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ESTIMATION OF DYNAMIC ERRORS IN LASER OPTOELECTRONIC DIMENSION GAUGES FOR GEOMETRIC MEASUREMENT OF DETAILS

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Abstract. The article reviews the capabilities and particularities of the approach to the improvement of metrological characteristics of fiber-optic pressure sensors (FOPS) based on estimation estimation of dynamic errors in laser optoelectronic dimension gauges for geometric measurement of details. It is shown that the proposed criteria render new methods for conjugation of optoelectronic converters in the dimension gauge for geometric measurements in order to reduce the speed and volume requirements for the Random Access Memory (RAM) of the video controller which process the signal. It is found that the lower relative error, the higher the interrogetion speed of the CCD array. It is shown that thus, the maximum achievable dynamic accuracy characteristics of the optoelectronic gauge are determined by the following conditions: the parameter stability of the electronic circuits in the CCD array and the microprocessor calculator; linearity of characteristics; error dynamics and noise in all electronic circuits of the CCD array and microprocessor calculator.

1 Introduction

Currently, the parts with complex curved surfaces are machined on six-coordinate machines with programmed control. The control module with optoelectronic gauges for geometric dimensions, coordinates, thickness, orientation angles and stroke speed measurements performs the required technological operations for the manufacture of parts. During the positional control of the machine's multiple connected mechanisms, it is necessary to solve the direct problem concerning the positions and geometric dimensions of the parts and the processing node in the absolute coordinate system OXYZ many times. The main obstacle to the automation of these processes is the difficulty in defining the coordinates for the operating profile points of the processed surface and measuring its actual geometric dimensions. The best way to solve this problem can be laser-optoelectronic dimension gauges for geometric measurement of details with the complex shape.

Laser-optoelectronic dimension gauge is designed for non-contact measurements of geometric dimensions simultaneously in three sections and parts position during the production process. Three interconnected optoelectronic cameras with a semiconductor laser are mounted

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on a positioning stage with numerical program control. The software of the three-dimensional laser-optoelectronic gauge is based on a modified hypsometric method with the interferometry principles [1].

The measurement error of laser-optoelectronic dimension gauges for geometric measurements increases in the dynamic mode, compared to the static one due to the time lag of the measuring channel nodes and fluctuations in the signal of the measuring information [2]. At the same time, the factors leading to measurement error in the static mode, have the same effect in a dynamic one as well. Errors do not remain constant over the time due to the changes affecting the factor measurement accuracy, for example, dynamic changes in the measurement signal, and temperatures in the structural elements of the system [3].

Laser-optoelectronic dimension gauge for geometric measurements is built according to modular principle with the use of high-speed video controllers. The structure of the gauge includes sequentially connected modules of a primary transducer (MPT), an analog-to-digital converter (ADC) and a video controller (VC). The formal identification of the gauge subsystems with dynamical systems under the deterministic approach leads to mathematical models belonging to the class of differential equations in the state space [4]. The sequence of state changes caused by the test action completely characterizes the dynamic properties of the laser gauge. For example, the method of test transient processes is realized by excitation of the transient process in the converters of the laser gauge, and the converted value affects the parameters of the converters by changing their transient characteristics in the state space.

Thereby, the interaction of the laser gauge with the object being measured can be qualitatively represented based on the general systems theory models. However, it should be noted that, in contrast to the dynamical systems themselves, characterized in terms of stability, controllability, and observability, in the optoelectronic measurement processes, the main issue is the problem of representing the properties of a measurement object by numerical values and the uniqueness of these values. That is, the solution to this problem depends on how the properties of the measured object are represented. Formation of the properties' operational values is based on the processes of identification, ordering, counting, and comparison.

2 Mathematical aspects of the estimation of dynamic errors in laser optoelectronic dimension gauges for geometric measurement of details

Any optical image can be characterized by a multidimensional function. Its arguments can be the coordinates $x, y, z,$ the time t (or the frequency ν, or the wavelength of the optical radiation λ, and in the case when the signal is described by the intensity function, the time t, the wavelength λ, and the polarization state ψ). The informativity of an optical signal is greater than that of an electric signal, but the conversion of such a signal is more complicated.

A fundamental feature of the converters of a laser gauge is the sequential conversion of multidimensional optical signals into one-dimensional electrical ones, and then, in the recording system, again into multidimensional signals, that are convenient for the visual perception. In addition, a large amount of naturally originated optical interference, usually accompanying the reception and processing of an optical signal should be noted. Therefore, special optical filters are introduced into the laser gauge to select a desired signal against the interference background.

