Investigation of Factors Determining the Accuracy of Dual-channel LMS

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***Abstract*— When measuring, centering and adjusting large-scaled objects and equipment, an extremely large share is occupied by laser measuring systems. Of essential importance when measuring with these systems is the compliance of the accuracy parameters with the requirements imposed on the objects. In order to evaluate the metrological characteristics of the developed laser system, the present paper presents a study of the factors affecting the accuracy when measuring with it. The characteristics of the photodetector and the photodetector block and the structure of the laser beams of the system were investigated. A functional check of the consistency of the individual modules of the receiving unit was also made.**

***Keywords—laser measurement system, accuracy assessment, form deviations, mutual location, direction characteristic, position-sensitive photodetector*.**

I. Introduction

The deviations of form, location and orientation of flat surfaces are basic geometric parameters characterizing the quality of a number of mechanical engineering details and assemblies [12].

The use of universal measuring tools and coordinate-measuring systems [21, 25] most often does not ensure the necessary accuracy and performance of the measurement process, as well as its expediency. This necessitates the search for solutions adequate to these requirements, i.e. the development of relevant methods and systems for their implementation [15, 17, 18, 22, 23].

The problems of measuring the deviations of form and mutual arrangement [10] of large-scaled objects and facilities are of essential importance for a number of enterprises from the transport and heavy engineering and energy industries. Solving such metrological problems is possible through the use of laser measurement systems (LMS) [1, 14, 16].

Of particular importance is the evaluation of the metrological and operational characteristics of these systems. The paper presents the results of the study of the accuracy characteristics of the dual-channel laser measuring system developed at the Research & Development Laboratory "Coordinate Measurements in Mechanical Engineering" at Technical University of Sofia for centering and angular orientation of flat surfaces measurements [2, 3, 4, 19, 20].

For the accuracy assessment of the developed measuring systems, the main factors influencing the metrological and functional indicators have been studied in this paper [5, 8]. The direction finding characteristics of the photoreceiver and the structure of the emitted laser beam were determined, and the consistency of the individual modules was checked when assembling the whole systems.

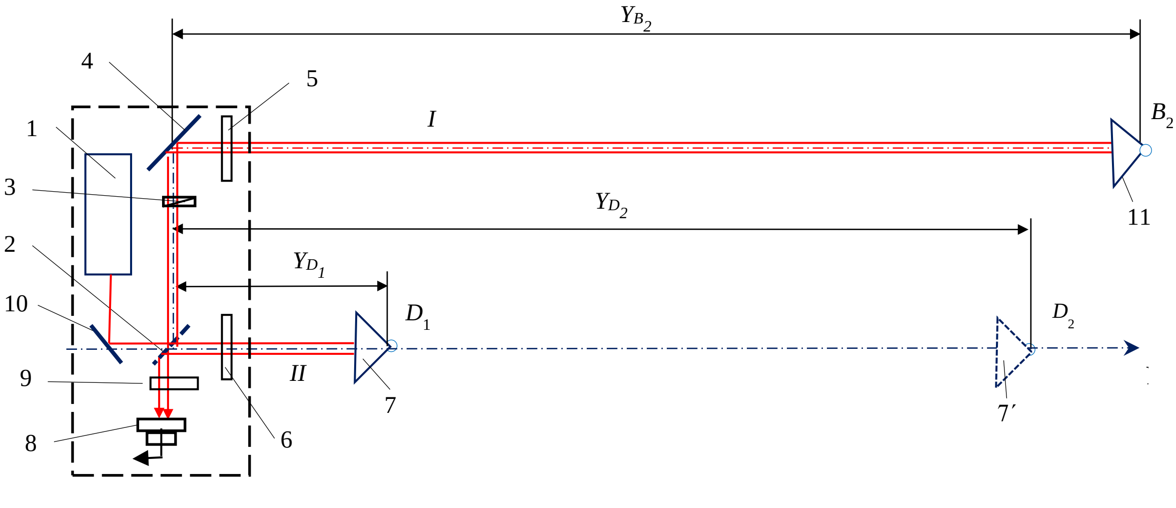


Fig. 1 Dual-channel laser system for control of surfaces mutual arrangement

II. Dual-channel Laser Measurement System

The principle scheme of the dual-channel laser measurement system is shown in Fig.1. The system contains the following main modules: laser diode emitting unit 1, reflector 10, beamsplitter 2, wedge compensator 3, reflector 4, polarization compensators 5 and 6, measuring retro-reflectors 7 and 11, PSD 8, and the polarization filter 9.

