Optical Measuring Systems and Laser Technologies for Scientific and Industrial Applications

Yu.V. Chugui

Technological Design Institute of Scientific Instrument Engineering (TDI SIE)
Siberian Branch of the Russian Academy of Sciences (SB RAS)
41, Russkaya str., Novosibirsk, 630058, Russia
Email: chugui@tdisie.nsc.ru

Abstract. *The novel results of the R & D activity of TDI SIE SB RAS in the field of the optical measuring technologies, as well as laser technologies for solving actual problems are presented. The metrological characterization of a perspective Fresnel method for high precision measuring the dimensions of objects is investigated. An optoelectronic noncontact method using diffractive optical element for the 3D inspection of article holes is presented. For permanent noncontact bearing position inspection of oil-drilling platforms on Sakhalin coast (Russia) under extreme temperatures (± 40°C) we have developed optical-electronic method and system SAKHALIN. Multifunctional laser technological system LSP-2000 equipped by two Nd-YAG lasers was developed for cutting, welding and surface micro profiling with ablation process (working range of* $3 \times 3 \times 0.6\ m^3$*, positioning error less than 10* μm*). Safety of Russian nuclear reactors takes 100 % noncontact 3D dimensional inspection of all parts of fuel assemblies, including grid spacers. Results of development and testing the specialized high productive laser measuring machine, based on structured illumination, for 3D inspection of grid spacers with micron resolution are presented.*

Keywords: optical inspection, structured light and shadow methods, laser technology, safety

1. Introduction

Solving many actual safety problems in mining, oil, atomic and railway industry as well as in science takes noncontact optical measurement technologies with micron resolution and productivity up to 10^5 meas/s [1]. We have researched, developed, implemented and tested some novel optical measuring systems and laser technologies.

Modern industry and market impose stringent requirements for noncontact meters as for the accuracy, price, mass, and their size. Since the shadow and laser scanning meters do not always satisfy these demands, we have investigated Fresnel method for dimensional inspection [2].

One of the urge measurement problems is inspection of object holes [3]. We have developed optical inspection method using diffraction optical element (DOE) as a ring diffractive focuser. It allows to create a small-size probe to inspect the hole diameter, nonstraightness of hole axis, deviation of the surface shape from a cylindrical one, and the surface quality [4].

Oil-drilling platforms which are placed on four friction pendulum bearings take permanent noncontact bearing position inspection and travelled distance measurement especially under operating extreme temperature range (± 40° C) in case of Sakhalin coast (Russia). We have developed optical-electronic SAKHALIN system [5]. Functional possibilities and experimental results for this system are presented.

For laser material processing (cutting, welding) of 3D large-size objects and treatment (ablation) of their surfaces we have developed multifunctional universal laser technological system equipped by two Nd-YAG lasers with 5-coordinate (X-Y-Z-φ-θ) table and CNC system. Below the LSP-2000 technical peculiarities and performances are given.

Safety of nuclear reactors VVER-1000 and VVER-440 [6] and ensuring their high exploitation reliability takes 100 % noncontact inspection of all parts of fuel assemblies, including grid spacers. We have developed and produced the specialized laser measuring machine, based on structured illumination, which enables 3D inspection of grid spacers with micron resolution and high productivity (some hundred times faster than CMM).

2. Dimensional inspection by Fresnel method

The essence of the Fresnel measurement method is presented below. The object described by amplitude transmission $f(x_1,y_1)$ (plane P_1) with geometrical parameters $\{D_i\}$ ($1 \le i \le M$) is illuminated by a plane monochromatic light wave with amplitude E_0 and wavelength λ (Fig. 1). At distance z from the object (under Fresnel number $N_{Fr} = D^2/4\lambda z >> 1$) a Fresnel image is formed as an amplitude distribution $g(x_2,y_2)$ (plane P_2), which is equal to the convolution of the input distribution $f(x_1,y_1)$ with the impulse response of free space $h(x_2,y_2) = (1/i\lambda z)\exp[ik(x_2^2 + y_2^2)/2z]$ [2]:

$$g(x_2,y_2) = E_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x_1,y_1)h(x_2 - x_1, y_2 - y_1)dx_1dy_1 \tag{1}$$

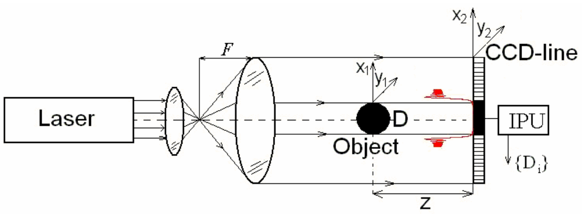

Fig. 1. Structure scheme of the Fresnel meter.