In [5], a system of criteria is described that makes it possible to evaluate the optimality of conditioning the optoelectronic converter (OC) with the optical system (OS) and the video controller, in which microprocessor information processing occurs. In this system of evaluation criteria, the following coefficients are used

$$\eta_1 = \frac{I_{oc}}{I_{os}}; \eta_2 = \frac{t_{oc}}{t_{os}}; \eta_3 = \frac{\vartheta_{oc}}{\vartheta_{os}}; \eta_4 = \frac{I_{vc}}{I_{os}},$$

where I_{oc}, I_{os}, and I_{vc} is the maximum possible information capacity of the image perceived by the OC, OS, and VC, respectively; t_{os} – the time of the optical image formation in the OS and t_{oc} –- the total processing time of the image in the OC; ϑ_{oc} and ϑ_{os} – productivity of OC and OS, respectively. The criterion η_1 characterizes the speed of the OC, η_2 and η_3 – the specific speed and specific performance of the laser gauge, η_4 – the load efficiency of the video controller in the laser gauge.

The proposed criteria render new methods for conjugation of optoelectronic converters in the dimension gauge for geometric measurements in order to reduce the speed and volume requirements for the Random Access Memory (RAM) of the video controller which process the signal. In addition to the above criteria, the stability and variation range of the parameters and characteristics of the optoelectronic converter are assessed under the specified operating conditions. The sensitivity of optoelectronic converters is determined by the charge accumulated in the potential energy well of the cell and by the signal level associated with this charge. For the estimation of the photodiode arrays capabilities, it is also important to know the sensitivity non-uniformity of its individual elements and the parameters' repeatability error of electronic systems for reading signals from individual elements. In arrays, the parameters' repeatability error can reach up to 50%, which reduces their dynamic range by two or more times. Such an error clearly reduces the possibility of the optical analysis of images, which are usually estimated using the temperature difference NEΔT equivalent to the noise. The value of NEΔT increases in direct proportion to the conversion coefficients' repeatability error of the individual elements in the photodiode arrays. Thus, that the digital processing of the output signal directly in the external microcontroller allows solving the problem of implementing a high degree of sensitivity uniformity across all the elements when the ambient temperature and background illumination change.

In the optoelectronic gauge [6] operating in real time, the sensitivity of each photodetector and the output signal of each reading cells are measured and stored in a special microcontroller. In addition, such a scheme makes it possible to approximate linearly the transfer function of each element of the photodiode array without significant deterioration of the signal-to-noise ratio. When the array is operating in the accumulation mode, a linear approximation of the relationship between the optical radiation flux incident on an individual element of the photodiode array and the output signal of the readout systems provides a sufficiently high accuracy of compensation, characterized by errors in measuring the temperature difference that equivalent to noise of thousandths of Kelvin.

When the photodiode array is operating in the immediate-action mode, the dependence of the current at the output of the photodiode array reading system on the value of the input signal is nonlinear. Here, the dynamic errors in compensation systems with linear approximation are greater than in systems with accumulation. To reduce these errors, for each element of the photodiode array, it is necessary to calculate and memorize not two but three parameters, which considerably complicates the compensation system and increases the dynamic error of calculation in a special microcontroller.

The main node for control and data processing in a laser optoelectronic dimension gauge for geometric measurements is the video controller with the RAM containing the corresponding programs for information processing and measurement. A variety of means that provides communication with a powerful PC can be connected to the video controller. The exposure time is calculated using the video controller timer. The reading of the photodiode array is determined by the time of the reliable resolution of the two measurement signals and can reach 10 ÷ 50 kHz.

The dynamic errors of the optoelectronic gauge are largely determined by the dynamic parameters of all the interrogators and signal processing in the photodiode array and digital processing elements on the microcontroller [7]. These errors have not been studied, and there is no methodology for calculating them. The conversion in the gauge is performed by a complex of nonlinear devices and the mathematical tool of linear systems is not applicable to its analysis [8]. In this regard, two types of dynamic errors for MPT occur: the first type, due to the inertial properties of MPT nodes, and the second type, associated with the change in the measured signal over the conversion cycle. Then, the dynamic characteristics of the MPT are determined as follows:

$$\begin{cases} |K(jw)| = \prod_{s=0}^{n} K_s(jw), \\ A(w) = \prod_{s=0}^{n} A_s(w), \\ \varphi(w) = \sum_{s=0}^{n} \varphi_s(w), \end{cases} \tag{1}$$

where $K(jw)$ – is the frequency response; $A(w)$ and $\varphi(w)$ – amplitude-frequency and phase-frequency characteristics; n – the number of analog function elements in MPT.

