3D optical measuring technologies for dimensional inspection

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Abstract. The results of the R & D activity of TDI SIE SB RAS in the field of the 3D optical measuring technologies and systems for noncontact 3D optical dimensional inspection applied to atomic and railway industry safety problems are presented. This activity includes investigations of diffraction phenomena on some 3D objects, using the original constructive calculation method, development of hole inspection method on the base of diffractive optical elements. Ensuring the safety of nuclear reactors and running trains as well as their high exploitation reliability takes a noncontact inspection of geometrical parameters of their components. For this tasks we have developed methods and produced the technical vision measuring systems LMM, CONTROL, PROFILE, and technologies for noncontact 3D dimensional inspection of grid spacers and fuel elements for the nuclear reactor VVER-1000 and VVER-440, as well as automatic laser diagnostic system COMPLEX for noncontact inspection of geometrical parameters of running freight car wheel pairs. The performances of these systems and the results of the industrial testing at Atomic and Railway Companies are presented.

1. Introduction

Modern industry needs measuring noncontact means for dimensional inspection of different articles with high accuracy (resolution is 1 mkm and more) and productivity (up to \(10^5\) measurement/sec) under the wide measurement range. Measuring systems, based on the optoelectronic measurement methods, meet these often contradictory requirements best of all. Absence of mechanical wear due to a noncontact measurement method as well as ability to obtain the detailed information for the inspected articles are additional advantages of such systems [1].

Increasing the safety of nuclear reactors [2] and running trains as well as their high exploitation reliability requires a 100% noncontact precise inspection of geometrical parameters of their components. We have developed methods and produced the technical vision measuring systems LMM, CONTROL, PROFILE, and technologies for noncontact 3D dimensional inspection of grid spacers and fuel elements for the nuclear reactor VVER-1000 and VVER-440, as well as automatic laser diagnostic system COMPLEX for noncontact inspection of geometrical parameters of running freight car wheel pairs.

Below the results of the R & D activity of TDI SIE SB RAS in the field of 3D diffraction and optoelectronic dimensional inspection technologies in atomic and railway industry are presented.
2. **Calculation for diffraction patterns of 3D objects**

For 3D bodies with clear shadow projection, which represent a wide class of objects, the shadow model appears to be approximate and may lead to considerable errors. Since the existing strict and approximate solutions for diffraction problem are extremely difficult for engineering applications [3], urgent necessity appears in creating constructive theory of image formation and filtering of 3D objects and their diffraction patterns. Such theory – simple, physically obvious and at the same time sufficiently strict – was suggested by author for 3D objects of constant thickness [4, 5]. It is based on the model of equivalent diaphragms (distributions) for 3D objects of constant thickness with perfectly absorbing, perfectly reflecting and grey inner surfaces. According to this model the front and rear faces of the object give the main contribution into the field, and the influence of their inner surfaces is supposed to be negligible small and, therefore, results in the absorption or reflection of the waves diffracted on the front face of the object. As a result, the problem of light diffraction on volumetric bodies is reduced to the analysis of diffraction phenomena on the plane objects using the Kirchhoff-Fresnel approximation.

Fraunhofer diffraction patterns (spectrum) of such typical elements of extended bodies as volumetric edge and 3D slit with the absorbing and reflecting inner faces were under investigation. In case of the 3D perfectly absorbing asymmetric slit (Fig.1, a) the generalized point model diffraction has four sources (Fig. 1, b) with the corresponding amplitudes and radiation diagrams (anisotropic Fresnel ones for front face and isotropic diagrams for back face). Their interference determines the distinctive peculiarities being introduced into spectrum by the extension \( d \) of the object. For example, for a symmetric volumetric slit \((D=D_1)\) the 3D effects in the low-frequency domain of its spectrum are reduced to the additional spectrum modulation by low-frequency ("Fresnel") oscillations with the minima when \( \varphi_m = (2m+1) \lambda / d \) \((m = 0,1,2..)\) and also to the decrease high-frequency ("Fraunhofer") oscillations with characteristic size \( \theta_m^{(i)} = \lambda / D \) (Fig. 2).

Using the previous results, one can obtain the dependencies between spectrum characteristic parameters \( (\theta_n, \varphi_m) \) and the geometrical dimensions of 3D absolutely absorbing and reflecting edge and slit. For instance, the width \( D \) and extension \( d \) of the first object can be reconstructed under \( N = \theta_n / \theta_0 \gg 1 \) \((\theta_0 = \sqrt{\lambda / d} \) is the critical angle, \( \theta_0 \) is observation angle) as follows:

\[
d = (2m + 1) \lambda / \varphi_m^2, \quad D = 0.225 \sqrt{d} + n \lambda / \theta_n
\]

According to estimations, the theoretical error to determine the longitudinal dimension with typical parameters of the optical system constitutes ~1%. As for the transverse dimension, the accuracy of its determination (as compared to the traditional method) increases ten times and can constitute ~ 0.1%.