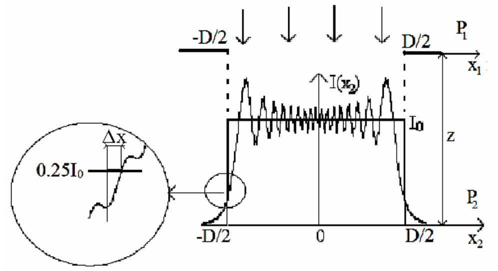

Fig. 2. Slit Fresnel image. P_1 and P_2 are object and image planes.

The light intensity distribution $I(x_2,y_2) = |g(x_2,y_2)|^2$ thus obtained is recorded by a multielement linear photodetector (CCD-line array). The sought-for geometrical parameters $\{D_i\}$ of the object are calculated after output signal processing by information processing unit (IPU). For instance, in case of inspected object as a slit with width D the locations of the object boundaries correspond to points $x_2 = \pm D/2$ (N_{fr}>>1), in which the output intensity constitutes 25% of the incident radiation intensity $I_0 = E_0^2$: $I_{thr} = 0.25 I_0 \approx I(x_2 \approx \pm D/2)$.

However, there are some factors, first of all, non-uniform illumination that can deteriorate the above characteristics. The non-uniform wave, illuminating the object as half-plane $Y(x_1)$ (Heaviside step function), was simulated by using a harmonic distribution (Fig. 3):

$$E_{out}(x_1) = E_0[1 + \alpha\cos(\omega x_1 + \varphi)]Y(x_1) \tag{2}$$

Here, $\omega = 2\pi/T$ is the angular spatial frequency of oscillations (T is the period), φ is the initial phase of oscillations, and the parameter α denotes the amplitude of non-uniformity ($0 \le \alpha \le 1$). Using Eq. (1), Eq. (2) one can obtain the following expression for the intensity distribution in the plane P_2:

$$I_{out}(x_2) = |g(x_2)|^2 = I_0 \left| \tilde{Y}(x_2) + 0.5\alpha e^{-iz\omega^2/2k} [e^{i(\varphi+\omega x_2)} \tilde{Y}(x_2 - \beta) + e^{-i(\varphi+\omega x_2)} \tilde{Y}(x_2 + \beta)] \right|^2 , \quad (3)$$

where $\beta = z\omega / k = \lambda z / T$. We have investigated measurement error due to object non-uniform illumination. It is evident that such illumination leads to object boundary displacement and, for instance, for a half-plane edge (typical fragment of many objects) this displacement Δx_{nonun} has analytical form and under $T >> \sqrt{\lambda z}$ can be decreased significantly by appropriate threshold correcting:

$$\tilde{I}_{thr} = 0.25 I_{in}(0)[1 + \Delta i / \sqrt{2}\pi I_{in}(0)], \quad (4)$$

where $\Delta i = I'(0)\sqrt{\lambda z}$, and $I'(0) = I_{\max} 4\pi^2 B / T^2$, B is distance between edge location and center of working field, where maximum output intensity $I_{\max}$ takes place (Fig. 4). One can see that the influence of non-uniformity on the structure of the edge Fresnel image is local. Moreover, this effect is determined by the degree of non-uniformity of the beam illuminating the object within the Fresnel zone size $\sqrt{\lambda z}$. According to algorithm (4) the value Δx_{nonum} can be decrease by a factor of more than 40.

We have investigated the effectiveness of the proposed algorithm (Eq. (4)) as for account of non-uniformity influence under object displacement in measuring area 5 × 5 mm^2 (for object diameter from 0.5 to 18 mm). The experimental error didn't exceed 1 μm. Using obtained results we have developed prototype of industrial device for diameter measurements of cylinder objects.