In such a representation, the sum of the dynamic errors of the first and second types of MPT is determined by the equation

$$\Delta U_{\mathrm{D}}^{1}(t_i) = U_{\mathrm{out}}^{1}(t_i + \Delta t_i) - U_{\mathrm{ma}}^{1}(t_i), \tag{2}$$

and by the inaccuracy of the algorithm being implemented for its processing.

However, considering that the actual value of the measured signal $U_{\mathrm{ma}}^{1}(t_i)$ at moment when the received response relates is unknown, as well as the time $t_i + \Delta t_i$ is unknown when the measurement was actually obtained, it is impossible to use the expression (2) to determine the dynamic error. Thus, various estimations for the magnitude or parameters of the dynamic error are adopted. From (2) it is seen that the value of this error depends on the type $U_{\mathrm{out}}^{1}(t_i)$ and function of its variation with time. Therefore, the initial data, which is necessary for obtaining the estimation of this error, should include the information on the parameters of the function being evaluated and data on the process being measured.

MPT is a collection of a large number of elements that interact in a certain way and it possesses the main features and characteristics of discrete-analog systems, in a broad sense of the term. The processes of their functioning are characterized by a sequential change in the state of the MPT elements in time and can be described by a number of states

$$Q = \{q_1, q_2, \ldots, q_i, \ldots\} \tag{3}$$

and by number of stay durations in each of them

$$T = \{\tau_1, \tau_2, \ldots, \tau_i, \ldots\}. \tag{4}$$

Then, in accordance with the assigned task, for the MPT consisting of a photodiode array, an amplifier, a double-correlated processing scheme and an active filter, we determine the stay duration of the measurement signal at a discrete moment τ , i.e. elements of a set T .

The scheme of combining the CCD (charge-coupled device) array with the electronic circuit is shown in Figure 1. When reading the optical information, each photosensitive element (5) is connected to the signal reading information bus through the corresponding signal key switches. The shutter of each key switch is controlled by a shift scan register. After reset, the potential at the amplifier input is measured when the key switch is off (9). This algorithm provides a double-correlated sampling mode that eliminates reset noise, which is the largest over all other noise in CCD arrays [9].

Through the input (6) an injection pulse is applied to the reading line, causing the disappearing of the potential well and the current flow, which ensures the recombination of the carriers accumulated in the well. The voltage difference between the sampled values is determined by the value of the charge injected from the potential well. During the interval between the reading processes, the key switches (3) are switched on and the reference voltage is set on all photodetectors.

For the given optical information, the conversion dynamic error in the CCD array can be described by a functional as follows:

$$\Delta_D = f\left(\frac{dx}{dt},\ \Delta t, t_{\text{int}}\right), \tag{5}$$

where $x(t)$ is optical information; Δt – conversion time; t_{int} – time of interrogation.

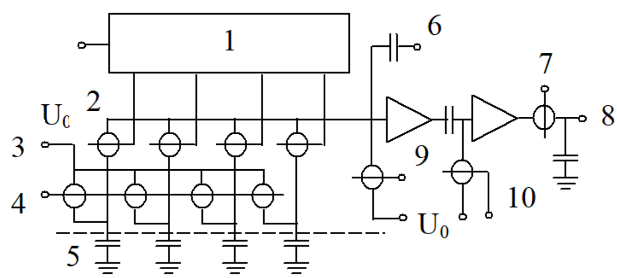

Fig. 1. The scheme of combining the CCD array with the electronic circuit:1 – scan registers; 2 – information bus key switches; 3 – addressing key switches; 4 – parallel reset key switches; 5 – photodetectors (represented in the form of capacity); 6— injection pulse; 7 – sampling;8 – output; 9 –reset; 10 – first sampling.

Assuming the measurement information $x(t)$ is continuous during the interrogation time $t_{\text{опр}}$, it can be represented as follows

$$x(t_i) = x(t_{\text{int}}) + x'(t_{\text{int}})\cdot\Delta t_i + \frac{x''(t_{\text{int}})}{2}(\Delta t_i)^2 + \ldots + \frac{x^{(n)}(t_{\text{int}})}{n!}(\Delta t_i)^n. \tag{6}$$

