Известия Гомельского государственного университета
имени Ф. Скорины, №6(39), **1**, 2006

UDC 535.423

Peculiarities of Bessel-beam-based profilometry for testing uneven surfaces

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Introduction

The capabilities of applied optics of cylindrical fields are naturally evident from their special physical properties which have been studied by now. These properties are well known and include the quasi-diffractionlessness [1] and reconstruction of the profile behind obstacles [2].

The spatio-angular properties of Bessel and conical light beams are optimal to control the form and quality of surfaces close to cylindrical and conical ones. This is related to the fact that a Bessel light beam enables one to realize the longitudinally uniform illumination at a certain angle. This angle is generally adjusted to be small, so that grazing incidence geometry is realized. This geometry of illumination permits one to significantly reduce the speckle noise in the field reflected and to extract, thereby, information on the macroscopic shape of the surfaces. In paper [3]) the grazing-incidence geometry was used for testing cylinders and tubes. To implement grazing-incidence geometry, the authors used diffraction optical elements.

In this work we suggest several new optical schemes intended for solving the problem of non-destructive profilometry of objects having the form close to the cylindrical one.

Characterization of two-arms profilometers

Two device prototypes for a laser profilometer using conical light beams are designed and created. The former device prototype is based on the Mach-Zehnder interferometric scheme (Fig.1) and the latter one is based on Twyman-Green scheme (Fig. 2) These schemes consist of two arms. The image pattern is formed in the CCD-plane by interference of the object and reference Bessel beams. The object Bessel beam is produced by a special system consisted of two lenses and a movable axicon. The reflected Bessel beam contains information about the shape of the cylindrical surface under test.

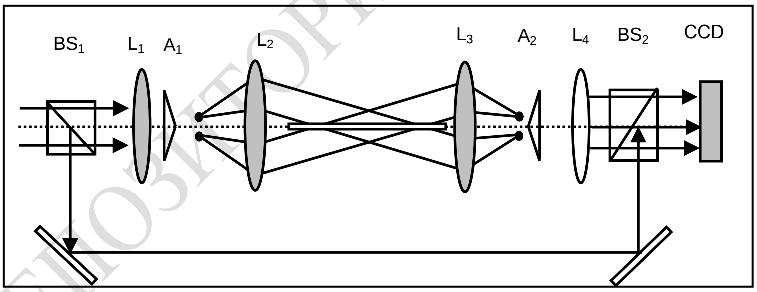


Fig. 1 Two-arm grazing-incidence profilometer based on interferometric scheme of Mach-Zehnder

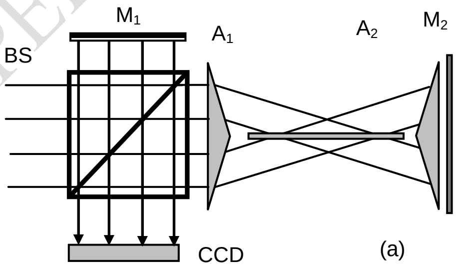


Fig. 2 Two-arm grazing-incidence profilometer based on interferometric scheme of Twyman-Green

Novelty and originality of the Mach-Zehnder profilometer consists in the possibility of tuning the cone angle of the incident and reflected conical waves. As a consequence, the interference fringes have the ring-like form (Fig. 3c) and the effective wavelength of the profilometer can be controlled. It enables one to adjust the sensitivity as well as the longitudinal

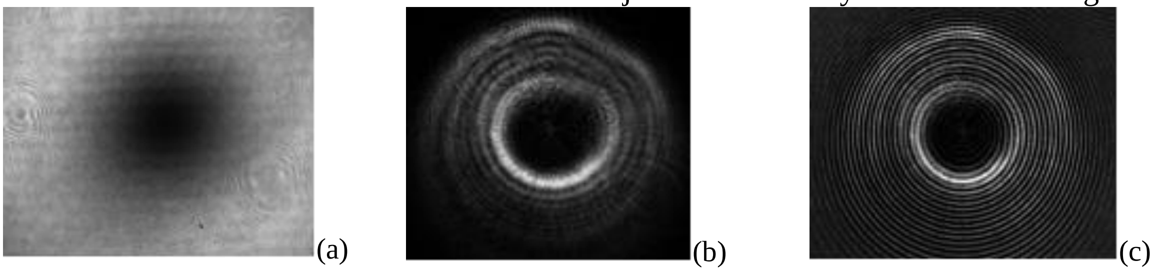


Fig. 3. Three optical images acquired during the interferometric measurement: incident conical beam (a); conical beam reflected from the cylindrical sample (b); interference picture (profilogram) (c).

resolution of profilometer and, thereby, to adapt measurements for the surfaces that have a various degree of roughness and different level of distortion of the profile.

The profilometer on the basis of interferometric schemes Twyman-Green has been investigated in detail. Two modifications of this scheme, i.e., single-pass and two-pass arrangements have been designed and tested experimentally. It was shown that the double-pass scheme is more optimal for creation of a prototype model because of a smaller diameter of an object conical beam and, accordingly, the smaller required working apertures of optical elements. Besides, in turn, the Twyman-Green profilometer is characterized by compactness and more high stability.

