Microrelief measurements for white-light interferometer with adaptive algorithm interferogram processing

Evgeny V. Sysoev, Rodion V. Kulikov

Technological Design Institute of Scientific Instrument Engineering (TDI SIE)
Siberian Branch of the Russian Academy of Sciences (SB RAS)
41, Russkaya str., Novosibirsk, 630058, Russia
Tel.: + 7 [383] 333-27-60 Fax: +7 [383] 332-93-42 E-mail: evsml@mail.ru

Abstract

The problem of reducing measurement errors of surface microrelief with nonuniform scattering properties using white-light interferometer was discussed. Adaptive algorithm of thresholding which allows us to set optimal threshold in every point of measuring surface was proposed. Application of this algorithm of threshold choice allows increasing dynamical range of interference detection more than in 10 times. The dependences of scanning interferometer resolution on differential interferogram thresholding have been discussed.

Keywords: Relief measurement, interference, surface quality inspection, thresholding

1. Introduction

The scanning interferometer of partially coherence light is widely used under noncontact measurements of surface relief in science and industry [1, 2]. The measurements are based on registration of interference of partially coherence light.

As it is known the interference of partially coherent light is observed while optical paths difference in reference and measurement arms does not exceed coherence length of light source used [3]. The condition of interference existence defines layer in a measurement field with depth about coherence length [4]. Mean part of this layer coincides with projection of mirror surface within a measurement field that installed in interferometer reference arm. Its position is defined from the condition of optical paths equality in reference and measurement interferometer arms. The differential interferograms are used to extract interference. They are formed by subtraction of CCD registered interferograms shifted by \( \pi \) phase.

Measurement of whole surface profile is performed by depth scanning of measuring surface. The scanning is realized by serial changing of interferometer position relative to measurement object with the given step size. For interference detection, as a rule, fixed threshold is used [5]. However, scattering properties of measuring surface can be significantly changed within the measurement field, for example, under the fuel element surface measurements [6]. In this case, the use of fixed threshold makes difficult interference detection in the fields, where amplitude of scattered light is too small.

We have studied problems of measurement for microrelief surface with nonuniform scattering properties. Adaptive algorithm for thresholding that allows decreasing the measurement errors was proposed.

The dependence of scanning interferometer resolution from used amplitude threshold was considered. The influence of threshold value on quality factor \( Q \) defined as ration of a number of reconstruction points to total ones within measurement field was demonstrated. The algorithm increasing quality factor \( Q \) was proposed.

2. The measurement principle

Setup for experimental investigations of the method was assembled. Figure 1 shows this setup.
Fig. 1. Scheme of experimental setup: 1 – interferometer, 2 – CCD camera, 3 – piezoceramics controller, 4 – computer, 5 – source of partially coherent light, 6 – beamsplitter, 7 – reference mirror, 8 – measured object, O1, O2, O3 – objectives, 9 – piezoceramics.

It includes interferometer 1, CCD camera 2, piezoceramics controller 3 and computer 4. Interferometer consists of source of partially coherent light 5 with effective wavelength $\lambda \approx 0.65 \, \mu m$ and coherence length $l_c = 1.8 \, \mu m$, beamsplitter 6, reference mirror 7, objectives O1, O2, O3 and measured object 8.

Reference mirror 7 of interferometer is installed on piezoceramics 9. The optical path length in the reference arm of the interferometer is adjusted by piezoceramics voltage. Piezoceramics was connected to controller 3. A halogen lamp serves as source of partially coherent light 5. Computer 4 controls the step and range of mirror displacement. The interferograms were registered by CCD camera 2 then transmitted to computer.

A scanning on the depth of measured surface was carried out by means of moving of interferometer 1 with step $\Delta z$ along optical axis. Two interferograms were registered on every step of scanning, one of which was shifted by $\pi$. Phase shifting was realized by mirror 7 position changing by means of piezoceramics 9 voltage changing. Differential interferogram (DI) is calculated as a result of absolute value after original interferograms subtraction. The experiments were carried out with scanning steps $0.5 \mu m$ and $1 \mu m$.

Typical distribution of intensity in white-light interferometer can be presented in the following form:

$$I(z,z_i) = I_0 \cdot \left[1 + \exp \left(-\frac{2 \cdot (z-z_i)}{l_c} \right)^2 \right] \cdot \cos \left(\frac{4\pi}{\lambda} \cdot (z-z_i) \right),$$

where $I_0$ is average value of intensity, $z$ is optical path difference between reference and measurable arms, $\{z_i\}$ is set of interferometer positions, and $i$ is scanning step number.

Typical view of real interferogram, which is described in (1), is shown in Fig. 2 (a).

For interference extraction, DI shown in Fig. 2 (b) is used. DI is described by the following form:

$$J(z,z_i) = \left|I(z,z_i) - I(z + \frac{\lambda}{4},z_i)\right|.$$ (2)

In experiments a scanning was produced with a step $\Delta z < l_c$. The set of values of intensity $\{J(z_i)\}$ was registered in every point of measuring surface. Finally, the absolute value of position $Z_{l,m}$ every element $(l,m)$ of measuring surface is defined by formula:
where $n_{l,m}$ is number of DI intensity values registered in point $(l,m)$ of surface for different $z_i$, and for which $J(z_0 + z_i) \geq P$, where $P$ is threshold of interference extraction.