The function of the interrogation speed of the CCD array during the time $[0;T_{\text{int}}]$ is represented in the following form

$$V_{\text{CCD}}(\omega_1) = \int_0^{T_{\text{int}}} V_{\text{CCD}}(\omega_1 t)dt = \int_0^{T_{\text{int}}} \left(V_{\text{CCD(N)}} + \Delta V_{CCD(A)} \sin(\omega_1(t))\right)dt, \tag{7}$$

and the function of changing the measurement information in the time interval $[0;T_i]$ is represented as follows

$$V_{\mathrm{mi}}(\omega_2) = \int_0^{T_i} V_{\mathrm{mi}}(\omega_2 t)dt = \int_0^{T_i} \left(V_{\mathrm{mi(N)}} + \Delta V_{\mathrm{mi}(A)} \sin(\omega_2(t))\right)dt, \tag{8}$$

where $V_{\mathrm{CCD(N)}}$ and $V_{\mathrm{mi(N)}}$ are nominal values of speeds; $V_{CCD(A)}$ and $V_{\mathrm{m}i(A)}$ - the amplitude values of the interrogation speed of the CCD array and speed of change in the measurement information.

Assuming $\int_0^{T_1} V_{\mathrm{CCD}}(\omega_2 t)dt = \int_0^{T_1} \Delta V_{\mathrm{m}i(A)} \sin(\omega_2(t))dt$, then the change in the measurement information in the time intervals $[0;T_1]$ and $[0;T_2]$ can be represented as follows

$$V_{\mathrm{mi}}(\omega_2 T_1) = \int_0^{T_1} \left(V_{\mathrm{mi(N)}} + \Delta V_{\mathrm{mi}(A)} \sin(\omega_2(t))\right)dt,$$

$$V_{\mathrm{mi}}(\omega_2 T_2) = \int_0^{T_2} \left(V_{\mathrm{mi(N)}} + \Delta V_{\mathrm{mi}(A)} \sin(\omega_2(t))\right)dt.$$

Integrating these expressions and solving them with respect to T_1 and T_2, the following equation is obtained

$$\Delta_{\mathrm{mi}}(T_2) \approx \frac{T_1}{T_2} = \frac{V_{\mathrm{mi}}(\omega_2 T_1) - 2\dfrac{\Delta V_{\mathrm{mi}(A)}}{\omega_2} \sin^2 \dfrac{\omega_2 \cdot V_{\mathrm{mi}}(\omega_2 T_1)}{2V_{\mathrm{mi(N)}}}}{V_{\mathrm{mi}}(\omega_2 T_2) - 2\dfrac{\Delta V_{\mathrm{mi}(A)}}{\omega_2} \sin^2 \dfrac{\omega_2 \cdot V_{\mathrm{mi}}(\omega_2 T_2)}{2V_{\mathrm{mi(N)}}}}. \tag{9}$$

For any T_i, this equation takes the form as follows (вместо we get)

$$\Delta_{\mathrm{mi}}(T_i) \approx \frac{T_1}{T_i} = \frac{V_{\mathrm{mi}}(\omega_2 T_1) - 2\dfrac{\Delta V_{\mathrm{mi}(A)}}{\omega_2} \sin^2 \dfrac{\omega_2 \cdot V_{\mathrm{mi}}(\omega_2 T_1)}{2V_{\mathrm{ms(N)}}}}{V_{\mathrm{mi}}(\omega_2 T_i) - 2\dfrac{\Delta V_{\mathrm{mi}(A)}}{\omega_2} \sin^2 \dfrac{\omega_2 \cdot V_{\mathrm{mi}}(\omega_2 T_i)}{2V_{\mathrm{ms(N)}}}}. \tag{10}$$

Due to the change speed irregularity in the measurement information, the relative error $\Delta_{\mathrm{ms}}(T_i)$ is determined as follows

$$\delta_{\Delta_{\mathrm{mi}}(T_i)} = \frac{2\Delta V_{\mathrm{mi}(A)}}{\omega_2} \left(\frac{\sin^2 \dfrac{\omega_2 \cdot V_{\mathrm{mi}}(\omega_2 T_i)}{2V_{\mathrm{ms(N)}}}}{V_{\mathrm{mi}}(\omega_2 T_i)} - \frac{\sin^2 \dfrac{\omega_2 \cdot V_{\mathrm{mi}}(\omega_2 T_1)}{2V_{\mathrm{ms(N)}}}}{V_{\mathrm{mi}}(\omega_2 T_1)} \right). \tag{11}$$

At small values ω_2

$$\delta_{\Delta_{\mathrm{mi}}(T_i)} = \frac{2\omega_2 \Delta V_{\mathrm{mi}(A)}}{V_{\mathrm{mi(N)}}} \left(V_{\mathrm{mi}}(\omega_2 T_i) - V_{\mathrm{mi}}(\omega_2 T_1)\right). \tag{12}$$

The lower relative error, the higher the interrogetion speed of the CCD array.

