finogenov¹, E S Zhimuleva¹, M S Kravchenko¹, D R Khakimov¹, K I Savinov¹, M V Savchenko¹, A V Beloborodov¹ and V E Karlin¹

¹Tecnologial Design Institute of Scientific Instrument Engineering SB RAS, Russkaya St. 41, Novosibirsk, Russia, 630058

e-mail: zavyalov@tdisie.nsc.ru

Abstract. The paper describes industrial products geometrical parameters inspection systems. The systems are developed from a structured illumination method. An illuminating structure is formed by diffractive optical elements. Inspected objects of the system are smooth-bore weapon, fuel pellets, fuel rods, spacer grids, ceramic ring insulators. Diffractive optical elements used in the performance are focusators into rings or segments of a straight line. A focusator into arc is made for cylinder objects inspection. In this case, a focal plane aligns with a plane of the cylinder generatrix.

1. Introduction

Diffractive optical elements (DOEs) are optical elements with unique characteristics within the framework of classical optics. It has been widely developed due to the use of computers for the hologram synthesis of mathematically defined objects [1]. DOEs are divided by structure into following types: a binary amplitude, a binary phase, continuous microrelief, a spherical surface microrelief, a halftone transmission structure. The first three types are primarily used for optical instrument-making purposes. DOEs are applied for an optical aberrations correction and mode structure of laser emission, for a high-precision inspection of aspherical surfaces in an optical instrument-making, and for several other problems [2].

DOEs are currently applied in a non-contact objects geometrical parameters inspection with a light-scattering surface. Such products are inspected by illumination of the measured surface with a light field of a complex configuration (stripes, dot matrix, grid, etc.) and image registration (by one or more optical sensors). Calculations of necessary geometrical parameters are performed as a result of subsequent processing. There are many similar methods that can be broadly called the methods of structured illumination [3]. It gives a possibility to measure the shape of 3D object by using only one image frame. In addition, these methods are used to digitize 3D objects and real time scenes due to the simple image processing [4]. Commercial LCD or DLP projectors are usually used as structured illumination generators, which limits the use of such devices due to its low measurement accuracy (an error is greater than 0.1 mm) [5]. This prevents the full use of such illuminators in industrial
production. It is necessary to apply high-precision projectors based on elements of a digital and diffractive optics to reduce the measurement error [6, 7].

TDI SIE SB RAS proposed the structured illumination methods based on DOEs and developed inspection systems for a range of important industrial products. The paper presents a review of obtained results with an emphasis on DOEs development and use issues in dimensional inspection problems.

2. Extended holes inspection method
An optoelectronic method of holes inspection with the use of a diffractive illumination focusator are proposed [8]. A small-sized probe for measuring of a hole diameter, unstraightness of its axis, surface shape deviation from a cylindricality and a surface quality inspection can be created based on these method. Such probe is most suitable for inspection holes with relatively free dimensions, for example, for smooth-bore weapon.

The measurement procedure consists of formation of illuminated area in a shape of a ring on inner cylindrical surface of the product, receiving and processing an image of this area. Illumination scattered from the inner surface of a cylindrical object falls on a CCD camera through a conical mirror. The entire surface is scanned by moving the object (figure 1).

![Figure 1. Principle of holes inspection. 1 – laser; 2 – collimator; 3 – DOE; 4 – cylindrical channel; 5 – conical mirror, 6 – camera; 7 – computer; 8 – product moving device.](image1)

The main issue of the proposed method is focusing of light beam into a narrow ring (figure 2). A diffractive focusator [9] is applied such as optical element with the following phase function [10]:

\[
\varphi(r) = -k \sqrt{f_0^2 + (r - r_0)^2}, \quad 0 \leq r \leq a.
\]

Here \(r\) is a polar radius, \(f_0\) is the focal length, \(a\) is a focusator radius, \(r_0\) is a focusing ring radius, and \(k = \frac{2\pi}{\lambda}\) is a wave number.

The range of measured diameters can be increased by synthesizing of several focusators into rings with a different diameters \(d_1, d_2, d_3\) and with a different focal lengths on the DOE surface (figure 3). In this case, size of the focal spot also increases.

![Figure 2. Ring focusing geometry.](image2)

![Figure 3. Truncated cone focusing.](image3)

For holes with diameter from 39 to 41 mm, the error did not exceed 3 μm. The unstraightness measurement results of extended holes using ring focusator showed, that the measurement error of the
displacement range of ± 200 μm equaled 5 μm. For extended holes focusator with the displacement range of ± 400 μm, the error was not more than 3 μm.

3. Spacer grid inspection

Structured illumination method based on multi-ring focusators was proposed for inspection of complex 3D-objects, such as spacer grids of fuel assemblies for nuclear power plants [10, 11]. The method provides the inspection of the following parameters of hexagonal spacer grids: cell diameters; channel holes diameters formed by their bulges; distances between centres of neighboring cells; shifts of cell centres relative to the rated drawing position; overall dimensions of fuel assemblies. For square spacer grids, distances between the opposite bulges are inspected instead of diameters. The errors in measurement of cells diameters and of channel holes diameters should not exceed ± 10 μm, the error in measurement of the distance between cells should not exceed ± 30 μm.

