Письма в ЭЧАЯ. 2015. Т. 12, № 7(198). С. 1264–1271

МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

THE SENSITIVITY LIMITATION BY THE RECORDING ADC TO LASER FIDUCIAL LINE AND PRECISION LASER INCLINOMETER

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For metrology setups using a laser beam (the laser fiducial line, the precision laser inclinometer), the recording noise has been determined. This noise is limiting the measurement precision of the beam displacement Δx and, consequently, the precision $\Delta\psi$ of measurement of the beam inclination angle. For a 10 mm laser beam diameter, $\Delta x = \pm 2.9 \cdot 10^{-9}$ m has been obtained. For a one-mode laser beam with a primary diameter of 10 mm and with subsequent focusing, a value of $\Delta\psi = \pm 1.7 \cdot 10^{-11}$ rad has been found.

Определен шум регистрации в экспериментальных установках, использующих лазерный луч (лазерная реперная линия, прецизионный лазерный инклинометр). Этот шум ограничивает точность измерения смещения Δx лазерного луча и, соответственно, точность $\Delta\psi$ измерения угла наклона луча. Для диаметра 10 мм лазерного луча получены $\Delta x = \pm 2{,}9 \cdot 10^{-9}$ м. Для одномодового лазерного луча с первичным диаметром 10 мм и с последующей фокусировкой определена величина $\Delta\psi = \pm 1{,}7 \cdot 10^{-11}$ рад.

PACS: 06.60.Sx; 42.62.-b

INTRODUCTION

For measurements of various linear and angular parameters of the extended setups (linear accelerators, large-scale physics research equipment), the Fiducial Line (FL) is being used. It serves to determine the displacement of measured points in a Global Coordinate System (GCS). In [1–6], a laser ray has been proposed as the Laser Fiducial Line (LFL). The Precision Laser Inclinometer (PLI) has been developed as a new type of sensor that is able to measure the slope of a surface. This is essential for spatial stabilization of the LFL.

In the article, the achievable limits of the LFL and the PLI precision measurements with the quadrant photoreceiver [7–14] are discussed and estimated.

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THE MINIMAL DISPLACEMENT OF A LASER RAY THAT CAN BE REGISTERED ON THE QUADRANT PHOTORECEIVER

The quadrant photosensor is composed of four individual photoreceiver's segments.

A quadrant photosensor (QP) registers the displacement of a laser beam falling on it (Fig. 1) and forms signals as follows:

$$I_1 = i_1 + i_2, \quad I_2 = i_3 + i_4, \quad I_3 = i_1 + i_3, \quad I_4 = i_2 + i_4,$$

where $i_1, i_2,\ i_3, i_4$ are the photoreceiver's currents.

The laser spot displacement in X direction is determined by the differential signal I_1–I_2; respectively, in Y direction by I_3–I_4.

The case of spot displacement in X direction is considered to determine the measurement precision of a laser-ray spot location by QPs. In this case, the QP acts in the dual option.

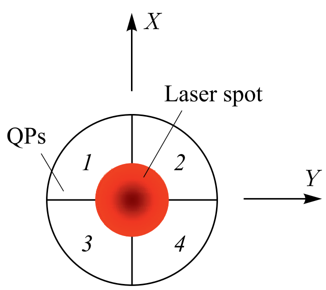

Fig. 1. Registration of a laser spot position by the quadrant photoreceiver

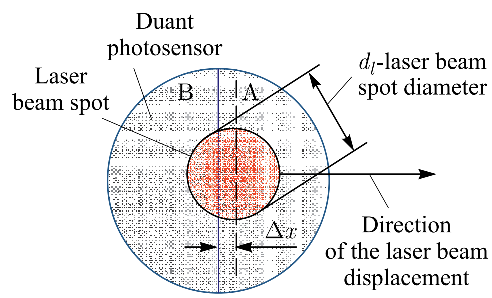

Fig. 2. Measurement of the laser beam displacement on the duant photosensor

Figure 2 shows the laser spot biased by the distance Δx relative to the beam central position on the duant photosensor (DP).