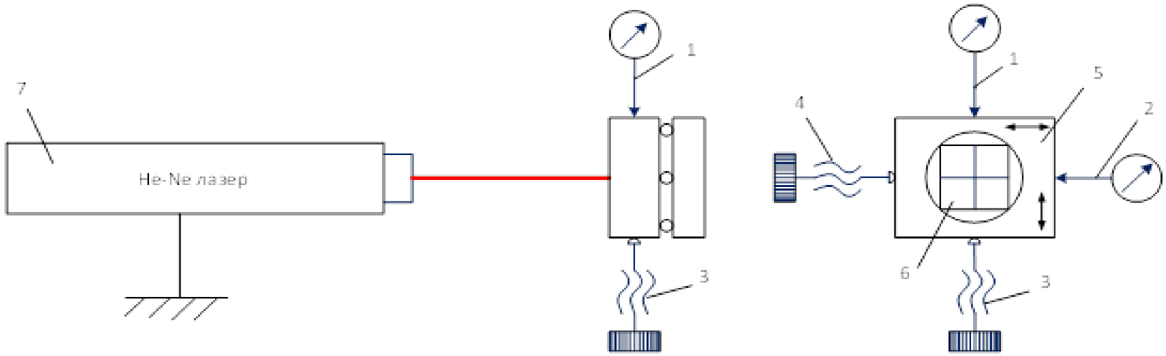
The beam emitted by the laser unit 1, reflected by the reflector 10, is split by the beam splitter 2 into two orthogonally polarized beams, one of which is oriented parallel to the other with the help of the reflector 4. The parallelism of the two measuring channels (I and II) is adjusted with the wedge compensator 3. The beams are reflected by the retroreflectors 7 and 11 (triple-prisms) and after reflection by the beamsplitter 2 (beam I) and reflector 4 (beam II), respectively, direct to the photo-receiving module with the PSD 8. In the beams, the polarization compensators 5 and 6 (plates $\lambda/4$) are introduced to rotate the plane of polarization.

The switching of the two measuring channels is carried out using the polarization filter 9.

III. Investigation of the Direction Characteristic of the Photodetector and the Photoreceiving Unit

The aim of the study is to determine the main metrological parameters of the position-sensitive photodetetor model SPOTANA-USB-9 of Duma Optronics Ltd. built into the receiving unit with the electronic unit: directional characteristic, positional sensitivity; measurement range and nonlinearity of the characteristic [9, 11, 14, 16].

The experimental set-up for the study of PSD is presented in Fig. 2 and Fig. 3. The collimated laser beam from a stabilized He-Ne laser 7 was used as a laser source. The laser beam 6 is established on the movable platform of the two-coordinate positioning module 5. The energy axis of the laser beam from the stabilized laser 7 is oriented against and perpendicular to the sensitive area of PSD.



1 - X axis reading device;
2 – Y axis reading device;
3, 4 – micrometric screws;
5 – two-coordinate positioning module;
6 - PSD;
7 – Stabilized laser source.

Fig. 2 Principle scheme of the setup for studying the positional characteristic of the PSD and the photoreceiving module

