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Surface defects evaluation system based on electromagnetic model simulation and inverse-recognition calibration method

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ABSTRACT

Digitized evaluation of micro sparse defects on large fine optical surfaces is one of the challenges in the field of optical manufacturing and inspection. The surface defects evaluation system (SDES) for large fine optical surfaces is developed based on our previously reported work. In this paper, the electromagnetic simulation model based on Finite-Difference Time-Domain (FDTD) for vector diffraction theory is firstly established to study the law of microscopic scattering dark-field imaging. Given the aberration in actual optical systems, point spread function (PSF) approximated by a Gaussian function is introduced in the extrapolation from the near field to the far field and the scatter intensity distribution in the image plane is deduced. Analysis shows that both diffraction-broadening imaging and geometrical imaging should be considered in precise size evaluation of defects. Thus, a novel inverse-recognition calibration method is put forward to avoid confusion caused by diffraction-broadening effect. The evaluation method is applied to quantitative evaluation of defects information. The evaluation results of samples of many materials by SDES are compared with those by OLYMPUS microscope to verify the micron-scale resolution and precision. The established system has been applied to inspect defects on large fine optical surfaces and can achieve defects inspection of surfaces as large as 850 mm×500 mm with the resolution of 0.5 μm.

1. Introduction

Recent years, the demand for large fine optical surface quality has been increasing in many fields, especially in optical and electronic domain. Tens of thousands of optics in the Inertial Confinement Fusion (ICF) system, various laser resonators in high energy laser system, silicon substrates in the Large Scale Integrated (LSI) circuit, the surface quality of all these optics impacts the operation of the related systems directly [1–3]. As is known, there are three important parameters in the precise evaluation of surface quality, figure, roughness and defects. Surface figure and roughness are of uniform distribution and can be measured by sampling. By now, they can be digitally evaluated and controlled with commercial digital wavefront interferometers and white light interference profilers, respectively. Surface figure measurement with wavefront interferometer can detect the low frequency information of the tested surface with a lateral resolution of submillimeter, while roughness detection with white light interference profiler can acquire the high frequency information of the microscopic profile with a lateral resolution of microns. But micro sparse defects, like scratches and digs of various sizes and shapes generated in optical fabrication process, are still challenging to be evaluated digitally, because it is different in defects evaluation that defects are of random distribution so that the whole surface should be detected. Since the widths of the scratches are of microns while the tested surfaces are usually of hundreds of millimeters, it is almost impossible to evaluate micron-scale defects on such a large surface in one single image. What's more, common microscopes are not practical for defects inspection either because of the contradiction between the magnification and the field of view (FOV). Micron-scale defects inspection needs large magnification, resulting in millimeter-scale FOV, so several thousand frames of images have to be captured to detect large optics, inevitably leading to low efficiency and data processing difficulty in terms of quantification and positioning, which is by now an challenge in digitized evaluation of surface defects.

To our knowledge, the reported methods for defects evaluation mainly include visual inspection [4], low-pass or high-pass filter imaging [5], self-adaptive filter imaging [6], angular spectrum analysis [7], etc. However, most of these methods are only feasible in the principle, not efficient or practical enough for actual application due to the small FOV and difficulty in the digital evaluation. For example, in the National Ignition Facility (NIF) system [8], the world's largest laser fusion system so far, the defects inspection is based on total internal

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reflection (TIR): the tested optics are illuminated by fibers around the edges, the lights are coupled into the optics and a mega-pixel camera collects the scatter lights induced by the surface defects, thus the bright image on dark background is recorded. Since only one image is captured for a tested optic, the resolution is about 5 μm [9]. The Laser Megajoule (LMJ) system in France [10,11] also adopts the TIR principle: the component is illuminated by an edge-illuminating frame that includes visible LED arrays and scatter light is induced by inner impurities, then a high resolution 45-Mpixels CCD is employed to capture a complete image of the tested component, and the resolution is about 10 μm [2]. In Inertial Confinement Fusion (ICF) in China [12], there is also a similar defects inspection system, but the resolution is not high enough for the quality control, instead, visual inspection is still the major way. Because of the high erroneous judgement rate introduced by individual experience and subjectivity, the poor quality control greatly constrains the ability of optics to resist intense laser.

An integrated surface defects evaluation system (SDES) is developed in this paper. A microscopic scattering dark-field imaging (MS-DFI) system [13] has been proposed and some relevant issues, such as scanning and stitching method [14], distortion correction [15] and automated discrimination between digs and dust particles [16] have been studied in our previous work. In this paper, a microscopic scattering dark-field imaging electromagnetic simulation model, which provides theoretical basis for defects evaluation is established on the basis of FDTD method and PSF is introduced in the model considering the aberration in actual optical systems. From the analysis of both simulation results and experiment results, it is found that defect size in the image plane could be the consequence of diffraction-broadening imaging or geometrical imaging. In order to effectively solve the confusion problem introduced by diffraction-broadening effect, a novel inverse-recognition calibration method is proposed, on the basis of which the defects evaluation method of SDES is performed. Defects are positioned at low magnification while evaluated at high magnification, which balances the inspection precision and efficiency. SDES can inspect various kinds of defects like scratches, digs, stains and dusts on smooth surfaces of multiple kinds of optics and metals and output electronic report of defects information. This system is able to achieve high resolution (the minimum size that can be detected and evaluated can reach 0.5 μm), high speed and digitized quantitative inspection.