The important technical development of the prototype schemes consists in using a donut optical beam (Fig.3a). This beam was generated by He-Ne laser with the specially designed resonator. The laser operates at 630nm and has an output power of 2mW. It is shown that the use of donut beam reduces considerably the systematic phase aberrations arising from the light field distortions in the vicinity of the axicon apex.

Algorithms and software

An algorithm and software are developed which can be used to measure the optical shape and other characteristics of the cylindrical surfaces. Specially developed programs cover all the aspects of interferogram processing, i.e.:

i) *Features of interferometric data acquisition*

To reduce distortions of profilograms due to random fluctuations of input signal caused by phase instability of laser mode, vibration of surrounding air etc., the method of averaging over realizations is developed and employed. For this purpose, a frame of images was acquired by CCD with repletion rate about 10 images/per second.

ii) *Images preprocessing*

The initial profilogram has the next intensity distribution:

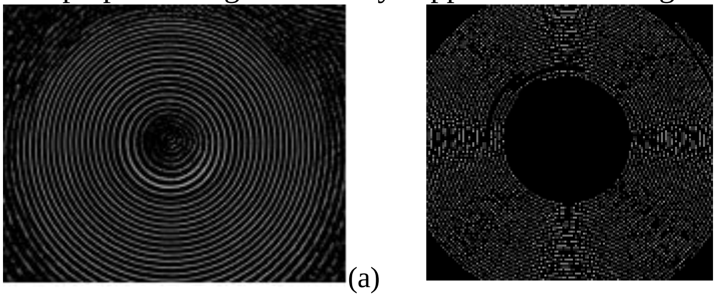
$$I(\rho,\varphi) = I_{ob} + I_{ref} + 2\sqrt{I_{ob}I_{ref}} \cdot \cos\left(k\Delta\gamma\rho + \delta\psi_{obj} + \delta\psi_{syst} + \delta\psi_{align}\right), \tag{1}$$

where I_{ob}, I_{ref} are the intensities of the object and reference waves; $\delta\psi_{obj}$ is the phase shift which arises from the change in radius of sample; $\delta\psi_{syst}$ is the phase shift due to systematic errors of the scheme; $\delta\psi_{alignt}$ is the phase shift due to misalignments of the setup; $\Delta\gamma$ is the difference of cone angles of the object and reference beams.

The first stage of images preprocessing was the extraction of the $\cos(\psi)$ term from above Eq. (1). This was done numerically by subtraction and dividing procedures. At the second stage, the spatial averaging of a cos-like image over some pixels was performed in order to eliminate the residual speckle noise. The intensity distribution is

$$I_2(\rho,\varphi) \sim \left\langle \cos\left(k\,\Delta\gamma\,\rho + \delta\psi_{obj} + \delta\psi_{syst} + \delta\psi_{align}\right)\right\rangle_{(2\div 3\,pixels)}. \tag{2}$$

The typical view of profilogram after the second stage of preprocessing is shown on Fig. 4a. It is seen that the preprocessing sufficiently suppressed the background noise of the image.



(a) (b)

Fig. 4. Averaged cos-like image (a) and the image after edge detection (b)

iii) *Detection of the edges*

On the next stage of profilogram processing the edge detection algorithm was applied. Edge detection procedure is intended to find edges by looking for local maxima of the intensity gradient. This processing stage is very helpful because it enables one to decrease dramatically the size of output signal and consequently to rise sharply the speed of operation. A subset of edges detected at this stage is shown on Fig. 4b. The robustness of image processing algorithm was checked up for various conditions of the image acquisition as well as applying to the surfaces with various degrees of roughness and different levels of distortion of the profile. The profilogram after edge detection is binary image. It represents itself the number of concentric rings with radii depending on azimuthal angle φ:

$$r_m(\varphi) = R_m + \delta r_{m,align}(\varphi) + \delta r_{m,obj}(\varphi) + \delta r_{m,syst}(\varphi), \tag{3}$$

where R_m are the fringes radii in the case of empty profilometer. The additional terms in (3) have the similar sense as the terms in Eq. (1).

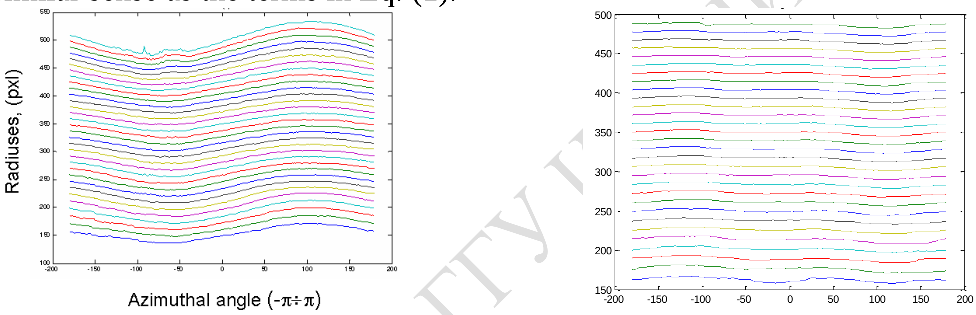


Fig. 5. The radii of interference fringes versus of azimuth angles for profilometer with cylindrical object (a), and without the object (b).