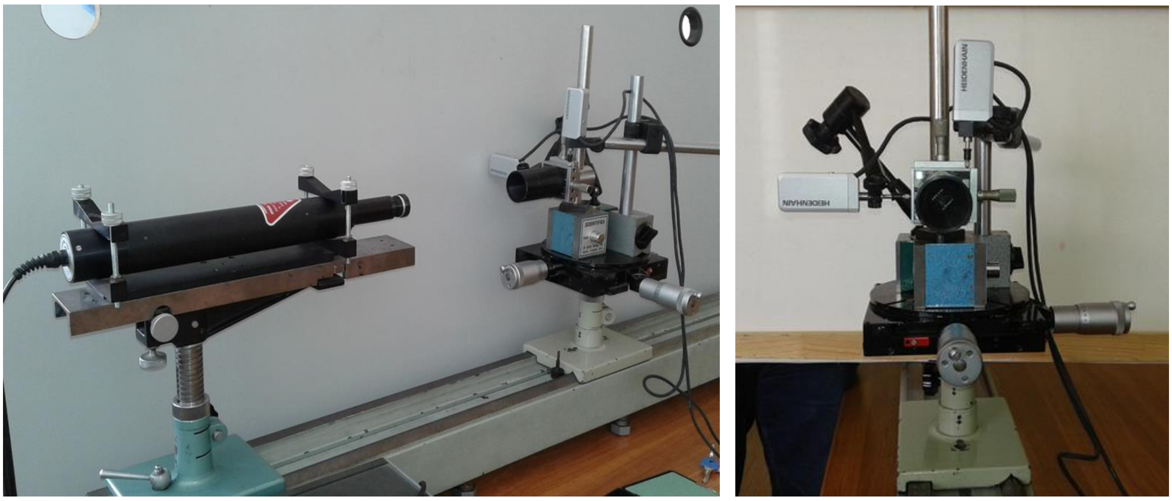


Fig. 3 Experimental set-up for studying the characteristics of PSD

TABLE I MEASUREMENT ERRORS DUE TO NON-LINEARITY AND LOCAL INHOMOGENIITIES OF PSD

X_{nom}, µm	Y_{nom}=-3000 µm		Y_{nom}=-2000 µm		Y_{nom}=-1000 µm		Y_{nom}=0 µm		Y_{nom}=1000 µm		Y_{nom}=2000 µm		Y_{nom}=3000 µm	
	X_{meas}, µm	Y_{meas}, µm	X_{meas}, µm	Y_{meas}, µm	X_{meas}, µm	Y_{meas}, µm	X_{meas}, µm	Y_{meas}, µm	X_{meas}, µm	Y_{meas}, µm	X_{meas}, µm	Y_{meas}, µm	X_{meas}, µm	Y_{meas}, µm
3000	-206	89	-197	4	-197	4	-104	8	-152	18	-123	26	-96	-74
2800	-176	90	-165	4	-165	4	-70	8	-116	17	-88	24	-61	-76
2600	-153	91	-140	5	-140	5	-42	9	-88	15	-62	23	-33	-78
2400	-134	92	-119	5	-119	5	-21	9	-66	15	-39	21	-11	-81
2200	-118	93	-103	6	-103	6	-7	9	-47	14	-21	18	8	-82
2000	-108	-93	-93	6	-93	6	3	9	-35	14	-8	17	21	-85
1800	-100	-81	-81	7	-81	7	8	8	-23	13	4	16	33	-87
1600	-93	-74	-74	6	-74	6	9	9	-15	13	10	14	40	-89
1400	-87	-68	-68	8	-68	8	10	8	-9	12	17	14	46	-91
1200	-86	-64	-64	9	-64	9	10	7	-4	12	22	13	51	-93
1000	-81	-61	-61	10	-61	10	8	7	0	12	26	8	54	-95
800	-79	-57	-57	10	-57	10	6	7	4	11	29	7	57	-95
600	-76	-54	-54	10	-54	10	5	5	8	11	32	7	60	-97
400	-74	-51	-51	10	-51	10	3	4	11	10	36	6	64	-98
200	-71	-48	-48	11	-48	11	0	6	15	10	39	5	67	-99
0	-69	-45	-45	11	-45	11	0	5	18	9	42	4	69	-99
-200	-67	-43	-43	12	-43	12	-3	5	22	10	46	8	71	-100
-400	-66	-42	-42	12	-42	12	-5	5	26	10	471	8	74	-100
-600	-65	-41	-41	12	-41	12	-5	5	27	9	49	8	76	-100
-800	-62	-38	-38	12	-38	12	-6	5	31	9	54	7	77	-100
-1000	-59	-34	-34	12	-34	12	-6	5	36	9	58	9	79	-100
-1200	-57	-31	-31	11	-31	11	-5	5	41	9	61	8	83	-98
-1400	-55	-27	-27	10	-27	10	-5	6	45	9	65	8	84	-97
-1600	-50	-21	-21	9	-21	9	-1	6	50	9	71	10	90	-95
-1800	-44	-14	-14	9	-14	9	3	7	58	8	77	11	100	-95
-2000	-35	-5	-5	7	-5	7	9	7	67	10	86	12	103	-93
-2200	-22	92	7	6	7	6	19	8	79	11	96	13	113	-91
-2400	-7	91	24	4	24	4	31	9	95	11	110	14	127	-90
-2600	13	89	45	3	45	3	49	9	115	12	129	14	145	-89
-2800	40	87	71	2	71	2	72	10	140	12	154	15	168	-87
-3000	74	86	105	1	105	1	103	10	172	13	184	17	196	-86

