Laser Measuring Systems for Precision CNC Machine Tools

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The paper deals with developing of laser optoelectronic measuring instruments ЛИР-1, ЛИР-350 for the coordinates' determining of the cutting tool edge and subsequent compensating its dimensional wear directly on machine tools. The laser instruments' application permits noncontact measuring geometric dimensions of both the cutting tools and the workpieces to within 0.05 to 1 μm with reducing set-up time.

Keywords: Laser, Optoelectronic measuring instruments, CNC, Machine tools, Laser meters, USSR.

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1. Introduction

Machine tools included in flexible automated systems should be fitted with output and machining quality control systems which are first of all implemented in the form of devices for monitoring the cutting tool positioning and state. Such systems should provide adaptation to the range of parts and conditions of their machining.

A rather wide and successful application has at present been gained only by contact probe-type monitoring devices, manufactured by the Renshow Co., installed on CNC machine tools for an automatic positioning of the cutting tool. The most promising, however, is the use of laser optoelectronic measuring devices, which are capable of effecting high-accuracy contactless remote measurements directly on the machine tool.

The simplest and cheapest among these devices are optical photometric and projecting devices based on measuring the power of the light flux that either has passed by the workpiece or has been reflected by its surface as well as on measuring the characteristic dimensions of a colinear image (projection) of the object with the aid of matrix image receivers.

Optical photometric and projection devices are capable of measuring geometric dimensions of workpieces accurately to within 5 to 10 μm, and therefore are preferably used on conventional machine tools for rough and semifinish machining. For monitoring the state of the cutting process on precision machine tools it is most advantageous to employ laser optoelectronic measuring instruments based on the phenomena of diffraction and interference of light waves as well as on the holographic diffractometry and interferometry.

Such devices can measure geometric dimen-

sions of workpieces or their displacements as well as the cutting tool wear accurately to within 0.05 to 1 μm. They are most promising for solving the metrological problems of the machine tool industry under conditions of a flexible automated production and therefore they are being continuously improved by many research laboratories of the optoelectronic instrument industry.

2. Theory

The authors have for the last seven years been conducting research and development work in the field of laser optoelectronic measuring instruments for determining the coordinates of the cutting edge of a tool and subsequently compensating for its dimensional wear directly on machine tools. By the present time, three types of laser meters, ЛИР-1, ЛИР-1МА, and ЛИР-1М, have already been created and passed laboratory test for positioning the cutting tool, and measuring the dimensional wear with subsequent compensating for its value by the CNC system by means of a radial feed (displacement) of the tool by the amount of its dimensional wear. The ЛИР-type instruments comprise a specialized optical system for producing the image of the cutting tool tip on a single-coordinate CCD-receiver containing 256 photocells each of 23 μm in width as well as a small-size helium-neon laser serving as the coherent emission source in the optical system. In addition the small-size laser meter ЛИР-350 МП has been developed for measuring the workpiece dimensions directly on the machine tool; it comprises the same CCD-receiver and a semiconductor laser with an emission wavelength $\lambda = 0.78$ μm and a spectral line width $\Delta\lambda = 0.1$ nm. Main specifications of the developed instruments are given in Table 1; their general views are shown in Figs. 1–4.

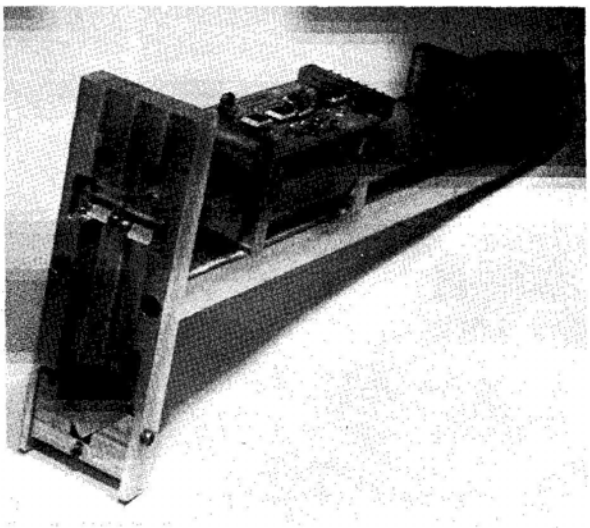

Fig. 1. Instrument ЛИР-1 with top and front covers removed.