![Figure 1. The 3D perfectly absorbing asymmetric slit (a) and its generalized diffraction model (b).](image1)

![Figure 2. Spectrum of the 3D symmetric perfectly absorbing slit \((d=1 \text{ mm and } D=0.277 \text{ mm})\), points are experimental data, solid line is calculated ones.](image2)
3. Inspection of holes parameters using a ring diffractive focuser

Dimensional inspection of articles with holes is a actual problem in industry. Since the known systems for hole inspection either are bulky and have a small measurement range (pneumatic sensors) or are affected by material parameters (capacity sensors) [6], we have developed noncontact laser method for holes inspection using diffractive optical elements (DOE). This measurement method involves DOE’s formation of an illuminated area as a ring on the inner cylindrical surface of the inspected article, and processing of the obtained image (Fig. 3). The mark is observed by a projecting conical mirror and a CCD camera. The image is processed by computer. Displacement of the article along optical system axis is produced by a transport device. Using this method, one can inspect the diameter, nonstraightness of the hole axis, deviation of the hole shape, and quality of the inner surface. As an example, Fig. 4 illustrates the behavior of the ring mark image under measurement of the hole axis nonstraightness.

![Figure 3. Principle of holes inspection: 1 – laser; 2 – collimator; 3 – DOE; 4 – object under inspection; 5 – conical mirror; 6 – CCD-camera; 7 – computer; 8 – transport device.](image1)

![Figure 4. Modification of the ring mark image versus the hole axis bending; a – object with axis bending; b – ring mark image.](image2)

Using this method, the diameter, shape, and hole axis deviation from straightness have been measured experimentally. The diameter measurement error and the axis deviation did not exceed ±3 μm.

4. Technical vision optical electronic systems for dimensional inspection

4.1. 3D grid spacers inspection technology

A grid spacer for reactor VVER-1000 is multicell piece like honeycombed cellular structure (Fig. 5). Each cell of the grid spacer represents a hollow thin-walled integral prism, 20 mm in height, with three cylindrical protrusions in the direction of the cell center. The measuring technology must allow to inspect the following parameters of grid spacers (Fig. 6): diameters of the circumferences inscribed in the cells; diameters of the circumferences inscribed in the guide channels; the distances between neighbouring cells (center-to-center distances), the centers shifts of the inscribed circumferences for cells relative to grid spacer design drawing (the position shifts); overall dimensions “for spanner”.

Since the use of contact coordinate measuring machines (CMM) for 3D measurements of grid spacer geometry is associated with high time expenditures (up to 64 hours), we have developed and created the specialized noncontact high-efficiency laser measuring machine (LMM) [7], which is based on a multipoint structured illumination. A cell image under multipoint structured illumination before and after digital processing is shown in Fig. 7.
The laser measuring machine includes the three-channel laser-electronic measuring head for cell and channel holes perception (according to three protrusions of a cell), scanning X-Y table, electronics and software (Fig. 8). The scanning X-Y table with the working displacements $300 \times 300 \text{mm}^2$ (OFL-2121 SM) ensures a controlled displacement of the grid spacer in the view of the photoreceiver unit and a rotation of the grid spacer in the X-Y plane. LMM allows to measure with some micron resolution all geometrical parameters of grid spacers.

Some methods of the measurement result visualizations have been developed. One of them represents diameters in the form of a cartogram of the grid spacer with colour distinction between cells and channel holes (Fig. 9).
According to another visualization method, shifts of centers cell and channels holes are displayed as the vector cartograms with vectors going out of cell and channel centers. The appropriate modules of vectors and their directions represent the centre cell shifts.

One can inspect the individual sizes and a 3D configuration of any cell or channel hole. The result of the measurement of one cell is shown in Fig. 10. Here, diameters $D_c(j)$ and coordinates $X_c(j), Y_c(j)$ of the inscribed circumferences centers in 16 cross-sections ($1 \leq j \leq 16$), as well as 2D graphs and 3D configuration of the cell hole are presented.

The laser measuring machine has gone through a complete cycle of tests at the Novosibirsk plant JSC NCCP and since 2002 year LMM is under industrial operation. Its productivity is 12 min, which is 300 times faster than CMM. Its application made it possible to obtain objective information about the geometry of grid spacers, which allowed to improve the manufacturing technology and to increase quality of fuel assemblies for nuclear reactors.

4.2. Optoelectronic systems for fuel elements inspection

The following geometrical parameters of fuel elements are liable to 100 % inspection (Fig. 11): the external diameter $D$ of the cladding, the length $L$ of fuel elements, the deviation from straightness of the cladding axis (curvature) $B$ on the 250 mm base, the deviation of the end of the upper end plug from the axial line $H$ (on the 125 mm base). Therein diameters $D$ must be measured in orthogonal (transverse) sections of the cladding for detection of possible ovality of tubes.

