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Some problems of a laser interferometric measuring system

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This paper emphasizes the importance of the interferometric methods for the measurements of lengths, flatness and other geometrical quantities. The solution of different types of interferometers with circularly and orthogonal linearly polarized beams and their compatibility in a laser interferometric measuring system are presented.

Introduction

For the most precise measurements of the lengths in metrology, engineering, electronics and many other branches, the laser interferometry which utilizes the wave definition of the meter length unit is used. The commonly used wave definition of the length unit based on the orange line of krypton-86 has a series of disadvantages and does not seem to be perspective. On the other hand, the laser interferometry offers wide possibilities of the direct measurement on the basis of the wave definition with all resulting consequences: high accuracy, large resolution and measuring ranges of several tens of meters.

A laser interferometer was elaborated in the Institute of Scientific Instruments of the Czechoslovak Academy of Sciences, Brno, in 1967-1969, and in 1971 it was introduced in the production at METRA Blansko [1, 2]. The properties of the single-frequency laser and some applications of the laser interferometer are presented in [3]. A remote laser interferometer which was built up in the following time period [4, 5] is now also produced at METRA Blansko. By introducing the laser interferometers into production and by matching the wavelength of the single-frequency lasers to the world length standard, preconditions have been created for the successful application of the laser interferometric methods in the ČSSR.

Besides the length measurements, one observes an even increasing importance of measurements of other geometrical quantities, such as straightness and flatness, rectilinearity and dynamic phenomena by means of the laser interferometry. These reasons have led to a laser interference system, designed for the measurements of lengths (possibly within more coordinates), velocity, straightness and flatness, angles, dynamic phenomena etc. Up to now interferometers for length and velocity measurements and a differential interferometer for straightness, flatness and small angles measurements have been developed and tested. At present our effort is concentrated on the work connected with an interferometer for dynamic phenomena and rectilinearity measurements.

Laser measuring system

The laser system operates on the interference principle and the quantity to be measured (length, angle, path difference) is expressed by a number of interference units, usually $\lambda/8$ which are indicated on a table, or converted automatically to a metric measure. The interference of two beams — the reference and measuring one — in a laser interferometer must fulfill a series of conditions for the achievement of the highest signal, and the interference signal must carry the information about the motion direction of the moving part. To determine the direction we employ two signals in quadrature (phase shifted by 90°) which result in the interference of two circularity polarized beams of the opposite orientation. The interferometers work either directly with this kind of beams polarization or they use two orthogonal linearly polarized beams which, after releasing the interferometer, are changed into circularly polarized beams of the opposite orientation.

In the laser interferometry system various types of interferometers operate, which employ the polarization optics to obtain two signals in quadrature. The polarization optics of each interferometer allowed interferometers of various types to operate in a system with a single common laser or a single common detection unit [6]. Hence the input of each interferometer type is adapted to the linearly polarized light of the laser (standardized input light), and the output is in the form of circularly polarized beams of the opposite orientation and of the same intensity.

The principle of an interferometer with circularly polarized light of the opposite orientation

The operation principle of the interferometer with the circularly polarized light of the opposite orientation, and generating two signals in quadrature used for determining the motion direction of the moving part is shown in [6]. The work of the linear interferometer for lengths measurements [5, 6] and of the differential interferometer for straightness and flatness measurements is based on this principle.

Fig. 1 shows an exemplified arrangement of the polarization optics in a differential interferometer. The properties of the dividing plate can be expressed by means of Jones matrices [7-11]:

$$\begin{bmatrix} \sqrt{R_\perp}\, e^{i\frac{\delta_2}{2}} & 0 \\ 0 & \sqrt{R_\parallel}\, e^{-i\frac{\delta_2}{2}} \end{bmatrix}, \begin{bmatrix} \sqrt{T_\perp}\, e^{i\frac{\delta_2'}{2}} & 0 \\ 0 & \sqrt{T_\parallel}\, e^{-i\frac{\delta_2'}{2}} \end{bmatrix}, \qquad (1a, b)$$

where $R_\perp$, $R_\parallel$ is the reflectance of the dividing layer for the light of the laser with the oscillation plane situated in a plane perpendicular to and parallel with the plane of incidence, respectively, δ_2, δ_2' is the difference of the phase shift of the dividing plate for reflection and transmission, respectively; $T_\perp$, $T_\parallel$ is the transmittance of the dividing plate for the radiation with the oscillation plane perpendicular to and parallel with the plane of incidence, respectively.

