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OPTICAL MEASURING TECHNOLOGIES AND SYSTEMS FOR ATOMIC INDUSTRY

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Abstract – Ensuring the safety of nuclear reactors and their high exploitation reliability requires a 100 % noncontact precise inspection of geometrical parameters of their fuel elements and grid spacers. For the solution of this 3D inspection tasks we have developed and produced laser measuring machine (LMM) using multipoint structured illumination and optoelectronic shadow systems «Control – 1» and «Control – 2». The measurement methods, structures, operation and software of LMM and systems are described. The results of their industrial testing are presented and discussed.

Keywords: optical inspection, nuclear reactor

1. INTRODUCTION

Safety of nuclear reactor and ensuring their high exploitation reliability are urgent problem of nuclear power engineering [1]. It makes strict demands on geometric parameters of fuel assemblies and first of all, fuel elements and grid spacers. It takes 100 % dimensional inspection of these pieces.

Measuring systems must be noncontact to avoid damage of the fuel element cladding tube surfaces which may lessen their corrosion resistance, ensure a high accuracy of dimensional measurements (resolution of a few µm) and high productivity (more than hundred measurements per second) within a wide range of measurements (tens of mm). These requirements are met in the highest degree by optoelectronic measurement means [2].

The equipment for atomic power stations produced in Russia by the plants of Joint-Stock Company (JSC) TVEL is based mainly on two pressurized water reactors VVER-1000 and VVER-440 using thermal neutron [1]. Their basic components, fuel assemblies contain several hundreds fuel elements with a diameter of more than 9 mm and a length of 2.5 to 4 m, grid spacers and the bearing skeleton (frame).

Due to the absence of available ready – made measuring equipment for this inspection problem, TDI SIE SB RAS has developed measuring technologies and manufactured laser measuring machine and optoelectronic systems for automated noncontact dimensional inspection of grid spacers and fuel elements for nuclear reactors.

2. LASER MEASURING MACHINE

2.1. Measurement task

A photograph of a grid spacer for reactor VVER-1000 is shown in Fig. 1. 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 (Fig. 2). The tension in the cell – fuel element junction arising in the process of assembly (due to the cell protrusions) forms and retains the fuel element in the preset position both in the course of transportation and during the fuel assembly service. The measuring machine must inspect the following parameters of grid spacers (Fig. 2): 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".

Fig. 1. A photo of a grid spacer for reactor VVER-1000

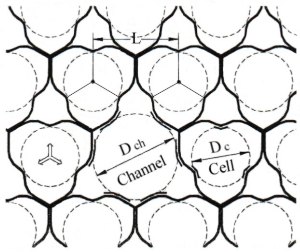

Fig. 2. Grid spacer geometric parameters under inspection

The machine must ensure measurement of geometrical parameters of grid spacers $D_c^{(n)}$, $D_{ch}^{(m)}$, $L^{(k)}$, $S^{(q)}$, $B^{(p)}$ with the errors less than the following limited values: $\Delta D_c = \pm\ 0.03$ mm, $\Delta D_{ch} = \pm\ 0.05$ mm, $\Delta L = \Delta S = \pm\ 0.04$ mm, $\Delta B = \pm\ 0.1$ mm. As for LMM productivity, the grid spacer inspection time must be less than 0.5 hr.

2.2. 3D inspection method

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 developed the specialized noncontact high productive laser machine [3].