The matrixing of the two-coordinate receiver was carried out according to the scheme of Fig. 2. The positional characteristic of the PSD is determined by reference displacements X_{nom} of the receiver relative to the laser spot along one of the coordinate axes (for example, the X axis) at certain discrete values of the displacement Y_{nom} relative to the center along the other axis (axis Y), and reading the results X_{meas} and Y_{meas} of the photoreceiving unit.

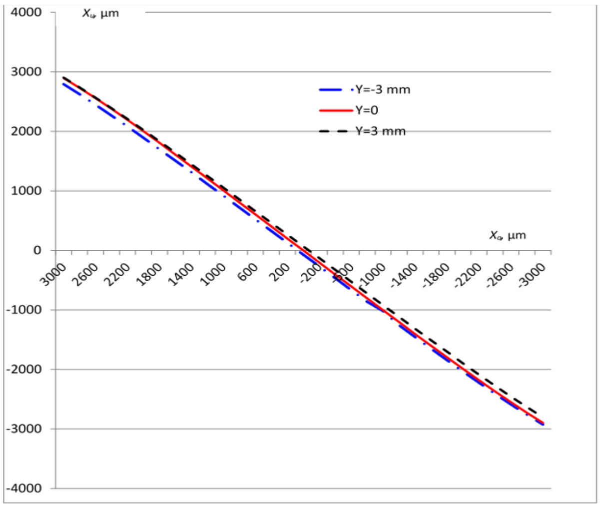


Fig. 4 Direction characteristic of the PSD

The displacements are realized with the micrometric screws 3 and 4 of the two-coordinate module 5, on which the photo-receiving unit 6 (PSD) is installed. By means of reading devices 1 and 2, which are linear photoraster transducers HEIDENHAIN MT12, with a resolution of 0.1 µm and a reading block HEIDENHAIN ND 2104 G Gage-check, the set position is checked.

The matrixing was repeated several times and the averaged results for the measured coordinates were determined.

Based on the obtained results, the direction characteristic of the photodetector (Fig. 4) was built for different displacements Y_{nom} (-3 mm; 0; 3 mm). The measurement errors ΔX and ΔY due to the non-linearity and local inhomogeneities of the photosensitive layer are determined, presented in Table 1 and Fig. 5, and the deformed matrix is constructed (Fig. 6).

The analysis shows that for the beam size emitted by the laser unit, the photodetector module can be used to measure displacements within ±2 mm. Outside of these limits, part of the energy falls outside the receiving area of the PSD and the centroid of the distribution of the received energy is shifted from the center of the Gaussian distribution.

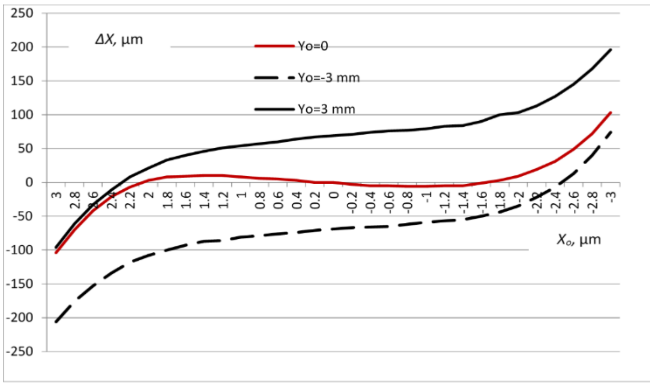


Fig. 5 Measurement error ΔX, µm of the X coordinate of the center of the laser spot

