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3D MEASURING TECHNOLOGIES FOR INDUSTRIAL AND SCIENTIFIC APPLICATIONS

Yuri Chugui, Sergei Plotnikov, Anatoly Potashnikov, Alexander Verkhogliad

Technological Design Institute of Scientific Instrument Engineering
of the Siberian Branch of the Russian Academy of Sciences (TDI SIE SB RAS)
41, Russkaya str., Novosibirsk, 630058, Russia, 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 safety problems are presented. To measure the rocks stress and to prevent the mountain impact, as well as for basic investigations, a set of optical-electronic deformers and systems was developed and produced. For permanent noncontact bearing position inspection of oil-drilling platforms on Sakhalin coast (Russia) 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 $3 \times 2 \times 0.6$ m^3, positioning error less than 10 mkm). Results of development and testing the specialized high productive laser measuring machine, based on structured illumination, for 3D inspection of grid spacers for Russian nuclear reactors with micron resolution are presented. Using high-speed laser noncontact method on the base of triangulation position sensors, TDI SIE has developed and produced automatic laser diagnostic system COMPLEX for inspection of geometric parameters of wheel pairs (train speed up to 60 km/hr.), which is used successfully on Russian railways.

Keywords: optical measuring technology, laser technology.

1. INTRODUCTION

Modern industry and science take novel optical measuring systems and laser technologies for solving actual tasks, including safety problems for mining, oil, atomic and railway industries [1-4]. The novel TDI SIE's results in these trends are presented.

Effective investigation of non-linear processes in block structures of geo medium requires comprehensive measurement of wave, deformation and power parameters using the multi-channel measuring systems [2]. The development of universal technical means (with enhanced metrological characteristics) for automatic measurement of these parameters in nature and laboratory conditions under the physical experiments is very actual. For measurement the rocks stress and prevention the mountain impact we have developed a set of optical-electronic deformers and systems for modeling and investigation of nonlinear deformation wave processes.

Oil-drilling platforms on Sakhalin coast (Russia) have seismic protection systems using massive platform (28 000 tons) and the four friction pendulum bearings. They have limited cumulative traveled distance (about 3 km). As soon as this distance exceeds that value, the bearings should be replaced. We have developed optical-electronic system SAKHALIN for permanent non-contact bearing position inspection and traveled distance measurement. Functional possibilities and experimental results for SAKHALIN are presented and discussed.

Laser material processing (cutting, welding) of 3D large-size objects and treatment (ablation) of their surfaces take multifunctional universal laser technological system. Such system (LSP-2000) was developed at TDI SIE. It has 5-coordinate (X-Y-Z-φ-θ) table with Computer Numerical Control system, table displacement range of $3 \times 2 \times 0{,}6$ m^3 (position error less than 10 mkm) and changeable Nd-YAG lasers for material processing and treatment. Below the LSP-2000 technical peculiarities and performances are given.

Safety of nuclear reactors VVER-1000 and VVER-440 [4] and ensuring their high exploitation reliability take 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).

Ensuring the safety of running trains is the actual task of railways exploitation and transport of passengers and cargoes all over the world. We have developed high-speed laser noncontact method for geometrical parameters inspection of moving 3D objects on the base of triangulation position sensors using fast-response PSD linear arrays and produced automatic laser diagnostic system COMPLEX for noncontact inspection of geometric parameters of wheel pairs. Principle of self-scanning for running freight cars and testing results for system COMPLEX are given.

2. ROCKS NONLINEAR GEOMECHANICAL STUDY BY MEASURING TECHNIQUES

In order to reveal the mechanisms of rock bursts in mines, it is necessary to study mining-induced movements of structural inhomogeneities of rocks, rock stratum displacement, and deformations. It is required to measure displacements of geoblocks and strains at different points of a massif depending on location of these points relative to underground working contour in geomedia with both natural and induced jointing, and with allowance for structural features (disintegration zones, tectonic faults, pillars or filling masses failed by rock pressure or blasting, etc.). Institute of Mining and TDI SIE SB RAS have developed a prototype of a borehole multichannel optical-electronic longitudinal deformometer (from here on meter).

The technical solution of measuring displacements of geoblocks in a rock mass is based on a “slide gauge idea”. The idea is realized using a measuring bar, which is fastened inside the massif in a borehole, and a position sensor with his sensing element attached to the rock and capable of moving freely along the bar. The bar consists of sections connected by pipe couplings. The sensor is set on a section of the bar. By doing so, we ensure the modular gathering of the instrument.