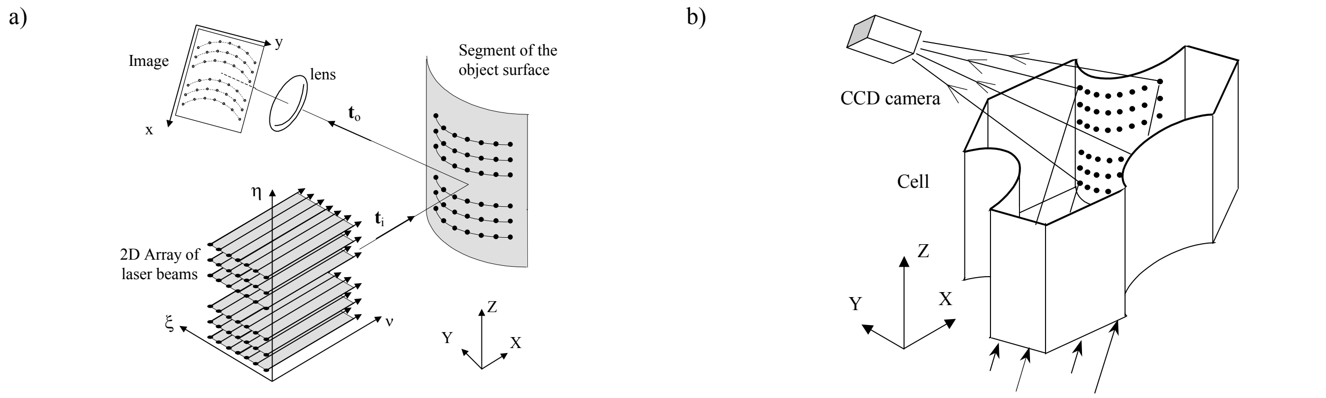

Fig. 3. Illustration of the multipoint structured illumination 3D inspection method applied to a single segment of object surface (a) and grid spacer cell (b)

As known, among the currently existing noncontact 3D inspection methods, the most promising are optical ones based on structured illumination method etc [4]. In this case the object is illuminated by the light beam of a known structure (line, array, etc.), image recording by the CCD camera and processing information. The shape and geometric parameters of the object surface within measuring volume $D_x \times D_y \times D_z$ are reconstructed using the set of object cross-sections.

Since the traditional structured illumination method application meets several problems related with generation of the required light structure, object image perception and processing, we have developed the modified method by using a multipoint structured illumination [5]. It ensures fast, noncontact, automated 3D-measurements for many objects. The essence of our method is illustrated by Fig. 3. The multipoint structured illumination is a 2D array matrix of laser beams (Fig. 3a), which may be generated by kinoform elements such as, e.g., two crossed Dammann arrays [6]. In order to overcome uncertainty in determining the object position and shape, we introduce singularity into the laser beam matrix structure as period malfunction. Parallel light beams create light spots on both object and image registered by the CCD matrix. Singular (empty) layer allows identification of light spots with respect to light beams. For two incident and observed beams (t_i and t_o), the equations of which are known, one can always determine the parameters of a 3D-segment corresponding to the minimum distance between the beams. Segment center corresponds to the illuminated point on the object surface, while segment length is determined by the multipoint system parameters.

In the case of 3D inspection of grid spacer cells, consisting of three protrusions (Fig. 3b), which may be approximated by the cylindrical segments, it takes three 2D laser beams matrixes (for simplicity only one light matrix is shown). Using this multipoint structured illumination method we have developed the laser measuring machine for 3D grid spacers inspection.

2.3. LMM structural block-scheme

This scheme of the laser measuring machine and its photo are shown accordingly in Fig. 4 and Fig. 5. The LMM includes the three-channel laser-electronic measuring head

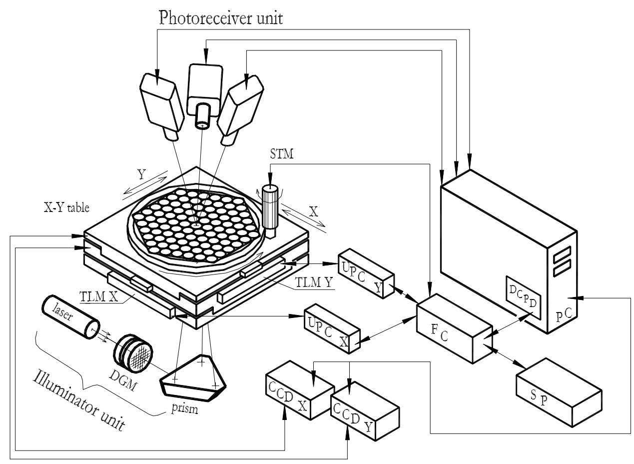

Fig. 4. Structural block-scheme of the laser measuring machine: DGM – Dammann grid module; STM – step-type motor; CCD X and CCD Y - control devices for X and Y coordinates; TLM X and TLM Y – opto-electronic transducers of linear motion on X and Y coordinates; UPC X and UPC Y – unified pulse converters on X and Y coordinates; FC – functional controller; SP – supply power; DCPD – device for collection and processing of data; PC – personal computer