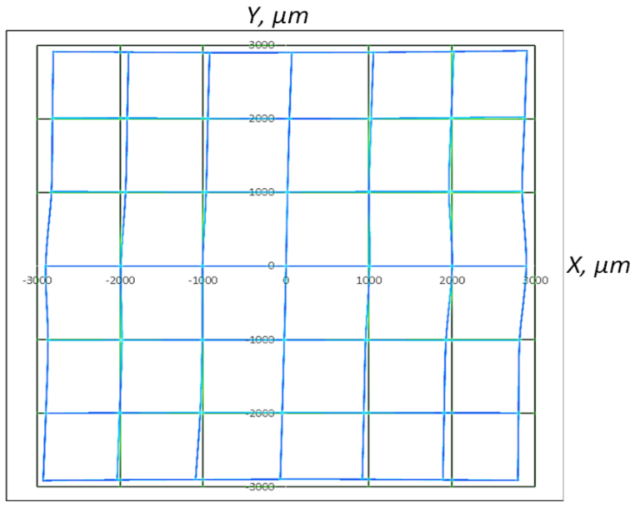


Fig. 6 Deformation of the matrix due to the non-linearity and non-uniformity of the PSD

The position characteristic within the limits of ±1 mm can be assumed to be linear. To increase the measurement accuracy and extend the range, the error matrix (Table 1) should be used for software compensation of the influence of nonlinearity [13].

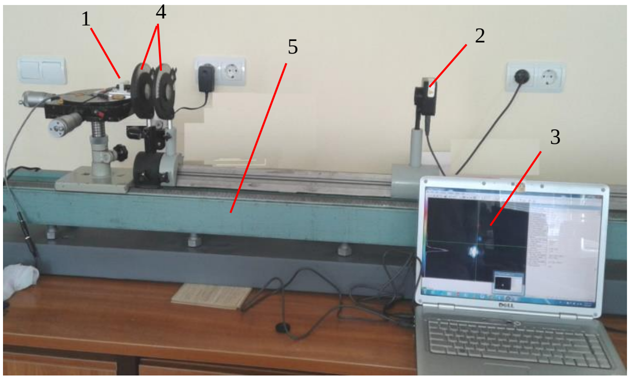
IV. INVESTIGATION OF THE STRUCTURE OF LASER BEAMS

The study of the dual-channel laser block includes the study of the structure and spatial stability of the emitted collimated laser beam and of the spatial mutual arrangement of the laser beams in the two measurement channels.

The study of the structure of the laser beam, conducted using the Laser Cam-HR Beam Diagnostics Digital CMOS Camera with Beam View-USB Version 4.6.3 software (Coherent, Inc.), aims to:

- establish the nature of energy distribution in the cross-section of the collimated beam;

- establish the consistency between the dimensions of the cross-sections of the beam in the direction of its propagation and the dimensions of the sensitive area of the used PSDs.



1 – laser diode   3 – display
2 – diagnostic camera   4 – polarizing filters
5 - support

Fig. 7 Experimental setup for studying the structure of the laser beam

The experimental setup is shown in Fig. 7. The diode laser with the collimator 1 and the receiving unit of the profilometer 2 are established on the linear guide 5 with a length of 4 m. The two polarization filters 4 are introduced between the laser beam and the receiving unit, with the help of which the energy density on the receiving CCD matrix is reduced to a level below the saturation limit. The type of laser spot is visualized on the screen 3 of the computer.

Fig. 8 shows the energy distribution and beam dimensions in one of the studied cross-sections of the laser beam visualized on the computer screen.

The diffraction patterns on the Gaussian distribution and the breaking of the circular symmetry are due to the diffraction caused by defects and contaminations on the surfaces of the polarizing filters and reflections from their surfaces.

As a result of the conducted research and measurement of the transverse dimensions of the beam, it was established that at a distance of 4000 mm from the output aperture of the emitting block, the transverse dimensions (2w) of the beam do not exceed 6 mm.