Operation of the instruments, both developed and under development, is based on the phenomena of interaction of a coherent narrow-angle laser emission beam with the profile and roughness of the surface of the object under monitoring. The diagram of divergence (convergence) of the narrow-angle beam is shaped by an anamorphotic optical system interposed between the laser and

Table 1
Instrument specifications

Characteristic	Unit of measurement	Instrument model			
		ЛИР–1	ЛИР-1МА	ЛИР-1 МБ	ЛИР-350МП
Year of development		1983	1984	1985	1986
Measurement range	μm	300	350	350	500
Measurement error	μm	2	1	1	2
Time for one measurement	μs	0.2	0.5	1	1
Overall dimensions	mm	320	310	307	150
		x70	x65	x63	x50
		x70	x55	x47	x20
Mass	kg	0.8	1.5	0.8	0.2
Power supply voltage	V	220	220	220	±6
Power consumed	W	25	25	15	1.9
Output videosignal Waveform		pulse	pulse	pulse smoothed	pulse smoothed

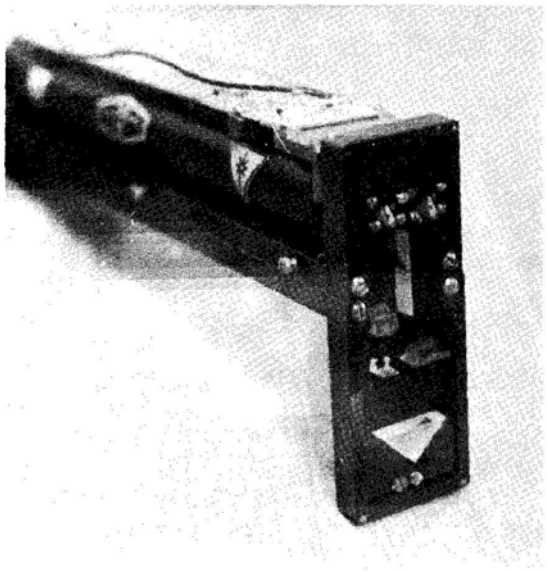

Fig. 2. Instrument ЛИР-1МА with front and top covers removed.

the object under monitoring, and the distribution of complex amplitudes $U(x, y)$ of the light wave of the field in the object illumination plane is described by an analytical relation of the following form:

$$U(x, y) = A_0 \frac{\omega_0}{\omega} \cdot e^{-(x^2+y^2)/2}, \tag{1}$$

where ω_0 is the radius of beam constriction in the laser cavity; ω is the radius of the beam in the object illumination plane; and A_0 is the amplitude of the light wave in the beam at its axis.

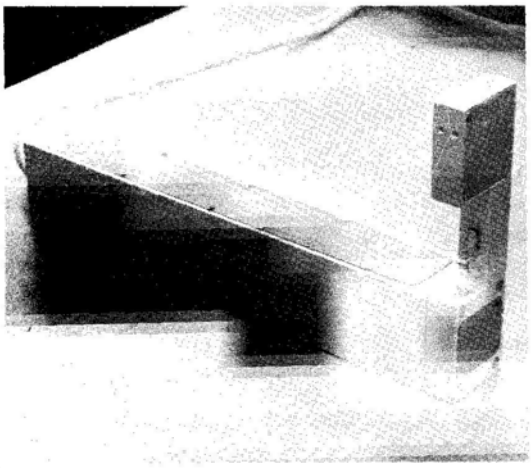

Fig. 3. Instrument ЛИР-1МБ.

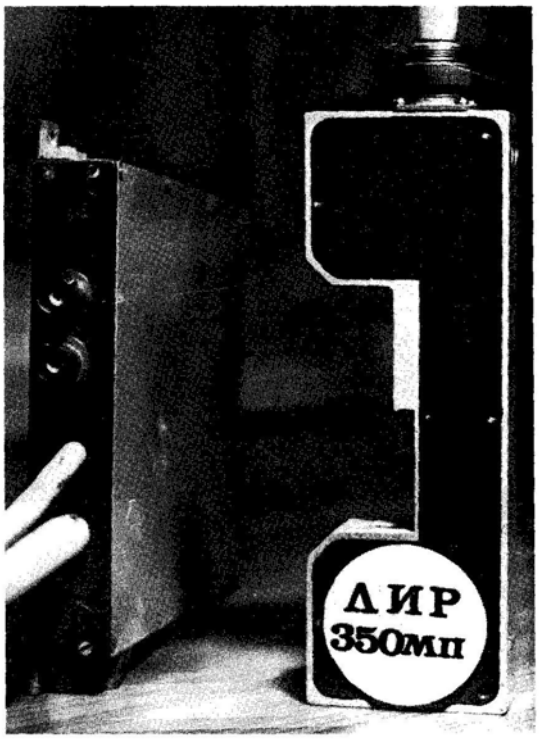

Fig. 4. Instrument ЛИР-350МП on lathe ТПК-125ВМ.