for cell and channel holes perception (hereafter the measuring head), scanning X-Y table, electronics and software. The measuring head includes an illumination unit positioned on the slab and a photoreceiver unit (PRU) disposed in the arch. The illumination unit contains a laser, a Dammann grid module (DGM), and a special prism. The DGM, consisting of two crossed grids, is intended for splitting the laser beam into 12 x 13 orders of two-dimensional light distribution which is further divided by the prism into three parts with equal intensities. In this way three sets of laser beam matrices (with periods Δy = 0.2 mm, Δz = 0.52 mm) directed at angles of 30 degrees at 3 inner surfaces of the inspected cell are formed. The photoreceiver unit includes three identical projecting objectives and three CCD cameras (XC-77/BBCE). The read-out image is digitized and transmitted to the controlling computer via appropriate video buffers SILICON VIDEO MUX.

Fig. 5. A photo of the laser measuring machine

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.

2.4. LMM operation

The LMM software contains the basic software, software for analysis of statistic data, received in the course of measurement, and software for the device for collection and processing of information. The basic software written in the programming language Microsoft Visual C++ version 5.0 works under the control of the operation system Windows 95/98. It provides a display of the current state of processes on the screen in a form convenient for the operator. For interaction with the operator, the window graphic regime is used. There are two regimes – preparative and working (measuring) in the basic software. In the preparative regime (with participation of the operator) the following operations are performed: testing the main LMM units, input of parameters of the grid spacers under inspection and of calibrated samples, calibration and metrological testing the LMM.

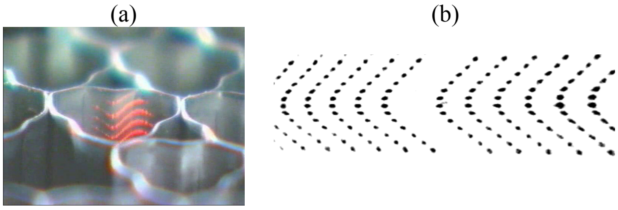

Fig. 6. A cell image under multipoint structured illumination (a) and after digital processing (b)

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 color distinction between cells and channel holes (Fig. 7).

According to the second visualization method, 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 shifts, the color of vectors designate their belonging to the tolerance.

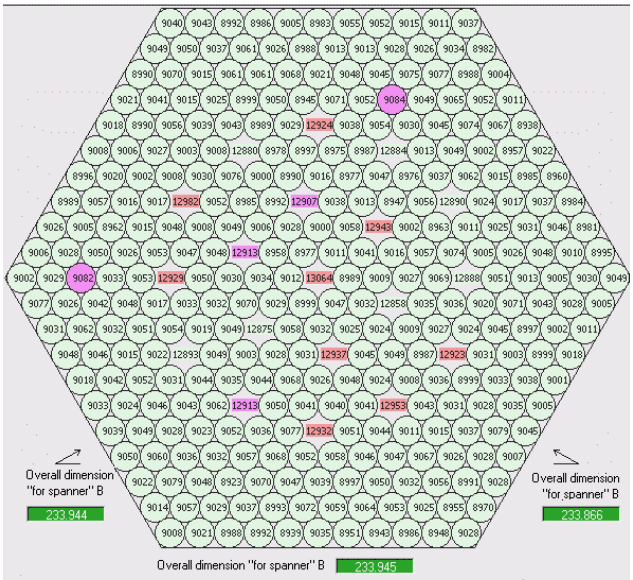

Fig. 7. Results of diameter measurements of two grid spacers by the LMM, one of them is defective

And, finally, in the representation of the distances between neighboring 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.

In all the representation 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. 8. 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. Besides, on the monitor screen, information about the mean, minimal and maximal diameter of the inscribed circumferences, and fitness indicators with respect to the following parameters: belonging of inscribed circumferences centers to the cylinders (tolerance margin) and belonging of the inscribed circumferences to the hollow cylinder (the lower and the upper tolerances limits) are given.