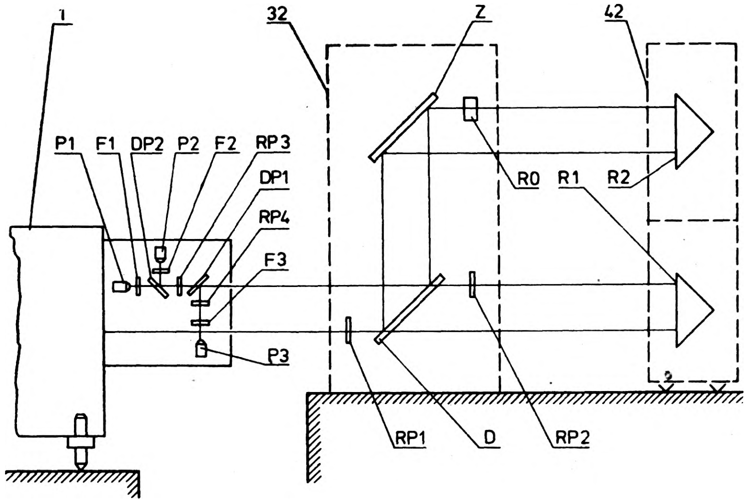

Fig. 1. Basic diagram of a differential interferometer: 1 — laser head with collimation optics and the detection part, 32 — the interference divider for straightness measurements, 42 — double retro-reflector; *RP*1, *RP*2, *RP*3, *RP*4 — retardation plates; *D* — dividing plate of an interferometer; *R*1, *R*2 — cube corner reflectors, R_0 — rotator, *Z* — plane mirror; *DP*1, *DP*2 — dividing plates; *F*1, *F*2, *F*3 — polarization filters; *P*1, *P*2, *P*3 — photoelectric detector

When the remaining members in the interferometer do not show any substantial influence on the change of the light polarization and the dividing plate meets the condition

$$R_{\perp}+R_{\parallel} = \frac{1}{1-Z_p}(T_{\perp}+T_{\parallel}), \tag{2}$$

then for the phase retardation δ, the orientation of the fast axis Θ, and the rotation angle of the rotator ζ of particular elements of the polarization optics we have the following values:

$$RP_1:\ \delta = 90°, \quad \Theta = \pi/4, \tag{3}$$

$$RO:\ \delta = 180°, \quad \zeta = 90°, \tag{4}$$

$$RP_2:\ \delta = 180°, \ \Theta = 45°. \tag{5}$$

The design of the detection unit and the values of the optical elements are given in [6].

The reference beam ε_r or the measuring beam ε_m can be written as follows:

$$\varepsilon_r = \begin{bmatrix} R_{\perp}^{1/2} e^{i\frac{\delta_2}{2}} & 0 \\ 0 & R_{\parallel}^{1/2} e^{-i\frac{\delta_2}{2}} \end{bmatrix} (1-Z_p)^{1/2} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix},$$

$$\begin{bmatrix} R_{\perp}^{1/2} e^{i\frac{\delta_2}{2}} & 0 \\ & R_{\parallel}^{1/2} e^{-i\frac{\delta_2}{2}} \end{bmatrix} 1/\sqrt{2} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} \begin{bmatrix} 0 \\ E_E \end{bmatrix} = -i\sqrt{\frac{T_{\perp} T_{\parallel}}{2}}\, E_E \begin{bmatrix} i \\ 1 \end{bmatrix}, \tag{6}$$

$$\varepsilon_m = \left[\begin{bmatrix} T_{\perp}^{1/2} e^{i\frac{\delta_2'}{2}} & 0 \\ 0 & T_{\parallel}^{1/2} e^{-i\frac{\delta_2'}{2}} \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\right], \left[\begin{bmatrix} T^{1/2} e^{i\frac{\delta_2'}{2}} & 0 \\ 0 & T_{\parallel}^{1/2} e^{-i\frac{\delta_2'}{2}} \end{bmatrix} E_E/\sqrt{2} \begin{bmatrix} i \\ 1 \end{bmatrix}\right]$$

$$= \sqrt{\frac{T_{\perp} T_{\parallel}}{2}}\, E_E \begin{bmatrix} 1 \\ i \end{bmatrix}, \tag{7}$$

where Z_p are losses of the mirror and E_E is the electric vector of the incoming light.