For automatic noncontact fuel element dimensional inspection we have developed and produced optoelectronic systems CONTROL using shadow image methods. They are incorporated into technological line of fuel elements production at the JSC NCCP (Fig. 12). The measurement error of the fuel elements geometrical parameters external diameter $D$, deviation $B$, and length $L$ (at the confidence probability of 0.95) were established as follows: $\delta D = \pm 0.008$ mm; $\delta B = \pm 0.015$ mm; $\delta L = \pm 0.15$ mm. Therein, the operation speed was 130 measurements per second. Since 2002 year the systems CONTROL are under industrial operation. On the course of industrial operation of the device CONTROL, tens of thousands of VVER-1000 fuel components have been inspected.

4.3. Low-coherent profilometer PROFILE for fuel element surface defect inspection

The surface defect inspection by noncontact methods is an important problem. The most promising method is the low-coherent interferometry [8]. Using two conjugated recording channels for selecting the interference fields doesn’t allow obtaining high accuracy characteristics due to the nonidentity of these channels. We have developed the new single-channel low-coherent method for 3D profile imaging, which provides high accuracy and reliability of the measurements. Using this method the profilometer PROFILE (3D digital microscope) and technology for surface defect measurements were developed (Fig. 13).
The results of measured 3D surfaces with defect as “mark” are represented in Fig. 14. The effectiveness of the profilometer is verified by the measurement of the profile defects, including the fuel element depth. PROFILE was successfully tested under the industrial conditions: measurement area is 2.3 mm × 2.3 mm; resolution equals to 1 μm; surface reconstruction error is less than 2 μm; surface reconstruction range on depth is 10 mm; scanning speed equals to 4 sections per sec. During two years the profilometer is under industrial operation at JSC NCCP.

Figure 13. The profilometer PROFILE for 3D surface measurements. Figure 14. Defect as “mark”. Measurement area: 0.43 × 0.43 mm².

5. Geometrical parameters inspection of running freight car wheel pairs
Ensuring the safety of running trains is the actual task of railways exploitation and transport of passengers and cargoes all over the world. Regular inspection of wheels for detection of defects is the main task of movement safety, especially for high-speed trains. We have developed high-speed laser noncontact method for geometrical parameters inspection of moving 3D objects with the fast position sensors PSD (5·10⁵ - 10⁷ meas/s). This method is based on the triangulation principle of wheel self-scanning (Fig. 15). A laser diode beam is focused on the surface of the moving object under inspection. The scattered beam is gathered by the aperture of a receiving objective, which forms an image of the illuminated surface zone in the PSD plane. Subsequent coprocessing of the signals (from different sensors) by signal processor makes it possible to determine the rolling surface profile and the required geometrical parameters.

Using this method we have produced automatic laser diagnostic system COMPLEX for noncontact inspection of the following geometrical parameters of wheel pairs: width and thickness of wheel rim, distance between inner sides of wheels, thickness of wheel flange, uniform rolling, wheel diameter, difference of wheel diameters for a wheel pair, axle sliding-off. The obtained measuring error is about 0.5 mm. Measurements are fulfilled at freight cars speed up to 60 km/hr. The range of working temperatures is from −50°C up to +50°C. External view of this COMPLEX is presented in Fig. 16. The developed diagnostic system COMPLEX corresponds to the best world prototypes. At present eleven systems COMPLEX are in operation on 6 Russian regional Railways (from Moscow to Far East). As a result, more than 40 million of wheels have been inspected and more than 14,000 freight cars with defective wheel pairs have been uncoupled. Using these systems allows to improve significantly the safety of railway industry in Russia.

6. Conclusion
The results of the R & D activity of TDI SIE SB RAS in the field of the 3D optical measuring technologies and systems for noncontact 3D optical dimensional inspection are presented. This activity includes investigations of diffraction phenomena on some 3D objects, using the original constructive calculation method, development of hole inspection method using diffraction optical
elements, as well as the methods and 3D optical measuring systems LMM, CONTROL, PROFILE, COMPLEX and technologies for safety increasing in atomic and railway industry.

The created systems LMM, CONTROL, PROFILE are incorporated directly into the technological lines of fuel assembly manufacturing at the JSC NCCP and make it possible to carry out 100% inspection of all the required geometrical parameters of fuel elements.

For the first time, we have developed the automatic laser diagnostic system COMPLEX for noncontact inspection of geometrical parameters of running freight car wheel pairs. Measurements are fulfilled at freight cars speed up to 60 km/hr under working temperatures ±50°C. At present eleven systems COMPLEX are successfully operating on Russian regional Railways and allow to improve significantly the safety of railway industry in Russia.

The obtained results are applied to many industrial fields, including mechanical engineering, automobile industry, hydropower engineering, etc.

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