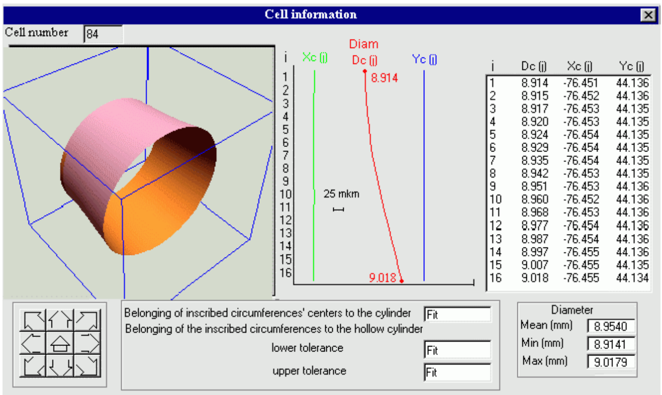

Fig. 8. Individual geometric information (received by the LMM) about every cell hole of the grid spacer including its 3D image, the diameters $D_c(j)$ and the centers coordinates $X_c(j)$, $Y_c(j)$

3. OPTOELECTRONIC DEVICES «CONTROL-1» AND «CONTROL-2»

3.1. Measurement task

Consider the geometric measurement task for fuel elements of nuclear reactors VVER-1000 and VVER-440 in detail.

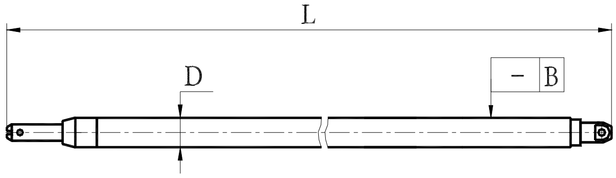

Fig. 9. Fuel element configuration of nuclear reactors VVER-1000 and VVER-440

The following geometric parameters of fuel elements are liable to 100 % inspection (Fig. 9): 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). It is essential, that in order to meet preset strict demands on the fuel elements geometry, it is necessary to perform the measurements of D and B parameters along it's whole length, with discreteness of 2,5 mm; therein diameters D must be measured in orthogonal (transverse) sections of the cladding for detection of possible ovality of tubes.

The optoelectronic fuel element inspection devices must ensure measurement of the above-geometrical parameters with the required accuracy characteristics determined by the preset tolerance gaps for these parameters according to the article draw. Measurement errors for parameters D, L, B, H don't exceed the following limited values: $\Delta D \le \pm$ 0,01mm; $\Delta L \le\pm$ 0,4 mm; $\Delta B \le \pm$ 0,05 mm; $\Delta H \le \pm$ 0,025 mm. Position and extension of defective (with respect to diameter) sites along Z axis must be determined with a measurement error of no more than $\Delta Z = \pm$ 2 mm.

3.2. Measurement method

For automated noncontact dimensional inspection of fuel elements of Russian nuclear reactors VVER-1000 and VVER-440 TDI SIE has developed and produced optoelectronic devices «Control-1» and «Control-2», incorporated to technological line of their production [7]. The measurement method here is based on the formation of an object shadow image and recording of this image by multi-element photoreceiver – photodiode linear array (PLA) and digital signal processing. (Fig. 10). The quasi-parallel light beam, formed by the illuminator, is modulated by the inspected object – fuel element with diameter D. The projecting system forms the object shadow image in the PLA plane. The photodiode linear array carries out the electronic scanning of this shadow image. The PLA output signal is digitized by analog-to-digital converter (ADC) and then is processed to receive the information about the diameter of the fuel element. Estimation of parameter D is based on threshold processing of the shadow image.

Application of this shadow measuring technique for the workshop industrial environment, in our opinion, is more preferable from the metrological point of view in comparison with the traditional laser scanning gages [8].

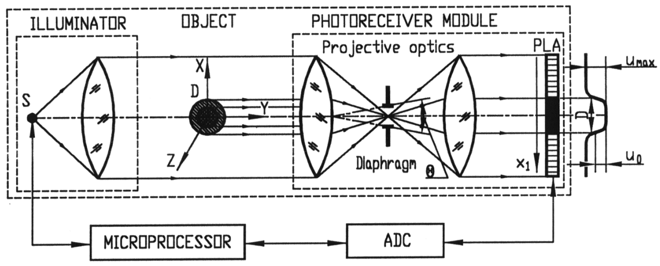

Fig. 10. A block-scheme of an optoelectronic measuring gage

3.3. The devices structural block-scheme

Using this shadow measurement method we have developed and manufactured the two optoelectronic devices «Control-1» and «Control-2» for noncontact dimensional inspection of fuel elements of nuclear reactors VVER-1000 and VVER-440 accordingly. A structural scheme of these devices is presented in Fig. 11.