Measurements in rock masses are frequently conducted using horizontal boreholes drilled in mine working walls towards the section to be inspected. In this case, the borehole (Fig. 1) usually intersects rock blocks C_1 …, C_i formed by disintegration zones [3] and gets deeper in an intact massif part C_n. Prior to installation, we need to choose a reference point *O* in C_n, check points in geoblocks C_1, C_2,…, C_i between the zones of disintegration, and number of sensors.

The bar sections and sensors together is a pickup probe. Measuring bar *2* is fastened at the reference point *O* via support *1* (Fig. 1). According to the number of measured blocks, sensors *3* are installed on the bar with the sensing elements fastened to the rock at the points C_1, C_2,…, C_n. Having such arrangement, displacement of the *i*-th block under inspection will cause the same displacement of the sensing element of the corresponding sensor along the bar, which is recorded by an electron device.

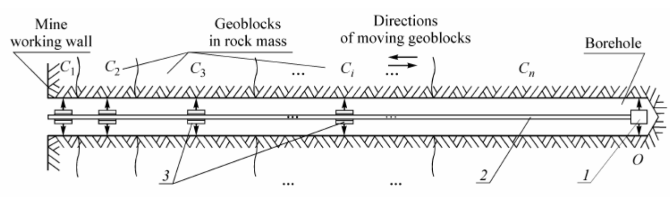

Fig. 1. Scheme of measuring bar and sensors in borehole.

The position sensor is based on an electron photosensitive recording device such as the position-sensing S3270-type photodetector PSD produced by Hamamatsu Co with a resistive layer and electrodes. The sensor equipped by LED has the following characteristics: the measurement range is ± 17.5 mm; the measurement error is ± 0.02 mm.

The sensor has the following design (Fig. 2): insertion *1*

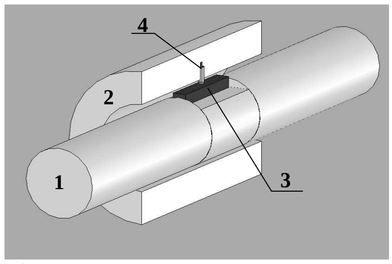

Fig. 2. Scheme of position sensor: 1 - insertion, 2 - movable bushing, 3 - photodetector, 4 – LED.

built-in into the bar section and movable bushing *2* mounted on the insertion so that to move longitudinally along the guide [6]. The current position of the bushing relative to the insertion is determined by the position of the spotlight on the photodetector. Such design allows minimization of the sensor size, simplifies fastening device, and decreases the mass and overall dimensions of the instrument. Using these sensors (Fig. 3) we have developed the measuring system providing automatic measurements of longitude shifts and deformations in rocks (actual tests in mine working).

Fig. 3. Position sensor.

Modern phenomenological theory of pendulumtype waves, based on studies of geomechanical wave processes in structurally inhomogeneous rock masses, takes carrying out the detailed laboratory testing of models of block geomedia under uniaxial and biaxial loading. In contrast to in situ experiments, stand trial conditions can be varied widely, and it is possible to analyze effects of stress state, strain rate as well as properties and behavior of rocks under complex loading modes. The obtained measurement data need being processed both in the course of experiment and after its completion. For these purposes we have developed a prototype of a micrometer position display sensor with a microprocessor data collection system.

When measuring equipment for the geomechanical stand, the main attention has been focused on an electronic micrometer display sensor and its design with the use of a photosensitive charge-coupled device (CCD) with a LED.

The sensor consists of two parts (Fig. 4): a casing serving a basis guide and a mobile stem capable of displacing along the guide. The LED is installed on the stem, and the photoreceiver, i.e. CCD-bar is arranged inside the casing along the guide. When the stem displaces, its current position relative to the casing is determined by the coordinate of the LED-generated spotlight on the photoreceiver. The micrometer sensor has been tested to determine precision of its characteristics. It is shown that the error is no more than ± 3 mkm, and with due regard for the gauging characteristic based on the average curves of repeatability, the sensor error can be reduced to 1 mkm.