This result indicates that the reference and measuring output beams of the interferometer are circularly polarized with the opposite orientation and have the same intensity. This property is a precondition for the full contrast C of the interference signal, which is defined as follows:

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{8}$$

where $I_{\max}$, $I_{\min}$ are the maximum or minimum intensities at the interference. An example of the contrast of a trial linear interferometer for both signals in quadrature was published in [6].

Operation principle of an interferometer with orthogonal linearly polarized beam

We assume that the light entering the interferometer is linearly polarized and expressed by the Jones vector

$$\varepsilon_L = \begin{bmatrix} 0 \\ E_E \end{bmatrix}. \tag{9}$$

The polarization optics of the interferometer consists for example of a rotator placed at the input of the dividing unit, a dividing polarizing element or of a dividing coating with polarizing properties and of a linear $\lambda/4$ plate situated on the output of the dividing unit. In the path of both measuring beams there are placed linear $\lambda/4$ retardation plates. We assume that the phase retardation δ, the orientation of the fast axis Θ, and the rotation angle of the rotator ζ have the following values:

$$RO_2\colon\ \delta = 90°,\ \zeta = 45°, \tag{10}$$

$$RP5, RP\ 6\colon\ \delta = 90°,\ \Theta = 45°, \tag{11}$$

$$RP7\colon\ \delta = 90°,\ \Theta = 45°. \tag{12}$$

For the reference beam we get:

$$\varepsilon_r = 1/\sqrt{2}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}K\begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix}1/\sqrt{2}\begin{bmatrix}1 & 1\\ 1 & 1\end{bmatrix}\begin{bmatrix}0\\ E_E\end{bmatrix} = K/2\cdot E_E\begin{bmatrix}1\\ i\end{bmatrix}, \tag{13}$$

where K is a constant, and for the measuring beam:

$$\begin{aligned}\varepsilon_m = 1/\sqrt{2}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}1/\sqrt{2}\begin{bmatrix}1 & -i\\ -i & 1\end{bmatrix}1/\sqrt{2}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}1/\sqrt{2}\begin{bmatrix}1 & -i\\ -i & 1\end{bmatrix}\\ 1/\sqrt{2}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}K\begin{bmatrix}0 & 0\\ 0 & 1\end{bmatrix}1/\sqrt{2}\begin{bmatrix}1 & 1\\ 1 & 1\end{bmatrix}\begin{bmatrix}0\\ E_E\end{bmatrix} = \frac{K}{2}E_E\begin{bmatrix}i\\ 1\end{bmatrix}.\end{aligned} \tag{14}$$

It can be seen from this result that in this type of interferometer the output is standardized — similarly to the previous case — in the form of circularly polarized beams of light of the same intensity and opposite orientation. In the practical case usually $K = 1$ and from the comparison with the expression in section: *The principle of an interferometer with circularly polarized light of the opposite orientation* it can be seen that the intensity of light beams is doubled with respect to the former case. Thus, the superiority of the polarizing elements or polarizing coatings over the nonpolarizing dividing elements is obvious. The next processing of the interfering light beams in the standarized detection unit is the same as that with the preceding type of the interferometer [6]. An example of this type is given in fig. 2. This interferometer is for length measurements in two coordinates using a plane mirror. At the input of the dividing unit there is a rotator $RO2$ and the dividing polarizing element is the polarization prism P, behind which the two beams are orthogonal

