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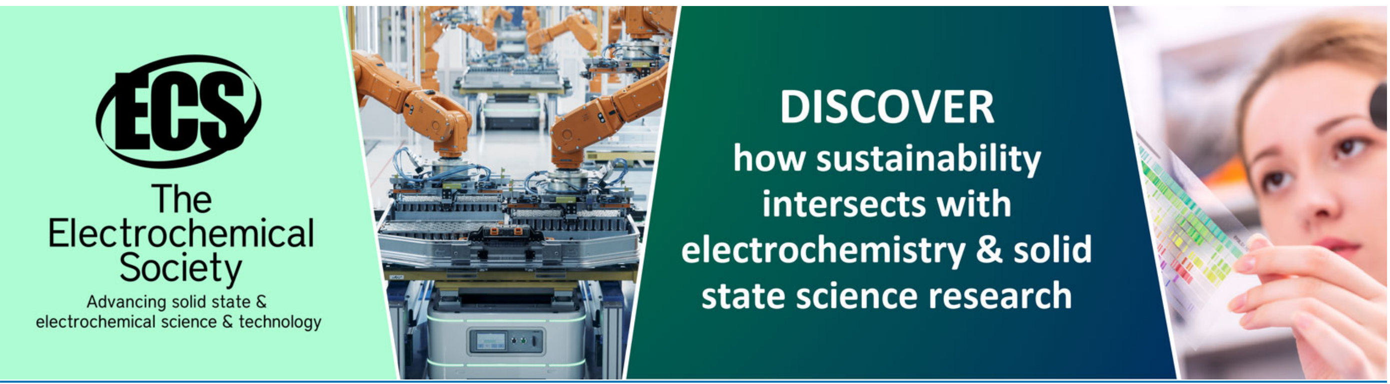

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Methodical errors caused by superposition of electrical and optical signals in a heterodyne laser interferometer

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Abstract. Distortions of the displacements measured by the heterodyne interferometer due to penetration of the electric excitation signal of the acousto-optic modulator into the path of registration and processing of optical signals are considered. The level of this type of noise is estimated and the ways of its elimination from data obtained using a three-coordinate heterodyne interferometer are proposed.

1. Introduction

Nowadays, the metrological certification of measuring equipment operating in the nanometer and micron range of displacements is performed in several ways. One of them is the development of special equipment combining the capabilities of atomic force microscopy and laser interferometry. The combination of a three-axis heterodyne laser interferometer and a nanopositioner makes it possible to create metrological atomic force microscopes (AFM) that measure the vertical and horizontal dimensions of microscopic objects under study with nanometer uncertainty and ensure the traceability of such measurements to the standard meter [1–2].

2. Interferometer

Laser interferometers for linear displacement measurement can be divided into two main types by the method of information signal generation: homodyne and heterodyne ones. The peculiarity of the heterodyne interferometer is the transfer of the measured optical phase shift δ to the radio frequency range. The transfer of an informative signal to an operating frequency significantly exceeding the flicker-noise band of a photodetector and a laser, and the subsequent narrow-band filtering allow the signal-to-noise ratio to be increased by several orders of magnitude.

An example of optical scheme of a three-coordinate heterodyne laser interferometer with a scanning field up to 100×100 μm in the sample plane and up to 10 μm vertically is shown in Fig. 1. The heterodyne frequency shift in this interferometer is realized with the acousto-optic modulator (AOM). Mirrors M1–M11 form three heterodyne interferometers that measure the movement of a nanopositioner, on which triple prisms (TP) are mounted in three orthogonal planes serving as reflectors [3]. The polarization is matched by means of a half-wave phase plate $\lambda/2$. After optical mixing on mirrors M9, M10, and M11, radiation with the help of collimators K is introduced into optical fibers, through which it is transported to an analog-digital module for photoregistration and processing of interferometer signals.

