Nanorelief measurements errors for a white-light interferometer with chromatic aberrations

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Abstract
Chromatic aberrations in white-light interferometer can dramatically increase measurement nanorelief errors. It is shown that these errors can be more than 70 nm. They are result of changing effective wavelength within the measurement field. We have proposed the method for error calculation using measurement data and then their correction experimentally up to 10 nm.

Keywords: Nanometer, resolution, white-light, interference, interferometer

1. Introduction
Scanning white-light interferometry is widely used in science and engineering for noncontact measurement of the surface microrelief [1, 2]. The measurement is based on recording and analyzing a set of interferograms obtained by scanning the surface along the optical axis z of the interferometer [3, 4, 5]. Scanning with interval of several tens of nanometers is usually carried out by displacing either the object [6] or the interferometer or its part [7].

In the work [8] the method of surface nanorelief measurement based on partial correlogram scanning in the period range about 1 - 2 (0.4 ÷ 0.8μm) was introduced. In this case the relative phase shift of the correlograms between the neighboring surface parts is measured. The advantage of this method is small interferometer reference mirror displacement (about fraction of micron). The use of partially coherent light source with broad bandwidth results in necessity of additional measure of wavelength, applied to nanorelief calculation. Moreover, chromatic aberrations of optical scheme of interferometer lead to effective wavelength change within a measurement field.

The aim of present work is estimation of nanorelief measurement errors by chromatic aberrations of optical system of white-light interferometer.

2. Nanorelief measurement method
To investigate the method experimentally, we have created a setup shown schematically in Fig. 1. It includes interferometer 1, CCD camera 2, piezoelectric transducer controller 3, and PC 4. Interferometer contains light source 5 (halogen lamp or LED), beam splitter 6, reference mirror 7, lenses O1
and O2.

Reference mirror 7 of the interferometer is placed on piezoelectric transducer 9. The optical path length in the reference arm of the interferometer is controlled by voltage applied to piezoelectric transducer, connected to controller 3. A LED serves as partially coherent light source 5. PC 4 controls the step and range of mirror displacement. The interferograms are recorded by CCD 2 and transmitted to PC, where correlogram is calculated for each surface point by special algorithms. As the reference mirror is continuously displaced along the optic z-axis, the light intensity (correlogram amplitude) recorded on the CCD array in each j-th pixel of the i-th row can be described by the function [9]:

\[ I_{ij}(z) = I_{ij}^0 (1 + A_{ij}(z) \cdot \cos(4\pi(z_{ij}^0 - z)/\lambda + \phi_{ij})) , \tag{1} \]

where \( I_{ij}^0 \) is the intensity, \( i = 0...N - 1, \quad j = 0...M - 1 \) (\( N \) is the number of pixels in row, and \( M \) is the number of rows); \( A_{ij}(z) = A_{ij}^0 \exp\left(-16\ln 2 \cdot \left[\frac{z_{ij}^0 - z}{l_c}\right]^2\right) \) is the correlogram envelope amplitude (\( A_{ij}^0 \) is defined by relationship between amplitudes and phases of the interfering fields, \( l_c \) is the coherence length, \( \lambda \) is the effective wavelength, \( z_{ij}^0 \) is the coordinate of the corresponding part of the measured surface (relative to some base), and \( \phi_{ij} \) is the initial correlogram phase.

In the experiments, the mirror in the reference arm placed on the piezoelectric transducer was displaced discretely with the step \( \Delta z \approx 3.2 \text{ nm} \). Fragments of correlograms \( I_{ij}(z_k) \), which are described by general function (1), were calculated for each pixel. Sample of the correlogram fragments for two arbitrarily chosen pixels are plotted in Fig. 2 versus scanning interval number.

The shift \( \Delta k \) in the scanning step \( k \) between correlograms in Fig. 2 is determined by the change in the microrelief height \( \Delta h \) between surface parts projected onto the pixels:

\[ \Delta h = \Delta k \cdot \Delta z , \tag{2} \]

The task of finding the shift \( \Delta h \) for each of the pixels between correlograms was solved numerically by the method of successive approximation with the use of minimization of the
root-mean-square deviation of fragments of two correlograms in the region of their intersection along $z$.

Since the mesh of correlogram values for the discreet parameter $k$ is rather rough, we replaced $k$ by continuous interpolating variable $\xi$: $k = (\xi)$, where the brackets mark truncation of $\xi$. Then equation for two correlograms in the pixels $(l,m)$ and $(n,q)$ may be written as:

$$I_{lm}(\xi) \approx a_{nq} \cdot I_{nq}(\xi + \Delta\xi_{nq}) + b_{nq}^r,$$  \hspace{1cm} (3)

where $|\Delta\xi_{nq}| \leq \xi \leq K - |\Delta\xi_{nq}|$. $K$ is full measurement points in a corelogram, $\Delta\xi_{nq}$ determines the shift in $\xi$ between the correlograms for pixels $(l,m)$ and $(n,q)$.

