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Приборы и системы измерения на основе акустических, оптических и радиоволн
Measuring Systems and Instruments Based on Acoustic, Optical and Radio Waves

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# Optical Control System for Displacement Monitoring of the High Precision Measurement Setup Elements

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**Abstract**

**Introduction.** When operating high-precision measurement setups, the reliability of measurements needs to be guaranteed. The displacement of elements from the measurement path can lead to a distortion of measurement results, especially in measurement setups operating in the microwave range. In order to ensure measurement reliability, the positions of elements in the measurement setup needs to be monitored. The monitoring should be per-formed during the measurement. The control device, which should be connected to the automatic control sys-tem of the measurement setup, should neither mechanically affect the setup elements nor introduce any interference. Currently used control systems for the technical characteristics do not meet the necessary requirements.

**Objective.** To design a control system which allows for the monitoring of displacements of elements in a high precision measuring setup with an accuracy of $1.0 \cdot 10^{-4}$ mm and digital signal processing. The control system thus designed should neither mechanically affect the controlled elements nor introduce electrical and electromagnetic interferences.

**Materials and methods.** The system thus designed utilises optical methods for displacement monitoring based on the principles of geometric optics. Mathematical modelling (Mathcad) methods were used to determine the reaction of the system to changes in the beam trajectory and to estimate the sensitivity of the optical control system. Charge-coupled devices (CCD) were used to record the system response to optical path changes.

**Results.** The study presents two designs of a control system for the displacement monitoring of high precision measurement setup elements. The first system design allows for the detection of the occurrence of displacement, while the second system design allows for the identification of the displaced element. The system is capable of registering displacements of elements up to an accuracy of $1.0 \cdot 10^{-4}$ mm and monitoring the position of elements while exposed to vibration. The system does not mechanically or electromagnetically affect the con-trolled elements. All system elements are resistant to microwave radiation and increased background radiation, excluding the CCD which needs to be placed outside the active zone. The monitoring system for movements of elements in the high-precision measuring setup allows for digital signal processing. The study proposes a method to increase system accuracy.

**Conclusion.** The system can be used in setups with increased microwave, x-ray and radiation emission. In comparison with systems based on other physical principles (inductive, capacitive and rheostat), the system thus developed is much easier to implement.

**Key words:** displacement control, structural integrity control, optical control system, measurement setup

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ORIGINAL ARTICLE

# Оптическая система контроля расположения элементов высокоточного измерительного стенда

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## Аннотация

**Введение.** При эксплуатации высокоточных измерительных стендов необходимо обеспечить достоверность измерений. Изменение расположения элементов измерительного тракта, особенно в стендах, работающих в СВЧ-диапазоне, приводит к искажению полученных результатов измерений. Для достижения достоверности измерений необходимо контролировать расположение элементов измерительного стенда. Контроль должен проводиться в процессе измерения, устройство контроля должно подключаться к автоматической системе управления измерительным стендом. Устройство не должно воздействовать механически на элементы стенда и не привносить помех. В настоящее время используемые системы контроля по совокупности технических характеристик не соответствуют необходимым требованиям.

**Цель работы.** Разработка системы контроля перемещений элементов высокоточного измерительного стенда с точностью $1.0 \cdot 10^{-4}$ мм, не оказывающей механического воздействия на контролируемые элементы и не вносящей электрических и электромагнитных помех с возможностью цифровой обработки сигнала.

**Материалы и методы.** В разработанной системе использованы оптические методы контроля перемещений, основанные на геометрической оптике. Методами математического моделирования (Mathcad) определены реакции системы на изменение траектории луча и оценена чувствительность оптической системы контроля. Для регистрации реакции системы на изменение положения оптического пути используются приборы с зарядовой связью.

**Результаты.** Разработаны 2 варианта системы контроля. В первом варианте система позволяет регистрировать изменения в расположении элементов стенда, во втором – идентифицировать элемент, изменивший геометрическое положение. Система способна регистрировать перемещения элементов стенда на $1.0 \cdot 10^{-4}$ мм и контролировать расположения элементов стенда при вибрационном воздействии. Система не оказывает механического и электромагнитного воздействия на элементы стенда. Все элементы системы не чувствительны к воздействию СВЧ-излучения и повышенного радиационного фона, за исключением прибора с зарядовой связью, который должен располагаться вне зоны облучения. Система контроля перемещений элементов высокоточного измерительного стенда позволяет производить цифровую обработку сигнала. Предложен способ повышения точности системы.

