Optics Communications 312 (2014) 110–116

Contents lists available at ScienceDirect

Optics Communications

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

Distortion correction in surface defects evaluating system of large fine optics

Shitong Wang, Dong Liu*, Yongying Yang, Xiaoyu Chen, Pin Cao, Lu Li, Lu Yan, Zhongtao Cheng, Yibing Shen

State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 22 August 2013
Accepted 29 August 2013
Available online 14 September 2013

Keywords:
Optical inspection
Image processing
Computer vision
Calibration

ABSTRACT

It is challenging to quantitate micron-scale defects on the surface of large optics. Based on microscopic scattering dark-field imaging, sub-aperture scanning and stitching, the Surface Defects Evaluating System (SDES) can spot and measure scratch and digs on large optics. In order to evaluate defects of down to sub-micron over apertures of hundreds of millimeters, high magnification zoom microscope and large format CCD camera are employed to balance between the efficiency and resolution. Unfortunately, large optical distortion in the sub-aperture images can be found, and feature recognition of defect images as well as mismatches of the sub-apertures stitching are greatly affected. In this paper, a distortion correction procedure based on the Brown–Conrady model is proposed. Grayscale surface fitting and bilinear interpolation techniques are employed to obtain better correction accuracy. A grids-patterned fused silica standard plate has been specifically made to calibrate the distortion. Comparison experiments indicate that the distortion in the SDES can be corrected by the proposed method very well.

1. Introduction

The lens application drives the requirements for surface irregularity and surface quality. Roughness, waviness and defects are all important parameters to characterize optical surfaces. Unlike the other two, which are usually distributed over the whole surface, defects (such as scratches, digs, bubbles and inclusions) usually exist arbitrarily. Currently, the visual comparison method, which is subjective, ambiguous and non-quantitative, is still employed to control surface imperfections by most optics manufacturers. Scanning Electron Microscopes (SEMs) and Atomic Force Microscopes (AFMs) are not considered because of their limited FOV (field-of-view) and low efficiency for large surface imperfection testing. Especially, the optical components used for Inertial Confinement Fusion (ICF) can be of hundreds of millimeters square, it is challenging to precisely characterize the size and position of the defects of micron over the whole aperture [1].

Laser MegaJoule (LMJ), the French ICF project, employs a high resolution 45-Mpixels CCD camera with an LED arrays edge-illuminating frame. The minimum detectable defects are of a few microns [2]. The Final Optics Damage Inspection (FODI) system is developed for the National Ignition Facility (NIF). FODI employs bright-field back illumination, dark-field back illumination and edge illumination. An optical telescope with megapixel camera tracks and records defects images. FODI can guarantee to verify defects of over 50 μm with 99% confidence [3].

Based on microscopic scattering dark-field imaging method, the Surface Defects Evaluation System (referred as "SDES" in the following of this paper) can distinguish surface defects as small as 0.5 μm [4–7]. Sub-aperture sampling and stitching are employed to collect the images of the micro defects on large aperture optical surfaces. To balance between efficiency and precision, zoom microscope and large format CCD camera are used. Along with the powerful digital image processing program, it takes about 1 h to evaluate the surface defects over a large optical component of 800 mm × 450 mm.

Nevertheless, there exists distortion in the SDES, which is mainly caused by the zoom microscope. The zoom microscope consists of several lenses, and zooming is implemented by the motion of one lens. During the movement, it is likely to introduce misalignments and tilts between the lenses. On the occasion of precise measurement, a tiny misalignment or tilt will cause fairly large distortion in the sub-aperture images. In the SDES, distortion would lead to the measuring errors in character recognition process and the mismatches between the two adjacent sub-aperture images. Therefore, it is necessary to correct distortion before image stitching and further processing.

Based on the Brown–Conrady model, a multi-step sub-image distortion correction procedure is proposed in this paper to solve the above drawbacks. In this procedure, a few pairs of corresponding points are firstly chosen from both single sub-aperture undistorted image (produced by computer simulation) and distorted image (captured by the SDES). The coordinates of these points are calibrated by working out the extreme point of the fitted grayscale surface. In this way, the coordinates can be as

* Corresponding author. Tel./fax: +86 571 8795154.
E-mail address: liudongopt@zju.edu.cn (D. Liu).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.08.083

precise as in sub-pixels. The distortion model is built by using the above coordinates of point-pair and then solving the coefficients of radial, tangential and prism distortion terms. Eventually, a bilinear interpolation method is applied to calculate grayscale for those non-integral pixels after correction. Experiments indicate that the method proposed is significant in reducing distortion in single sub-aperture image, which is accompanied by the well match of neighboring sub-aperture images. The method in this paper is very suitable for full-aperture defects detection of large optics.

The content of this paper is constructed as below: Section 2 gives a brief introduction to the SDES and the existing problems with optical distortion; the distortion correction procedure and theoretical model of each step will be illustrated in detail in Section 3; the results of distortion correction are shown in Section 4, and some analyses are made as well; in Section 5, conclusions will be summarized.