In the proposed method, the speedup is achieved by 3D object inner surface illumination by a multi-ring light probe, which can be created on the basis of DOE. In this case, the measurement of a spacer grid single cell throughout the length is performed by one frame containing all information about its geometry. Also for the multi-ring structured illumination method, the number and location of the cell bulges have no crucial significance, thus the method allows to inspect geometrical parameters of both hexagonal (Russian) and square spacer grids.

The principle of the method is illustrated in figure 4. Rings set structured illumination is formed by a specially designed DOE (multi-ring focusator). It focuses the laser illumination falling on it into a system of rings with equal diameters, which are located along the Z cell axis with a certain step Δz. Illuminated surface of the cell is projected onto the camera photodetector through a special holes inspection lens with a large field curvature and distortion. It focuses sections of a different depth into the plane of the photodetector, while the closer object section is, the greater its image radius is. Two-axis table scan is used for measurement of all cells geometrical parameters and spacer grid geometrical parameters in general. Two-axis table scan moves it in a plane perpendicular to the optical axis of the system.

DOE has the following requirements. It is necessary to inspect from 10 to 15 sections to ensure inspection informativity over the length of a bulge, therefore multi-ring focusator should form the same number of rings on the bulges with a step Δz = 0.5-1 mm. A ring focusing range in radial axis should correspond with a tolerance on a cell center position (0.15-0.3 mm).

Diffractive elements focusing illumination into a system of rings can be created in two ways. First, diffractive element surface can be divided in radial sections, each of which creates one light ring. Secondly, it is possible to create a diffractive element forming a set of light rings along the optical axis.
by the entire surface. In this case, it performs as a hologram, and the transfer function of multi-ring focuser has the following form:

\[ H(\rho) = \sum_{i=0}^{N-1} \sqrt{I_i} \cdot \exp\left[jk\sqrt{(\rho + r_0)^2 + (f_0 + i \cdot \Delta z)^2}\right], \quad \rho_{\text{min}} \leq \rho \leq \rho_{\text{max}} \quad (2) \]

Here, \( I_i \) is a relative intensity of the \( i \)-th light ring, \( r_0 \) is a radius of rings, \( f_0 \) is a multi-ring focuser focal length, \( \Delta z \) is the rings step, and \( k \) is a wave number.

The multi-ring focusators with a diameter of 45 mm can generate up to 20 narrow light rings of equal diameter with a width of 50-100 μm and a depth step in the range 0.5-1 mm. Figure 5 (a) shows the structure of the developed multi-ring focusators.

![Figure 5](image)

**Figure 5.** Diffractive optical element: structure of DOE (a); beam path of the multi-ring focuser (b).

The multi-ring focuser has an operating field, a nontransparent region in the center and an alignment DOE on the periphery. The nontransparent region performs several functions. First, it does not let pass direct radiation from the laser into projection lens. Secondly, this region reduces the angular aperture \( \alpha \) of the operating field (figure 5 (b)), resulting in the surface illumination by radiation without grazing beams. The alignment DOE creates two rings of the same diameter as the operating field (figure 5 (b)). However, in this case, the alignment beams do not intersect the optical axis. Thus, these beams do not enter the aperture of projection lens, if a cell is placed in the inspection area and therefore no aligner rings are observed. DOE operating field radiation scattered from the cell does not fall on the lens aperture, when the cell is absent. In this case, two aligner rings are visible. And it is possible to adjust the receiving optical part relative to the illuminating optical system.

![Figure 6](image)

**Figure 6.** Experimentally obtained intensity distribution of the multi-ring focuser generating 16 rings with a step \( \Delta z = 1 \) mm (a), 2 aligner rings (b).

Figure 6 shows the distribution intensity formed by manufactured DOEs and registered by CCD-ruler (pixel width 14 μm). A special sign (skip of one ring in the middle, figure 6 (a)) is intentionally introduced into the operating field. It allows to number the light stripe correctly during image processing.

Inspection systems of the spacer grid geometrical parameters ("Grid-N") have been developed and created on the basis of the proposed method. The developed system is in operation in "NCCP", Novosibirsk since January 2009. During this time, the system inspected several thousands of spacer grids. Using statistical control methods, "Grid-N" system operation allows to stabilize production.
technological process of the spacer grids, to reduce the number of improvements in products, and to increase the profitability of production.

4. Object cylindrical surface inspection
Measurement objects are fuel pellets of uranium dioxide and fuel rods for nuclear power plants. 3D shape of inspecting surface is reconstructed by applying the DOE. In case of any defects, its geometric dimensions (length, width, depth) calculation is made [12].

Figure 7 illustrates a block diagram of a channel implementing the proposed method of the defects depth determination. The illumination part includes a light source 1 (a semiconductor laser), a collimator 2, a former 3 of light stripe 4 on the inspected object surface 5. The object moves along a guide 6 with a slit 7. The receiving channel consists of a photo camera 8 including a lens 9 and a matrix photodetector 10.