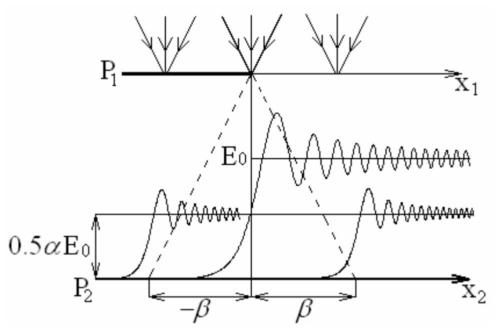

Fig. 3. Edge Fresnel image under non-uniform harmonic type illumination.

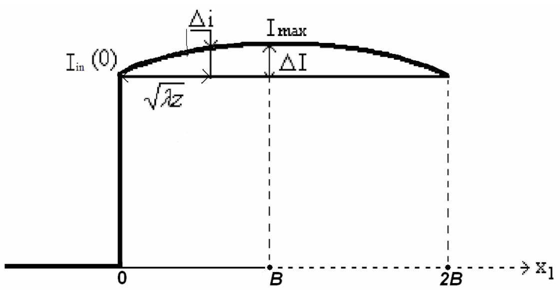

Fig. 4. Threshold choosing for weak non-uniform illumination under information processing.

3. Inspection of holes parameters using a ring diffractive focuser

The quality of articles with holes is characterized by the following parameters: straightness, deviation of the diameter from a nominal value and the shape deviation from a cylindrical one. The contact devices for the inspection of holes (plug gauges, like plugs and inside callipers) have significant disadvantages: the working surfaces wear rapidly, the efficiency is low and there is a high risk of inspected surface damage. The proposed structured noncontact method for the inspection of the parameters of holes is free from the above disadvantages [4].

The principle of hole inspection is illustrated by Fig. 5. A laser beam impinges to collimator 2 and DOE 3, which forms a ring mark on the inner surface of article 4. The mark is observed with the help of projecting conical mirror 5 and camera 6. The image is processed by computer 7. Device 8 moves the article along optical system axis. With this method, one can inspect the diameter, nonstraightness of the hole axis, deviation of the hole shape, and quality of the inner surface.

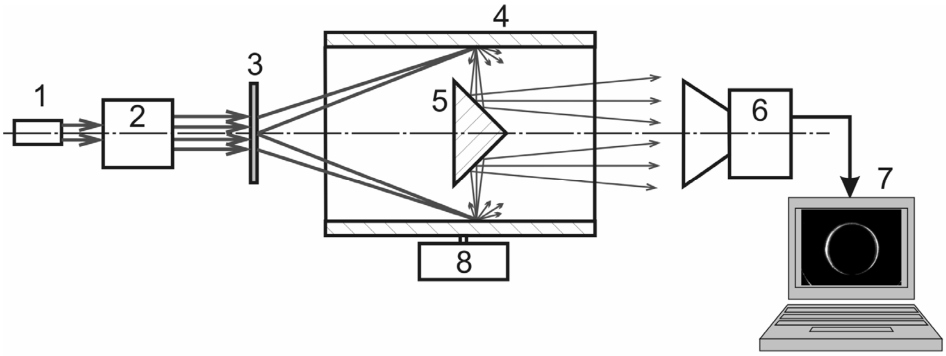

Fig. 5. Principle of holes inspection by DOE: 1 – laser; 2 – collimator; 3 – DOE; 4 – object under inspection; 5 – conical mirror; 6 – CCD-camera; 7 – computer; 8 – device for detail moving.

Measurement of the hole axis nonstraightness is illustrated by Fig. 6. In position I (Fig. 6a), the axis of the hole coincides with that of the measurement system. The image of the ring mark (Fig. 6b) in the photodetector matrix is a circle with its center at the optical axis. In cross-sections II and III (Fig. 6a), the axis of the article does not coincide with that of the system. Therefore, the images of the ring mark are shifted with respect to the center.

As the diameter of the hole changes, and the optical axis of the system is not shifted with respect to that of the hole, the image of the optical mark is a circle whose radius changes depending on the diameter of the hole. As the diameter of the hole increases, the radius of the circle decreases.