**Заключение.** Система может использоваться в стендах с повышенным СВЧ-, рентгеновским и радиационным излучением. В сравнении с системами, основанными на других физических принципах (индуктивный, емкостной и реостатный) разработанная система значительно проще в реализации.

**Ключевые слова:** контроль перемещений, контроль структурной целостности, оптическая система контроля, измерительный стенд

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**Introduction.** The development of high precision measurement devices with increasing requirements for reliability has led to demands for new control systems to monitor measurement setup states and displacements of its constituent elements. In particular, these requirements apply to setups operating in the microwave range. In this case, the monitoring systems should not affect the controlled parts mechanically, nor by introducing electrical and electromagnetic interference [1].

In addition to setups working with microwave devices, there is a need for the precise monitoring of the position of setup elements in the field associated with holography, especially when studying the properties of newly formed structures. For example, researchers have emphasised the importance of resolving problems associated with the alignment of optical elements which can arise due to the high sensitivity of these devices to external mechanical effects. For example, when developing setups to study interference properties of layered structures based on bacteriorhodopsin [2].

At the present time, the main monitoring methods for the displacement monitoring in experimental setups are:

– inductive methods based on the conversion of the displacement of elements being monitored into changes in electric circuit inductance;

– capacitive methods based on the conversion of displacement into changes in electric circuit capacitance;

– resistive methods based on the conversion displacement into changes in the position of precision potentiometer wiper [3].

Ultrasonic displacement sensors and accelerometers mounted on controlled elements are also used for the displacement monitoring. Ultrasonic sensors measure the time before the arrival of the ultrasonic pulse reflected from the controlled element [4].

Pneumatic transducers are also used to measure the displacement of elements. The working principle is based on compressed air flow changes due to linear displacements of the controlled elements. Air flow varies due to changes in the cross section of the exhaust channel passage. Thus, information about the displacement of the controlled element can be obtained by measuring the air flow under constant pressure. Pneumatic control systems for displacement monitoring are highly accurate and relatively small in size, but their application requires the use of a constant pressure air network which in some cases can be difficult. In addition, the inertia of pneumatic systems adversely affects their performance and can lead to problems when controlling vibration effects [5].

The study describes an attempt to solve the problem of displacement control by using optical control systems [6–8]. The most common optical control methods for linear displacement monitoring are based on the diffraction and interference phenomena [9].

The working principle of laser interferometers is based on a summation of two coherent beams from one laser radiation source. In this case, the first beam path remains unchanged, while the second beam path depends on the distance to the controlled element. Thus, the change in distance leads to a redistribution of intensities and a total flux increase or decrease (depending on the phase difference). The disadvantages of interferometers include their sensitivity to vibrations, the requirement for an undistorted reference coherent wave, and difficulty in the processing of interferograms [10, 11].

Diffraction displacement sensors are based on a shift in interference fringes when a controlled element is displaced. The disadvantages of such type of devices include insufficient accuracy, large dimensions and high requirements for radiation source coherence [12].

Another method of measuring distances consists of laser rangefinders based on measuring phase shifts between emitted and reflected signals (continuous mode), or time intervals between emitted and reflected pulses (pulse mode) [13]. A serious disadvantage of such devices is the difficulty of their application at short distances [14].

A common disadvantage of the above devices is their insufficient sensitivity. This requires a more complex system and the use of expensive high precision components.

**Description of the working principle of the optical control system for displacement monitoring of elements in the measurement setup.** A solution which allows for the removal of the disadvantages associated with the insufficient sensitivity of the measurement system and the need to use expensive components is a development of an optical control system using the optical multiplier and reflection of a laser beam from a curved surface [15] (Fig. 1).