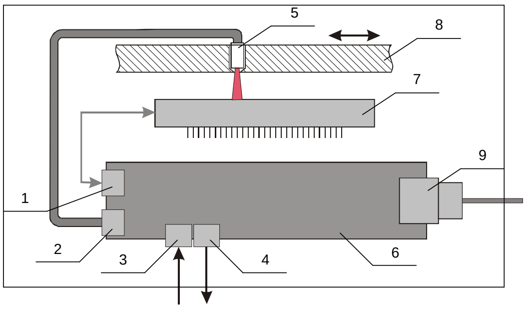

Fig. 4. Functional arrangement of sensor: 1 - mobile stem; 2 - light source; 3 - CCD-bar; 4 - CCD-bar control; light source control; 6 - synchronization input; 7 - synchronization output; 8 - KLM-1 microcontroller; 9 - USB output.

The information measuring system on the base of electronic micrometers as a laboratory equipment (providing the investigations on the processes models that take place on structured rocks) has been developed. The system ensures the data collection within the process of model objects disintegration as well as their transmission on USB channels into personal computer. This system has 8 functionally finished position sensors, unified into the common system using the switchboard. The quantity of sensors can be increased when needed. It is provided by system architecture.

3. 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 and inert (Fig. 5). In order to avoid excessive

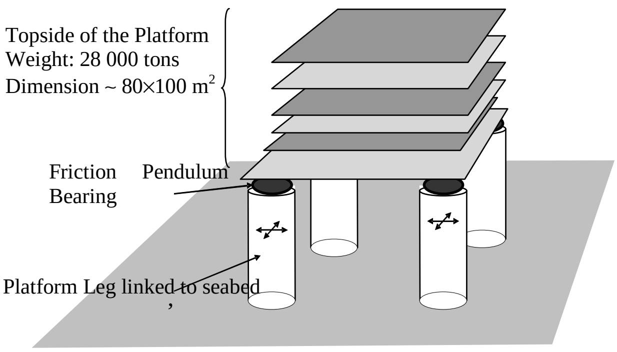

Fig. 5. An oil-drilling platform scheme.

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 estimation the bearing resource, is measuring the cumulative distance traveled 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. 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. 6) 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 of these two parts of construction is obtained with high degree of accuracy.

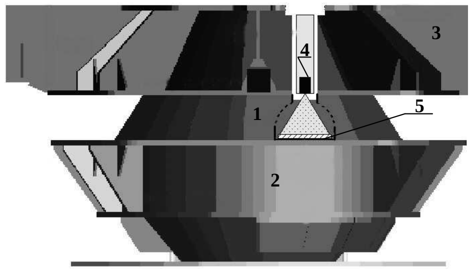

Fig. 6. Measurement system location: 1 - slider bearing, 2 - support, 3 - platform, 4 – image unit, 5 – target.

The system SAKHALIN (Fig. 7) 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 ± 350mm; absolute error in the measurement range is ± 0.6mm; 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.;

Fig. 7. System SAKHALIN: optical measuring and electronic units.

working temperature for control panel is from 0 up to + 40ºC. This system was put through tests accepted by customer.

4. LASER TECHNOLOGICAL SYSTEM LSP-2000

We have developed the multifunctional laser technological system LSP-2000 for processing and treatment of 3D articles: cutting, welding and surface micro profiling with ablation process. The LSP-2000 system 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 mkm for any point of trajectory. The general view of the system is presented in the Fig. 8. The LSP-2000 was

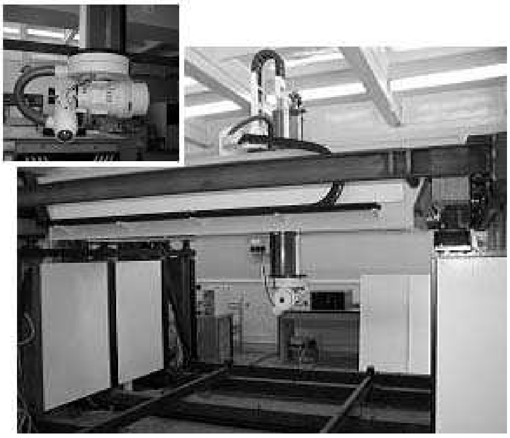

Fig. 8. Laser technological system LSP-2000 and enlarged fragment of its working processing head.

developed as the universal laser processing system with unique combination of the certain parameters / technical characteristics. These characteristics are listed below:

- **Multifunctionality.** It means the ability to perform a range of technological and processing operations. Each operation using custom laser processing heads, requires custom 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 mkm. 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 mkm, 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 mkm. 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 mkm).
- **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.** The expected time for the single article processing is approximately 30 hours. The system is designed for continuous 24 hours work. 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.