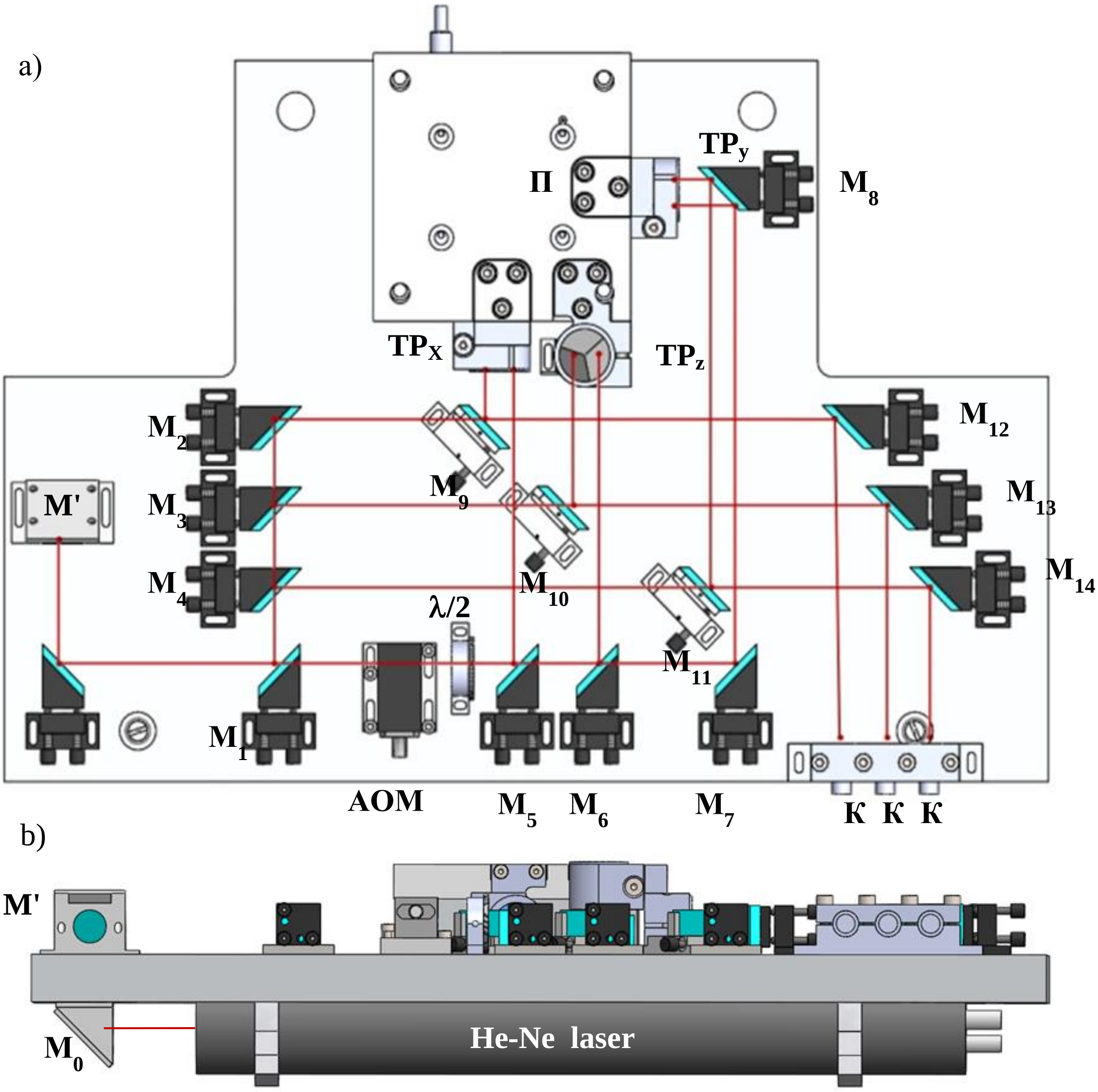

Figure 1. Optical scheme of a three-coordinate heterodyne interferometer: a) top view, b) side view (P—piezoelectric table, M0—mirror for laser input to the circuit from the laser, AOM—acousto-optic modulator, M1–M14—optical mirrors, λ/2—half-wave plate, K—collimator, X, Y, Z—triple prisms).

