Optics & Laser Technology 67 (2015) 86–92

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Methods of resolution enhancement of laser diameter measuring instruments

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ARTICLE INFO

Article history:
Received 30 May 2014
Received in revised form
11 September 2014
Accepted 29 September 2014
Available online 24 October 2014

Keywords:
In-process diameter measurement
Diffraction
Spectral analysis

ABSTRACT

The paper presents the implementation of diffraction and spectral analysis methods allowing 1 μm resolution enhancement of optical instruments intended for measurements of such round wire materials as cables, wires, cords, etc. with diameters exceeding the wavelength (~0.5 mm and large). The transformation function suggested allows detecting geometrical boundaries of object's shadows that are used to calculate its diameter independently from its location in the gaging zone. The real-time detection algorithm is described for diffraction extreme values in the analog video signal produced by the charge-coupled device sensors. A method of additional improvement of resolution is shown on the basis of spectral analysis.

1. Introduction

A range of advantages in relation to other optical measuring methods is achieved when the diameter of round wire materials is measured with the help of the laser beam divergence technique [1,2]. Particularly, the lack of catadioptric optical system and movable optical components essentially simplifies the optical system and design of a primary measuring transducer. Design and production of two-dimensional diameter measuring instruments based on this method, is a promising trend in cable instrument engineering due to their reliability, relative ease of fabrication, and objective adjustment.

The laser beam divergence technique for diameter measurement used for long wire materials is based on detection of shadow boundaries of the object by means of multielement linear photodetectors placed in two orthogonal measuring channels. Fig. 1 shows a schematic layout of the optical two-dimensional primary measuring transducer which implements this measurement technique. Traces of laser beams emitted by point radiation sources LAZ_1 and LAZ_2 are shown by dashed lines. These laser beams are directed tangentially to the work piece edges and form light–shadow boundaries t_1f, $t1s$ и t_2f, t_2s on the respective multielement photodetectors CCD_1 and CCD_2. This technique and functions of primary measuring data transformation are described in detail in works [3] and [4].

In practical application, an accurate detection of geometrical boundaries of rising and falling edges of a work piece shadows using a multielement photodetector is rather complicated. This is because the slew rate and the shape of boundaries depend on a local lighting of photodetector and a position of the work piece in a plane orthogonal to the photodetector surface. Scratches, dust, dirt and other during-operation defects of optical glass of measuring instruments affect the accuracy of shadow boundary determination. Even though these defects will be taken into account or effectively eliminated, the accuracy of optical instruments is restricted by diffraction effects occurring at the work piece boundaries that results in a blurring effect of a shadow.

In the patent [5], the principle of the shadow boundary determination is described on the basis of the extreme value distribution from the edge of the opaque object. It is a well-known technique that was investigated in the works [6] and [7]. The principle of the shadow boundary determination is widely used in science and technology [8–16]. In particular, it is applied to enhance the accuracy of geometry measurements of various wire materials. In order to improve a resolution of optical transducers based on a laser beam divergence measurement technique, the analysis of the Fresnel diffraction pattern of large-scale objects was carried out by instruments produced by Sikora and Zumbach Companies. However, in the above mentioned literature, the transformation function allowing the accurate mathematical calculation of the boundary position in measuring wire materials with diameters exceeding the wavelength is not described. This fact restricts the application of Fresnel diffraction by optical transducers based on this technique. In addition to the transformation function, the authors present research into the object movements within the gaging zone affecting the diffraction pattern

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http://dx.doi.org/10.1016/j.optlastec.2014.09.017
0030-3992/

that is very important for the industrial development of measuring devices.

2. Boundary detection method

As shown in Fig. 2, the principle of Fresnel diffraction occurs on the boundary of opaque cylindrical objects. Partially the light penetrates into the shadow region while in the illuminated region it forms the system of diffraction minima and maxima, the difference between them monotonically decreases, and the intensity of light goes to the initial illumination I_0. The distance L between the point source and the multielement photodetector depends on the structural properties of the optical transducer and is constant. The distance y may vary depending on the position of the work piece under control.

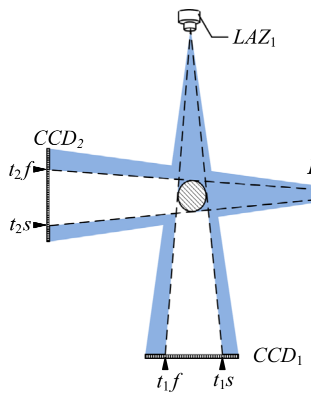

Fig. 1. Laser beam divergence technique for diameter measurement; LAZ_1 and LAZ_2 are point radiation sources; CCD_1 and CCD_2 are multielement photodetectors for the 1st and the 2nd measuring channels, respectively; the quantities t_1f, t_1s and t_2f, t_2s are the shadow boundaries of a work piece under evaluation.

