Analysis of errors in measuring displacement by a laser interferometer used as a feedback sensor precision lathe module feed drive

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Abstract. The article considers the structure of errors in measuring the displacement by a laser interferometer used as a feedback sensor for the feed drive of a turning module, and the conditions for their minimization to ensure precision machining of parts.

1. Introduction
The increasing requirements for the quality of manufacturing of parts for aircraft, instrument and mechanical engineering products necessitate ensuring the accuracy of precision machining on automated metal-cutting machines [1, 2]. With precision machining, the removable allowances and, accordingly, the cutting forces, vibrations and heat generation are small, the machines operate in a thermo-constant room, the influence of other disturbing factors is minimized. In this case, a significant role is played by the positioning accuracy of the working body, which directly determines the size of the parts [3]. With a certain design of a precision automated metal-cutting machine, the positioning accuracy is determined by the accuracy of the feedback sensor of the feed drive [4]. Currently, inductive and photoelectric sensors, as well as laser interferometers, are used as a feedback sensor, and their application is expanding for precision and super-precision automated metal-cutting machines [5]. The highest accuracy is possessed by measuring systems based on laser interferometers, which provide a sampling rate of up to 0.001 ... 0.01 µm [6, 7, 8]. PJSC “Tantal” (Saratov) has developed a precision turning module of the TPARM type, intended for processing parts with dimensions of about 50 ... 80 mm in 1-3 grade, which required ensuring a positioning error of no more than 0.3 ... 0.8 µm [4]. The implementation of the above is achieved by using aerostatic sup-port guides, a multistage frictional transmission in the feed drive and laser interferometers as a feedback sensor with a sampling rate of 0.2 µm. In laser interferometers, an unstabilized helium-neon laser was used, the choice of which was justified by the fact that it had a low cost, high reliability for use in industrial conditions and provided a measurement of displacement up to 200 mm. In the module feed drive, laser interferometers with external mechanical modulation by a rotating diffraction grating were used. A rotating diffraction grating converts single-frequency radiation into two-frequency: into two spatially separated frequency components, which are then used in the optical scheme of laser interferometers, similar to the use of a two-frequency laser, which is discussed in detail in [8, 9]. In connection with the above, the scientific and practical interest is the estimation of the error in measuring the displacement of the indicated laser interferometers as a feedback sensor of the feed drive.
2. Displacement measurement error analysis

The formation of signals about the movement in the laser interferometer is carried out from the Doppler change in the radiation frequency \( f_d \), which is extracted from the comparison of the signals of the reference and measuring channels of the laser interferometers. The calculation of the displacement \( S \) according to the known speed of the object \( \nu(t) \) is carried out according to the formula:

\[
S = \frac{c}{2\nu} \int_0^t f_d \, dt
\]

where \( t_m \) – measurement time, \( \nu \) – radiation frequency, \( c \) – speed of light.

In the electronic unit of information processing, the Doppler frequency is allocated, after the integration of which the measured movement of the module support is recorded. The information about the movement is then used in the control system of the automated cutting machine. The result of measuring the amount of displacement, displayed by the indication of the electronic unit, is represented by the expression

\[
S + \Delta S = R_o \lambda N
\]

where \( S \) - the measured displacement, \( \Delta S \) - the measurement error, \( N \) - the number of counting pulses of the interferometer, \( \lambda \) - the laser radiation wavelength, \( R_o \) - the conversion factor.

The use of laser interferometers with a rotating diffraction grating on a turning module requires an analysis of the structure of the displacement measurement error \( \Delta S \), which is determined by many factors depending on the physical processes and design features of the device. Errors of any measuring device can be classified according to various criteria: by dimension, by the conditions and reasons for their occurrence, etc. [9, 10]. Let us evaluate the measurement accuracy of laser interferometers of the caliper displacement, aimed at minimizing measurement errors. Let us single out two groups of errors according to the conditions of their appearance: static and dynamic.

Static errors \( \Delta S_{st} \), expressed in the units of the measured quantity, occur in a steady state measurement, when the measured quantity and the output signal hold a constant value. Dynamic errors \( \Delta S_{dn} \) occur in a transient measurement mode and are added to the static ones. The total error of laser interferometers is:

\[
\Delta S = \Delta S_{st} + \Delta S_{dn}
\]

The static error is divided into two parts: main and additional [10].