The principle of the phase meter is based on the quadrature-differential scheme of direct analog-digital conversion of the phase-modulated signal with the subsequent digital processing of informative counts in the programmable logic integrated circuit (FPGA) [4].

The clock frequency f for the synchronization of the operation of the entire circuit is determined by a quartz generator (G). After passing the divider (f/4), which reduces the frequency of the signal fourfold, subsequent filtering and amplifying, the control signal from the generator goes to the input of the AOM driver (Fig. 2).

Since the generator and the interference signal recording system are located in the same electronic unit, there is a certain level of penetration of the electric signal that supplies the AOM into the path of receiving and processing signals from the photodetectors, which leads to an error in the phase measurement. The sign and magnitude of this error depend on the current value of the phase difference between the optical and electrical signals. The nature of mutual influence of these signals becomes clear when analyzing the electrical circuit of a three-coordinate heterodyne interferometer. In Fig. 2 electrical noise pickup is shown as a dashed wavy arrow.

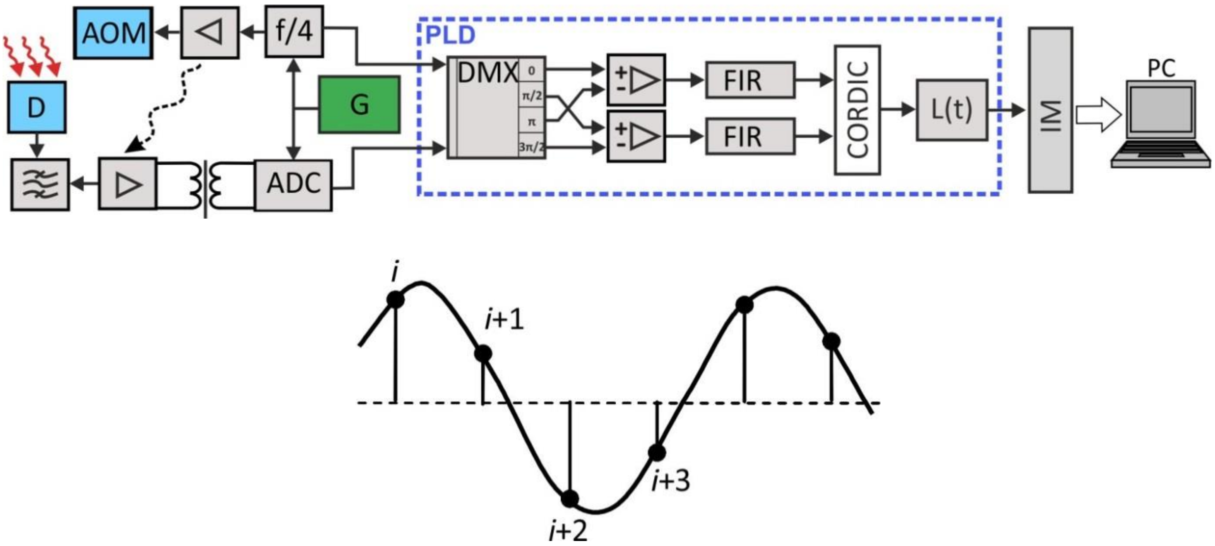

Figure 2. Functional scheme of recording and analog-digital processing of signals of the interferometer (a) and time diagram of sample reading of ADC (b). D – photodetector, AOM – acousto-optic modulator, G – control oscillator, ADC – analog-to-digital converter, *f*/4 – frequency divider, DMX – demultiplexer, FIR – low pass filter with finite impulse response, PLD – programmable logic integrated circuit, CORDIC – module that implements the CORDIC algorithm for phase calculation, *L*(*t*) – phase shift length modulation module, IM – interface module, PC – personal computer.