The laser gauge must have the required dynamic accuracy which means that the error for all given measurement conversions and perturbation influences should not exceed a certain permissible value. Complete information on dynamic accuracy is given by the law of time error variation. For the deterministic change in the input effect, the error consists of two components

$$\Phi(t_i) = \Phi_{st}(t_i + \Delta t_i) - \Phi_{tr}(t_i + \Delta t_i), \quad (13)$$

where $\Phi_{st}(\cdot)$ and $\Phi_{tr}(\cdot)$ – stimulated and transient errors, respectively, which depend on external influences and on the change of all parameters of the interconnected converters of the laser gauge. To reduce these errors, various methods of dynamic correction are used. However, for the solution, the structure and parameters of measurement circuits with correcting elements in numerical form should be set, while for the dynamic synthesis case, the choice of the structure and parameters of the correcting systems is the main task. Because of that, the methods based on solving differential equations, at the stages of synthesis of structures and parameters cannot achieve the desired results.

At the stage of the synthesis of the laser gauge, it is rational to apply frequency methods that allow a direct and visual connection of the dynamic properties of functional subsystems with metrological parameters and characteristics. The main correction tools are the correcting elements, the inclusion of which to the measuring circuits provides the required improvement in characteristics. The task is even more complicated if the dynamic characteristics in the analogue part of the information conversion do not remain constant but change in time randomly.

One of the types of such correction is dynamic reflex transformation [10]. When this method is used at the output of the CCD array, which has unstable dynamic properties, a chain of correcting elements is switched on, dynamic characteristics of which are automatically maintained in accordance with the current state of the photoconverters dynamic parameters. To simplify the recording, the photodetector circuit of the CCD array consists of two elements: an inertial linear one, the static conversion function of which is stable, and the inertialess linear one with time-dependent conversion function. Let us assume that the inertial element of the photodetector circuit of the CCD array is described by the equation

$$L(K_i^*) = W(p)L(\varepsilon_i), \quad (14)$$

where K_i^* is the variable corresponding to the output signal of the inertial element. Then the conversion function of the inertialess linear element is determined by

$$K_i = f_0(t) + f_1(t)K_i^*, \quad (15)$$

where $f_0(t)$ and $f_1(t)$ is a function of time. In turn, the function of the correcting element is defined as follows

$$\varepsilon_{k(i)} = a_0 + a_1 K_i. \quad (16)$$

To determine K_i^*, the inverse Laplace transformation is used:

$$K_i^* = L^{-1}[W(p)L(\varepsilon_i)]. \quad (17)$$

Then K_i takes the form as follows

$$K_i = f_0(t) + f_1(t)L^{-1}[W(p)L(\varepsilon_i)]. \quad (18)$$

By selecting parameters for $f_0(t)$, $f_1(t)$, $W(p)$ and $L(\varepsilon_i)$ the required value K_i is achieved.

3 Conclusions

Direct parallel or sequential correction devices in electronic circuits of the CCD array with a microprocessor calculator provide the maximum dynamic quality of the optical signal conversion with a wide range of perturbation influences such as ambient temperature and background illumination. The requirement to provide an independent choice of parameters and quality criteria regarding the effective influences and to each of the perturbation influences leads to the necessity to organize its own combined measurement contour for each influence. From the point of view of achieving high dynamic measurement accuracy with a wide range of changes in the environment and the variety of background illumination, the multichannel structure of digital processing of CCD array sensor signals is the most rational.

Thus, the maximum achievable dynamic accuracy characteristics of the optoelectronic gauge are determined by the following conditions: the parameter stability of the electronic circuits in the CCD array and the microprocessor calculator; linearity of characteristics; error dynamics and noise in all electronic circuits of the CCD array and microprocessor calculator. The following factors determine the achievement of high dynamic characteristics of a laser optoelectronic dimension gauge for geometric measurements: nonlinearity, dynamics of the errors, intrinsic noise, deviations of parameters due to changes in ambient conditions, mutual cross-links generated by the practical implementation specifics of the electronic circuits in the CCD array and a microprocessor calculator.

Based on the obtained theoretical and experimental results, the recommendations for the parameter selection for laser optoelectronic dimension gauge for the industry application are proposed. The results for the dynamic error calculation of the developed dimension gauge are well consistent with the results of real metrological tests with an accuracy of 3 ÷ 5%.

4 Conflict of interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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