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

5. 3D GRID SPACERS INSPECTION TECHNOLOGY

As known, a grid spacer for reactor VVER-1000 is multicell piece like honeycombed cellular structure (Fig. 9). 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. 10): 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".

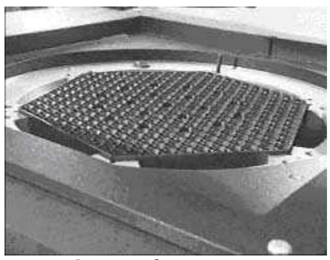

Fig. 9. A grid spacer for reactor VVER-1000.

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) [4].

For solving this task we have developed the modified method, which is based on a multipoint structured

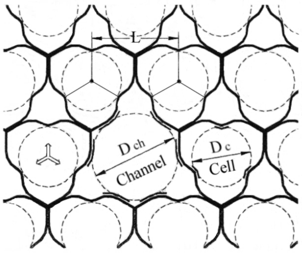

Fig. 10. Grid spacer geometric parameters under inspection.

illumination. It ensures fast, noncontact, automated 3D-measurements of many objects (Fig. 11).

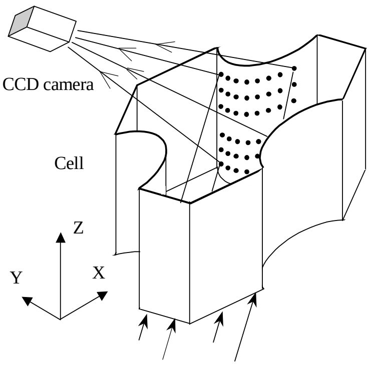

Fig. 11. The multipoint structured illumination 3D inspection method applied to a single segment of grid spacer cell.

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 the three-channel laser-electronic measuring head for cell and channel holes perception, scanning X-Y table, electronics and software (Fig. 12). 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 color distinction between cells and channel holes. 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. 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

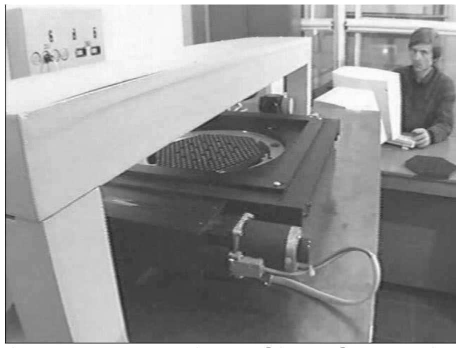

Fig. 12. Laser measuring machine under operation.

is shown in Fig. 13. 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.

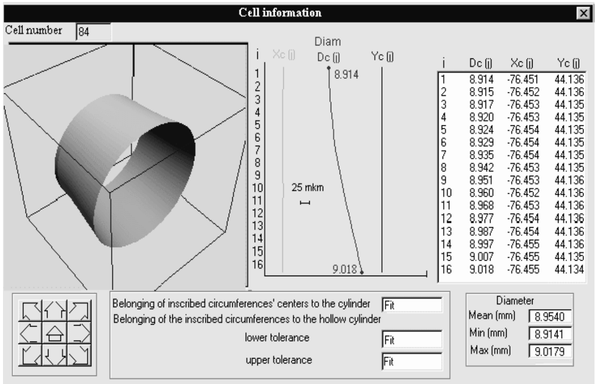

Fig. 13. Individual geometric information from LMM about every cell hole of the grid spacer: its 3D image, the diameters $D_c(j)$ and the centers coordinates $X_c(j)$, $Y_c(j)$.

6. LASER WHEEL PAIRS DIAGNOSTIC INSPECTION FOR RUNNING TRAINS

For regular dimension inspection of wheels we have developed high-speed laser noncontact method and measuring technology for geometrical parameters inspection of moving 3D objects on the base of triangulation position sensors using fast-response position sensor detector PSD (50 000 meas/s). This method is based on the principle of wheel self-scanning (Fig. 14a) by using active measuring sensors of the triangulation type. In this case, a beam produced by a laser diode is focused on the surface of the moving object under inspection. The scattered beam is gathered by the aperture of a receiving objective. The objective forms an image of the illuminated surface zone in the PSD plane (Fig. 14b).