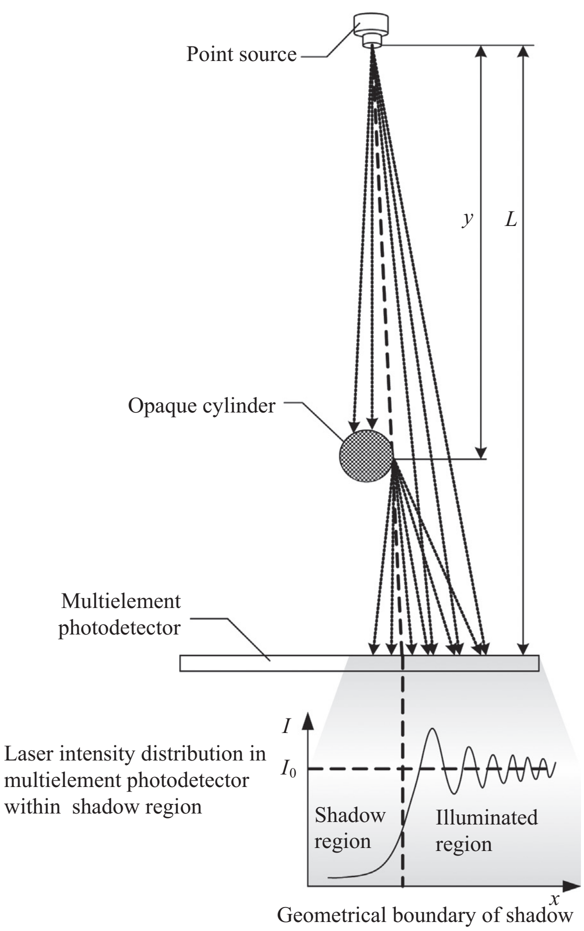

Fig. 2. Fresnel diffraction at the boundary of opaque cylinder: I_0 is the initial illumination; L is the distance between the point source and the multielement photodetector; y is the distance between the point source and opaque cylinder.

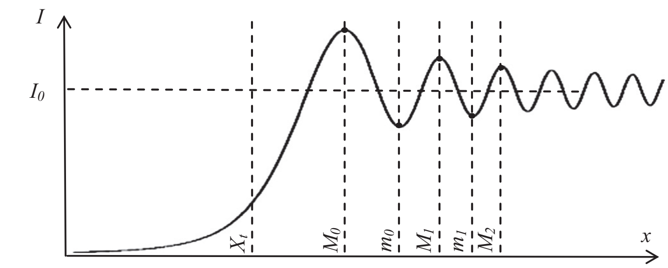

Fig. 3. Diffraction extremum distribution in the vicinity of geometrical boundary: X_t is the geometrical boundary of shadow; M_0, M_1, M_2 are the minima of the first, second and third orders, respectively; m_0, m_1 are the minima of the first and second orders, respectively.

Fig. 3 allows the study of diffraction extremum distribution in the vicinity of geometrical boundary. In case the shadow boundary is projected orthogonally to the photodetector plane, the distance X_i from the point X_t to its respective maximum M_i and the distance x_i from the same point X_t to its respective minimum m_i are defined by formulas

$$X_i = \sqrt{\frac{\lambda L(L-y)}{2y}\left(4i+\frac{3}{2}\right)},\ x_i = \sqrt{\frac{\lambda L(L-y)}{2y}\left(4i+\frac{7}{2}\right)}, \quad (1)$$

where i is the number of the respective maximum or minimum starting from zero; λ is the wavelength of the point source (Fig. 3).

A position of the boundary X_t on the multielement photodetector is the original value for the calculation of diameter using method presented in [3]. Having determined the distance between the first two maxima (interval M_0M_1) or minima (interval m_0m_1) shown in Fig. 3, the boundary X_t can be found. Since factor $\sqrt{\lambda L(L-y)/2y}$ in Eq. (1) is fixed for all extreme values, distribution of these values will then be defined by factors $\sqrt{4i+3/2}$ and $\sqrt{4i+7/2}$ for maxima and minima, respectively. Thus, the distance between the extreme values can change proportionally depending on parameters of L and y, however, correlation between them is being constant. In particular, the interval X_tM_0 correlates with the interval M_0M_1 with fixed coefficient 1.093, while a correlation between intervals X_tm_0 and m_0m_1 equals 2.154. Thus, the formulas below can be derived to find coordinates of geometrical boundaries of rising and falling edges:

$$X_{ft} = 1.093(M_0-M_1)+M_0 = 2.154(m_0-m_1)+m_0$$
$$X_{st} = M_0-1.093(M_1-M_0) = m_0-2.154(m_1-m_0), \quad (2)$$

where X_{ft} and X_{st} are positions of geometrical boundaries of rising and falling edges; M_0, M_1, m_0, m_1 are the extreme values of diffraction distribution.

3. Experimental

3.1. Measurement setup

The test installation was designed to conduct the experiment. The block diagram of the test installation is shown in Fig. 4, and its implementation in Fig. 5.

The angle measurement was provided by the mechanical dial with 1′ angle-error detection. In the centre of the mechanical dial a board with the multielement photodetector was fixed. The cylindrical object ~4 mm diameter was also mounted in the centre