3. Error of registered signals

In the ideal case, the signals detected by the photodetectors are:

$$A(t) = A_0(t)\cos(2\pi f_o t+\delta(t)), \quad (1)$$

where $A_0(t)$ is the slowly varying photocurrent amplitude, f_0 is the working frequency of the received signal, $\delta(t)$ is the phase difference of the interfering beams. In the presence of electrical noise pickup from the AOM supply channel to the amplifiers recording the photocurrent, the signal arriving at the digital quadrature detection system is distorted and becomes:

$$A'(t) = A_0(t)\cos(2\pi f_0 t+\delta(t))+a_2\sin(2\pi f_0 t)+a_1\cos(2\pi f_0 t), \quad (2)$$

where $a_2\sin(2\pi f_0 t)$ and $a_1\cos(2\pi f_0 t)$ describe the parasitic electrical signal that penetrates the photorecording path. If $A_0 >> a_0$, then after quadrature detection, i. e. multiplying by $\sin(2\pi f_0 t)$ and $\cos(2\pi f_0 t)$ (hardware, synchronous detection takes place in digital form, by multiplying the current sample of the recorded signal by the values $\sin(2\pi f_0 t)$ and $\cos(2\pi f_0 t)$ at the sampling points), we receive not the expected signals $A(t)\sin\delta(t)$ and $A(t)\cos\delta(t)$, but the distorted $A(t)\sin\delta(t)+a_2$ and $A(t)\cos\delta(t)+a_1$ instead. By choosing the initial phase, one can ensure $a_2 = 0$ and simplify further analysis. Such pattern corresponds to the presence of parasitic phase modulation of the detected signal, and when the interferometer signal is recorded during linear scanning of the measured displacement of the AFM positioning system, it appears as specific sinusoidal deviations of the recorded displacement from the linear graph (see Fig. 3). Shifting one of the quadrature components results in distortion of the signal recorded by the CORDIC algorithm (COordinate Rotation DIgital Computer). As a result, the phase angle $\delta_i(t)$ will be described by the formula: $\delta_i(t) = \delta(t)+(a_1/A_0)\cos\delta(t)$.

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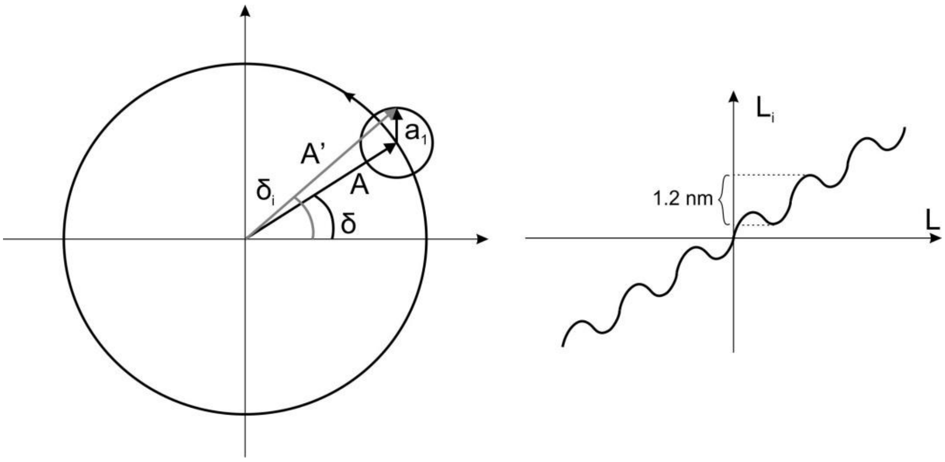

Figure 3. Phase diagram of the detected signal and a typical view of the visible displacement during linear scanning of the positioning system.

Since the achieved accuracy of the displacement measurement for the NanoScan-3Di device is better than 1 nm and the noise level in digital recording of the phase shift signal is less than 0.1 nm, these distortions are clearly visible on the recorded signals. Moreover, they clearly appear when the level of the optical signal is decreased at the photodetector input and lead to an increase in the measurement error.