The system consists of the following parts: laser *6* located on the base site *1* and emits the laser beam *7*; controlled elements *2*–*4* with mirrors *8*–*10* mount-

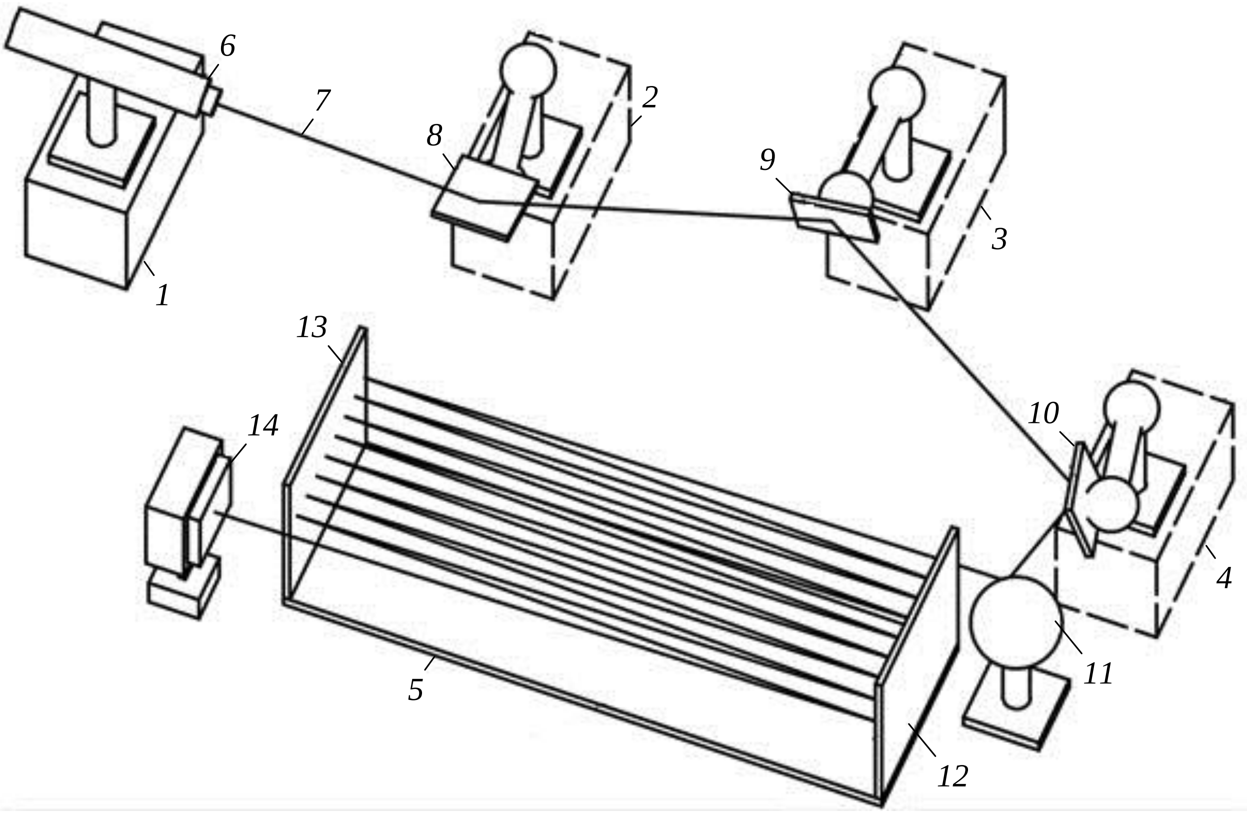

*Fig. 1*. Optical control system for monitoring of the measurement setup elements displacement relative to each other: *1* – base site; *2–4* – controlled elements; *5* – multiplier; *6* – laser; *7* – laser beam; *8–10* – mirrors mounted on the controlled elements; *11* – corrective reflector; *12, 13* – multiplier mirror system; *14* – CCD.

ed on them; corrective reflector *11*; multiplier *5* with mirror system *12*, *13* and charge-coupled device (CCD) *14*.

The proposed optical control system for monitoring the measurement of the displacement of setup elements *2–4* relative to each other works as follows: laser *6* is installed on the setup base site and generates a light beam *7*, which is successively reflected from the mirrors *8–10*, which are mounted on the controlled elements, and enters the corrective reflector *11*. Next, the laser beam *7* repeatedly reflects from the mirrors *12* and *13* and enters the CCD *14*.