For a small beam displacement $\Delta x \ll d_l$ (d_l is a beam spot diameter), the current change on each photoreceiver will be small and linear with Δx. In these conditions, the changed duant photosensor's currents are

$$I_{\mathrm{B}} = I + \Delta I, \quad I_{\mathrm{A}} = I - \Delta I, \quad I_{\mathrm{B}} - I_{\mathrm{A}} = 2\Delta I, \tag{1}$$

where I is the photoreceiver's current in case of a symmetric location of the laser spot.

The smallest detectable laser beam spot displacement Δx is determined by the DPs' current sensitivity and resolution. This is the value, which defines the measurement precision for a beam displacement on the DPs.

The current of the recording noise (no displacement) is considered conditionally as a "signal". We call this "displacement" (determined by the noise) as the precision of measurement of beam displacement on the DPs.

The largest part of the noise is the so-called *positional noise* of the laser irradiation, while the DP records the spot location. It is essentially the fluctuations of power across the beam. It appears due to air media turbulence, presence at weighted dust and slowly changing temperature gradients. If this noise is decreased (positioning of laser beam inside a pipe with the standing acoustic waves, use of the vacuum tubes or thermostabilization [4–6]), the next level noise is due to the ADC *recording* and to the short current noise in the photoreceiver [15]. These two influences get dominating for the 1 mW laser used in this experiment.

According to [15], the ADC noise and short noise are the "white" ones, and therefore the distribution of differences of the noise currents $I_{n,\mathrm{B}} - I_{n,\mathrm{A}}$ from DPs' photoreceivers has the σ(rms) by factor $\sqrt{2}$ larger than σ(rms) in the distribution of an individual current. This is confirmed by direct measurements of the ADC noise. For the ADC, the registered signal is the voltage fall after the current passed through the same resistance.

Figure 3 contains a one-day record of internal noise of channels A and B, their difference $\mathrm{A} - \mathrm{B}$ and their sum $\mathrm{A} + \mathrm{B}$ for the 24-bit ADC board LA-I24 [16]. The corresponding time integrated (projected on the vertical axis in Fig. 3) distributions are presented in Figs. 4–7.

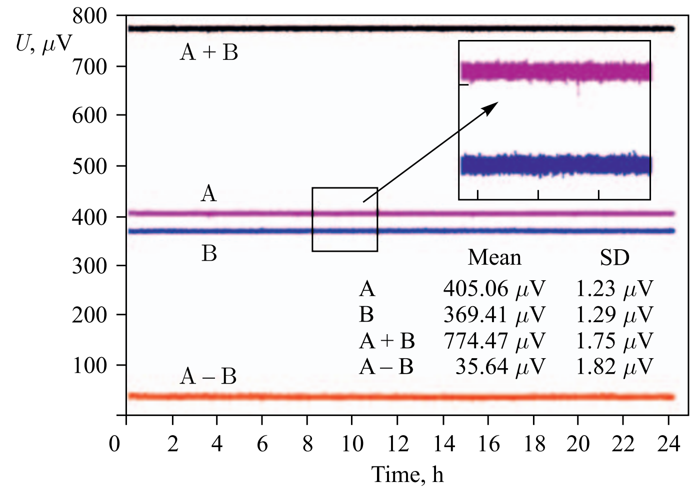

Fig. 3. One-day record of the noise signal U (μV) from channels A and B, their difference A–B and their sum A+B for the ADC board LA-I24 in the absence of laser ray