We use $\Delta\xi_{nq}$ to calculate the axial change in the height of surface profile between surface parts mapped onto these pixels:

$$\Delta h_{nq} = \Delta\xi_{nq} \cdot \Delta z .$$ \hspace{1cm} (4)

Since, the optical ray path in the reference and measuring arms (Fig. 1) is doubled, the function $Q$ is periodical with respect to $\Delta\xi$ with a period defined by the condition $\Delta\xi \cdot \Delta z = \lambda/2$. Hence, the calculation of the change in the microlief height between two arbitrarily chosen parts of the surface is unique if the change in the height between them doesn’t exceed $\pm \lambda/4$. The problem of multiple-valued of $\Delta h_{nq}$ from $\Delta z$ can be solved, for example, by using multispectral light source as shown in [10].

The function of discrepancy $Q(\Delta\xi_{nq}, a_{nq}, b_{nq})$, that represents a normalized root-mean-square difference between the correlograms, was used to find $\Delta\xi_{nq}$:

$$Q(\Delta\xi_{nq}, a_{nq}, b_{nq}) = \frac{1}{K - \Delta\xi_{nq}} \sqrt{\theta + \sum_{k=0}^{k=K-\Delta\xi_{nq}} (I_{lm}(k) - I_{nq}(k + \Delta\xi_{nq}))^2},$$ \hspace{1cm} (5)

where $\theta = [I_{lm}(K - \Delta\xi_{nq}) - I_{nq}(K)]^2$. Figure 3 shows a plot of part of $Q(\Delta\xi)$, which was calculated for correlograms shown in Fig. 1.

![Fig. 3. The function of discrepancy $Q$.](image)

The minimum of $Q$ corresponds to the value of the shift $\Delta\xi$, when the compared correlograms coincide best of all.
The parameter $\Delta \xi_{lm}$ was found by fitting the correlograms with respect to $\Delta \xi_{nq}, a'_{nq}, b'_{nq}$ in such a manner that the function $Q$ takes the minimum value:

$$
\Delta \xi_{nq} = \min_{\Delta \xi_{nq}, a_{nq}, b_{nq}} Q(\Delta \xi_{nq}, a_{nq}, b_{nq}), \quad (6)
$$

When the shift of the reference mirror of the interferometer is linearly dependent on the voltage across piezoelectric transducer, we obtain the calculated value of the surface nanorelief change $\Delta h_{nq}$ from (4).

3. Results

In the experiments, measurement of the surface profile was carried out by a setup shown schematically in Fig. 1. An 8-bit video camera with CCD array of 576 rows, 740 pixels each, recorded the interference. The scanning interval was 3.2 nm.

The effective wavelength LED was $\lambda = 645$ nm. The controller was used for programmable displacement of the mirror placed on the piezoelectric transducer in the interferometer reference arm.

To investigate the influence of interferometer chromatic aberrations we perform two experiments using the same measurement object. For the first experiment we have used a halogen lamp as a broad bandwidth light source, and for the second experiment a LED with narrow bandwidth was used. In the both cases scanning of parallel-sided plate nanorelief was carried out. Then the correlogram period for every measurable points of surface was calculated. To measure a correlogram period the algorithm in accordance with (6) was used. As the second correlogram one has used the primary correlogram with amplitude inversion but with a same mean value. Results of measurements and calculations are shown in Fig. 4.

It can be seen that under the use of light source with broad bandwidth the chromatic aberrations can substantially change the effective wavelength along lateral coordinates of object measurement field.

![Fig. 4. Interferogram in relative units for a halogen lamp (1), correlogram period subject to lateral coordinates on the object: halogen lamp (2), LED (3).](image)

It is seen that halogen lamp correlogram period (and accordingly effective wavelength) is changed more than 20% from left to right. Under the use of source with narrow bandwidth, the influence of optical system chromatism on nanorelief measurement error is decreased.
In this figure $\lambda$ dependence on pixel number for a LED is also shown. The change of $\lambda$ is less than 10 nm. Thus, a replacement of light source with broad bandwidth by narrow bandwidth allows substantially reducing change of $\lambda$ on the measurement field and reducing errors of measurement nanorelief concerned with optical system chromatism of white-light interferometer.

The measurement of correlogram period along the field for every point of measured surface allows us to calculate effective wavelength variation depending on lateral coordinates. Using these results one can determine the systematic error, which can be used under surface nanorelief precision measurement.

4. Conclusion

In this paper we have discussed the method of surface nanorelief measurements using white-light interferometer applied to reducing measurement errors due to chromatic aberrations. It was shown that these errors can be more than 20% and they are result of changing effective wavelength within the measurement field. The method of effective wavelength variation measurement within the field for every point of measured surface was proposed that allows us significantly to reduce nanorelief measurement errors. In our experiments we decrease this error to 10 nm.

The results can be used to design high-resolution system for surface measurement in the nanometer range resolution, and also system surface inspection of articles in the industrial production.

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References