In experiments we have used DOE with diameter 40 mm and the minimum period of diffractive zone 2,5 μm, which was produced by a circular laser photoplotter CLWS-300/C-M [7] by using a thermochemical technology on the base of chromium films on glass substrates with subsequent liquid etching. The diameter of the conical mirror was 15 mm. A standard article with cylindrical step-shaped holes with diameters from 39,3 mm up to 40,7 mm was used. The location of the light distribution maximum on the inner surface is a nonlinear function of the hole diameter. This dependence was determined experimentally for each DOE. Experimental error didn't exceed 2,5 μm for the measurement of hole diameters by a ring focuser.

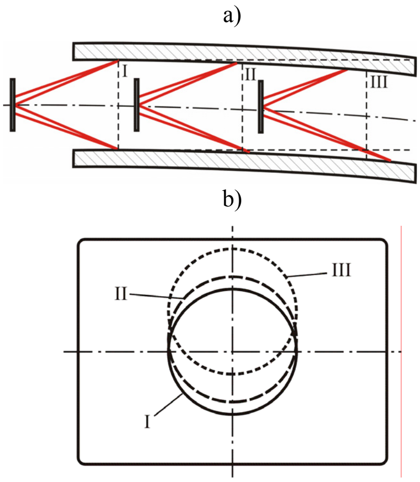

Fig. 6. Modification of the ring mark image versus the hole axis bending; a – object with axis bending; b - ring mark image.

4. Friction pendulum bearing displacement measuring technology for oil platform

As it is known, the mining of oil and gas offshore is carried out using the drilling platforms, which are extremely massive (28 000 tons) and inert (Fig. 7). In order to avoid excessive stresses on platform it consists of few large parts (normally base and legs). Four friction pendulum bearings are used for mechanical link between the base and legs. The bearings functionality is to provide the protection of the platform from all possible mechanical loadings on the legs that might affect the base with the drill and other sensitive equipment (seismic movements, ice shifts, etc.).

Normally in the majority of regions around the world the bearings lifetime is at least 30 years of continuous use. The corresponding lifetime for the Sakhalin shelf, according to the estimations of scientists, can be from one to ten years, which is much shorter that the normal service life period of the drilling platform. The most important parameter, which allows to estimate the bearing resource, is measuring the cumulative distance travelled by the bearing from the beginning of its service (no more than 3 km). As soon as cumulative travel exceeds that distance the bearings should be replaced.

For measurements of bearings movements the automatic optical-electronic system SAKHALIN was developed [5]. Its main aim is continuous noncontact measurement of the bearing location and calculation of the total distance traveled by the bearing for any defined time period.

Measuring principle of the system (Fig. 8) is based on optical image processing. The passive part of the system (optical target) is fixed on one part of construction, while active part – a field measurement sensor – is installed on another part of construction that moves relative to the first one. This sensor continuously captures and processes the image of optical target. On the output, after processing the relative displacement these two parts of construction is obtained with high degree of accuracy.

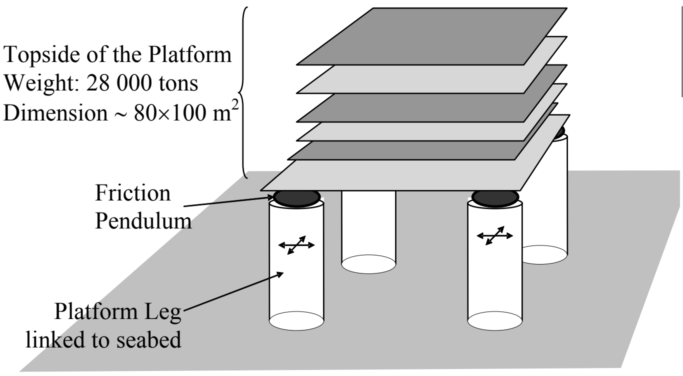

Fig. 7. An oil-drilling platform scheme.