Using this method TDI SIE has produced automatic laser diagnostic system COMPLEX for noncontact inspection of geometric parameters of wheel pairs (Fig. 15), including: width (A) and thickness (B) of wheel rim; distance between

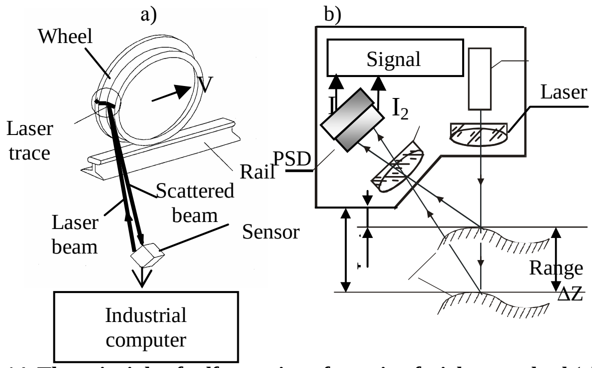

Fig. 14. The principle of self-scanning of running freight car wheel (a) using active measuring sensors of the triangulation type (b).

inner sides of wheels (E); thickness of wheel flange (C); uniform rolling (F); wheel diameter (D); difference of diameters of wheels in a wheel pair $D=D_1-D_2$. 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° up to +50° C.

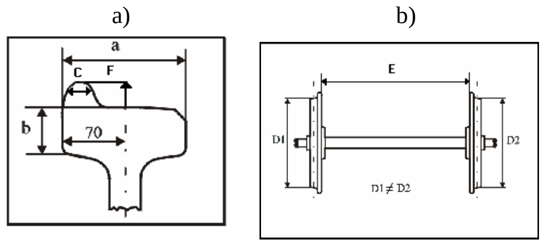

Fig. 15. Wheel parameters under inspection.

Figure 16 shows an example of the wheel reconstructed profile (cross-section). The required geometrical parameters are calculated from the reconstructed profile, in so doing, the algorithm of calculating the parameters follows the method of their measurement by means of a standard contact meter.

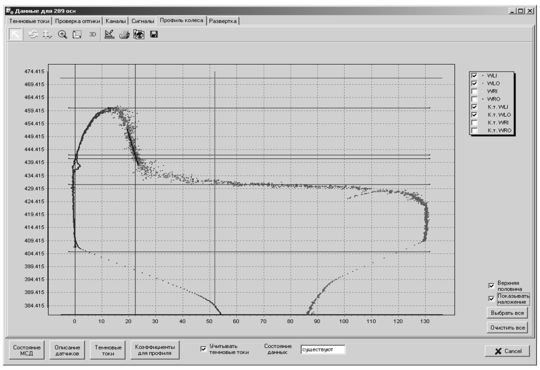

Fig. 16. A wheel reconstruction profile (cross-section).

External view of this system COMPLEX is presented in Fig. 17. The developed diagnostic system COMPLEX corresponds to the best world prototypes. At the present time, COMPLEX more than two years is in operation at West-Siberian Railway. Today 20 systems COMPLEX are in operation on 6 Russian regional Railways (from Moscow to Far East). There were inspected more than 23 million wheel pairs for the period of system COMPLEX exploitation. 300000 alarming reports were received, more than 17000 carriages were rejected. The application of these systems allowed to improve the safety of railway industry in Russia.

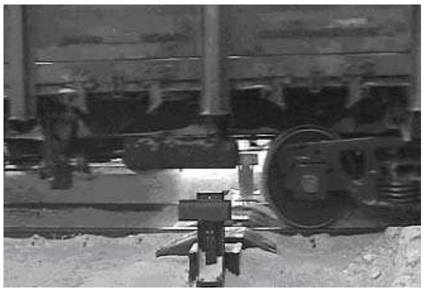

Fig. 17. System COMPLEX under operation in winter (West-Siberian railway).

7. CONCLUSION

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 from 500 to 10 000 meas/s. We have developed, implemented and tested some novel optical measuring systems and laser technologies. For mining applications there were developed and produced two types of sensors for industrial and scientific works. The developed system SAKHALIN can also be used for the 24-hours 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, built-in additionally by measuring probes, can be used as coordinate measuring machine with very large measuring volume. In atomic industry the developed and produced laser measuring machine LMM 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. Application of automatic laser diagnostic system COMPLEX for noncontact wheel pairs dimensional inspection for running trains makes possible to increase the safety of Russian railways.

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