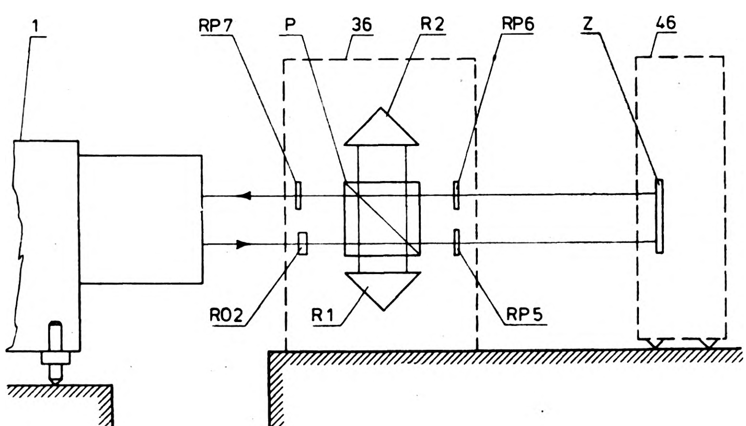

Fig. 2. An example of an interferometer for the length measurements in two coordinates: 1 — the laser head with the collimation optics and the detection part, 36 — the interference divider for the length measurements in two coordinates, 46 — the retro-reflection element for the length measurements in two coordinates, $RO2$ — the rotator at the input of the dividing unit, P — the polarizing dividing prism; $R1$, $R2$ — retro-reflectors; $RP5$, $RP6$, $RP7$ — linear retardation plates, Z — the reflection mirror

linearly polarized. The reference beam is reflected by the retro-reflector *R*1 and after the reflection from the polarization coating it passes through the linear retardation plate *RP*7 and proceeds to the detection unit. The measuring beam passing through the polarization element *RP*5 is reflected by the mirror *Z*, it passes again through the polarization element *R*P5 and is reflected first by polarizing coating, then by the retro-reflector *R*2 and reflected again by the polarizing coating, it passes through the polarization element *RP*6, is reflected by the mirror *Z*, passes first through *RP*6 and next through the polarizing coating, the linear retardation plate *RP*7 and then together with the reference beam they proceed to the detection unit as two circularly polarized beams of the opposite orientation, that is, in the form standardized for all the types of interferometers.

Properties of interferometer and examples of application

The interferometer for length measurement offers the length measuring range 0-30 m, and the basic resolution 0.08 μm at the operation mode $\lambda/8$. At the measurements in machinery workshops the practical accuracy is of about 1 μm/m.

The differential interferometer for straightness, flatness and angle measurements has the measuring range 0-0.1 rad with the limit accuracy at the straightness measurement of ± 0.5 μm/m.

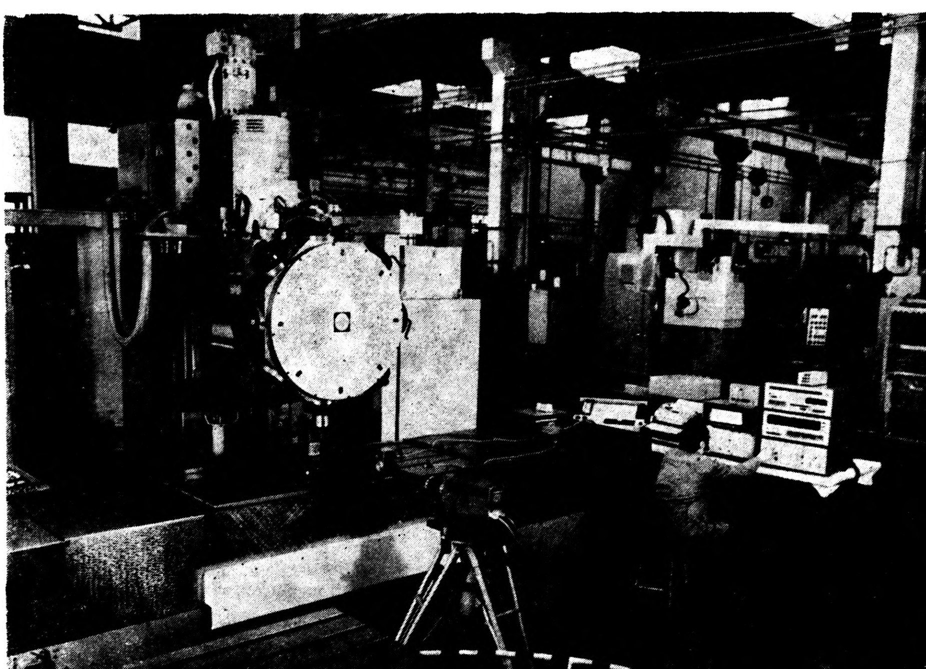

Fig. 3. Arrangement of the laser measuring system for the straightness measurement of the spindel motion of a NC machine

More detailed description and parameters of both the types of interferometers are presented in [5].

An example of the application of the laser interferometer in industry is shown in fig. 3. There the straightness of the spindel movement of a NC machine is measured by means of the differential interferometer. For the X-coordinate the deviations from the straight motion of the spindel of the NC machine are plotted in fig. 4. It is seen that the maximum deviation from the straight motion on the path 1500 mm is 5 μm. The region enclosed within two curves denotes the region of measurement errors.