We determine the light field that has been reflected by the surface of the object or has passed by the object in the tangential direction in the form of the Huygens-Fresnel integral transform; since the paramaximum region of a scattered light field is most accesible for photometric measurements, i.e.,

$$U(\xi, \eta) = \iint_S U(x, y) \cdot \theta(x, y) \cdot e^{jkr(x,y)} \, dx \, dy, \tag{2}$$

where $r(x, y) = \sqrt{(x-\xi)^2 + (y-\eta)^2 + z^2}$ is the distance between two arbitrary points, one of which is in the illuminated region of the object, and the second is in the plane of detection of the emission scattered by the object; z is the distance from the object to the plane of detection of the emission scattered by the object; S is the range of integration, coinciding with the shape and dimensions of the illuminated region of the object; and $\theta(x, y)$ is the function describing the topology of the scattering surface of the object at its illuminated region.

The integral expression (2) can be considerably simplified for some particular cases taking place for specific configurations of optical systems of the ЛИР instruments. Thus at a tangential illumination of the surface of a cylindrical workpiece, produced in the course of machining on a lathe, the distribution of amplitudes of the scattered light field in the paramaximum region of the optical system can be represented as follows:

$$U(f_x) = \frac{e^{-j(af_x+\pi/2)}}{jf}\left(\frac{1}{f_x} - \frac{e^{j\alpha}}{\sqrt{3}\,(f_x - f_x^0)} + \frac{\sqrt{\pi R f_x}}{2k}\cdot e^{-j\psi - j\pi/4}\right), \quad (3)$$

where $\alpha = 2kR(2a/3R)^{3/2}; f_x^0 = 2k\sqrt{2a/3R}$;

$$\psi = f_x a - kR\left(\frac{f_x}{2k}\right)^3, \quad (4)$$

where, in its turn, $k = 2\pi/\lambda$ is the wave number; λ is the laser emission wavelength; R is the workpiece radius; a is the distance from the workpiece surface to the half-plane of the limiting aperture; and f_x is the spatial frequency coordinate in the scattered field detection plane.

Analyzing expression (3) shows the function to be monotonically oscillating, and hence the spatial distribution of the scattered light field intensity, proportional to the square of its amplitude, will be spatially oscillating as well. Having singled out the phase of oscillations and having differentiated it with respect to coordinate f_x, we obtain the expression describing the period of oscillations of the field intensity:

$$T(f_x) = \frac{\lambda f}{a}\left(1 - \frac{3R}{8a}\left(\frac{x}{f}\right)^2\right)^{-1}. \quad (5)$$

The existence of a unique dependence of light field intensity oscillation period T on distance a to the aperture and radius R of the workpiece in fixing point x makes it possible to detemine radius R (or diameter) sought for by analyzing the periodicity of the scattered light field; just this has been realized in the ЛИР-350МП instrument.

In another particular case which in practice occurs in monitoring the dimensional wear of the cutting tool, expression (2) by means of analytical transformations can be reduced to a relation describing the distribution of intensity of the light field scattered by the cutting tool tip:

$$W(f_x) = \{1 - 2\langle J_0(2\pi A f_x)\rangle A \cdot \cos 2\pi a f_x + \langle J_0^2(2\pi A f_x)\rangle A\}/(2\pi f_x)^2 + \sum_{n=0}^{+\infty}\left\langle \frac{j_n^2(2\pi A f_x)}{(2\pi A f_x)^2}\right\rangle A \cdot \left\langle B^2 \frac{\sin^2(\frac{1}{2}nB\omega)}{(\frac{1}{2}nB\omega)^2}\right\rangle \omega, \quad (6)$$

where A, ω are instantaneous amplitude and frequency of microirregularities of the cutting tool tip profile; J_n is the Bessel's function of the nth order; a is the distance from the cutting tool tip to the half-plane of the limiting aperture; B is the width of the illuminating beam at the tool tip; and $\langle \ldots \rangle$ is the operator of a statistical averaging with respect to random parameters A or ω.

For a new cutting tool, when $A = \omega = 0$, expression (6) takes the following form:

$$W(f_x) = 2 \cdot \sin^2 \pi a f_x/(2\pi f_x)^2. \quad (7)$$

The analysis of expressions (6) and (7) demonstrates that, as in the preceding case, the distribution of the intensity of the scattered light field is of an oscillating nature and comprises alternating maximums and minimums of the light field intensity, converted by the CCD-receiver, which is subsequently analyzed by the digital computing system of the CNC apparatus.