2. Distortion in the SDES

2.1. System layout

A brief review on the SDES is presented here and more information can be found in Ref. [5]. The SDES has been set up

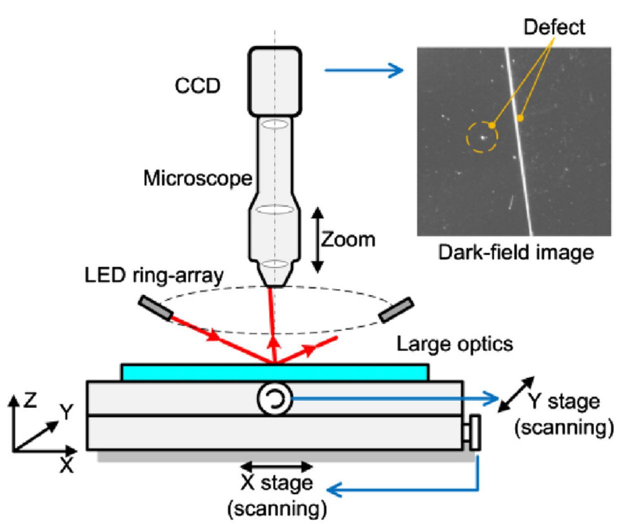

Fig. 1. Schematic of Surface Defects Detecting System and dark field image of defects.

as shown in Fig. 1. Odd numbered collimated beams emitted by LED ring-array converge to produce uniform illumination. The perfect surface would reflect the incident light to the other side, while defects would scatter the incident light into the microscope to image on the CCD camera. A typical dark-field image is shown in the upper right corner of Fig. 1. Defects create bright features and patterns, whereas the zero-defect area forms the uniform dark background.

Limited by the FOV of the microscope, it is impractical to capture all the defects on the whole optical surface of hundreds of millimeters at one time. Sub-aperture scanning is considered to be a direct solution. In order to precisely quantitate defect of sub-micron, microscope is required to work at about 16 × magnification. However, even mounted with 1.2″ CCD camera, the FOV at 16 × is just 0.90 mm × 0.90 mm. Both the testing time and image data volume are unacceptable. For instance, it takes more than 10^4 sub-apertures, i.e. 40 gigabytes amount of sub-images, to cover a surface of 100 mm × 100 mm. To improve efficiency without loss of accuracy, the SDES has two operating modes: *mapping mode* and *evaluating mode*. In the mapping mode, the microscope works at fairly low magnification (1 × ~4 ×), and the *XY* two-axis stages hold the test optics and move in a zigzag path to achieve sub-aperture scanning, as illustrated in Fig. 2(a). The largest FOV is 15 mm × 15 mm (1 ×), which dramatically decreases the total number of sub-aperture images and thus enhances inspection efficiency. In this mode, the mapping and longitude information of defects are extracted by stitching and processing all the sub-images. Then the SDES operates at the evaluating mode: the microscope switches to high magnification (16 ×), and the *XY* stages position at each coordinates of the defects obtained by the mapping mode in an optimized path (Fig. 2(b)). The SDES observes each defect successively, and makes an analytical summary of width and other characteristic information. The two-mode testing procedure guarantees both the efficiency and precision. In this way, the SDES is able to locate, classify and evaluate all sub-micron-scale defects on the entire optical surface with the largest aperture of 850 mm × 550 mm.

2.2. Distortion in SDES and its consequences

The ideal imaging system has exactly the same magnification for both on-axis and off-axis imaging, and therefore straight lines are rendered as straight, no matter where they occur. Distortion, which is caused by radial curvature and malposition (misalignments and tilts), exists in most practical lenses. Especially,

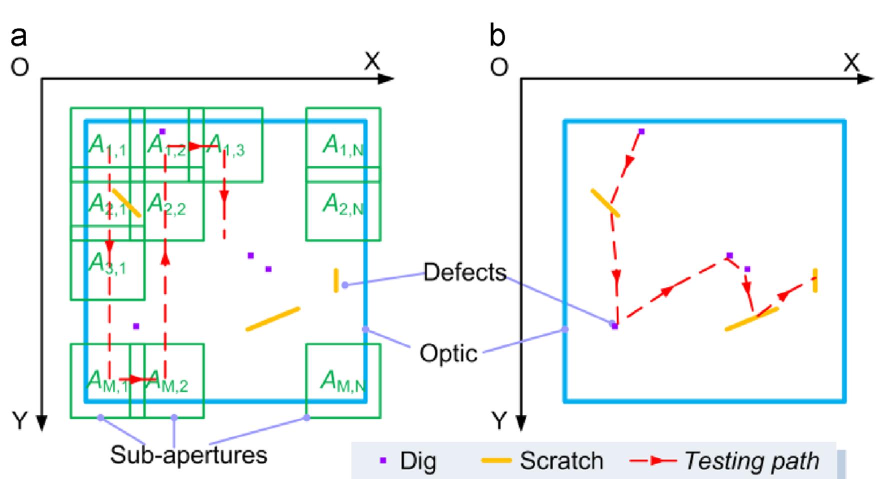

Fig. 2. Two working mode of the SDES, (a) mapping mode, the SDES scan the optical surface in a zigzag path at low magnification; (b) evaluating mode, the SDES successively collects images of each defect in the optimized path at high magnification.