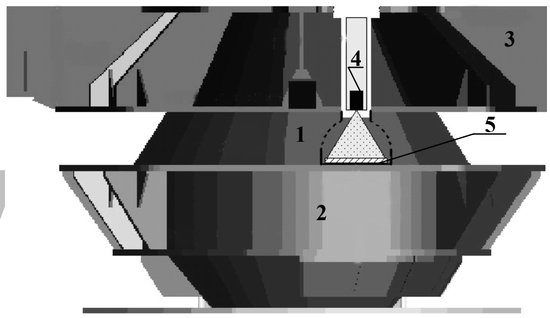

Fig. 8. Measurement system location on oil-drilling platform: 1 - slider bearing, 2 - support, 3 - platform, 4 - image unit, 5 - target.

The system SAKHALIN (Fig. 9) is certified as a measuring tool as well as for the use in explosive environments (for gas and oil industry). It is designed for continuous 24-hours operation during 30 years. Its main technical characteristics are the following: measurement range on the X and Y axes is ± 350 mm; absolute error in the measurement range is ± 0.6 mm; measurement rate is 30 meas./s.; maximum movement speed of the objects under measurement without accuracy loss is from 0 up to 4 m/s.; working temperature for control panel is from 0 up to + 40ºC. This system was put through tests accepted by customer.

This system SAKHALIN can also be used for the 24-hours monitoring of shifts and deformations of different parts of another mechanical and engineering constructions. It has capability to provide alerts in emergency cases, i.e. excessive construction strains, displacements, earthquake, tsunami events, etc. At the present time this system is installed on Sakhalin oil-drilling platform (Fig. 10).

Fig. 9. System SAKHALIN: optical measuring and electronic units.

Fig. 10. System SAKHALIN.

5. Laser technological system LSP-2000

For processing and treatment of 3D articles – cutting, welding and surface micro profiling with ablation process – we have developed the multifunctional laser technological system LSP-2000, which is equipped by two Nd-YAG lasers. The robotics for the laser head positioning and CNC control interface are provided for processing and treatment of parts with arbitrary topology. The system spatial working range is about $3 \times 3 \times 0.6$ m^3. Inside this range all types of laser processing operations can be performed with contour displacement accuracy about ± 10 μm for any point of trajectory. The general view of the system is presented in the Fig. 11.

The LSP-2000 was developed as the universal laser processing system with unique combination of some technical parameters. These characteristics are listed below:

- **Multifunctionality.** It means the ability to perform a range of technological and processing operations. Each operation using laser processing heads requires positioning accuracy, different positioning speed and movement patterns depending on the operation. This requirement was fulfilled using two types of technological lasers. The first laser MLTI-500 for cutting and welding (produced by "Tulamashzavod") has the following parameters: the pulses repetition frequency is 300 Hz, average power output is 500 Wt, laser wavelength is 1.064 μm. Its purpose is laser cutting and laser welding of any metals with thickness of less then 6 mm. The second laser for ablation of thin metal films on dielectric surfaces has pulses repetition frequency of 300 Hz, high pulses power (> 10^7 Wt), laser wavelength is 0.532 μm, and average power output is 10 Wt.

- **Large processing working field ($3 \times 3 \times 0.6$ m^3).** The absolute positioning accuracy in the whole working field is better than 10 μm. The special XYZ movement stage was developed in order to move the tool (laser processing heads, etc) to anywhere in the working field with required accuracy. The stages movements are controlled by the special CNC system. The positioning of each stage is feedback-controlled and based on the linear incremental optical sensors, which provide the required stage position information (position error 1 μm).