Because the behavior of this kind of distortion is periodic in relation to the phase, it allows us to offer a fairly simple mechanism for suppressing this type of noise by Fourier filtering of the measured displacements. Such an approach is applicable when the range of recorded movements significantly exceeds several wavelengths of the laser radiation used. An example of the sinusoidal distortions of the recorded displacement is shown in Fig. 4. These data were obtained with a deliberate attenuation of the signal at the photodetector input by a factor of 2, for greater intensity of the effect. With qualitative adjustment of the entire interferometer and the effective introduction of laser radiation into fiber-optic communication lines (transport fiber), the sinusoidal form of the interference is distorted by noise originating from temperature fluctuations in the refractive index of air in the interferometer’s operating and reference arms.

As can be seen from the experimental data, this type of error can reach several nanometers and strongly resembles the so-called non-quadrature error caused by ellipticity of the polarization of the interfering light and the incorrect tuning of the quadrature detector (the difference in the phase shift between the reference signals and/or the difference in signal amplitudes, etc.). The ellipticity of the polarization of the interfering beams, in the case of heterodyne interferometry, does not contribute to the detected signals. In the registration scheme considered, the error associated with the tuning of the quadrature detector is negligible, since digital quadrature heterodyning is used to generate quadrature signals by processing four “instantaneous” samples over the period of the detected signal (see Fig. 2b). Formation of the phases of the digitizing signals and the signal going to the AOM occurs by the method of digital division of the initial highly stable frequency (144 MHz) signal (Fig. 2). The level of phase instability (jitter) inherent in the utilized microcircuits allows us to assert that the error caused by non-quadraturity of the digitization does not exceed 0.3 mrad, and the resulting geometric error is be less than 0.1 nm.

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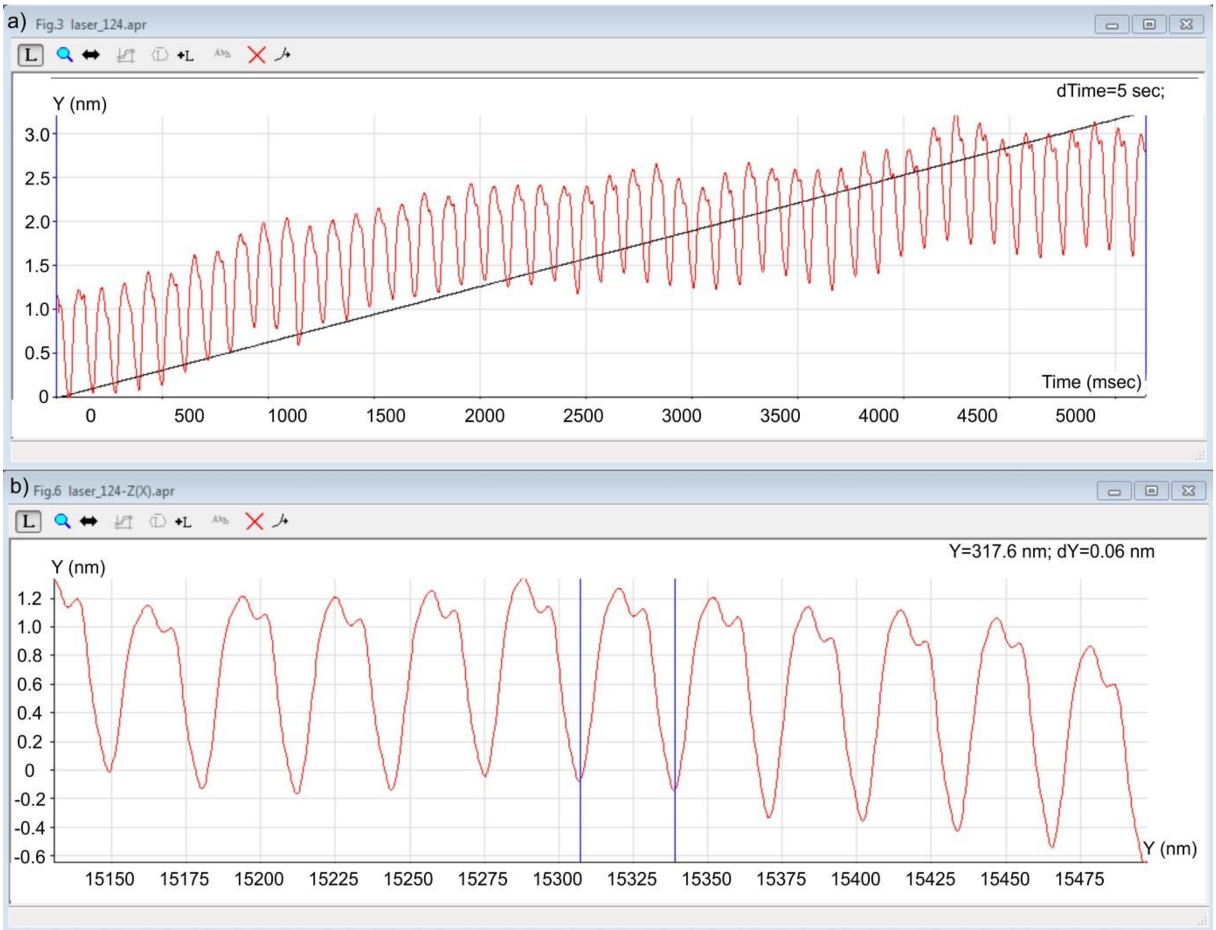