The main error occurs under normal conditions, which correspond to normal climatic conditions, the normal position of the measuring device, etc. The main error for laser interferometers consists of the approximation error, the error due to changes in internal parameters, and the error due to the action of internal destabilizing factors. The approximation error is determined, firstly, by the fact that an indirect method is used to calculate the desired displacement, in which the phase difference of the signals \( F \) of the reference and measuring channels is measured. The latter is carried out by counting the number of counting pulses generated in the electronic unit, and the fractional part of the interference fringe \( \Delta S_1 \) is not taken into account. In this case, the resulting error does not exceed one counting pulse, that is, 0.2 \( \mu \)m. The approximation error, secondly, is determined for laser interferometers by the pulse counting error in the electronic unit \( \Delta S_2 \). Modern microprocessor-based pulse shaping and counting circuits reduce this error to zero. It follows that the error of the approximation does not exceed one counting pulse in magnitude:

\[
\Delta S_1 + \Delta S_2 \leq 0.2 \ \mu m
\]

The error from changes in internal parameters arises due to the instability of the frequency and power of the laser radiation, production and technological errors of the modulator on a rotating diffraction grating and changes in the linear dimensions of laser interferometers during thermal deformations due to the release of heat by the laser into the volume of the device.
A change in the radiation frequency during the measurement leads to the appearance of a random error $\Delta S_v$, which is due to a random change in the value $F$. The value $v$ has a uniform distribution in the interval $\Delta v$ with the probability density $w(v) = 1/\Delta v$. We get that the value $f_d$ also has a uniform distribution in the interval $\Delta f_d$, at that $\Delta f_d = \frac{2v}{c} \Delta v$. The error due to frequency instability is $\Delta S = \Delta S_v = \frac{\Delta v}{v} S$.

For an unstabilized laser, the relative frequency stability is $\Delta v/v = 3 \times 10^{-6}$, then $\Delta S = 3 \times 10^{-6} S$. Under the condition of the onset of the laser thermal stabilization mode, the frequency instability is $\Delta v/v = 0.1 \times 10^{-6}$, then we find that the desired error will not exceed the value $\Delta S = 0.1 \times 10^{-6} S \mu m$. (5)

Fluctuations in the radiation power lead to fluctuations in the level of the output signals of the laser interferometer, which can cause malfunctions in the formation of counting pulses in the electronic unit and lead to a significant uncontrolled error in measuring the displacement. The elimination of this error is achieved by introducing an automatic signal gain control circuit. Production and technological errors for the laser interferometer are associated with the errors of the modulator on the rotating diffraction grating: instability of the rotation frequency of the rotating diffraction grating, period errors (grating irregularity) and basing errors, which affects the formation of information signals in the laser interferometer. A detailed analytical analysis of these errors, given in [9], showed that under the established limitations corresponding to the real technical and technological capabilities of manufacturing a modulator on a rotating diffraction grating, they introduce negligible errors in the measurement of displacement of the order of $10^{-5} \mu m$, that is, not affect the stability of the laser interferometer as a feedback sensor for the feed drive.

Thermal deformations of the device associated with the release of heat by the laser into the volume of the optical unit of the laser interferometer are manifested in the zero drift in the electronic unit. To assess the effect of temperature deformations on the measurement accuracy, we assume that the temperature conditions are quasi-static, i.e. let us neglect temperature variability not only in time, but also within the interferometer volume. The influence of temperature fluctuations on the optical scheme is determined by a change in the value $\Delta \ell$, reflecting the difference in the change in the optical paths of the reference and measuring beams. It can be assumed that the change in the optical paths of the rays is influenced by changes in the following factors: the geometric dimensions of the optical elements, the refractive indices of air in the volume of the device, the geometric dimensions of the base of the device. The dominant factor is the change in the geometric dimensions of the basic element of the interferometer (the base). Then the error of the device for quasi-static conditions when the temperature changes by 1 °C will be expressed by the formula

$$\Delta S_t = \alpha \cdot \Delta \ell,$$

where $\alpha$ - temperature coefficient of linear expansion of the base material.

Taking into account the geometric parameters of the device, when $\Delta \ell = 100 \text{ mm}$ and values $\alpha$ ($1.16 \cdot 10^{-6}$ / deg for steel 45 and $1 \cdot 10^{-6}$ / deg for alloy 32NKD), we obtain the following error values: $\Delta S_t$ is equal to $1.2 \mu m$ / deg (base from steel 45) and is equal to $0.1 \mu m$ / deg (base from alloy 32NKD).