Curved mirror surfaces should be used as mirrors *8–10* to avoid mutual compensation occurring when one element displacement is compensated by displacement of the other or when a displacement occurs along a mirror surface.

The control system for displacement monitoring of measurement setup elements as shown in Fig. 1, is easy to implement.

A mirror holder (Fig. 2) has been developed for the accurate positioning of the laser beam. The mirror holder is equipped with hinged clamps *4–6*, which allow mirror *2* to be mounted in the required position. The reflection angle is set by using a micrometre screw located in the upper part of the mir-

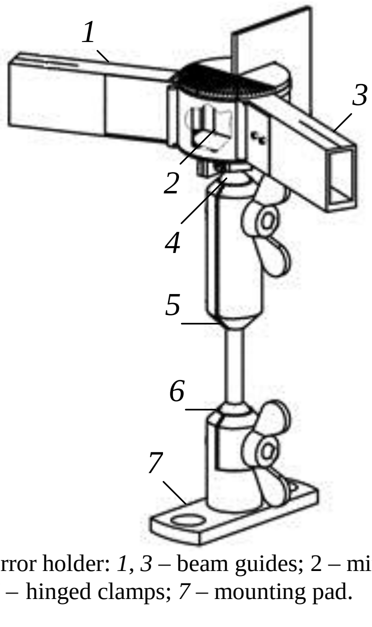

*Fig. 2*. Mirror holder: *1, 3* – beam guides; 2 – mirror; *4–6* – hinged clamps; *7* – mounting pad.

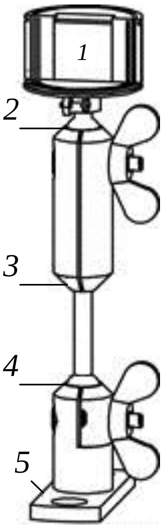

*Fig. 3*. Corrective reflector:
*1* – curved mirror; *2–4* – hinged clamps; *5* – mounting pad.

ror holder. The laser beam propagates along the beam guides *1*, *3*. The mirror holder is mounted on the controlled element by using the mounting pad *7*.

The corrective reflector thus designed (Fig. 3) consists of a spherical or cylindrical curved mirror *1* located in the frame. The corrective reflector design includes the hinged clamps *2–4* for adjusting its position in space and micrometre screw for its fine alignment. The corrective reflector is mounted by using the mounting pad *5*[*].

**Optical system for monitoring the displacement of measurement setup elements relative to the base point.** One of the disadvantages of the optical control system described herein for displacement monitoring of measurement setup elements is the possibility of registering the displacement of controlled elements as a single design, while missing information concerning the displacement of an individual setup element. This issue can lead to complications in troubleshooting. This study proposes a control system for monitoring the displacement of individual setup elements relative to the base point.

The working principle of the optical control system for monitoring the measurement of displacement of setup elements relative to the base point (Fig. 4) is as follows: lasers *6a, 6b, 6c* emit laser beams *7a, 7b, 7c* of different wavelengths. Each of these beams is incident on one of the mirrors *8–10* mounted on the various controlled elements of the setup *8–10*, then it is reflected from the corrective reflector *11*, mirrors *12*, *13* of the multiplier *5*, and hits the CCD *14*. The different beam wavelengths allow for the registering the displacement of each controlled element relative to the laser base point *15*.

In the event of insufficient CCD resolution for colour separation, several CCDs can be used for each controlled element.

**Sensitivity of the optical system for displacement monitoring of high precision measurement setup elements.** The sensitivity of the optical control system designed herein is determined by the optical multiplier mirrors system in accordance with the beam path in the multiplier (Fig. 5).

The optical multiplier mirror system *12*, *13* increases the displacement of the laser beam *7* spot on the CCD *14* in a limited range, as well as dependent on the inclination angle β change, thereby increasing system sensitivity.

As shown in Fig. 5, the optical multiplier sensitivity μ is determined by the dependence of the displacement $x$ change on the angle β change.