The above expressions (6) and (7) have been taken as the basis in developing the algorithms of processing the output videosignal of the ЛИР-1, ЛИР-1МА, and ЛИР-1МБ laser instruments for monitoring the dimensional wear of the cutting tool.

The essence of the algorithm for the digital processing of the videosignal of the instruments consists in performing a number of computational procedures with a single-dimensional array of numbers whose values are proportional to the readings of the videosignal amplitudes. Such an array is generated by an analog-digital converter (ADC) and introduced through an interface into the internal memory (IM) of the microprocessor of the CNC system of the machine tool. The microprocessor, by a successive comparison of all

the numbers of the array of videosignal amplitudes, determines the Nos of the numbers whose values are minimum among all numbers arranged in succession in the array. Next, every of the found extremes is interpolated by quadratic parabola over five numbers, and the coordinates of the vertex of the parabola are calculated, which allows determining the coordinates of the videosignal extremes with the fractional part of a number after the decimal point. Next, distances P_i between all ith and $(i+1)$th extremes of the videosignal are determined, i.e. the array of videosignal periods P_i is generated, and average period P of the videosignal is calculated as the ratio of the sum total of all periods P_i to the total number N_p of the periods:

$$\overline{P} = \sum_{i=1}^{N_p} \frac{P_i}{N_p}, \tag{8}$$

and then distance a from the cutting tool tip to the limiting half-plane of the aperture is found as

$$a = \lambda l / \overline{P}, \tag{9}$$

where l is the distance from the half-plane to the CCD-receiver, and also dimensional wear h of the tool as the difference between current a values and initial a value measured before operating the cutting tool.

3. Conclusions

The main technical characteristics of the instrument itself as well as of the "machine tool-instrument" machining unit have been experimentally determined in the course of operation-statistical tests of one of the developed instruments, in particular ЛИР-1, on the ТПК-125ВМ machine tool with the Electronika K.60.680-CNC system. This made it possible to formulate a number of practical recommendations on operating the instrument under industrial production conditions as well as technical requirements and specifications for the improvement of newly designed instruments in the further developments.

Figures 5 and 6 present the main results of the operation-statistical tests of the ЛИР-1 instrument. Figure 5 shows the time fluctuation of the measurement zero of the instrument versus its operating time. From this graph it follows that during the first 90 minutes of operation the instrument should be recalibrated as often as possible in order to reduce the systematic measurement error; that is what has been incorporated by the authors in the CNC system software.

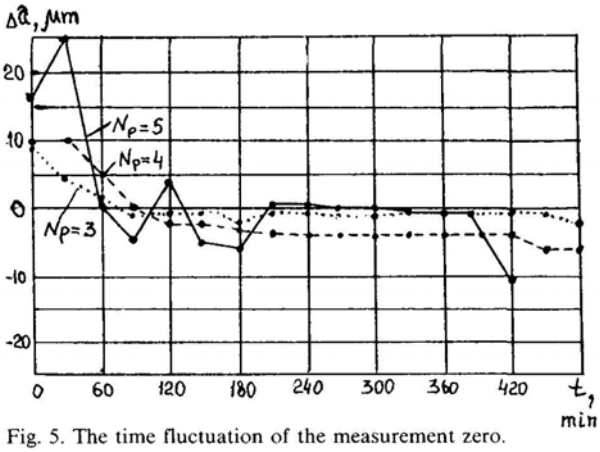

Fig. 5. The time fluctuation of the measurement zero.

Figure 6 graphically shows the dispersion of instrument indications depending on the number N_p of periods P_i in the output videosignal of the instrument for 1, 9, and 36 averagings of the videosignal. The graph shows the dispersion of instrument indications to be independent of the number of videosignal averagings; therefore, to attain the maximum speed of measurements by the instrument, only a single reading of the videosignal with the aid of the ADC can and should be made.

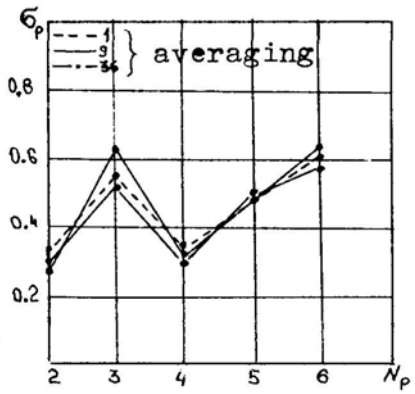

Fig. 6. The dispersion of instrument indications depending on the number N_p of periods P_i.

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