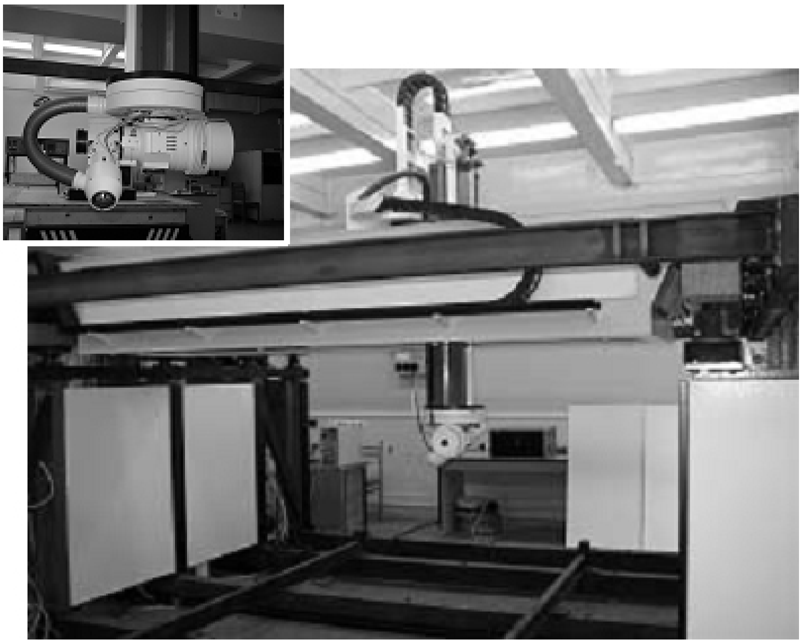

Fig. 11. Laser technological system LSP-2000 and enlarged fragment of its working processing head.

- **The ability to process the articles with the arbitrary surface shapes.** For that purpose the processing head can make the movements with 5 degrees of freedom. The processing head can be moved by XYZ carriage for bringing the head to the desired processing region. Also, two more possible movements are added in polar coordinates system. The head could rotate azimuthally and vertically (C and B coordinates) in the processing region, thus it allows to orient the head perpendicularly to any of surface element of the arbitrary 3D object, which is under processing.

- **Long term parameters stability.** One of the main tasks of the current system is micro profiling of the large-size articles. The expected time for the single article processing is approximately 30 hours. The system is designed for continuous 24 hours work. At the same time it is required to keep high reproducibility and high processing accuracy for the all service life of the current system without any additional tuning. The long term stability of this device was provided using the linear motors and sliding parts having the air gap. The air gap in the moving parts makes the system mechanics frictionless and it is provided with the compressed air or pneumatic bearing principle.

The LSP-2000 system has the following technical performances:

Coordinate table travel range	$3 \times 3 \times 0.6$ m^3
Maximum size of the processing parts	$3 \times 3 \times 0.6$ m^3
Geometrical shapes of the processing parts	arbitrary
Uncertainty of system positioning in start-stop regime	≤ 2 μm
Uncertainty of system positioning along arbitrary movement loop	≤ 10 μm
Maximum head movement speed	10 m/min
The material for ablation	Al, NI-Cr alloy
Optical head weight	≤ 6 kg

The material for laser cutting and welding	Ti, stainless steel
The maximum cutting thickness (for Ti)	6 mm

At the present time LSP-2000 is under industrial operation.

6. 3D grid spacers inspection technology

As known, a grid spacer for reactor VVER-1000 is multicell piece like honeycombed cellular structure (Fig. 12). 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. 13): diameters $D_c^{(n)}$ of the circumferences inscribed in the cells; diameters $D_{ch}^{(m)}$ of the circumferences inscribed in the guide channels; the distances between neighboring cells $L^{(k)}$ (center-to-center distances), i.e. distances between the centers of the inscribed circumferences in the cells; the centers shifts of the inscribed circumferences for cells relative to grid spacer design drawing $S^{(q)}$ (the position shifts); overall dimensions $B^{(p)}$ "for spanner".

Since the use of existing universal contact coordinate measuring machines (CMM) for 3D measurements of grid spacer geometry is associated with high time expenditures (up to 4 hours), we have created the specialized noncontact high productive laser measuring machine (LMM) [6].

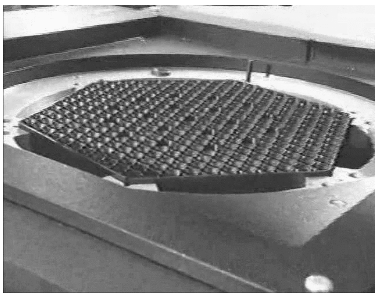

Fig. 12. A grid spacer for reactor VVER-1000.

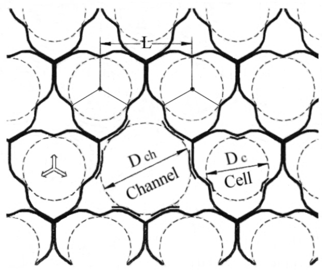

Fig. 13. The grid spacer geometric parameters under inspection.