Fig. 5 also shows that displacement magnitude is defined as $b = a\,\mathrm{tg}\beta$, where $a$ is the distance between the mirrors; β is the angle between the optical beam and axis 0$A$. Then, for the total optical beam displacement $x$ after $n$ reflections, we obtain:

$$x = \left[(n+1)a + h\right]\mathrm{tg}\,\beta, \qquad (1)$$

where $h$ is the distance between the CCD *14* and mirror *12*.

For the optical multiplier sensitivity $\mu = dx/d\beta$ by using (1), we obtain:

$$\mu = \frac{(n+1)a + h}{\cos^2\beta}. \qquad (2)$$

The displacement $\Delta x$ of the laser beam spot on CCD *14* is determined as:

$$\Delta x = \left[(n+1)a + h\right]\mathrm{tg}\left(\beta + \Delta\beta\right) - \left[(n+1)a + h\right]\mathrm{tg}\,\beta, \qquad (3)$$

where $\Delta\beta$ (Fig. 5) is the angle β increment.

The value $\Delta x$ is determined from (3) by using an approximate expression for sensitivity and equation (2):

$$\Delta x \approx \mu\Delta\beta. \qquad (4)$$

Thus, for example, when $\Delta\beta = 2\cdot10^{-5}$ rad, $a$=500 mm, $h = 0$ and $n = 100$ in accordance with (4) we obtain $\Delta x$=1.01 mm.

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[*] In Fig. 1 and 4, the mirror holders and corrective reflector are shown schematically.