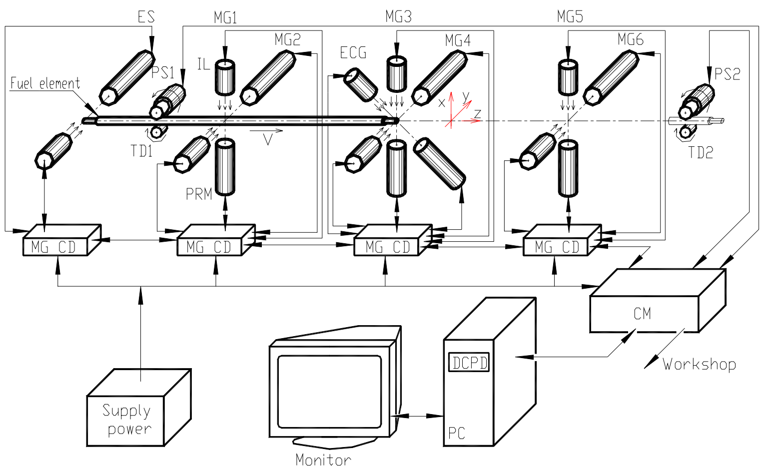

Fig. 11. The structural block-scheme of the devices «Control»: ES – edge sensor; MG1-6 – measuring gages; PS – position sensor; IL – illuminator; ECG – edge coordinate gage; TD – transport device; PRM – photoreceiver module; CM – conjugating module

The devices consist of an optoelectronic measuring unit and controlling computer (P/100/16 type). The measuring unit includes the following (constructively united) basic modules: 6 identical measuring gages (MG1-6), each of which consists of an illuminator (IL), photoreceiver module (PRM) and its electronic control device (CD); a fuel element edge coordinate gage (ECG); a transport device (TD), combined with the position sensor (PS) and a conjugating device (CM). In addition, the devices contain a power supply and a device for collection and processing of data DCPD, located in the computer crate.

3.4. «Control» device software

The software using Windows 95 includes: the basic preparation and measurement program; analysis of statistics collected in the course of measurements; the program for DCPD; the program for measuring sensors, and the program for microprocessors.

The main program is intended for control of the device «Control-2» by means of personal computer. It enables a screen display the current state of processes carried out by the device. As a rule, this is made in a form convenient for the system's operator, who directs the actions of the device to the desired channel by a "mouse" type manipulator.

The program provides for performance of the following basic functions of the device: its preparation for measurements (all adjustments of the device); checking the device before the start of work; calibration and metrological; statistical processing of measurement data.

4. RESULTS OF INDUSTRIAL TESTING

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 program of industrial testing the LMM included estimation of metrological characteristics by the certified calibrated samples and a long-term functioning of the device in the regime of inspection of regular products especially prepared for the experiments. As a result of this testing, the following accuracy characteristics (at the confidence probability of 0.95) have been established (see Table 1).

TABLE 1. Results of LMM industrial testing

Inspected parameters	Experimental measurement error	Error value
Cell diameter, $D_c^{(n)}$	δD_c	0,016 mm
Channel diameter, $D_{ch}^{(m)}$	δD_{ch}	0,018 mm
Center shift, $S^{(q)}$	δS	0,015 mm
Overall dimension, $B^{(p)}$	δB	0,032 mm

One can see that the attained precision characteristics exceed by 2-3 times the required ones.

The time of measurement of the indicated grid spacer parameters does not exceed 20 min, which is than 12 times faster than existing universal contact coordinate measuring machines.

Testing the devices «Control-1» and «Control-2» were carried out on the currently working line for production of fuel elements at the Novosibirsk plant JSC NCCP during 2001- and 2002 (Fig. 12). The program of testing included checking the device in all working regimes, estimation of the metrological characteristic by certified calibrated samples and of long-term work in the regime of inspection of regular articles, specially prepared for performance of tests (on some parts of articles, sites with defects with respect to diameter were made on purpose).