An analytical calculation of the temperature error at the design stage of measuring device allows obtaining its approximate value due to a number of assumptions. Another disadvantage of the calculation is the need to use tabular coefficients, the values of which may not correspond to the real
ones. As a result, it is advisable to study the zero drift of a laser interferometer under the action of internal and external thermal disturbances and determine the patterns of its change for the introduction of corrections, as well as the conditions for its minimization due to design solutions, for example, the use of 32NKD alloy for fabricating the base of a laser interferometer, or providing a thermal stabilization, which will reduce the temperature error to almost zero [9].

The error from the action of internal destabilizing factors is determined for a laser interferometer by the noise of the gas discharge of the active laser element, the noise of the photodetector and internal interference in the electronic unit, which are superimposed on the useful harmonic signal, which can lead to measurement errors. Schematic solutions practically exclude the influence of these factors.

An additional static error is added to the main one when the operating conditions of the measuring device deviate from normal. For a laser interferometer, it is determined, first, by a change in climatic conditions, i.e. temperature, pressure and humidity of the air, which leads to a change in the wavelength of laser radiation; secondly, a change in the linear dimensions of the interferometer and the control object when the ambient temperature changes; thirdly, the error in the installation of the interferometer.

There is a known formula that determines the measurement error of displacement due to a change in the radiation wavelength when climatic conditions deviate from normal [11]:

\[ \Delta S_5 = S\left(0.93\Delta t + 0.36\Delta p - 0.06\Delta \ell\right) \cdot 10^{-6}, \]

where \( \Delta t, \Delta p, \Delta \ell \) - deviations, respectively, of temperature, pressure and humidity of the air from normal conditions \( (t = 20^\circ\text{C}, p = 760\text{ mm Hg}, \ell = 10\text{ mm Hg}) \).

Provided that the turning module is placed in a thermo-constant room, slight deviations of the medium parameters from the normal ones (temperature fluctuations \( 0.2 \ldots 0.5^\circ\text{C} \), pressure fluctuations no more than \( 2\text{ mm Hg} \)), the error \( \Delta S_5 \) equal to

\[ \Delta S_5 = 1.2 \cdot 10^{-6} \text{ S } \mu\text{m}, \]

Another factor affecting the zero drift of a laser interferometer is a change in the geometric dimensions of the device and the machine tool due to changes in the ambient temperature, as well as due to heat generation inside the machine tool. The resulting error is determined in each case specifically, since it depends on the design of the interferometer, the physical properties of the materials from which the device and the test object are made, as well as the nature of thermal deformations of the machine and the device. Specified error \( \Delta S_6 \) can be calculated analytically for quasi-static conditions similarly to calculating the temperature error \( \Delta S_4 \) of the device, however, from a practical point of view, the calculation \( \Delta S_6 \) is inexpedient due to the difficulty of taking into account the temperature distribution of massive structural elements of the machine tool, which depends on the nature of thermal processes in the machine. To minimize this error, firstly, various methods are used to reduce heat generation in the nodes of precision machine tools, and secondly, high-precision parts are processed in thermosts-constant rooms, where temperature fluctuations do not exceed \( 0.2 \ldots 0.5^\circ\text{C} \). Considering that changes in the ambient temperature and thermal transients in the machine are processes of average speed, then with short measurement cycles during the processing of one part (on the order of several minutes), the elimination of errors that determine the zero drift of the laser interferometer is carried out in the module control system by returning to the point of conditional zero. In this case, the error \( \Delta S_6 \) can be neglected.

The interferometer installation error \( \Delta S_7 \) is the sum of the error from the mismatch between the direction of movement \( \Delta S_7' \) of the reflector and the direction of measurement and the error from turning the test object at a certain angle relative to the perpendicular to the direction of movement when it is parallel to the direction of measurement \( \Delta S_7^* \) (Abbe error). The error in determining the true
displacement with a mismatch between the directions of movement of the reflector and the direction of measurement has the form

\[ \Delta S_7 = S_1 \left( \frac{1}{2} x^2 - \frac{1}{8} x^4 + \ldots \right), \]

where \( x \) – the angle between the direction of movement of the reflector and the direction of measurement. When installing and adjusting the laser interferometer on a precision machine that processes small-sized parts, the \( x \) angle will be determined by the non-straightness of the guides. Since the latter does not exceed \( 2 \ldots 4 \) \( \mu \)m for precision machines at a length of 200-300 mm, so far we obtain

\[ \Delta S_7 \leq 10^{-6} \mu m. \quad (9) \]

The installation error of the interferometer \( \Delta S_7 \), while observing the Abbe principle, is determined only by the value \( \Delta S_7 \). On a precision machine that processes small parts, this error is negligible.