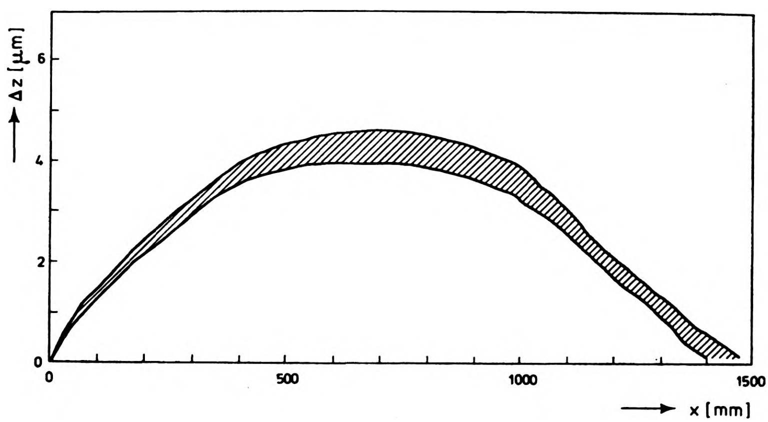

Fig. 4. Deviation Δz from the straight motion of the spindel in the X-coordinate of the measured NC machine

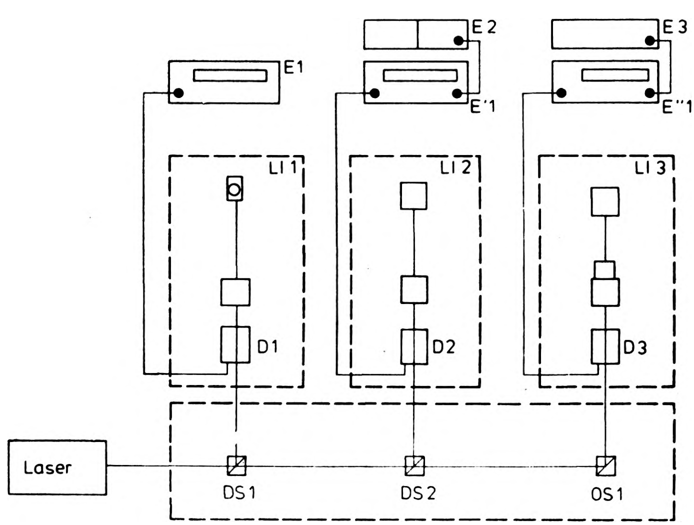

Fig. 5. The operation principle of a laser measuring system: *DS*1, *DS*2, *OS*1 — light dividers and reflectors; *L*11, *L*12, *L*13 — various types of interferometers; *EL'*, *E*+1, *E*2, *E*3, *E*1 — digital electronic units; *D*1, *D*2, *D*3 — separated detection units

General arrangement of a laser measuring system

The arrangement can be seen in fig. 5. The whole system consists of several units. The source of radiations is a single-frequency laser, giving a linearly polarized beam of light. In the unit of dividers, the division of the light beam into several parts takes place in the case of length measurements in several coordinates. The input light in all the types of interferometers is standardized having the form of a linearly polarized beam of light. Thus individual types of the interferometers operate either with circularly polarized beams of light of opposite orientation, or with orthogonal linearly polarized beams. The output form interferometers is standardized again in the form of circularly polarized light of opposite orientation. The detection unit is standardized being either built in the laser or separated.

Conclusions

The design of a laser interferometric measuring system requires the solution of a series of problems in the field of optics and electronics. A very important presumption for this system is the solution of universal units with standardized input and output quantities. These units must allow the application of various variants of the units arrangement within a system. This paper shows an example of the units (interferometers) with circularly and orthogonal linearly polarized light, and the general arrangement of the detection unit.

The laser measuring system, introduced into the production, enables the extension of the precise interference methods to other fields of the measuring technique.

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Избранные вопросы лазерных интерферометрических систем

Подчёркнуто значение интерферометрических методов для измерений длины, плоскости и других геометрических величин. Представлено решение важных типов интерферометров с круговой или ортогонально-линейной поляризацией пучков, а также их применяемость (совместимость) в лазерных интерферометрических системах.