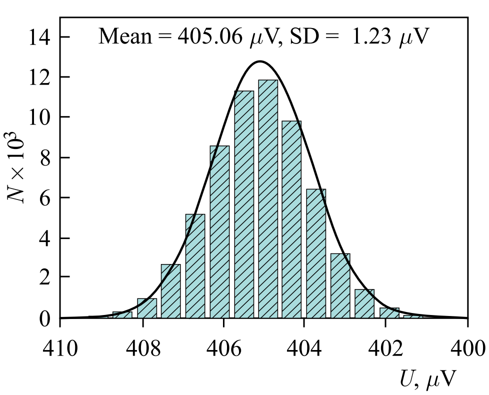

Fig. 4. Signal distribution for channel A

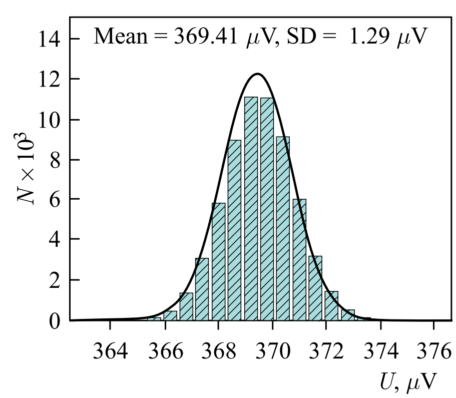

Fig. 5. Signal distribution for channel B

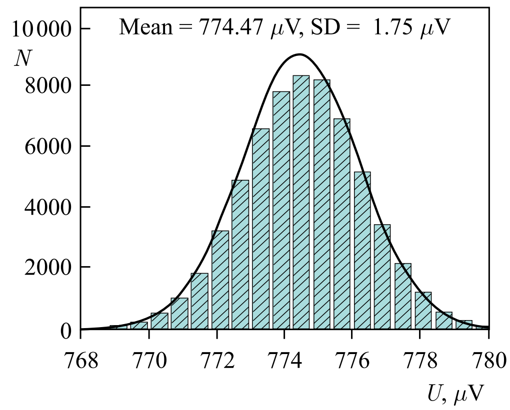

Fig. 6. Signal distribution of the sum A + B

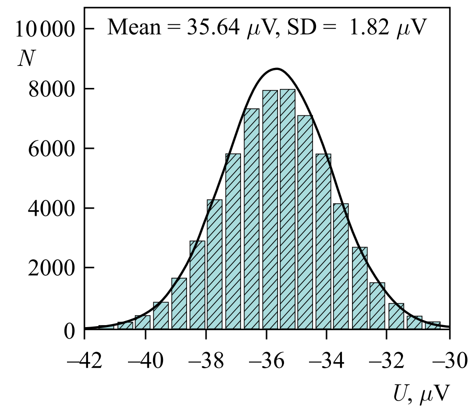

Fig. 7. Signal distribution of the difference A − B

For the approximately equal values of σ(rms) in distributions of signals A and B ($\sigma_{\rm A} = 1.23\ \mu$V, $\sigma_{\rm B} = 1.29\ \mu$V), the σ(rms) values σ_Σ and σ_Δ for "A + B" and "A − B" are expected to be $\approx \sqrt{2}$ time larger, which has been indeed registered: $\sigma_\Delta = 1.82\ \mu$V, $\sigma_\Sigma = 1.75\ \mu$V.

The distribution of $I_{n,\,{\rm A}} - I_{n,\,{\rm B}}$, of $I_{n,\,{\rm A}} + I_{n,\,{\rm B}}$ and the distributions of the photoreceiver's noise currents $I_{n,\,{\rm A}}$ and $I_{n,\,{\rm B}}$ are connected:

$$\sigma_\Delta = \sqrt{2}\sigma_n, \quad \sigma_\Sigma = \sqrt{2}\sigma_n, \tag{2}$$

where σ_Δ is the σ(rms) of the noise currents $I_{n,\,{\rm A}}$, $I_{n,\,{\rm B}}$ from the photoreceivers. Here and further $\sigma_n = \sigma_{\rm A} = \sigma_{\rm B}$.

Taking into account that the mathematical expectation of the mean in the distribution of the current differences is zero (because of two parts of DP's identity and independence), this is the $\sigma_\Delta = \sqrt{2}\sigma_n$ that is taken into account for the signal current.

