Design of a new multiapertured diffraction interferometer scheme for small angular displacement control

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Abstract. The compact diffraction circuit controlling small angular movements with small errors (2") and implementation simplicity is considered. The mathematical model describing the radiation intensity distribution in a receiver is obtained. The experiment results (at TU Ilmenau, Germany) confirmed the basic theoretical principles described in the paper.

1. Introduction
At present, various optoelectronic devices and sensors are widely used for positioning and carrying out angular measurements. The bitmap sensors and autocollimators are used to solve many angular measurement problems [1]. The advantages of photoelectric autocollimators are their small measurement errors (0.01 - 1") [2,3], as well as high speed and the possibility to automate the measurements. Their disadvantages are high cost and large dimensions of the devices, as it is necessary to use long lenses \( f = (300-1000) \text{ mm} \). Compared to them, the coherent optical diagrams for controlling angular values are characterized by the same accuracy and greater construction simplicity.

But there are some drawbacks limiting their application areas: significantly smaller measuring range with comparable sensitivity (diffraction control circuit) [4]; structure complexity with large measuring range (interferometric control circuits) [1]; specific construction making autocollimation measurements difficult and having high sensitivity and large measurement range used as an angle measurement circuit sensor [5]. In this connection, the development and research of new control diffraction methods without the aforementioned drawbacks is of interest.

The scheme of measuring small angular displacements is researched in this paper. It is based on the analysis of the interference pattern formed by a multi-aperturated diffraction interferometer. Unlike other interferometer circuits dividing the grating interferometer radiation beam, the interfering wave fronts are formed by diffraction elements, such as slotted apertures. This approach simplifies the interferometer construction and its alignment reducing its size and price.

The scheme researched in paper is presented in figure 1. Here, the plane-parallel glass plate (2) with a reflective coating, in which the same rectangular holes are made, is mounted in front of the lens (1). Using an autocollimating mirror (3), the plate is illuminated by an oblique collimated radiation beam from a laser source (4). The interference pattern superposition from each of three pairs of slotted apertures and the diffraction pattern from a single aperture is observed in the receiver plane (5). Sensitivity to the autocollimation mirror rotation angle at all points in one interference pattern is constant. At the same time, sensitivity of the interference pattern formed by a pair of axial apertures (having zero lateral displacement from the vertical dash-dotted line \( v_1 = v_2 = 0 \text{ mm} \)) is minimal. It is...
determined by the distance between the apertures along the dash-dotted line and the incidence radiation angle. Sensitivity of the off-axis interference pattern (from a pair of apertures positioned on a sloping dash-dotted line with the value \( v_1 = 0; v_4 \neq 0 \)) is increased with the aperture lateral offset from the system axis \( v_4 \) (figure 1). It is not dependent on the incidence radiation angle and the prism-plate distance (6). Having a higher sensitivity and measurement range, the circuit is more compact compared to that without any prism and with one pair of apertures researched in [6].

![Figure 1. The multiaperture diffraction autocollimator circuit.](image)

The mathematical expression describing two-dimensional radiation distribution in the thin lens focal plane at collimated radiation beam diffraction in several apertures disposed on either side of a plane-parallel glass plate, which thickness is equal to the axial ray stroke geometric length in the prism \( d \) (figure 1), has been derived in studying the circuit and assessing its sensitivity. The engineering calculation method of the basic circuit parameters has been developed to evaluate the measurement range of the diffraction autocollimator and its dimensions.

As it is shown by the calculation results, the scheme resolution capability is about 1.5"; the measurement range varies from -2000" to +3000" with the circuit’s overall dimensions equal to (200 x 135) mm with the beam radiation diameter \( D_{cl.ap.} = 27.5 \) mm; the wavelength \( \lambda = 0.405 \) micron; the controlled mirror distance \( L_{meas.} = 200 \) mm; the beam splitter width \( D_{b.s.} \approx 43 \) mm; the axial ray stroke length in the prism \( d \approx 65 \) mm; the aperture sizes \( a = 11 \) micron; the off-axis aperture maximum displacement \( v_4 \approx 8 \) mm and the lens focus \( f \approx 106 \) mm.

2. Experimental

To verify the obtained theoretical propositions and formulas, two glass masks with different sizes and mutual aperture arrangements («Compugraphics Jena GmbH») were developed and the experimental installation was assembled at Ilmenau Technical University. The EVS VEI-535 color camera with 2.775 x 2.775 mm pixel size operating in monochromatic mode was used during the experiments. The photos of interference patterns from the camera and its parameter adjustment were carried out automatically in the MatLAB medium. The sequential two-shot recording with different levels of maximum exposure was taken to neutralize the interference pattern illumination (due to the intensity difference between the diffraction pattern principal and minor maximums) for each mirror rotation angle. The mirror rotation angle was monitored with the help of the Elcomat 3000 autocollimator with 0.1" resolution capability.
The incidence radiation angle \( \lambda = 0.65 \) effect on the interference patterns was researched at three different plate-prism distances and various transverse distances between the apertures \( v_3, v_4 \) (figure 1) for the mirror rotation angles from 0 to 2000" in increments \( \sim 1.7" \).

3. Discussion
The examples of intensity oscillations graphs, which are obtained from the central point of each interference pattern, are shown in figure 2. The experimental results show that the mathematical model adequately defines the sensitivity of the interference patterns formed by different apertures pairs.

Determination of the mirror rotation angle from the obtained photographs is carried out with a proprietary algorithm. The maximum modulo deviation obtained in the experiment from the autocollimator readings is 2.2" for most sensitive third interference pattern (figure 2, curved line (c), the standard deviation is 1.2").

![Figure 2. Experimental diffraction pattern with three interference patterns from three pairs of slits (50 x 100) \( \mu \text{m} \) (Figure 1.).](image)

4. Conclusions
The study results proved the possibility of developing a new means of small angular value measurements having higher compactness (200 x 135) mm. and the measurement range [-2000"; + 3000"] in comparison with the photoelectric autocollimator with comparable measurement error (1-1.5") . To verify the theoretical propositions, the measuring bench was assembled and the experimental researches were carried out in the laboratory of TU Ilmenau (Germany). The error obtained experimentally was about 2.2". The obtained metrological parameters are not ultimate and they can be made better by improving the method of processing the interference fringes and/or modifying the circuit parameters (for example, by compensation of intensity difference between principal and minor diffraction maximums with the aid of gradient filter). Further researches are directed at developing a compact two-dimensional diffraction autocollimator with improved metrological parameters.

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