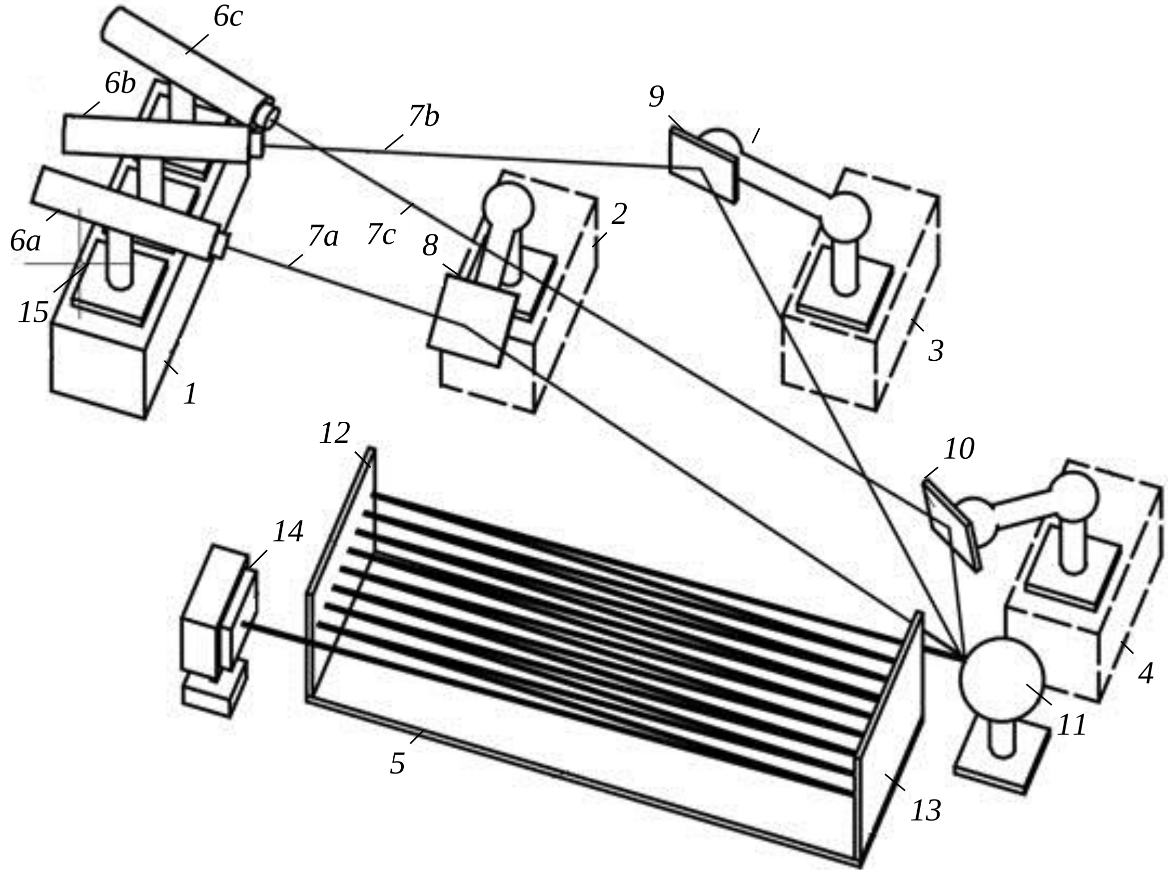

*Fig. 4*. Optical control system for monitoring of the measurement setup elements displacement relative to the base point: *1* – base site; *2–4* – controlled elements; *5* – multiplier; *6a–6c* – lasers; *7a–7c* – laser beams with different wavelengths; *8–10* – mirrors mounted on the controlled elements; *11* – corrective reflector; *12*, *13* – mirror system; *14* – CCD; 15 – base point

The change in the position of the light beam spot on CCD by 1.01 mm is sufficient to determine the presence or absence of displacement of setup elements relative to each other.

At the deflection angle of $\Delta\beta=2\cdot10^{-6}$ rad, we obtain $\Delta x=0.101$ mm.

The number of illuminated pixels when the laser beam spot displacement equals $\Delta x=0.101$ mm is (2181/25.4)0/101=8, even when using a CCD with a relatively low density of photosensitive elements (for example, Kodak 1D [16] with resolution of 2181 DPI (about 85.6 dots per millimeter)). This is sufficient to capture the light beam deflection.

The 7 pixels respond at the deflection angle of $\Delta\beta=2\cdot10^{-7}$ rad when CCD with a high pixel density (OmniVision iPhone 4s with 18100 DPI or 712.598 pixels per millimeter resolution [16]) is used.

The proposed method for the displacement monitoring of measurement setup elements allows for the accurate determination of the deflection angle equal to $\Delta\beta=2\cdot10^{-7}$ rad by using CCD with the density of 18100 DPI, distance between mirrors of 500 mm and hundredfold reflection in an optical multiplier.

The proposed method allows it to be used as a control and measuring system for determining displacement of elements, in addition to registering the presence of displacements in setup elements. To this end, the dependence of the deflection angle β (Fig. 5) on the displacement $x_\text{d}$ (Fig. 6) of the mirror (for example, *8*) mounted on the controlled element and the radius *R* of the corrective reflector *11* (see Fig. 1) needs to be defined.

The principle of using the proposed system as control and measuring device lies in mounting mirrors at an angle known in advance (Fig. 6) and determining the dependence of the light beam spot position on CCD on the controlled element displacement $x_\text{d}$.

It should be noted that the working principle of the proposed method for displacements monitoring

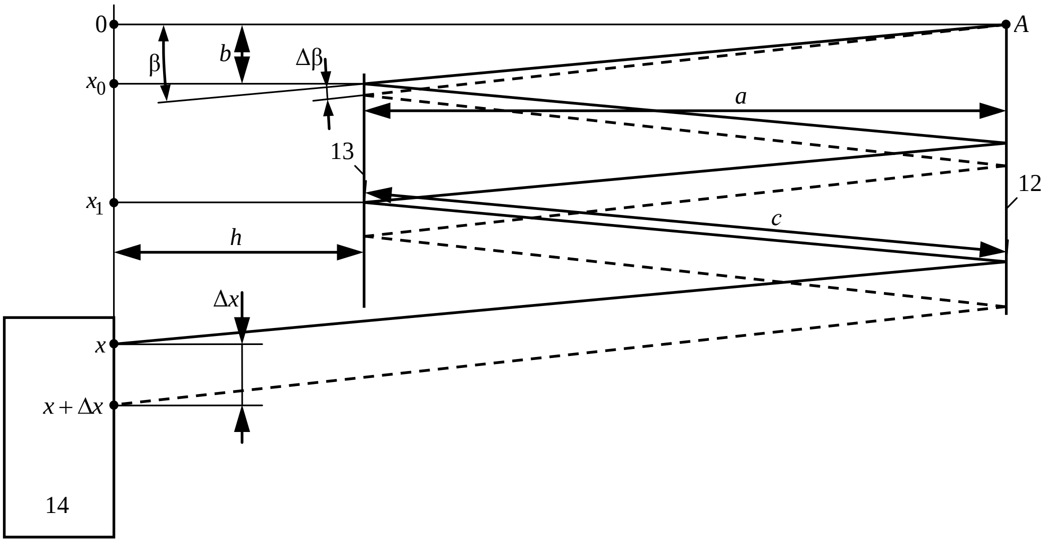

*Fig. 5*. Multiplier beam path: *12*, *13* –mirror system; *14* – CCD.