2. Microscopic scattering dark-field imaging electromagnetic simulation model

All optical inspection systems depend on scatter light from the inspected object. Compared with bright-field imaging method, smaller defects can be detected by dark-field imaging method [17]. Besides, dark-field images of bright defects against dark background usually have high contrast, suitable for digital image processing. Therefore, microscopic scattering dark-field imaging method is adopted for purpose of micron-scale resolution. Taking advantages of FDTD method [18] based on vector diffraction theory, the electromagnetic simulation model for the microscopic scattering dark-field imaging of micro surface defects is built in this section.Fig. 1(a) illustrates dark-field configuration to image micro defects. Incident lights, which are parallel and in annular distribution, irradiate on the component surface at angle α with surface normal. If the surface is smooth, the reflected light cannot enter the optical imaging system according to light reflection principle and totally dark images will be got. If there are defects on the surface, light scattered by the defects within the range of θ_{NA} angle can be captured by the CCD of imaging system, and bright defect images on dark background, namely dark-field images, can be got.The simulation model established according to Fig. 1(a) is implemented with the geometry shown in Fig. 1(b) using a high performance 3D Maxwell solver [19a]. There are two kinds of media, the air and the medium with a refractive index n and the topographic features in the boundary between the two media are introduced as defects. The total-field scattered-field (TFSF) sources available in the software package [19b], symmetrically irradiating the surface at angle α and $-\alpha$, are employed to separate the simulation area into scattered-field zone (dashed line area) and total-field zone (gray solid line area) which includes the sum of the incident field, the reflected field and the scattered field. The total-field (TF) monitor and the scattered-field (SF) monitor (both indicated by green lines) are located in the upper region of both zones. TF monitor records the incident field, reflected field and scattered field, while SF monitor only records the scattered field. If E_i, E_r, E_s represents the electric field distribution of incident light, reflected light and scatter light and the magnetic field is represented similarly, the total electric field E and the total magnetic field H satisfy the following relations, Since the light intensity is proportional to the square of the electric field, it is the electric field the one that is mainly discussed below.

$$\begin{cases} E = E_i + E_r + E_s \\ H = H_i + H_r + H_s \end{cases} \tag{1}$$

Since only the electromagnetic field in the near field can be calculated with FDTD method, intensity distributions after an optical system with a given NA in the far field are simulated by post-processing the near-field data with the help of built-in scripting language of this Maxwell solver. A simplified ideal imaging system includes at least an aperture, an equivalent lens and an image plane. According to the angular spectrum theory [20], near-field scatter electric field distribution obtained from the SF monitor can be decomposed into a series of plane waves, which propagate at different angles θ_i, $i = 1, 2, \ldots, k$. There are two transformations when plane waves pass through lens. One is the influence of the magnification, the other is the aperture filtering. Numerical Aperture (NA) limits the finest details that can be resolved. To some extent, an aperture in the system limits the angles of light that can travel through the lens system to create the final image. The filtering can be expressed by an aperture function T as follows. For a beam of plane wave propagating at a certain angle θ_i, the electric field components of the scattering field in Cartesian coordinate system are $E_{x,i}$, $E_{y,i}$, $E_{z,i}$ before filtering and become $E'_{x,i}$, $E'_{y,i}$, $E'_{z,i}$ after filtering. They satisfy the following relations,

$$\begin{aligned} E'_{x,i} &= E_{x,i}T \\ E'_{y,i} &= E_{y,i}T \\ E'_{z,i} &= E_{z,i}T \end{aligned} \tag{2}$$

where the aperture function T is expressed as

$$T = \begin{Bmatrix} 1, & \sin\theta_i \le NA \\ 0, & \sin\theta_i > NA \end{Bmatrix} \tag{3}$$

In Eq. (3), θ_i are the incident aperture angles of the decomposed plane waves. After filtering, implemented by built-in functions of the high performance 3D Maxwell solver employed, the imaging process is equal to performing Fourier transform on the electric field components in the plane of SF monitor [21]. The electric field components in the far-field image plane are,

$$\begin{aligned} E_{x\,image,i} &= cF(E'_{x,i}) \\ E_{y\,image,i} &= cF(E'_{y,i}) \\ E_{z\,image,i} &= cF(E'_{z,i}) \end{aligned} \tag{4}$$

where, c is a constant, and $F()$ stands for the Fourier transform. The scatter light intensity in the image plane I_{FDTD} can be considered as the sum of the square of three Cartesian electric field components.

$$I_{FDTD} = E_{x\,image}^2 + E_{y\,image}^2 + E_{z\,image}^2 \tag{5}$$

where $E_{x\,image}$, $E_{y\,image}$, $E_{z\,image}$ are the Cartesian components of the total electric field in the image plane which result, respectively, from the sum of the filtered angular spectral components $E_{x\,image,i}$, $E_{y\,image,i}$, $E_{z\,image,i}$ given by Eq. (4).

The above transformation takes no aberration into consideration,