Consequently, the analysis of the static errors of the laser interferometer as a feedback sensor makes it possible to reduce the total error \( \Delta S_{st} \) to the sum

\[ \Delta S_{st} = \Delta S_1 + \Delta S_3 + \Delta S_5, \quad (10) \]

Dynamic error is divided into main and additional [10].

The basic dynamic error occurs under normal operating conditions of the measuring device. It manifests itself when measuring displacement and is expressed for a laser interferometer in dynamic distortion of the amplitude and shape of the output signals, which leads to an incorrect reading of the displacement. Circuitry solutions for signal processing ensure its elimination.

An additional dynamic error occurs when the operating conditions deviate from normal and when additional external influences are imposed on the measuring device. This error is determined for the laser interferometer, firstly, by electrical and electromagnetic influences, and secondly, by vibration influences. The use of special methods of signal processing in electronic equipment, as well as minimization of machine vibrations by design solutions leads to the fact that the indicated error becomes negligible. Therefore, for a real laser interferometer, the dynamic error in measuring the movement of the support is practically excluded.

Let us consider the conditions for minimizing the total displacement measurement error.

The calculated expression of the measurement error of the laser interferometer is determined by the previously obtained formula (10). It is possible to distinguish an additive (independent of \( S \)) error \( \Delta_a \) and a multiplicative (proportional to \( S \)) error \( \Delta_m \), then

\[ \Delta S = \pm \left( \Delta_a + \Delta_m \right), \quad (11) \]

where \( \Delta_a = \Delta S_1 \); \( \Delta_m = \Delta S_3 + \Delta S_5 \), at the same time, as indicated above, a number of errors are not taken into account, since they are minimized by constructive and other methods.

Under the above conditions and restrictions, an expression follows for the total measurement error of the laser interferometer displacement

\[ \Delta S = \pm \left( 0.2 + 1.3 \cdot 10^{-6} S \right) \mu m. \quad (12) \]

It follows from the obtained formulas that with a measurement discreteness of 0.2 \( \mu \)m (one counting pulse), the total measurement error of the displacement of the order of 100 mm is about 0.3 \( \mu \)m. The performed analysis determines the conditions when the laser interferometer, as a feedback
sensor of the feed drive, ensures the stability of measurements of the displacements of the working body, which makes it possible to carry out stable processing of parts with a given accuracy on a precision automated metal-cutting machine.

It was noted above that due to a number of design features of TPARM-type turning modules, the positioning error is determined by the discreteness of the feedback sensor - a laser interferometer. To determine the actual positioning accuracy of the support, a series of experiments was performed, and the verification was carried out according to the methodology described in detail in [3, 12]. The measurements were carried out on the TPARM-100, TPARM-100M and TPARM-80 modules (figure 1). The modules differ in a number of constructive improvements made during operation, in particular, the TPARM-80 uses the laser interferometer “Electronics PLPI-2000” with a single-frequency stabilized laser, while the readout resolution is 0.1 μm, and the total error ΔS for moving 100 mm is about 0.2 μm.

![Figure 1. Histograms of positioning errors distribution on the TPARM modules.](image)

3. Results
The results of measurements on the automated metal cutting machine of various models indicate that the modules have a high positioning accuracy, and the TPARM-80 module has the highest accuracy. The histograms of the distribution of errors gradually become narrower. The above is associated with the improvement of both the MFP configuration technology (it is an almost linear gap-free link) and the control system (in particular, the laser interferometer as a feedback sensor of the feed drive). It can be seen from the figure that the positioning error is actually determined by the discreteness of the feedback sensor: for the TPARM-100M module - 0.2 μm, for the TPARM-80 module - 0.1 μm. The specified modules, under appropriate operating conditions (thermos-constant room, vibration isolation from external disturbances), provide precision machining of parts made of aluminum and copper alloys with dimensions up to 100 mm with an error of no more than 0.5 ... 1.0 microns and a roughness Ra (with diamond turning) 0.02 ... 0.04 μm

4. Conclusion
To assess the measurement error of the displacement of the laser interferometer - feedback sensor of the feed drive, their structure is determined, the influence of factors of different physical nature and design features of the measurement circuit on the machine is determined analytically, and then the
conditions for minimizing the total measurement error are determined. The experimentally obtained values of the caliper positioning errors, determined by the discreteness of the laser interferometer measurement, were achieved precisely by the joint use of aerostatic caliper guides, laser interferometer, and MFP in the feed drive.

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