With the simplification that the irradiation power distribution in the laser-ray spot is uniform (Fig. 2), the *ratio* of the area $2\Delta S = 2\Delta x\, d_l$ (appeared due to the noise displacement Δx) to the laser-ray area $S = (\pi/4)d_l^2$ will be proportional to the *ratio*

$$\frac{\text{signal current} \equiv \text{noise current} = \sigma_\Delta = \sqrt{2}\sigma_n}{\text{total current from both photoreceivers} = I_l}$$

or

$$\frac{2\Delta S}{S} = \frac{\sqrt{2}\sigma_n}{I_l} = \frac{\sigma_\Delta}{I_l}. \tag{3}$$

Using (3), one obtains

$$\frac{2\Delta S}{S} = \frac{2\Delta x d_l}{\frac{\pi}{4}d_l^2} = \frac{\Delta x}{\frac{\pi}{8}d_l} = \frac{\sigma_\Delta}{I_l},$$

where

$$\Delta x = \frac{\pi}{8} d_l \frac{\sigma_\Delta}{I_l}. \tag{4}$$

The $\sigma_\Delta / I_l = K_n$ ratio essentially determines the relative resolution of detecting setup being a ratio of the measurement tract noises to the photoreceiver's current I_l.

Below the estimation of the K_n parameters connected to the ADC and short noise is described.

First, $K_{n,\,\mathrm{ADC}}$ for the 24-bit board LA-I24 is estimated. The rms values of the distribution of an internal noise (in the absence of laser irradiation), Figs. 3–5, of board measurement channels have been equal to $\sigma_{n,\,\mathrm{A}}(U_{n,\,\mathrm{A}}) = 1.23\ \mu$V, $\sigma_{n,\,\mathrm{B}}(U_{n,\,\mathrm{B}}) = 1.29\ \mu$V with a maximal signal of $U_l = 2.5$ V.

The measured σ_Δ(rms) in distribution of differences of noise signals has been (Figs. 6 and 7) equal to $\sigma_\Delta(U) = 1.82\ \mu$V.

Consequently, the $K_{n,\,\mathrm{ADC}} = \sigma_\Delta(U)/U_l$ value is estimated to be $K_{n,\,\mathrm{ADC}} = 7.3 \cdot 10^{-7}$ and practically coincides with the $K_{n,\,\mathrm{ADC}}$ passport value on the manufacturer's homepage.

Now, $K_{n,\,\mathrm{sn}} = \sigma_{\Delta,\,\mathrm{sn}}/I_l$ for short noises is estimated. These kinds of noises appear due to quantum nature of electron current in a conductor.

The current in a conductor has a short-noise component that is determined by Schottky's formula [15]:

$$I_s^2 = 2eI_l\Delta f, \tag{5}$$

with Δf as the bandwidth of signal to be measured and

$$I_l = \frac{\eta e}{h\nu} P_l, \tag{6}$$

P_l is the laser irradiation power; η is the quantum efficiency of the photoreceiver; e is the electron charge; h is the Planck constant, and ν is the laser irradiation frequency.

By using (4) and (6), the value of constant $K_{n,\,\mathrm{sn}} = \sigma_{\Delta,\,\mathrm{sn}}/I_l$ can be determined:

$$K_{n,\,\mathrm{sn}} = 2\sqrt{\frac{h\nu\Delta f}{\eta P_l}}. \tag{7}$$

For $\lambda = 0.63\ \mu$m, $\Delta f = 1$ Hz and $P_l = 1$ mW, we obtain $K_{n,\,\mathrm{sn}} = 5.5 \cdot 10^{-8}$.

The value of the short noise is essentially smaller than the one of the ADC, and therefore does not affect significantly the total noise.

Taking into account that the main noise source is the registration noise connected to the ADC, let us estimate the value of the noise-like displacement Δx of the laser spot on duant photosensor when registrating the laser beam axis in the laser fiducial line. By using formula (4), we obtain

$$\Delta x = \frac{\pi}{8} d_l K_{n,\,\mathrm{ADC}}. \tag{8}$$

At the laser beam diameter of 10 mm, it gives $\Delta x = 2.9 \cdot 10^{-9}$ m.

THE LASER BEAM SLOPE CAUSED BY THE MEASUREMENT SYSTEM NOISE

In numerous applications, where a laser beam is used as a reference line, there is a necessity to measure the angular beam displacement.