In the inspection position, the light stripe is created on the product cylindrical surface. The light stripes form a ring along its perimeter in a plane perpendicular to the longitudinal axis and at an angle \( \alpha \) to the optical axes of the illuminating blocks. DOEs are operated as light-stripes formers. In case of a defect, the light striped is places. The displacement is determined with a subpixel resolution. A depth of the defect is determined by a calibration curve.

It is necessary to form a light arc on the cylindrical surface by the DOE to measure a defect depth. Light arc is a circle fragment with a diameter equal to the diameter of the inspected cylinder \( D_c \). When using four (three) optical channels, the angular dimension of the arc should be 90° (120°). Here, the calculation method based on the numerical solution of the Fresnel-Kirchhoff integral is operated. The generated field is given in a form of a set of \( N \) dot sources (\( \delta \)-functions) lying on the arc of circle with step \( \Delta \) (figure 8).

![Figure 7. Block diagram of the measuring channel of the fuel pellet inspection device.](image)

![Figure 8. DOE calculation based on the Fresnel-Kirchhoff transformation.](image)

The field at each point of the DOE is described by a superposition of \( N \) impulse responses:

\[
E(x, y) = \sum_{i=1}^{N} \sqrt{I_i} \cdot \frac{e^{ikr_i}}{j \cdot \lambda \cdot r_i}, (2)
\]

Here \( r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + z_i^2} \); \( x, y \) are the coordinates of the point in the DOE plane; \( x_i, y_i, z_i \) are coordinates of the points lying on the arc; \( 1 \leq i \leq N \); \( k \) is a wave number; \( \lambda \) is an optical wavelength, and \( I_i \) is a relative intensity of the points. Figure 9 shows a fragment of a synthesized diffractive structure.
Presented calculation method has a limitation connected with a sampling of the formed light pattern. On the one side, the sample rate $\Delta$ should not be too large. In this case, a broken light stripe is visible on the inspected object. On the other hand, the sample rate should not be reduced greatly due to the interference of neighbour points in the forming stripes. Thus, the optimal value of the sample rate $\Delta_{opt}$ is defined by the condition:

$$\Delta_{opt} < R_{min} \cdot M$$

Here $R_{min}$ is a size of the minimum detected defect (resolution), $M$ is a lens magnification.

5. Ceramic products flatness inspection

At the present day, ceramic products are widely used in many industries. Ceramic products are often produced with high accuracy and tolerances of the order of tenths and hundredths of millimeter. Due to the technological properties of the material, such parts are exposed to 100% dimensional inspection, usually by contact means. Contact of the measuring tool with ceramics leads to rapid wear and to significant economic losses accordingly. The optoelectronic systems for non-contact dimensional inspection of the ceramics products such as ceramic rings, high-voltage insulators, armor plates were developed at TDI SIE SB RAS [13, 14].

Structured illumination as a set of light stripes is used for measuring of the side surfaces position and shape. DOE is used as a former of such illumination. Figure 10 illustrates the DOE beams path. If two DOEs are located on the opposite sides of the object at a certain distance, it is possible to determine a thickness of the product.

DOE focuses falling laser radiation in a system of $N$ light stripes with a step of 1 mm. In order to ensure equal conditions throughout the measurement range, the angle of incidence $\alpha$ and the angular aperture $\Delta\alpha$ for each stripe are equal. The illumination geometry is chosen in such a way that zeroth order of diffraction moves away from the measuring position. To identify the structured illumination stripes correctly, a feature is introduced into the formed pattern. The feature is interval increase between the light stripes in the middle to 1.5 mm. During processing, the feature is detected by a correlation algorithm, and all stripes are numbered from it.

DOEs were produced by using of a circular laser recording system CLWS-300C/M in a binary phase version (diffraction efficiency of about 40%) [15].

When measuring, the position of stripes centers on the side surface of the image is calculated. Calculated values are compared with the reference position of the stripes obtained by calibration with a caliber in the form of a plate with a high degree of surface flatness. Examples of the structured illumination stripes images on metallized and nonmetallized rings are shown in figure 11.

As a result, the industrial inspection systems of ceramic rings and armor plates were created, introduced and actively used. For example, "Ring", "Ring-M" and "KBK-1". The systems have improved characteristics (in comparison with existing ones). It fully meets technical requirements: measurement errors is 5-15 $\mu$m (depending on the parameter), performance speed is not exceed 1 pcs/s. Application of systems in production allows to increase the accuracy and productivity of inspection, to reduce labor costs, to increase the reliability of measurements, to remove the "human factor".
The IV International Conference on Information Technology and Nanotechnology

IOP Conf. Series: Journal of Physics: Conf. Series 1096 (2018) 012009
doi:10.1088/1742-6596/1096/1/012009

Figure 11. The image of the structured illumination stripes on the metallized ring (a); on the nonmetallized ring (b).

6. References

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