allows, if necessary, the measurement setup sensitivity to be increased both by reducing the corrective reflector *11* radius (Fig. 6) and by increasing the number of reflections *n* from the mirrors *12*, *13* (Fig. 5).

When using the corrective reflector *11* with a radius of 5 mm and laser beam *6* aimed at the point located from the circle centre at a distance of 4.95 mm, i.e. when the mirror displacement is $x_d$ = 0.0001 mm, then the beam deflection angle is Δβ=0.00028369 rad. This is sufficient for displacement registration by using CCD with a resolution of 2181 DPI, when *a*=500 mm, *h*=0 and *n*=100 in accordance with (3).

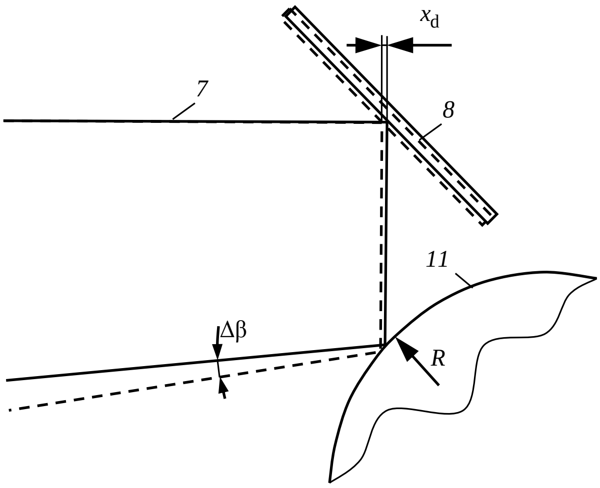

*Fig. 6*. Beam path when using the corrective reflector and mirror mounted on the controlled element: *7* – laser beam; *8* – mirror mounted on the controlled element; 11 – corrective reflector

The laser output power can be increased to compensate for signal attenuation due to increasing reflections from the mirrors. The physical limit associated with a possibility of burning a mirror with a laser beam can be increased by using high-temperature materials, as well as a mirror cooling system [16].

**Conclusion.** The advantage of the proposed optical control system for the displacements monitoring of the measurement setup elements lies in its ease of implementation. This allows for the creation of high precision control devices that do not mechanically and electromagnetically affect the work of the latter.

The use of the optical multiplier and laser beam reflection from the curved surface in the optical control system allows for the optimisation of the control system during design, depending on the required sensitivity, complexity of the system alignment, and overall dimensions. The required system sensitivity can be provided by the optical multiplier with a simple adjustment system when the overall dimensions allow it. If it is not possible to provide the necessary sensitivity with the optical multiplier (it is impossible to position the mirrors at the required distances, or the necessary reflections number exceeds the optical system attenuation ability), then it can be obtained by using the curved reflector by increasing the surface curvature. The originality and novelty of the proposed system is confirmed by the patent [15].

Unlike prototypes, the proposed optical system can work under vibration exposure by determining the sub-critical level of elements displacements from shock and vibration effects through monitoring the light beam spot displacements on CCD. At the same time, the developed system allows vibration or shock directions by beam spot displacements to be determined, in contrast to the existing control systems, including those using interferometers.

The proposed optical control system can be used not only in high precision devices, but also as the primary or secondary control system for displacement monitoring, as well as in large-sized devices and structures, considering the low cost of CCDs and laser emitters.

Optical displacement control systems can be used under the exposure to microwave, as well as X-ray and background radiation.

The proposed control system for displacement monitoring of measurement setup elements was implemented as part of the homogeneity determination setup at the high precision mechanical effects control unit at CJSC NPO "Sredmash".

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