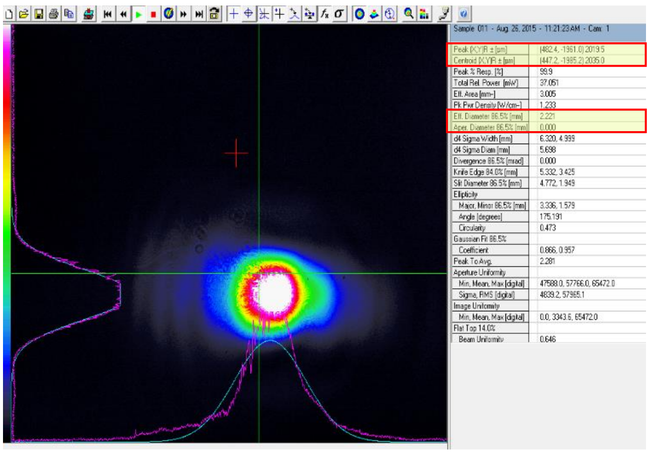


Fig. 8 Energy distribution in the cross-section of the laser beam at a distance L= 1400 mm from the exit aperture of the laser beam

V. Functional Compliance Check on the Separate Modules of the Receiving Unit

The basic modules of the receiving unit (Fig. 1) are the position-sensitive photodetector and the two-coordinate XZ table with the micrometric measuring heads.

The functional check consists in establishing the deviation from parallelism of the OX_F and OZ_F axes of the PSD coordinate systems and the two-coordinate X-Z table and the discreteness of the PSD readings and the micrometric heads [6, 7, 24]. The check is carried out according to the scheme presented in Fig. 9.

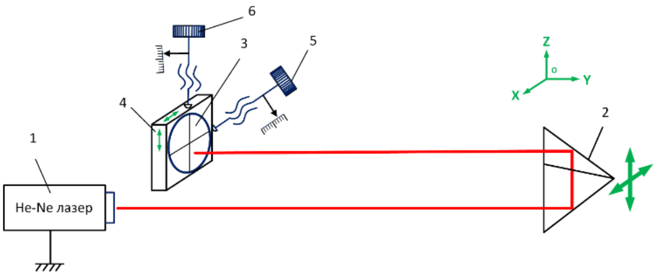


Fig. 9 Consistency check of receiving unit modules

By moving the retroreflector 2, the spot center of the reflected laser beam emitted by the laser source 1 coincides with the center of the PSD 3, where the PSD readings are X_{F0} and Z_{F0}. With the micrometric head 5 (or 6), the PSD is moved in the direction of one of the axes of the coordinate table 4 of the receiving block (for example, the OX axis). The readings of the micrometric head (X_{M0} and X_{M1}) and of the PSD (X_{F0}, Z_{F0}) are read and compared. The angular deviation (non-parallelism) of the PSD coordinate system relative to that of the coordinate table is determined by the formula:

$$\gamma = \frac{\Delta Z_{FM}}{\Delta X_M} = \frac{Z_{F1}-Z_{F0}}{X_{M1}-X_{M0}}. \qquad (1)$$

A laser beam with a size of 2ω = 4 mm was used in the adjustment of the receiving block. The plane of the sensitive area of the PSD has dimensions of 9x9 mm, and with a realized displacement ΔX_M = 4 mm (±2 mm relative to the center of the PSD), a change in the PSD readings for the Z_F coordinate of the center of the spot was recorded ΔZ_F = 7 µm, corresponding to non-parallelism of the coordinate axes:

$$\gamma = \frac{\Delta Z_{FM}}{\Delta X_M} = 1{,}75 \times 10^{-3} \text{ rad} \quad \text{or } \gamma = 6'.$$

VI. Conclusion

The developed dual-channel laser measurement system for assessing the form, location and orientation of large-scaled objects or details with flat surfaces was investigated.

The main factors influencing the metrological and functional indicators of the system were studied. The direction finding characteristics of the photoreceiver and the structure of the emitted laser beam were determined, and the consistency of the separate modules was checked when assembling the systems.

The position characteristic within the limits of ±1 mm is practically linear, which satisfies the requirements for the accuracy of the system.

The error matrix allows increasing the measurement accuracy with the system through software compensation.

As a result of the conducted research, the size of the cross-section of the beam at a distance of 4000 mm from the output aperture of the emitting block was confirmed, which determines the limits of measurement with the system.

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