For example, in the precision laser inclinometer of a new generation [17, 18], which is currently under development in our group (RF PATENT #2510488), one registers the angular displacement of a laser beam reflected from surface of liquid by the quadrant photoreceiver.

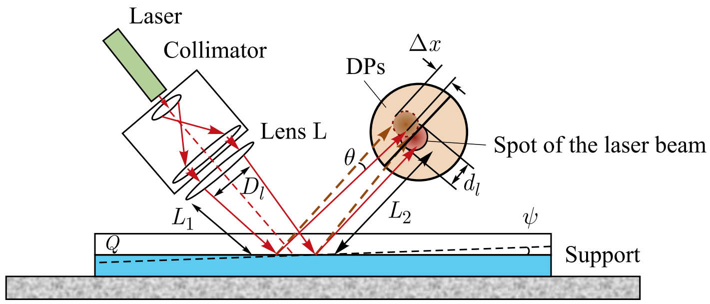

Fig. 8. Measurement of the inclination angle θ of the laser ray reflected from the liquid's surface

Now we estimate the value of the minimal angular displacement θ of a laser beam, which can be registered by the precision laser inclinometer.

Figure 8 shows a principal scheme of the precision laser inclinometer.

The tilt angle θ of the beam after reflection from the liquid's surface due to vessel basement inclination on angle ψ is measured by the DPs. To be specific, one measures the laser beam displacement Δx caused by an angular deviation θ of the laser beam.

To increase the sensitivity of the laser beam, it is focused by long focused lens L with the following condition: the distance L_1 between lens and the liquid's surface is much less than the distance L_2 between the liquid's surface and the DPs ($L_1 \ll L_2$).

The one-mode laser beam focus diameter is determined by the formula [19]:

$$d_l = 1.22\lambda \frac{F}{D_l}, \tag{9}$$

where D_l is the beam diameter at exit.

The solid lines correspond to laser beam location before the vessel basement has been tilted by the angle ψ. In this case,

$$\psi = \frac{1}{2}\theta. \tag{10}$$

The task is to determine the laser beam tilt angle $\theta_n = \Delta x / F$ that corresponds to the noise of the measurement setup. Using (8) and (9), one obtains

$$\theta_n = \frac{\Delta x}{F} = \frac{\pi}{8} 1.22 \frac{\lambda K_{n,\,\mathrm{ADC}}}{D_l}. \tag{11}$$

Having in mind that $\psi = (1/2)\theta$, we obtain

$$\psi_n = \frac{\pi}{16} 1.22 \frac{\lambda K_{n,\,\mathrm{ADC}}}{D_l}. \tag{12}$$

So, as a result, for $\lambda = 0.63\ \mu$m, $K_{n,\,\mathrm{ADC}} = 5.5 \cdot 10^{-7}$ and $D_l = 10$ mm, the minimal value for angle θ_n of laser beam inclination is obtained: $\theta_n = 1.7 \cdot 10^{-11}$ rad.

Correspondingly, the minimal measurable ψ_n of cuvette base inclination in the inclinometer is $\psi_n = 8.5 \cdot 10^{-12}$ rad.

CONCLUSION

The setup of the laser fiducial line has been considered using a duant photosensor and the limitations on the precision of measurement of laser beam displacement caused by different noises have been analyzed.

The analysis shows that the dominating noise comes from the data taking ADC. For one-day use of 24-bit ADC LA-I24, the ADC noise introduced unprecision of a 10 mm laser beam diameter displacement measurement estimated to be at the level of $2.9 \cdot 10^{-9}$ m.

When a one-mode laser beam inclination recording is used in the precision laser inclinometer, the ADC contributed noise applies limitation of the measurement precision of angular displacement of $\varnothing\,10$ mm laser beam with its focusing used. This uncertainty is at the level of $1.7 \cdot 10^{-11}$ rad. The smallest surface tilt that is detectable by the precision laser inclinometer is $8.5 \cdot 10^{-12}$ rad.

Acknowledgements. The authors thank V. Bednyakov and V. Glagolev for scientific support and financial help to perform this study. The financial support by the BMBF (Germany) made our research possible.

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Received on February 5, 2015.