Figure 4. Examples of periodic interference caused by penetration of the electrical signal of the AOM supply into the photocurrent registration path, a) the red line is the recorded displacement vs. time, obtained by subtracting the approximated line from the received signal (black line, scale in arbitrary units); b) the period of the resulting sine is 317.6 nm.

When studying the size and shape of real structures in an AFM, height differences often do not exceed the wavelength of the laser radiation used. In a situation where the shape of the surface is not plane, the effect of the error caused by the penetration of the signal of the AOM electrical supply into the optical signal processing channel of the interferometer results in a systematic error depending on the current phase shift of the interference signal with respect to the AOM signal. It is impossible to eliminate this error without knowing the current value of the phase shift between optical and electrical signals.

Thus, one of the requirements for radio electronic equipment used in heterodyne laser interferometers with direct digital quadrature heterodyning is to minimize the level of electrical interference induced by the AOM circuit in the circuits that record the interference signals. In the Michelson interferometer used in the NanoScan 3Di, the phase shift of 2π occurs when the scanner is displaced by 316 nm and, correspondingly, at a level of penetration of the electric signal into the optical path of the order of 1%, the relative error in displacement measurements in the 50 nm range (~ 1 rad of the phase shift) would not exceed 1%, while the absolute error in the entire range of the scanner can reach 1.2 nm. Hence, in order to realize the possibility of measurements with an accuracy better than 0.5 nm, the radio electronic system should guarantee the level of the electronic noise under discussion below 0.1%, i. e. –60 dB, which is quite feasible in the frequency range of tens and hundreds of MHz commonly used in radio electronic systems of heterodyne interferometers.

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4. Conclusion

The discussed phase-dependent error along with the well-studied Abbe errors, the mutual non-orthogonality of the positioning and measuring system, the influence of thermal electronics noise and shot noise of light should be taken into account when assessing the metrological capabilities of heterodyne interferometers. Along with the elaborated layout and screening of radio electronic elements, one of the most effective methods for combating the error due to the direct penetration of the radio signal of the AOM supply into the photocurrent registration path, is to increase the power of light interfering in each channel and to struggle for the contrast of the interference image, since the more intense the light signal, the less the effect of the carrier frequency electrical pickup on the results of phase measurements and, respectively, on the measured displacement.

Acknowledgments

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References

[1] Wilkening G, Koenders L, 2005 *Nanoscale Calibration Standards and Methods: Dimensional and Related Measurements in the Micro and Nanometer Range* (Wiley-Vch Verlag GmbH & Co. KGaA, Federal Republic of Germany).
[2] Harding K, 2013 *Handbook of Optical Dimensional Metrology* (CRC Press Taylor & Francis Group, Boca Raton London New York).
[3] Gogolinskii K V, Gubskii K L et al. 2012 *Meas. Tech.*. **55** pp 1–6.
[4] Kazieva T V, Kuznetsov A P et.al *Proc. of SPIE* **9636** p 96360.