For solving this task we have developed the modified method, which is based on a multipoint structured illumination. It ensures fast, noncontact, automatic 3D-measurements of many objects. The multipoint structured light method based on illumination of 3D inspected objects by 2 D point array matrix, which may be generated by kinoform elements such as, e.g., two crossed Dammann arrays (Fig. 14). In order to overcome uncertainty in determining the object position and shape, we have introduced singularity into the laser beam matrix structure as period malfunction.

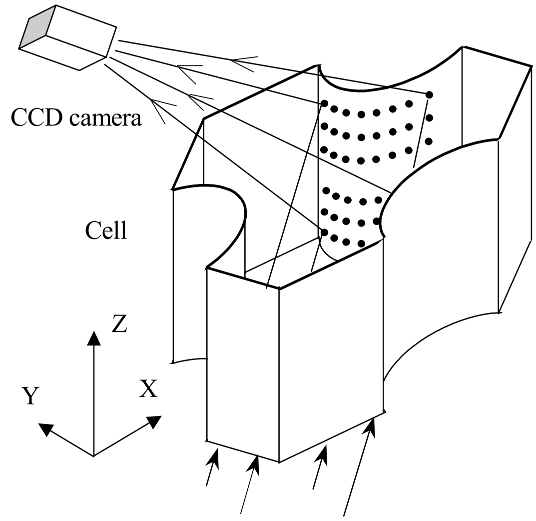

Fig. 14. The multipoint structured illumination 3D inspection method applied to a single segment of grid spacer cell.

In the case of 3D inspection of grid spacer cells, consisting of three protrusions, it takes three 2D laser beams matrixes (for simplicity only one light matrix is shown).

The laser measuring machine includes three-channel laser-electronic measuring heads for cell and channel holes perception, scanning X-Y table, electronics and software (Fig. 15). The scanning X-Y table with the working displacements 300 × 300 mm^2 (OFL-2121 SM) ensures a controlled displacement of the grid spacer in the view of the photoreceiver unit in the direction of X and Y coordinates and a rotation of the grid spacer in the X-Y plane.

Three methods of visualization and inspection of measurement results are envisaged. The first of them represents diameters in the form of a cartogram of the grid spacer with colour distinction between cells and channel holes. According to the second visualization method, the shifts of centers cell and channel holes ($S^{(q)}$) are represented as grid spacer cartograms with vectors going out of cell and channel centers. The module of vectors and their directions on appropriate scale illustrate the inspected shifts and the colours of vectors designate their belonging to the tolerance. And, finally, in the representation of the distances between neighbouring cells (center-to-center distances) $L^{(k)}$, one can see on the screen the grid spacer "skeleton": dashed lines connecting the drawn centers of cells and channel holes designate normal situations (within the tolerance), while solid lines designate distances between cells going beyond the tolerance gap.

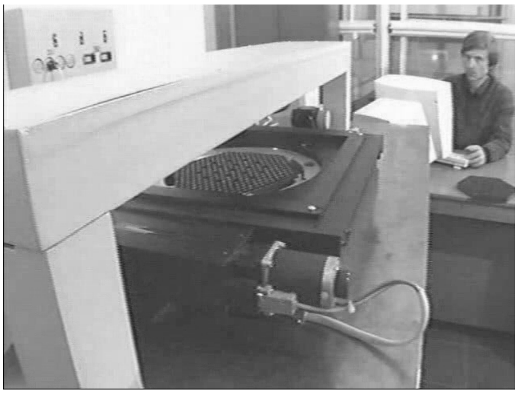

Fig. 15. The laser measuring machine under operation.