Fig. 12. Operation of the device «Control-1» at JSC NCCP

As a result of the testing, the following precision characteristics of «Control-1» and «Control-2» have been established. The measurement error of the fuel elements geometric parameters external diameter D, deviation B, deviation H and length L (at the confidence probability of 0,95) were established as the follows: $\Delta D = \pm\ 0{,}008$ mm; $\Delta B = \pm\ 0{,}015$ mm; $\Delta H = \pm\ 0{,}015$ mm; $\Delta L = \pm\ 0{,}15$ mm. Error of positioning and extension of sites with defect respect to diameter was $\Delta Z = \pm\ 2$ mm. There in, the operation speed was 130 measurements per second. In this way, the metrological characteristic of the devices met fully the requirements of fuel element manufacturing.

Since April 2001 and up to the present time «Control-1» has been in a pilot industrial scheme. During this time, tens of thousands fuel elements VVER-1000 have been checked. The use of the device «Control-1» has made it possible to obtain accurate information about the geometry of the manufactured articles which was subsequently used to improve the technological process of fuel elements production.

Measurements have demonstrated that the inspected parameters of fuel elements are very significantly within the tolerance margin. As an example illustrating the high quality of production technology at the JSC NCCP, geometrical parameters of fuel elements and statistical data on a sample of 597 articles (see Table 2).

5. CONCLUSION

Ensuring the safety of nuclear reactors and their high exploitation reliability requires a 100 % noncontact precise inspection of geometrical parameters of their fuel elements and grid spacers.

To solve this problem we have developed and produced at TDI SIE a laser measuring machine for Russian plants of

TABLE 2. Statistical measuring data on a sample of 597 fuel elements.

Inspected parameter	Value (mm)		Mean value (mm)	r.m.s (mm)	Nominal (mm)
	Min	Max			
Cladding diameter	9.068	9.134	9.108	0.007	9.100
Lower end plug diameter	9.063	9.201	9.116	0.009	9.100
Upper end plug diameter	9.024	9.133	9.081	0.011	9.100
Curvature	0.127	0.334	0.155	0.028	0.500
End plug deviation	0.000	0.300	0.163	0.071	0.250
Length	3837.711	3838.786	3838.295	0.144	3837.0

JSC TVEL which enables for a noncontact 3D inspection of grid spacers for the nuclear reactor VVER-1000. Its operation is based on the multipoint structured illumination method (proposed earlier at TDI SIE).

The measuring regime automatically permits determination of the geometrical parameters of the grid spacer under inspection and visualizing the measurement results and the state "fit/defect" with respect to each parameter, and giving out measurement and inspection protocols in a brief or full form. The developed software allow to inspect the individual sizes and a 3D configuration of any cell or channel hole using measurement information about diameters and coordinates of their inscribed circumferences centers in 16 cross-sections.

As a result of the industrial testing it has been established that the measurement errors for the cell diameter, the channel hole and the center shift didn't exceed 18 μm, and LMM productivity is 20 min. LMM has gone through a complete cycle of testing at the Novosibirsk plant JSC NCCP. Its application will make it possible to obtain objective information about the geometry of grid spacers, which will contribute to an improvement of the technology of their production and of the quality of produced fuel elements for nuclear reactors.

For fuel elements inspection of nuclear reactors VVER-1000 and VVER-440 the opto-electronic automated measuring devices «Control-1» and «Control-2» have been developed and produced at TDI SIE.

The created devices are incorporated directly in the technological lines of fuel element manufacturing at the JSC NCCP and make it possible to carry out inspection of all the required geometrical parameters of fuel elements at the rate of the production line: cladding external diameter in two orthogonal cross-sections, deviation of the cladding from straightness (curvature), deviation of the lower end plug from the axis line, length of fuel element, position and extension of detective regions with respect to diameter along the fuel element axis.

As a result of pilot industrial test, it has been established that the metrological characteristic of the devices perfectly met the requirements of fuel element production (e.g. measurement errors for fuel elements diameters are less than 8 μm). The working speed of response for the devices was 130 meas./sec. On the course of pilot industrial exploitation of the device «Control-1», tens of thousands VVER-1000 fuel components have been inspected, which has made it possible to obtain objective information about the geometry of products which was subsequently used for further improvement of production of fuel elements for Russian nuclear reactors VVER-1000 and VVER-440.

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