Noise value in the registering interferograms depends on intensity $I$ and its amplitude is defined by the dispersion $\sigma^2 \sim I$. Differential interferograms thresholding is used for interference detection against a background of noise. The magnitude of optimal threshold value $P$ at small difference of intensity on CCD matrix for measuring amplitude value of differential interferogram is defined by maximum noise value. This threshold is used for all points of measurement area. Thus, $P \approx \sigma_{\text{max}}$, where $\sigma_{\text{max}} \sim \sqrt{I_{\text{max}}}$, $I_{\text{max}}$ is maximum intensity of measurement field. If scattering properties of surface in measurement field have significant differences, then, in CCD matrix sights where intensity smaller than $\sigma_{\text{max}}$, application of thresholding leads to the fact that interference for such surface regions will not registered.

To obtain the set $\{J(z_0 + z_i)\}$ corresponding to a $\{z_i\}$ the scanning of parallel-sided plate has been done. Interference is registered not in all surface points of measuring area. In this case:

$$\sigma^2 = \frac{\sum_{k=1}^{m} (Z_{l,m} - \bar{Z})^2}{m},$$

where $\sigma_z$ is dispersion of $Z$ and it defines resolution of surface profile measurement, $m$ is the number of points an interference was registered. The results of experiments of dependence $\sigma_z$ on $P$ measured at scanning parallel-sided plate are presented in Fig. 3(a).

Fig. 3. (a) Rms dependence on threshold and (b) quality factor dependence on threshold.
The reliable detection of interference on a background of noise is carried out by thresholding, which concludes in the choice of optimum value of threshold. Dependences $Q$ on $P$ for different scanning steps are presented in Fig. 3 (b). From this figure evidently, that for every value of scanning step $\Delta z$ there is a value of $P$ for which the coefficient $Q$ begins strongly to diminish. Thus, for a receipt maximal $Q$, as is seen from Fig. 3 (b), it is necessary to choose a minimum threshold $P$. If scattering properties of surface in the measuring area have insignificant illumination overfalls of CCD matrix, then an optimum threshold is $P \geq \sigma_{\text{max}}$.

To decide this problem the following method was proposed. This method allows us to set relative threshold identical for every points of measuring surface in every scanning step. It consists of the following. For a DI obtaining it is necessary to register two interferograms one of which was shifted by $\pi$. For the calculation of adaptive threshold at every $i$ matrix of correction coefficients $\alpha_{i,m}$ is calculated:

$$
\alpha_{i,m} = \sqrt{\frac{\bar{T}_{i,m}}{\text{max}(\bar{T}_{i,m})}},
$$

where $I_{i,m}$, $I_{i,m}(z_i + \frac{\lambda}{4})$ are interferograms one of which was shifted by phase on $\pi$ at every $z_i$.

Value $\bar{T}$ does not contain interference and $\bar{T}/2$ is a total distribution of brightness in the image of measured surface under scanning step $i$. Then adaptive threshold $\tilde{P}_{i,m}$ for every point of measurement is calculated by formula:

$$
\tilde{P}_{i,m} = P \cdot \alpha_{i,m}.
$$

Since $P \sim \sqrt{I_{i,m}}$, then from expressions (5), (6) one can obtain that $\tilde{P}_{i,m} \sim \sqrt{\bar{T}_{i,m}}$. If dynamical range of interference detection is determined as $D_f = \frac{I_{\text{max}}}{P} \approx \sqrt{I_{\text{max}}}$, then under adaptive threshold a dynamical range will be $D_a = \frac{I_{\text{max}}}{(\tilde{P}_{i,m})_{\text{min}}}$, where $(\tilde{P}_{i,m})_{\text{min}}$ is minimal registered intensity level. Under the use of CCD camera, the value $(\tilde{P}_{i,m})_{\text{min}}$ is equal to 1, hence, $D_a$ equals to $(D_f)^2$. For example, for 10-bit CCD camera the dynamical range of interference detection is increased in $\sqrt{2^{10} - 1} \approx 32$ times.

Application of expression (6) under interferograms processing allows us substantially to promote measuring quality of surfaces relief. The grayscale image of measured surface, which is resulted on CCD camera (see Fig. 1) is shown in Fig. 4 (a). From Fig. 4 (a) it is seen that scattering properties of surface are highly differed. Reconstructed 3D reliefs without adaptive algorithm usage and with its usage are shown in Figs. 4 (b), (c) correspondingly.

As seen from Fig. 4 (b), measurement of surface relief with threshold fixed for all points leads to large number of blanks in the measured relief. It takes place because of interference amplitude for a many regions of measured surface is lower than fixed threshold and, thus, interference is not registrated. Application of the proposed algorithm results in the substantial
improvement of measurements quality. Quality factor $Q$ in a first case equals to 0.72, and in a second case is equal to 0.96.

![Image](image.png)

Fig. 4. Experimental results, (a) grayscale image of measured field, (b) 3D surface relief measuring without adaptive algorithm usage, (c) 3D surface relief measuring with adaptive algorithm usage.

Measurement results of 3D surface relief with usage of adaptive algorithm is shown in Fig. 4 (c). From this figure it is seen that number of blanks have became significantly smaller.

3. Conclusion
We have discussed the problem of reducing measurement errors for surface microrelief with nonuniform scattering properties in the white-light interferometer. Adaptive algorithm of interferograms thresholding for measurement quality improvement of surface profile was proposed. We have shown experimentally that adaptive algorithm of threshold choice allows one to increase dynamical range of interference detection more than in 10 times.

Due to an estimation of surface scattering properties under surface microrelief measurements with adaptive algorithm one can completely automatize the measurement process.

Results of present work can be used for development programmatically algorithmic software of interference profile-meters for precision measurements.

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References