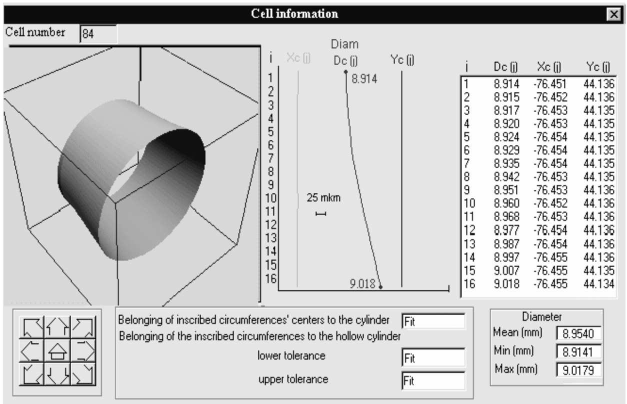

Fig. 16. The individual geometric information from LMM about every cell hole of the grid spacer: its 3D image, the diameters $D_c(j)$ and the centers coordinates $X_c(j)$, $Y_c(j)$.

In all represented methods, 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. 16. Here, diameters $D_c(j)$ and coordinates $X_c(j)$, $Y_c(j)$ of the inscribed circumferences centers in 16 cross-sections ($1 \le j \le 16$), as well as 2D graphs and 3D configuration of the cell hole are presented.

The laser measuring machine for 3D inspection of grid spacers has gone through a complete cycle of tests at the Novosibirsk plant JSC NCCP. The time of measurement of the indicated grid spacer parameters does not exceed 12 min, which is more than 300 times faster than existing universal contact coordinate measuring machines. At present LMM is under operation at the Novosibirsk plant JSC NCCP.

7. Conclusion

The novel results of TDI SIE in the field of the optical measuring and laser technologies applied to science, oil and atomic industries as well as railway transport are presented and discussed.

The metrological characteristics of a Fresnel method for dimensional measurement have been investigated. The proposed algorithms allow to decrease measurement error up to one micron. The Fresnel method allows to develop compact nonexpensive meters.

An optoelectronic noncontact method for the inspection of article holes using DOE was studied. The method makes it possible to measure the deviation of the hole axis from a straight line, to inspect the shape, diameter and hole surface. Experimental error didn't exceed 2,5 μm.

For the first time we have developed system SAKHALIN for the 24-hours for noncontact bearing position inspection of oil-drilling platforms on Sakhalin coast (Russia), as well as for monitoring of shifts and deformations of very huge mechanical and engineering constructions in emergency cases, i.e. excessive construction strains, displacements, earthquakes, tsunami events, etc.

Multifunctional laser technological system LSP-2000 is effective equipment for material processing and 3D treatment. If one built-in the additional measuring probes, LSP-2000 can be used as coordinate measuring machine with very large measuring volume.

In atomic industry the developed and produced laser measuring machine has allowed to obtain objective information about the geometry of grid spacers which were subsequently used for further improvement of production of fuel assemblies for Russian nuclear reactors VVER-1000 and VVER-440.

The obtained results are applied to other industrial fields, including mechanical engineering, automobile industry, hydropower engineering, and so on.

References

[1] Brown Gordon M., Harding Kevin G., Stahl H. Philip: Industrial Application of Optical Inspection, Metrology, and Sensing. Proc. SPIE, 1992, 1821.

[2] Chugui Y.V., Yakovenko N.A., Yaluplin M.D.: Metrology for Fresnel measuring method. *Measurement science and technology*, Institute of physics publ., 2005, 16, 1-4.

[3] Garbini J.L., Saunders R.A., Jorgensen J.E.: In process drilled hole inspection for aerospace applications. *Precision Engineering* IV, 1991, 125-134.

[4] Chugui Yu.V., Finogenov L.V., Kirianov V.P., Nikitin V.G., Sametov A.R., Zavyalov P.S.: An optoelectronic method for comprehensive hole inspection. Proc. 8th International Symposium on Measurement and Quality Control in Production, Erlangen, Germany, 2004, 635-642.

[5] Chugui Yu.V, Plotnikov S.V., Potashnikov A.K., Verkhogliad A.G.: Novel optical measuring systems and laser technologies for science and industry. Proc. SPIE, 2006, 6280.

[6] Bityutsky O.I., et al.: Laser measuring machine for 3D noncontact inspection of geometric parameters of grid spacers for nuclear reactors VVER-1000. Proc. SPIE, 2002, 4900: 202-212.

[7] Kiryanov V.P.: Laser setup for flat optical components fabrication with submicron resolution. Proc. SPIE, 1997, 3091: 66-70.