The set of functions $r_m(\varphi)$ can be viewed in the Cartesian coordinates (Fig. 5).

iv) *Elimination of the systematic errors*

Elimination of profilograms distortions caused by a relatively small systematic modulation of the object and reference conical beams is a significant stage in the process of the software development.

Two different methods of measuring the systematic errors and performing the calibration procedure are proposed. The first of them involves the usage of an etalon specimen. The second calibration method does not require any etalon surface and can be realized on the base of an empty profilometer. This method was chosen in the upshot as a working tool.

Fig. 5b shows the profilogram acquired by empty profilometer after performing the edge detection procedure. From the Eq. (3) it follows that the set of radii r_m can be written as

$$r_m(\varphi, empty) = R_m + \delta r_{m,syst}(\varphi). \tag{4}$$

From Eq.(4) the systematic errors can be expressed as $\delta r_{m,syst}(\varphi) = r_m(\varphi, empty) - R_m$.

v) *Elimination of misalignment aberrations*

The development of appropriate algorithms which allow one to eliminate the misalignments of the tested surface relative to the interferometer's axis, was performed. The positional deviations of the cylindrical workpieces are characterized by two components of the lateral shift and two components of rotations

$$\delta r_{m,align}(\varphi) = \delta r_{m,shear}(\varphi) + \delta r_{m,tilt}(\varphi)$$

Elimination of the shift- and tilt- induced aberrations was made by using the analytical equations for

$\delta r_{m,shift}$ and $\delta r_{m,tilt}$. The typical result of working the algorithm is illustrated on Fig. 6.

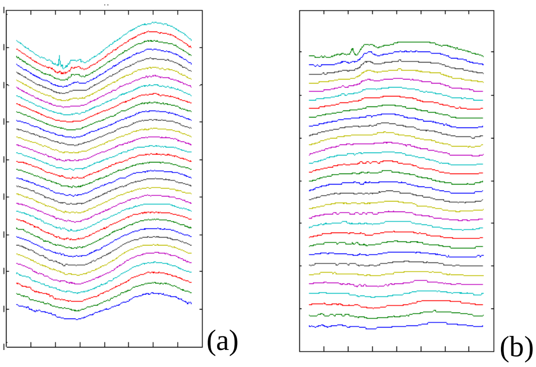


Fig. 6. The set of curves $r_m(\varphi)$ before - (a), and after elimination of distortions caused by lateral shift and tilt of the cylinder.

Development of a method of vibration-proof laser profilometry based on the use of the superposition of two conical beams

A novel method of vibration-proof profilometry based on using the superposition of two conical beams is proposed. The laboratory optical setup of the profilometer is designed and developed. The developed prototype device includes two-rings diaphragm as a basic element for production of two conical beams. One of these beams serves as a reference beam and the second – as an object one. As a result, an independent reference arm was removed and a single-arm schemes are realized (Fig. 7). Two types of single-arm profilometer are introduced (see Fig. 7a,b).

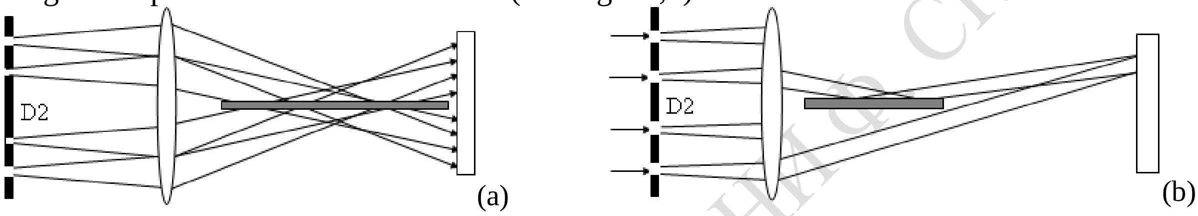


Fig. 7. Single-arm optical profilometers. (a) differential type; (b) non-differential type; D2 is two-rings diaphragm.

The former is so-called differential profilometer. It realized if two conical beams are relative shifted along the surface under test. Interference pattern of these beams provides information about the differences in the form of a tested surface in the adjacent regions. The latter is realized when the conical beams are spatially separated so that one beam illuminated the cylindrical surface and the another beam is freely propagates. It is shown that above mentioned scheme is non-differential profilometer. Due to single-arm configuration, this profilometer differs in high mechanical stability. The experimental testing of the laboratory setup has confirmed this property of a device prototype. The calibration procedure of the single-arm profilometers is less complicated and more time-consuming. It is experimentally verified also that single-arm profilometer is a much low noisy device as compared with the two-arm one.

Abstract. We have presented our developments of some new schemes for nondestructive optical profilometry of cylindrically shaped surfaces by using spatially matched conical light beams. These schemes are related to the grazing- incidence profilometry for controlling cylindrical objects.

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